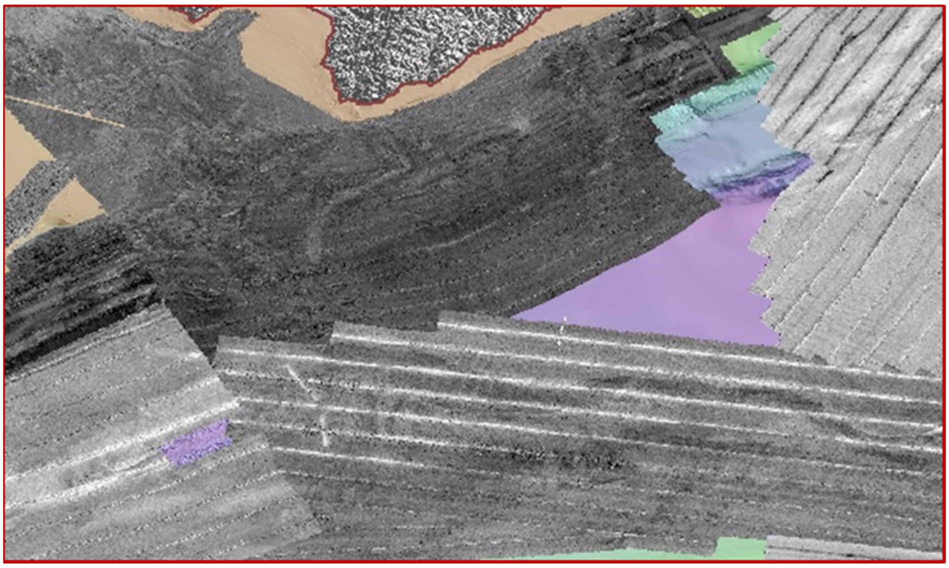
Backscatter measurements by seafloor-mapping sonars

Guidelines and Recommendations

A collective report by members of the
GeoHab Backscatter Working Group



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Cover image

Multiple backscatter data in Cook Strait, New Zealand, collected by *R/V Tangaroa* (NIWA).

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Foreword

In 2009 and 2014, the attention of the world was focused on the tragic losses of Air France Flight 447 in the South Atlantic and Malaysian Air Flight 370 in the Indian Ocean. Vessels and aircraft scoured the areas towing passive hydrophones and dropping sonobuoys seeking a simple return from the location pingers attached to the black boxes of the aircraft. Failing to locate the pingers, massive sonar searches were then started, mapping tens of thousands of kilometers of deep seafloor, trying to detect the wreckage from high-resolution sidescan images recorded from surface ships and towed vehicles. While the AF 447 wreck was finally discovered, still no trace of MH 370 has been found. These tragic events emphasize the vastness and complexity of the deep seafloor and epitomize the fundamental role that sound plays in the sea and the historic roots that measurements of seafloor backscatter have had in ocean exploration.

While the earliest use of sonar in the sea was for simple echo-ranging, the need to locate and image objects on the seafloor led, mostly in the post-WW II era, to the development of side-scan sonar imagery systems. Improvements in transducer materials and array design offered the ability to transmit a narrow (in the along-track direction), fan-shaped pulse across a relatively wide (dependent on frequency) swath of sea floor. Constrained in early days to analog electronics and paper recorders, early side-scan sonar systems produced a simple amplitude-modulated image of the strength of the acoustic return as a function of travel time across the insonified swath of seafloor, transformed into a geometrical “sonar image” by assuming a flat seafloor. These early records were uncalibrated, though typically compensated for geometric spreading losses. While often difficult to interpret in terms of the nature of the seafloor, the geometry of the side-scan when deployed near the bottom cast shadows that proved extremely useful in the identification of small (e.g. mines) or large (e.g. wrecks) objects and other natural or manmade structures that stood proud of the surrounding seafloor. This concept of a “shadowgraph” was used very effectively for many years to identify objects in mine-hunting sonars (Fish and Carr, 2001) and the use of shadows for the identification of natural and man-made targets in side-scan sonar records has persevered to today.

The high-frequencies (200 kHz to 1.4 MHz) used to achieve the resolution necessary for small object detection, limited the range of coverage available to these sonar systems and thus when there was a need to search for objects in the deep sea (e.g. the U.S. nuclear submarine *Thresher* in 1963 or the hydrogen bomb lost off Spain in 1966), deeply towed side-scan sonars were developed (Spiess, 1980; Tyce, 1986). Lower frequency (12 kHz or less) towed side-scan sonars were also developed providing broad, but low-resolution coverage for regional deep-sea geological studies and allowing the identification and mapping of large-scale (e.g. ridge crests, seamounts, fracture zones, channels) geologic structures and processes (Rusby and Somers, 1977; Kasalos and Chayes, 1983).

With advances in transducer design, digital electronics, signal processing capabilities, navigation, and graphic display devices, the resolution and particularly the dynamic range available to sonar and processing software manufacturers greatly improved. These improvements led to higher resolution displays and the ability to more appropriately compensate the backscatter imagery produced by side-scan sonar for geometric distortions as well as the production of sonar mosaics – composite georeferenced images of the backscatter, typically normalized to a single angle (e.g. 45°). The resulting acoustic images began to offer a more realistic and more consistent picture of the seafloor leading to a rapid expansion of the applications of backscatter imagery for many geologic, engineering and environmental studies where information about the nature of the seafloor was required. The relationship between backscatter and seafloor type derived from these systems often depended on many "ground-truth" samples and years of user experience relating the returns from a particular system to the ground-truth samples. At best these studies were qualitative as the backscatter returned from these systems was uncalibrated with respect to output or received levels (either relatively or absolutely) and assumed a flat seafloor (thus not compensating for the angular dependence of backscatter). Despite these limitations, many valuable conclusions could still be drawn from major changes in average backscatter levels and the ability to manually separate regions of differing image texture. Focusing on a textural analysis of the returned backscatter image, more quantitative image-processing techniques began to be applied to the returned acoustic images (e.g., Reed and Hussong, 1989) segmenting the acoustic returns based on inter-pixel statistics and relating these segments to areas of differing geologic character or process.

Concomitant with the improvements described above were several significant technological advances that have dramatically changed the nature of seafloor mapping. The use of multiple rows of side-scan sonar transducers and interferometric or phase-measuring processing (Blackington et al., 1983) allowed bathymetry to be measured along with backscatter and thus obviated the need to assume a flat seafloor when interpreting seafloor backscatter. Even more importantly, multibeam echosounders (MBES) became generally available (Renard and Allenou, 1979; Farr, 1980). Multibeam echosounders transmitted with the same geometry as a side-scan sonar but received the seafloor backscatter return on a series of narrow (in the across-track direction) formed beams and thus allowed the determination of both depth across the swath (at the resolution of the receive beam spacing) and the recording of the backscatter time series at known angles across the swath (again at the resolution of the receive beam spacing).

With the introduction of multibeam sonar and the ability to measure backscatter as a function of true angle of insonification across the seafloor came a new recognition of the *potential* to use backscatter measurements as a means to remotely characterize the properties of the seafloor. An improved theoretical understanding of the interaction of sound with the seafloor (well summarized in Jackson and Richardson, 2007) indicated the angular dependence of backscatter as a key parameter in identifying seafloor type and opened the door to more quantitative analyses of multibeam sonar backscatter (e.g., Hughes Clarke et al., 1997; Fonseca and Mayer, 2007; Lurton et al., 2008). Further improvements in the capabilities of the sonars including improved motion compensation, greater spatial and angular resolution and most importantly, increased bandwidth have now set the stage for truly addressing the potential of quantitative analysis of backscatter for seafloor characterization and its broad range of military, geologic, engineering and environmental applications. The stage is set, but the production is not complete until we have fully resolved the challenge of robust seafloor characterization. To achieve this, we must do all we can to ensure that we fully understand the nature of the data produced by our sensing systems and how these data have been modified through the acquisition and processing streams. It is this over-arching concern – the desire to better understand and quantify the characteristics (e.g., frequency, source levels, beam angles and patterns, response to gain changes, etc.) of the backscatter data collected by the range of sensors available to the community, as well as to understand corrections applied to these data (e.g., angular dependence, absorption and spreading losses, area insonified, etc.) so that we can strive to derive consistent, comparable, and perhaps even calibrated backscatter data that are representative of changes in the nature of the seafloor rather than an instrumental or processing artifacts, that forms the context of this report. The report is also driven by a desire to ensure the growing community that uses and appreciates the broad applications of quantitative backscatter and seafloor characterization, also fully understands the limitations and constraints of our current technologies. With these purposes in mind, we hope to set the scene for enhanced and appropriate use of seafloor backscatter data and for a next generation of research efforts that will bring us even closer to our ultimate goal of robust and quantitative remote seafloor characterization.

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CHAPTER 1 INTRODUCTION TO BACKSCATTER MEASUREMENTS BY SEAFLOOR-MAPPING SONARS

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1.1 Background and objective of the report

Marine scientists have long recognized the potential of using remotely-sensed data as a proxy of biophysical indicators. Such data are most often acquired using sonar systems, since acoustic waves are the most suitable mechanism for transmitting information through the water column. Research and development that look at using marine acoustics for environmental science spans the entire spectrum from fundamental science to engineering. One research group that supported and encouraged this line of research is the **GeoHab** group, an international association of scientists focusing on marine **Geo**logical and biological **Hab**itat mapping (see http://geohab.org/). GeoHab started in 2001 as a group of research scientists gathered to discuss potential and advances of using remotely-sensed data to develop quantitative study on the relationships between seafloor substrate and benthic ecosystems.

In 2013, QPS (www.qps.nl) organized a parallel event at the GeoHab annual meeting (Heffron et al., 2013) in Rome on "Multibeam Backscatter – State of the Technology, Tools & Techniques". It is during this workshop, attended by about 100 participants, that the need for a compendium on backscatter acquisition, processing and interpretation came up. The ***Backscatter Working Group*** (BSWG) was created in the wake of the workshop and a first draft of the guidelines and recommendations was presented one year later at the 2014 GeoHab meeting (Ierodiaconou, 2014) in Lorne, Victoria, Australia and led to its release at the 2015 GeoHab conference in Salvador, Brazil.

The founding ideas of the BSWG originate from the discussions (see http://tinyurl.com/geohab2013workshop) that happened at the QPS workshop. These discussions identified a patent lack of commonly accepted acquisition procedures and processing methodologies of backscatter data recorded with **multibeam echosounders** (MBES) commonly used for seafloor surveys. Similarly, gaps in the documentation and literature pertinent to backscatter theory and applied operations were recognized. Concerning the acquisition procedures, it was found that a lack of consistency between the backscatter acquisition systems proposed by various manufacturers had never been addressed, and was widening because of the rapidly evolving development; the same issue is valid, too, for successive generations of sonars built by one same manufacturer, or the performance continuity of one same system along its life cycle. This lack of consistency (typically imaged in Figure 1-1) was regarded as an obvious hindrance to the progress of backscatter science that all participants agreed was possible.

The vision of the working group can be worded thus: *"Backscatter data acquired from differing sonar systems, or processed through differing software tools, generate consistent values over a same area under the same conditions; these data are scientifically meaningful and usable by end-users from all application domains (geoscience, environment, hydrography, industry, fisheries, monitoring, cultural…)"*.

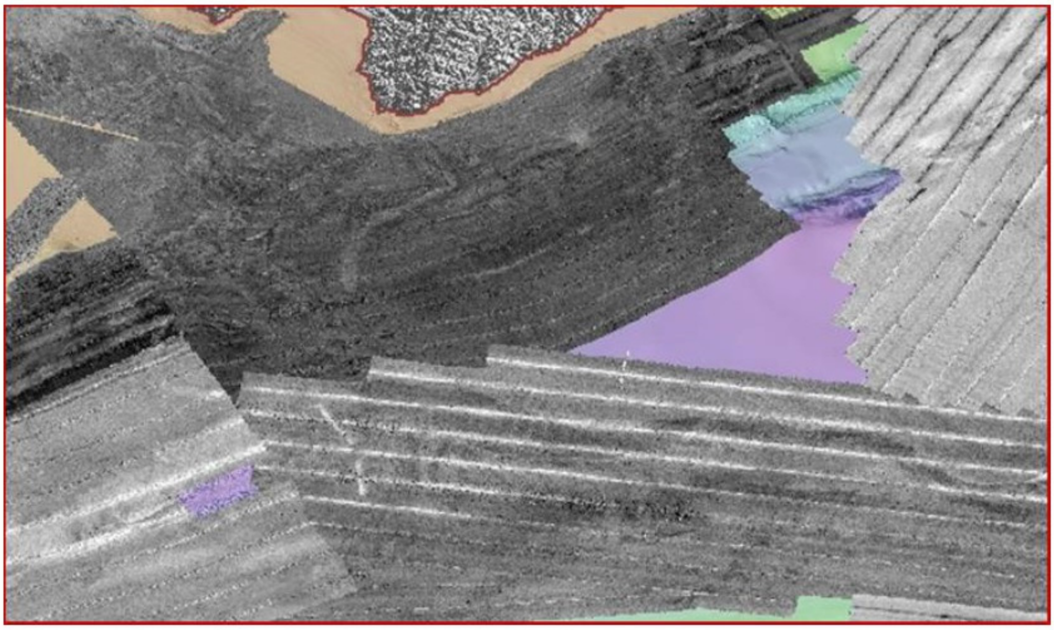

Figure 1-1 Example of multiple backscatter surveys collected in the same area during different survey cruises using the same MBES (Cook Strait, NZ; the sonar was the EM 300 on R/V Tangaroa). This figure illustrates the discrepancy between the reflectivity by one same MBES along the years. Regardless of the equipment used and the post-processing sequence applied, the overlapping regions should produce a similar image, which is obviously not the case here.

With this in mind, the aim of the BSWG and of the report presented here is twofold: (1) agree on, and provide, guidelines and best practice approaches for the acquisition and processing of backscatter data from seafloor-mapping sonars; and (2) provide recommendations for the improvement and further development of seafloor-mapping sonar systems for acquisition of backscatter data and related processing tools.

Three primary themes have emerged during the initial discussions and are addressed and discussed in the document:

1. **Sonar hardware manufacturing** issues, including interactions between users and manufacturers, sonar configuration and related instrument uncertainty levels and best practices for sonar configuration focusing on backscatter data collection;
2. **Data acquisition** issues and protocols, including best configuration, survey purpose and strategy, as well as best practice for backscatter acquisition;
3. **Post-processing approaches**, for a variety of use and purpose.

More specifically, the group felt that the following goals should be addressed in detail in this document:

- Propose **common terminology and definitions,** agreed upon by the authors of the document, applicable to the physical phenomena, to the processing operations, and to the data at their various stages of elaboration;

- Summarize **useful fundamental notions at an affordable level** for many users, about physical phenomena or sonar engineering;
- Review the **needs expressed by users** from various fields, and their associated technical requirements regarding both the **sonar systems** and the **processing software suites**;
- Illustrate the potential of backscatter data for mapping substrate and habitats;
- Provide a series of **recommendations for sonar manufacturers and software developers** for future development as well as for users and operators for best acquisition procedure and post-processing approaches;

Indeed, proposing recommendations and guidelines for best use of any technologies needs to be robustly justified and explained.

The BSWG is open to all. At the time of publishing more than 120 users and stakeholders with direct or indirect interests in seafloor mapping had registered and expressed an interest in the group, either to actively participate in the discussion and generation of this present document, or in following and benefiting from its progress. This document is indeed addressed to them and their pairs, including, but not limited to:

- **Hardware engineers** involved in the manufacturing of seafloor-mapping sonars and more specifically multibeam echosounders;
- **Software developers** with interest in processing and post-processing of backscatter data;
- **Surveyors** and equipment operators, as well as program managers;
- **Marine scientists** with interests ranging from environment science (geoscience, biology) to underwater acoustics.

1.2 Limitations

This report specifically **focuses on seafloor backscatter processes**, as it is a traditional domain of investigation for the GeoHab group and the various communities using seafloor-mapping sonars. The direct corollary is that this document does not address the particularity of water column backscatter, even though this area of research is developing rapidly and with much potential for application. Whilst some GeoHab members advocated in favor of including water column backscatter in this document, it was felt that water column backscatter is technically a newer topic, still under development. The issue was widely discussed, and while the interest of an extension to the water column techniques was acknowledged, it was eventually decided, for a number of practical reasons and to avoid redundancy with current initiatives undertaken by other communities (Demer, in prep), that the report should be limited to the seafloor interface issues.

Practically, the only sonar systems considered here are the **swath bathymetry systems**, primarily designed for measuring sounding points at oblique angles over a wide stripe of seafloor. These are in majority multibeam echosounders; however a number of PMBS (Phase Measuring Bathymetry Systems), based on a somehow similar design, can be included in the same category. The work does not address other sonar systems of interest in seafloor surveys, such as side-scan sonars (usually unable to provide bathymetry measurements), single-beam echosounders (only receiving vertical echoes) and sub-bottom profilers (designed for imaging the buried sediment layers).

This report does not address either the final stages in backscatter data environmental studies, such as data segmentation, the process of partitioning a dataset in clusters of contiguous and similar pixels (Lamarche et al., 2014), and classification, where segments are grouped into homogeneous subsets of objects (e.g. Lucieer and Lucieer, 2009). Since backscatter data is well suited to segmentation and classification, and is an accepted proxy for substrate or habitat it bodes well to habitat mapping studies. However, data segmentation and classification are methods that are still developing, involving statistical and environmental considerations outside the scope of this report and that are, arguably, not well-adapted yet to formulating common rules of best-practice.

1.3 Basic concepts

The remote observation of the inner oceans relies widely on the use of underwater acoustics; and in particular seafloor mapping implies the generalized design and operation of specialized sonar systems (Lurton, 2010, Chapter 8). Along the years, the technology available has evolved (Figure 1-2) from single-beam echosounders (measuring one sounding point vertically under a ship or an underwater vehicle) to sidescan sonars (towed at a low altitude above the seafloor and recording "acoustic images" of the interface details at shallow grazing angles) and to multibeam echosounders (scanning the seafloor interface though a high number of narrow beams covering a wide swath across the ship's route) which are prevalent today in mapping operations.

These various seafloor-mapping sonars rely on one same physical phenomenon: **backscatter** of the sound wave by the seafloor interface; or in other words, the generation, by the target-seafloor, of a return wave as an echo to the incident signal sent by the sonar. The reflective quality of the seafloor is something very intuitive, more or less associated with the optical character of an object relative to an incident light; or, a better analogy in our case of *mechanical* acoustic waves, with the behavior of a ball bouncing on the floor – indeed everyone instinctively expects a rock seafloor to send back more energy (and randomly!) than a sand bank, which is itself more reflective than a soft mud area… This **backscatter strength** associated to the type of seafloor has been used implicitly for years in the design and operation of sonars: highly reflective seafloors have been known as detectable from further by a sonar, while being also prone to generate more parasitic echoes than softer sediments. Progressively the idea emerged that reflectivity could be as well an ***observable*** by itself, since it provides information pertinent to the nature and the structure of the target.

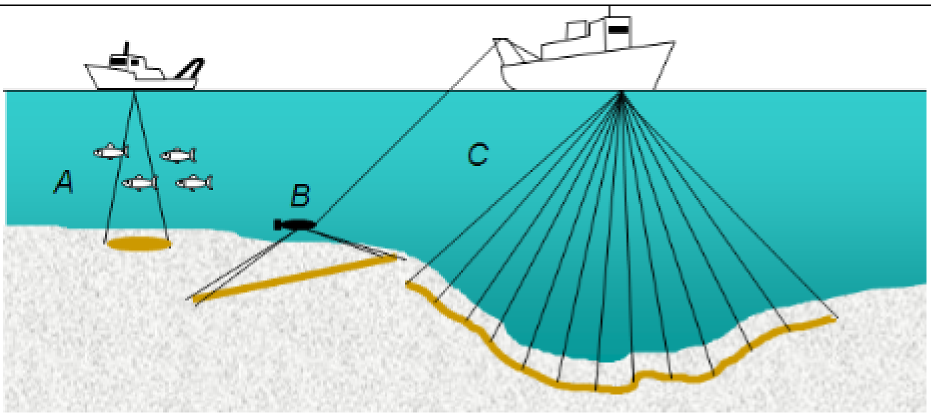

Figure 1-2 Schematic representation of the three main types of seafloor-mapping sonars (A: single-beam echosounder; B: sidescan sonar; C: multibeam echosounder).

A strong point of seafloor-mapping sonars is that they are intrinsically able to record the two types of information (target geometry and reflectivity - Figure 1-3) altogether in an ideally compatible way, since one same echo signal can be used for both purposes! However, it took years for the two functionalities to be usable at the same level of quality – and there is still some ongoing progress… Nevertheless, and without being over-optimistic, there is a widely accepted agreement today that sonar systems used for seafloor mapping (which by the way is potentially true for any type of active sonar system) can usefully provide two levels of information from the same recorded signals (Figure 1-3):

- water-depth or bathymetry, i.e. a geometrical information from measured echo times and angles;
- seafloor acoustic reflectivity, i.e. a measure of energy obtained from the echo intensity, which relates directly to the nature of the seafloor.

Conceptually, bathymetry is relatively straightforward information to derive from the record of time delays of echoes: it is all a matter of time measurements and geometry (at least in theory; accurate measurements actually require sophisticated technologies and demanding procedures). Matters are far less obvious when the aim is to obtain information on the nature of the seafloor from echo intensities. Indeed, the backscatter phenomenon (and hence its measurement) is a peculiar concept… it is both intuitive (a sound that is sent back towards its source, more or less intense according to the target and its range) while still very complex structurally – the received echo is a combination of acoustic and geophysical processes, accounting for both transmitting and recording electronics of the sonar and intricate physical phenomenon happening both in the water and at the interface.

Hence, in order to access the backscatter information intrinsic to the seafloor, the recorded echo first needs to be rid of that part of the signal that is not directly related to the target itself. This means first that the characteristics of the sonar sensor per se (obviously the transmission level and the reception sensitivity, but also the beam aperture and the signal duration) should not affect the estimation of the target reflectivity, while they certainly impact the received echo observable intensity. It is also intuitive that the measured echo level depends on the range between the sonar and the target – a distant target obviously raises a fainter echo than a close one; hence the propagation loss inside the water column needs to be corrected, according to the local environmental conditions and to the particular acquisition geometry. After these appropriate compensations have been applied, the measured echo intensity can be reasonably considered as representing the seafloor effect alone, and can be translated into the backscatter strength of the target, which is its inherent capability for sending back acoustic energy to the sonar system. This "reflectivity" characteristic is linked fundamentally to the target's material mechanical characteristics (a "hard" material sends back higher echoes than a "soft" one) and its fine-scale geometry (a "rough" interface scatters more acoustical energy than a "smooth" one). Hence measured backscatter can, up to some point, be considered as a first-order indicator or proxy for the seafloor interface nature, composition and small-scale structure, and hence provide a direct link with geology, biology and ecology – which is indeed the goal to keep in mind.

The angular dependence of the backscatter response is a paramount feature, implying both constraints in the data processing and in the potentialities of their interpretation (Hughes Clarke et al., 1997; Le Chenadec et al., 2007). A rough and hard seafloor interface (coarse material or rocks) tends to scatter the sound waves homogeneously in all directions, and the echo level depends little on incidence angle; the intensity recorded over the swath width is then rather stable whatever the angle (Figure 1-4). On the other hand, a soft and flat fluid-like sediment has a mirror-like response, sending back a maximum of intensity at the vertical and very little at oblique angles; the sonar image shows then a strong maximum in its center, and a fast decrease on the sides. All intermediate cases are indeed possible, depending on the interface roughness and the presence of scatterers either lying on the interface or buried in the surficial layers.

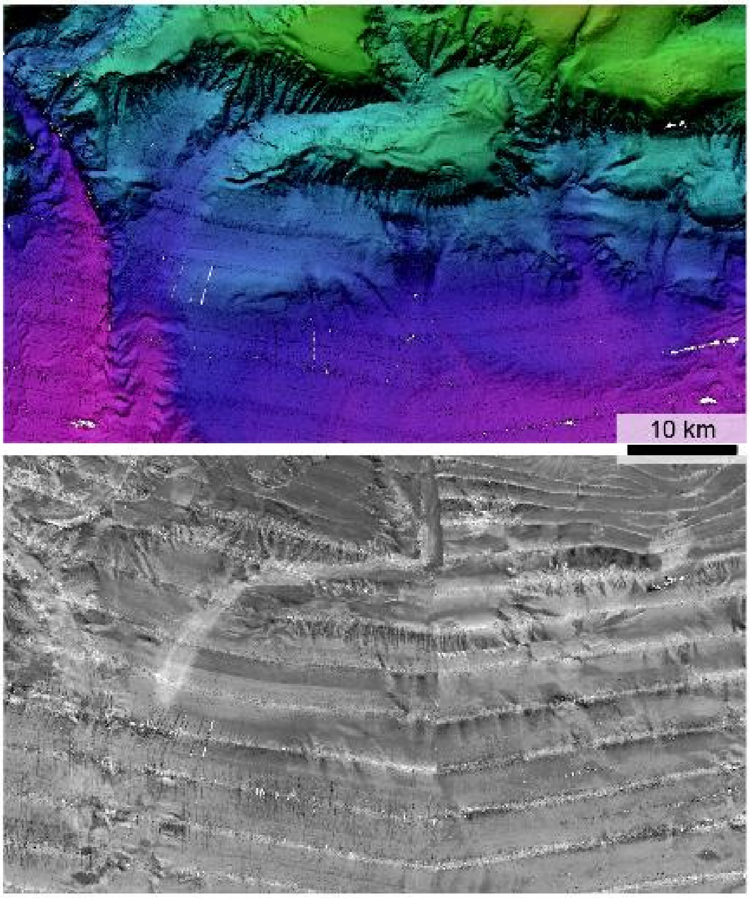

Figure 1-3 Bathymetry (top) and backscatter (bottom) collected over the same area (Cook Strait, New Zealand). The bathymetry is coded in colors; whilst the echo amplitude for the same area is coded on a grey scale.

The intensity modulations caused by the angle dependence in the seafloor image require specific compensations in order to make the graphical display easily interpretable. Dedicated processing operations are hence devoted to flattening the angle response so that a geologically-homogeneous flat seafloor appears at a constant level on the processed image, whatever the original angle dependence.

On the other hand, the angular dependence, if correctly preserved, is a very powerful tool for a classification operation. These contradictory objectives imply in both cases to master accurately the angle characteristics of the observed scenes, implying a correct estimation of the local bathymetry. This justifies the interest found in the backscatter measurement by MBES: these sensors are the first ones able to provide angular reflectivity concurrently with a bathymetry obtained at a comparable resolution, making it possible to fulfil both expectations.

The **spatial resolution** (a.k.a. footprint extent) of a swath seafloor-mapping sonar is given basically by the extent of the beam section intersecting the seafloor interface; hence it is obviously a function of both the range to the seafloor (increasing at oblique angles, for a given water depth) and the beam aperture (typically 1° hence about 2% of range). Hence the resolution of ship-borne MBES is indeed very fine, let alone that of remotely-operated or deep-towed vehicles working close to the seafloor. It is debatable in any case, as to whether habitat mapping applications need such a high resolution capability for reflectivity data.

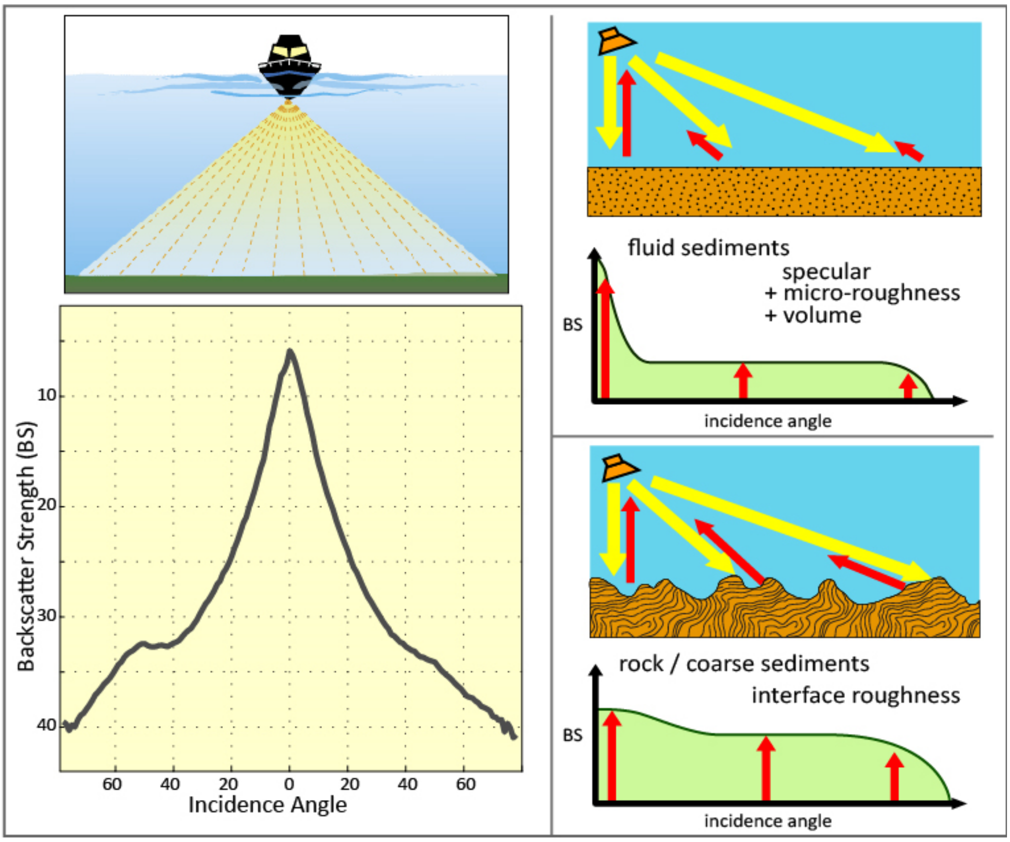

Figure 1-4 The angular dependence of Backscatter Strength (BS). The rapid decrease in the BS intensity with incidence angles shows well in the BS angular profile (bottom left): high BS values at the nadir (0° incidence) decrease rapidly with gazing angle. The shape of the angular profile is directly influenced by the interface roughness (right); it is not necessarily symmetrical in practice (example shown here), depending on local features

1.4 From backscatter to seafloor characterization

The prime and arguably the most objective information derived from MBES acoustic data, after water depth, is the **acoustic facies**, i.e. the spatial organization of seafloor patches with common acoustic responses and the measurable characteristics of this response. Maps of acoustic facies – most often simply represented by the post-processed backscatter data – are the initial material available to scientists to interpret habitat from remotely-sensed data. Although ultimately the classification of the acoustic facies in **sediment classes** is arguably the best approach to derive substrate and habitat maps, one should keep in mind that acoustics is not a direct measurement tool for seafloor characteristics (according to geoscience or biology criteria), and hence that backscatter data cannot directly provide an objective information about the substrate – again in the sense of these discipline expectations. The acoustical facies correspond correctly to the habitat typology only on a relative scale, and some ambiguities remains as acoustic reflectivity may be not a fine enough indicator of habitat nature subtleties.

Seafloor backscatter measurement has long been considered as a by-product of multibeam bathymetry and, at best, as a qualitative high-level indicator of the possible nature of the seafloor.

Because backscatter data directly relates to sediment grain-size (Figure 1-5) and seafloor roughness, it has the ability to provide qualitative and quantitative information on the composition, i.e. the nature, of the substrate (e.g. Jackson and Briggs, 1992; Hughes Clarke et al., 1996). Furthermore, because the seafloor is the physical support of the benthic habitat, backscatter data has the added advantage to indirectly provide information related to fauna, flora and biodiversity at large (e.g. Cochrane and Lafferty, 2002; Anderson et al., 2008; Brown and Blondel, 2009; Brown et al., 2011). However, regional-scale quantitative applications of backscatter data for habitat mapping are recent and technically challenging (Brown and Blondel, 2009; Lamarche et al., 2011; Lucieer and Lamarche, 2011), but clearly, one of the key potential of backscatter data lays in its ability to represent a proxy for substrates and benthic habitat. This potential, in parallel with the need for objective and quantitative information on the seafloor from remote-sensed data has resulted in a line of research that has developed acquisition, processing and interpretation of the backscatter signal as quantitative tools for geological and environmental purposes.

The term "**habitat**" captures the combination of environmental and biological conditions that promote occupancy by a given group of seabed species. Benthic habitat can therefore be defined using physical descriptors, such as seafloor morphology, substrate or physical oceanography character of the place where microorganisms, plants or animals live. In that context, habitat mapping aims to represent different types of habitat, delineated spatially by distinct combinations of physical, chemical and biological conditions (Greene et al., 1999; Kostylev et al., 2001).

Mapping habitats is inherently problematic, as boundaries between mapped habitats assume that discontinuities in environmental gradients occur, and that distinct living assemblages can be paired with distinct environmental factors (Snelgrove and Butman, 1994). As such, boundary recognition across large areas of the seascape is fundamental to habitat mapping despite our understanding that obvious discontinuities are not always apparent in nature. Biophysical variables can be indirectly mapped using proxy – or surrogate - correspondence to the occurrence of substrate, benthic species or communities.

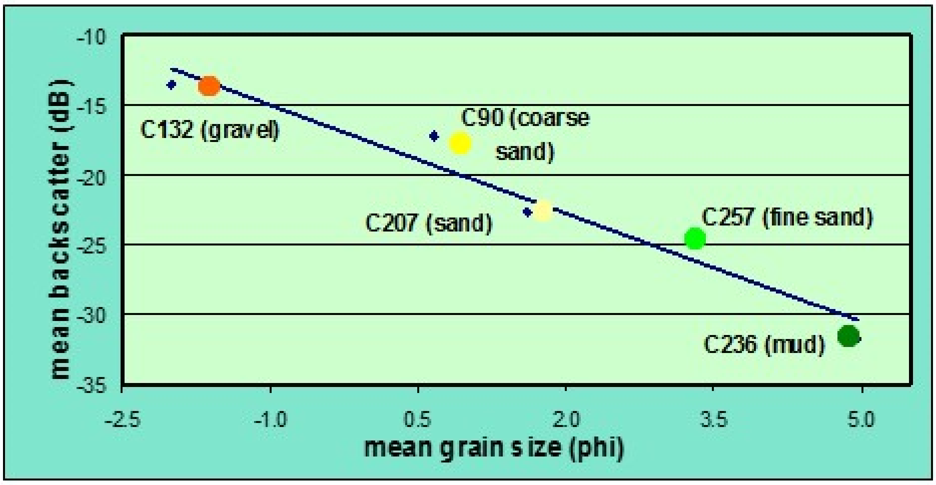

Figure 1-5 Relation Backscatter Strength (in dB) vs. sediment grain size (phi = -log2 (d), d=grain diameter in mm) on samples collected in Cook Strait, New Zealand (Lamarche et al., 2011). The plot makes clear the increase of BS with the grain size, caused by both the substrate hardness and its roughness, both correlated with grain size. Data recorded with the MBES Kongsberg EM 300 (30 kHz) on R/V Tangaroa.

An important component of the immediate sub-seafloor, although much smaller than the mineral component in volume, is the organic component. That latter component includes biology, fauna and derived products (burrow, organics matter...) and has a direct impact the sediment volume heterogeneity and density and therefore on the backscatter strength. One, often forgotten, corollary is the **seasonality** of the backscatter response, according to biological activity. This indeed is the focus of specific research project (e.g., Freeman et al., 2004).

Lastly, because habitat maps are essentially statistical models, they require rigorous testing – or validation. This validation is most usually done through **ground-truthing** against targeted physical or biological samples to attach a degree of confidence to the end product (e.g. Anderson et al., 2008). Geological and biological seabed attributes can be ground-truthed through a range of methods, but this is generally achieved through physical sampling of the seabed (sediment cores or grabs) and assessed visually through camera or video techniques (which can provide information about the interface roughness and the presence of biological or mineral scatterers). Sediment grains size and density, as well as seafloor roughness often require separate analysis prior to ground truthing.

1.5 A short historical perspective

Every active sonar (or radar) system is built on a common principle: transmit a short signal with a sufficient power, and receive (detect and measure) its echo from a target. Whatever the category of the target considered (seafloor, fish schools, submarines, wrecks, seaweeds, mines…) this recorded echo can be processed from two points of view.

First, its time delay gives a measurement of the range between the sonar and the target; this was the primary purpose of active sonar sensors when they appeared over a century ago, which can be applied to a number of usages (detection of natural obstacles and hostile naval threats, echosounding the seafloor for navigation and charting, searching for fish schools…).

Less frequently, a second feature of the echo can also be used: the intensity level, providing information about the target nature – and hence about some of its characteristics. The first generations of sonars made little explicit use of this potentiality; the main objective was then detection and localization of targets, and the rudimentary techniques for signal processing and display certainly did not allow much subtlety in observing reflectivity variations. Even the first sonars devoted to seafloor mapping (echosounders and sidescan sonars, see Lurton, 2010) could not offer echo intensity as a qualitatively useful output. Decisive progress was achieved with the apparition of digital processing of the sonar signals, and the design of seafloor-mapping sonars with electronics of increasing quality. Sidescan sonars could produce seafloor images of better quality, in which the geometrical imaging of the scenes was embellished by echo intensity modulations - giving a supplementary tool for interpretation, e.g. in roughly distinguishing sediments of different types. A breakthrough happened in the early 1990's, when Simrad (today Kongsberg) issued multibeam echosounders with a dedicated “sonar image” capability, to complement the bathymetry measurement. This functionality was improved along their various new models of multibeam echosounder, and adopted as well by other constructors. Today MBES data cannot be imagined without a “reflectivity” component, and the quality of the backscatter maps of the seafloor has become indeed very attractive. On the one hand the pictorial quality of these maps has tremendously improved, until the point where they can be compared to good-quality black and white photos (although with coverage capabilities of tens to thousands of meters that no underwater optical system can pretend to approach). On the other hand, the best of these systems are able to provide objective measurements of the absolute reflective power of underwater targets, hence opening new ways to the interpretation of seafloor scenes.

Up until recently, backscatter related applications were considered rather exploratory techniques and mainly remained the focus of the scientific community, mostly geologists, biologists, environmental scientists, and marine acoustics engineers. Whilst scientists still have a strong (and even increasing) interest in developing the potential associated with backscatter data, the industry sector is starting to pay more attention to this approach, as the practical interest becomes more obvious for operations related to offshore engineering and mineral resource exploration and exploitation. Most generally, these end-users have prior experience with sonar systems for bathymetry purposes.

At this point, one cannot but observe that the various communities motivated in using the backscatter data are largely left to themselves regarding the acquisition, processing and interpretation of backscatter. The understanding and modeling of the backscatter phenomena remains a specialist’s domain, as does the knowledge of the functionalities of the specialized sonars. The manufacturers' instructions regarding backscatter acquisition and processing are often succinct and usually insufficient for being directly usable for objective and qualitative interpretation. Furthermore, no real collaborative synthesis effort has been undertaken yet by the seafloor-mapping community in order to define needs, expectations, methods and practical procedures. This situation is somewhat frustrating since:

- The **bathymetry/hydrography** community has conducted this effort for the particular techniques of sonar bathymetry applied to seafloor charting. This led to IHO-supported standardizations that are today agreed and applied worldwide. Since sonar systems, including today's MBES, used for bathymetry and reflectivity measurements use the same technology, the standardization should be facilitated for backscatter related issues!
- The **fisheries acoustics** community is confronted to the issue of accurate objective estimation of biomass quantities (which is a requirement for defining quotas in national fishery policies), implying the definition of procedures for a quantified measurement of the echoes from the water column. Fisheries acousticians have defined their own corpus of recommendations, procedures and standards (Foote et al., 1987; Demer, in prep).
- The **remote-sensing** community concerned with space-borne radars has taken the issue of reflectivity very seriously, for several decades now. The user’s needs have been surveyed, and translated into objective technological requirements (Brown et al., 1993); calibration procedures have been defined (Freeman, 1992; Luscombe and Thompson, 2011), as well as processing steps. It should be noted that satellite-borne radars (either *Synthetic Aperture Radars* for high-resolution imaging of the Earth’s surface, and lower-resolution *Scatterometers*) are indeed very similar structurally and functionally to MBES (while plagued by much less severe constraints, in particular regarding the propagation medium effect and the acquisition geometrical configuration) (Figure 1-6). However such radars have been in use for a long time. The radar backscatter measurement is commonly applied for various purposes such as the monitoring of the sea-state or sea-ice, forest and agriculture mapping and control, etc. The success of these techniques and applications bodes well for similar results with seafloor mapping sonars.

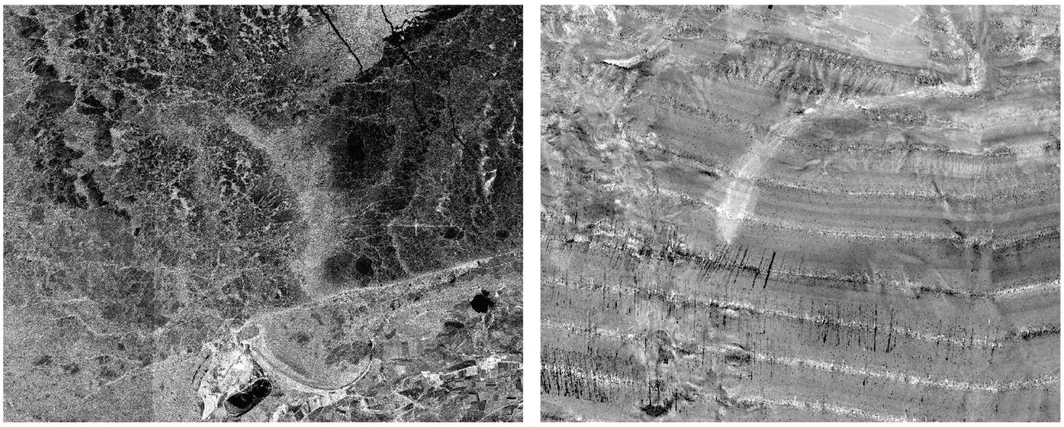

Figure 1-6 Comparison of satellite radar data (left, image from http://aerometrex.com.au/blog/?p=470)) with MBES backscatter (right from Lamarche et al., 2011).

1.6 Document layout

This document is organized in seven chapters, the first one being this Introduction.

Chapter 2 - *Background and fundamentals* - provides a description of the physical backscatter phenomena followed by the fundamental elements of modeling from a user's and engineer's point of view, useful in backscatter processing (Weber et al., this issue). This chapter is not a textbook about backscatter theory but rather is setting the scene, attempting to define seafloor backscatter both intuitively and theoretically, including notion of wavelength, incident angle, impedance, interface rugosity, seafloor heterogeneity… the chapter aims at explaining fundamentals and provides classical tools for physical modeling. The result is essentially a background for the next chapters**,** including references toward more specialized literature.

Chapter 3 - *Users need* - goes over the present and potential use of backscatter data as well as user aspirations and needs (Lucieer et al., this issue). This chapter includes the results of a survey on user's need, conducted in July-August 2014 for the purpose of this document. The chapter also provides an overview on the development and need in benthic habitat mapping related activities, since it arguably is one area the most in demand for backscatter data. It includes a short discussion on the use of backscatter data for classification of substrate and habitat approaches, as well as the limitation of such data today. The Chapter addresses issues such as the potential utility of backscatter data for various end-users; the limitations for using BS in habitat mapping; and the benefit of being able to use backscatter for predicating substrate and benthic habitat.

Chapter 4 - *Backscatter measurement by bathymetric echosounders* - elaborates about the process of estimation of seafloor reflectivity by sonars, and consequently the level of confidence of the BS data (Brown et al., this issue). The purpose of this chapter is to describe what is actually applied inside a sonar measuring backscatter – from the physical echo at the receiver array input to the datagram of reflectivity data. The chapter reviews the characteristics of the various systems available on the market today, to our knowledge. This chapter contributed for the input from the sonar manufacturers themselves. The chapter remains impartial and there are no critical comparisons of the various systems, but rather a description of the functionalities they offer and approaches used for providing the data to the users. An important part of the chapter is the need for calibration and the practical way this could be undertaken.

Chapter 5 - Acquisition: best practice guide - uses the information available in the previous chapters and provides practical guidance and recommendations for running surveys effectively and for obtaining the best backscatter data possible (Rice et al., this issue). It deals with engineering considerations such as practical sounders calibration and settings issues, as well as the various strategies possible for optimizing coverage, data quality and outcomes, including issues such as system configurations and management of environment parameters. The chapter is mainly based on field work considerations, and the methodological analysis normally to be followed by an operator.

Chapter 6 - *Processing Backscatter Data: From Datagrams to Angular Responses And Mosaics* - addresses all methods currently available in post-processing software suites (Schimel et al., this issue). It does not deal with the processing applied inside the sonar systems, as this is addressed in previous chapters, but with the once-recorded data (hence the *post-processing* appellation used in this document). The processing operations presented here are restricted to the early stages of signal normalization, geometrical corrections and mosaicking, for which procedures can be defined. The downstream steps of segmentation, classification and characterization are out of scope, since they variants are many and a field for innovation and experimentation rather than routine activities prone to standard procedures. The chapter recommends optimal processing sequences. A number of characteristic operations from each software are presented and discussed, but (akin to sonar systems presentations in Chapter 4) the chapter put no emphasis on any one particular commercially available methods and is not favoring one software rather than another.

Chapter 7 - *Discussion and Synthesis* – will endeavor to compile and rationalize the recommendations in a usable fashion for all stakeholders (Lurton and Lamarche, this issue).

The document also includes a glossary of acronyms and definition and a broad list of references in the appendix.

Overall this large document is made to help all stakeholders, manufacturers, scientists, operators and decision makers to make better use of the backscatter data. It is the product of a group of such stakeholders that genuinely and sincerely believe that the backscatter data is an underused element in the quest to discover and understand the seafloor and its dynamics. Our aim in editing this document is that it will instigate more research, motivate manufacturers and convince skeptics that there is much potential in using seafloor backscatter reflectivity in marine activities.

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CHAPTER 2 BACKGROUND AND FUNDAMENTALS

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2.1 Objectives

The purpose of this chapter is to provide an overview of the physical phenomena causing seafloor backscatter measured with hydrographic echosounders, setting the scene for the following chapters. This is done for a generic sonar with little concern for the specifics of the equipment itself: the goal is to focus (albeit at a high level) on the physics of the acoustic signal and interacting with the water-seafloor interface. The chapter starts with a general discussion of echosounding of the seafloor, and then introduces the sonar equation and definition of terms relevant for echosounding. The remainder of the chapter describes how echosounding systems acoustically interrogate a target such as the seafloor, and finally considers some of the physical causes of seafloor acoustic scattering. There is a substantial amount of literature addressing these topics in more detail, from which the material presented here is drawn and to which an interested reader is referred (e.g. Urick, 1983; Jackson and Richardson, 2007; Lurton, 2010).

2.2 Echosounding of the Seafloor

Mapping the seafloor is normally undertaken using dedicated **echosounders**, including those described in this chapter and the following ones. The working principles for echosounders are similar to those for all active sonar systems. A short signal (in the millisecond range) is transmitted at a known time, travels through the water column, and generates an echo when it reaches the seafloor. The echo travels back toward the sonar and is recorded by the sonar receiver after a delay T (Figure 2-1). The echosounder has two overarching functions when used for seafloor mapping: it generates and transmits an acoustic signal toward the seafloor; and it measures **the time delay and intensity of the received echo at a controlled angle** of arrival.

The information made available from the seafloor echo can be used in two ways. First, the time delay T between transmission and reception gives a means to derive the water depth or bathymetry (provided the angle of propagation is taken into account). The **bathymetry measurement** is the primary functionality of hydrographic echosounding systems. The primary goal of developing echosounders, starting in the 1920’s, and multibeam echosounders (MBES) half a century later, was to make available accurate measurements of **water depth** either under a vessel (usually in real time, for navigation safety purposes) or around a vessel’s route (possibly in delayed time, for mapping purposes). Secondly, the **echo intensity** provides an indication about the **nature of the seafloor** and its physical character. In the common vernacular, a “hard” seafloor causes echoes of higher intensity than a “soft” one. This simple-sounding description of seafloor echoes hides the complications that seafloor mappers face: how does one measure with good confidence the intensity of an echo on an absolute scale and in a manner that isolates the effect of the seafloor alone in the received echo?

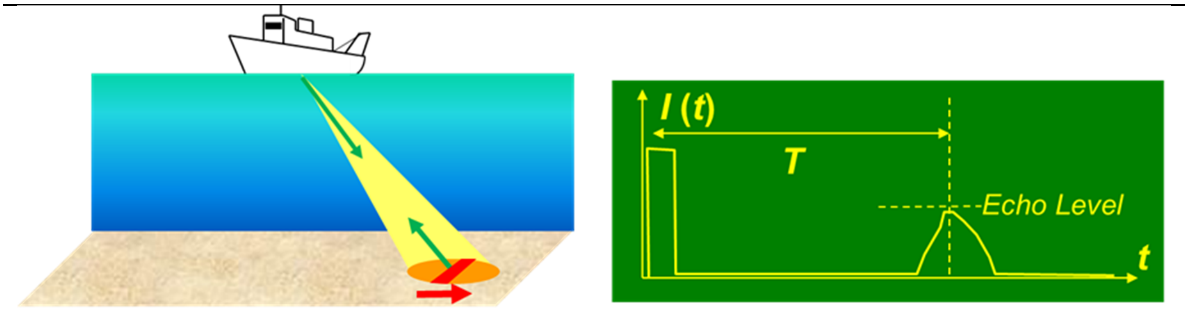

Figure 2-1 The echo recorded by a seafloor-mapping echosounder. The sonar beam delimitates a footprint (orange) on the seafloor, which is swept outwards by the (short) signal (red), generating a backscattered signal varying with time. The echo intensity $I(t)$ is recorded by the receiver: the shape of its time envelope is determined by the footprint geometry, and its intensity level by the seafloor reflectivity. The delay T of the echo relatively to the transmission instant is used to compute the range (at a fixed angle) from the sonar to the sounding point.

The fundamental principle of bathymetry measurement is related to the length of the sonar-to-seafloor-to-sonar propagation path (i.e., range) and the associated time delay. Range R and time t are proportional and linked by the sound speed c. The range can be translated in water depth, D, provided that the propagation angle, θ, and the sound speed profile are both known - or can be estimated along the propagation path. Complications arise in these simple sounding operations, particularly for echosounder beams steered at oblique angles. Nevertheless, all the computations needed for bathymetry are related to time, length, and sound speed. To estimate the depth of the seafloor, the basic measurement of the processed echo is time of arrival, which is easily measured with little sensitivity to the signal amplitude deformations - as long as the echo can be recognized and extracted.

In contrast to the bathymetric measurement, characterizing the physical make-up of the seafloor from a sonar echo is more complex and requires more parameters to be known or estimated. The physical quantity of interest is now the echo amplitude which depends on many factors:

- The **amplitude of the acoustic signal projected** into the water, depending on the transmission power setting and the projector angular directivity pattern;
- The **loss and redistribution of acoustic energy** as the signal travels through the water to the seafloor and back again, depending on the signal-target range, on the physical properties of seawater (temperature and salinity *vs* depth) and on the signal frequency;
- The **sensitivity of the sonar receiver** to acoustic signals, which depends on the hydrophone sensitivity at the observation angle, the receiving electronics response, and the sonar settings;
- The contribution of **unwanted signal fluctuations** caused either by additive noise generated by other sound sources and receiver's electronics, or by the intrinsic variability of the echo itself;
- The physical phenomena of **interaction of the pulse arriving at the seafloor** that generate the echo itself.

Of these factors, we wish to isolate the last one (the physical interaction process) in order to help identify characteristics describing the seafloor. In doing so, we must understand and then remove the influence of the other factors on the list. These factors may be predictable under given circumstances (e.g., propagation losses through the water) but the predictions are not trivial to make in practice, and as a result the generation of reliable echo intensity data for seafloor characterization is often neglected in the literature about seafloor acoustic backscatter. Accurate quantitative measurements of echo intensity require efforts towards calibration of sonar characteristics, mastery of acoustic propagation conditions, and understanding the physical phenomena associated with the echo generation. In this chapter, the focus is on the latter, while the former are addressed in Chapters 4 and 5.

2.3 The sonar equation and Target Strength (generic)

2.3.1 *Active sonar equation*

The Sonar Equation

Active sonar systems, including the echosounders that are of interest here, transmit a pulse of sound into the water from an acoustic **projector**. This pulse of sound travels or propagates through the water, reflecting or scattering from objects in its path. Some portion of the scattered wave is then received by the sonar. This process is most simply described by the **active sonar equation**. This concept, which has several variants depending on the nature of the sonar and its operational environment, was first developed in World War II (Urick, 1983) in order to synthetize in a convenient form the **overall performance of a sonar** system, by **balancing the energy quantities associated to transmission, propagation, target interaction, noise and processing**. The sonar equation is used here to characterize the behavior of multibeam echosounders, noting that some of the physics (e.g., sound refraction) and some of the sonar hardware aspects (e.g., analog-to-digital conversion) that are relevant for a complete understanding of acoustic backscatter measurement are addressed in subsequent chapters, whereas some others (e.g. seafloor echo detection) are not addressed altogether as considered out of the scope of this document. That is, the sonar equation presented here includes only those components that are purely acoustic, and even then these components are only considered at a level sufficient to develop a general idea about the aspects of echosounders that should be addressed in further detail.

Acoustical pressure

Development of the sonar equation usually starts with the generation and transmission of a sound pulse. As this signal propagates away from the projector to range R we assume that the acoustic pressure wave spreads as a spherical wave with the form:

$$p(R)=\frac{p_0}{R}e^{j(\omega t-kR)}e^{-aR} \tag{1}$$

Here $\omega=2\pi f$ is the angular frequency at sonar frequency f, k is the acoustic wavenumber $k=\omega/c=2\pi/\lambda$ where c is the **speed of sound** and $\lambda=c/f$ is the **wavelength**. The exponential decrement coefficient *a* due to absorption in the water is defined below. The $1/R$ range dependency of (1) is often called **spherical divergence** or spherical spreading; very widely used, it expresses in first approximation the pressure decrease away from the source.

Far-field vs near-field

The spherical divergence loss is strictly applicable to infinitesimal (<< λ) sources. In case of a projector of significant dimensions compared to λ, it is valid at large enough ranges (***far-field***) so that all the source points of the projector radiating surface contribute in phase at the target; otherwise, in the ***near-field***, the elemental contributions create intricate interference patterns. The hypothesis that the target is located in the far-field regime is usually implicit (but possibly erroneous).

Peak and RMS values

The pressure amplitudes $p(R)$ and p_0 in (1) represent the **peak values** respectively at range R and at a reference distance of 1 m. It is often more appropriate to describe the source reference amplitude using a statistical measure of the magnitude such as the **root mean square** (***rms***) value, which is calculated as the definition implies: the square root of the mean (over time) of the square of, in this case, the sonar pulse. For constant-amplitude sinusoidal signals (CW), such as the pulses used by many echosounders, the relationship between the rms pressure and the peak pressure is $p_{rms} = p / \sqrt{2}$.

Acoustic wave energy

The energy associated to the acoustical wave can be separated into a kinetic (due to the fluid particle local motion) and a potential component (due to the elasticity of the fluid medium). The acoustic **intensity** (flux of power through a unit surface) of a propagating plane wave is given by (Kinsler et al., 1999):

$$I(R) = \frac{\left\langle p^2(R) \right\rangle}{\rho c} = \frac{p_{rms}^2(R)}{\rho c} \tag{2}$$

Hence the source intensity I_0 at 1 m is expressed as $I_0 = p_0^2 / 2\rho c$ (in W/m^2).

For echosounding sonars I_0 is often directional, and so in terms of the sonar equation we use a source intensity I_0 that is appropriate for the direction where we expect the target echo. The **acoustical power** (in W) is the integration of the intensity over a given surface (e.g. a sphere surrounding the source, to estimate the total radiated power). Finally, the **signal energy** (in J) is the result of the integration of its power over time.

Decibels and their use

A common use in acoustics is to express the quantities related to level in **decibels** (dB), according to a **logarithmic scale** that is better adapted to the huge dynamic ranges of the sound wave characteristics.

The decibel is a comparative logarithmic unit defined as **ten times the base-10 logarithm** of the ratio between two quantities homogeneous to energies (intensity, power…). However it is a common use as well to express quantities in decibels referred to a conventional reference value. For instance, the reference value for acoustic pressure is 1 µPa, and the pressure values should be expressed in dB re. 1 µPa. Mentioning the dB reference value is sometimes omitted in current use (a reprehensible habit); hence an acoustic pressure value simply expressed “in dB” is normally referenced to 1 µPa.

The sonar equation is conventionally written using the decibel (logarithmic) scale in terms of sound levels. The most common form of these is the *intensity level*, IL, defined in dB as:

$$IL = 10\log_{10}\left[\frac{I}{I_{ref}}\right] \tag{3}$$

where I_{ref} is a reference intensity. Accordingly, we can define a source level, SL, as:

$$SL = 10\log_{10}\left[\frac{I_0}{I_{ref}}\right] \tag{4}$$

In underwater acoustics the reference intensity I_{ref} is the intensity of an acoustic plane wave with an rms pressure of 1 µPa (I_{ref} = 6.7x10^{-19} W/m²). When using decibel notation, it is important to provide the reference, and in the case of SL this is done using a shorthand notation "re 1 µPa @ 1 m" standing for "with reference to the intensity of a pressure wave with an rms pressure of 1 µPa at a distance of 1m". It is important to note here that the SL may not be the IL actually observed at a distance of 1 m in front of the projector: if the reference distance of $R_{ref} = 1\text{ m}$ falls within the near-field of the projector then the actual IL at this distance may be substantially less due to deconstructive wave interference.

In case of operations over a number of acoustical data expressed in dB (ensemble statistical processing such as averaging, higher-order moments computation etc.) the correct way to proceed is to convert the values from dB into intensity (typical for statistical treatments of seafloor scattering) or other linear values, perform the operations, and transform the final result into decibels again.

Transmission Loss

As the acoustic wave leaves the projector and travels out into the water, the amplitude of the pressure signal decays (or attenuates) for two reasons: **spreading** and **absorption**. To account for these phenomena we define the transmission loss, TL, at range R to be:

$$TL = 10\log_{10}\left[\frac{I(R_{ref})}{I(R)}\right] \tag{5}$$

where R_{ref} =1 m. Using (1) in (5) results in

$$TL = 10\log_{10}\left[\frac{e^{-aR_{ref}}}{R_{ref}}\frac{R}{e^{-aR}}\right]^2 \approx 20\log_{10} R + \alpha R \tag{6}$$

The two terms on the right-hand-side of (6) are typically called **spherical spreading** and **absorption**, where α is a logarithmic absorption coefficient with units of dB/m (or dB/km for practical convenience), and related to the exponential decrement a by $\alpha = 10\log_{10} e^{2a} \approx 8.686 \times a$. The inherent assumption in this definition of TL is that the acoustic waves spread spherically from the projector.

The combination of SL and TL is used to estimate the **sound pressure level**, SPL = SL-TL at some range of interest. For echosounding systems, this range of interest is typically the range to the target.

Target Strength

When the sonar pulse reaches the target (e.g., a fish, turbulent microstructures in the water column, the seafloor) some portion of the pulse energy is redirected or scattered toward the sonar receiver. The **target strength**, *TS,* is used to describe how much of the sound wave is redirected, relative to how much got to the target in the first place:

$$TS = 10\log_{10}\left[\frac{I_s}{I_i}\right] \tag{7}$$

where I_i is the incident intensity at the target ($SPL = SL - TL$, using decibels) and I_s is the scattered intensity in the direction of the receiver and at a reference distance of 1 m from the target. In general, the scattered intensity depends on the characteristics of the target as well as the sound wave itself. For a given target, I_s can change depending on the sonar frequency, the orientation between the target and both the incident and reflected waves, the length of the sonar pulse, and other properties of acoustic projector, receiver, and target. For the purposes of measuring acoustic backscatter, understanding TS is of such critical importance that a full discussion of this is deferred to the next section.

Echo Level

After interacting with the seafloor, a portion of the scattered wave propagates back toward the target (**backscatter**), once more experiencing the same type of spreading and absorption losses as on the way to the target. The received intensity can be described as an echo from the target, which in decibel notation is referred to as the echo level, EL:

$$EL = SL - 2TL + TS \tag{8}$$

Note that this form of the sonar equation assumes – for the purposes of estimating the sound pressure level – that the transmission loss is identical on the way to the target and on the way back to the receiver (that is, the sonar being described is essentially **monostatic**, as is the case for most hydrographic echosounders). It is also worth noting that the sonar equation can be expressed in terms of intensity values rather than intensity level (in dB) as

$$I_r(R) = \frac{I_0}{R^4}\frac{I_s}{I_i}e^{-2aR} \tag{9}$$

where I_r is the intensity of the echo observed at the receiver, R being the sonar-target range.

The echo level (8) is typically not reported as such by sonar systems – it simply represents the sound pressure level that would be observed at the receiver due to the echo from the target. Sonar manufacturers are faced with the task of amplifying and digitizing this signal on the sonar “dry end”, and then reporting the relevant values in a datagram. The complexities associated with this conversion are discussed in Chapter 4.

Noise contribution

The echo level quantifies the sound wave that we are typically interested in measuring; however the target echo is not the only sound wave to be received. When we measure the echo level, we are often confounded by unwanted acoustic waves, that we refer to globally as **noise**: either **ambient noise** (e.g., ship traffic, bursting bubbles under breaking waves, marine animals), **self-noise** (generated by the sonar itself or by its platform) or **reverberation** (e.g., the sound wave we projected that scatters from objects we are not interested in). It is assumed here that the echo level is sufficiently high so that noise level is negligible; useful discussions of noise in this context can be found, however, in Urick (1983, Chapters 7, 8, 11, and 12).

2.3.2 Target strength of discrete targets

While it is useful to think of the sonar equation in terms of the echo level observed at the receiver, the quantity relevant to acoustic backscatter from the seafloor is the **Target Strength** (TS) which includes a combination of effects related to the sonar and to the target. The nature of this combination is dependent on the morphological characteristics of the target (size, shape, material) and characteristics of the sonar (frequency, angular orientation).

The simplest TS scenario is that of a **discrete target** (i.e., small compared with the sonar beam and pulse length). For a discrete target we consider the total acoustic power Π scattered in all directions from the target by integrating the scattered intensity over some bounding surface Σ surrounding the target $\Pi = \int_{\Sigma} I_s dS$. Π is proportional to the incident intensity I_i at the target, (that is, the higher the incident intensity, the higher the scattered power), and so we define a quantity σ_T that is related to the total scattered power and the incident intensity as

$$\sigma_T = \frac{\int_{\Sigma} I_s dS}{I_i} \tag{10}$$

The units of σ_T are that of area (m^2), and σ_T is traditionally called the **total scattering cross section**. Of course, it is unpractical (and usually unnecessary) to measure directly the total scattered power, and more often the scattered intensity is only measured in a single direction. Accordingly, we define a **differential cross section** as

$$d\sigma = R^2 \frac{I_s(R_{ref})}{I_i} \tag{11}$$

where R_{ref} is the range (nominally, 1 m - note that some older literature uses yards rather than meters) at which the scattered intensity is measured or referenced to. Echosounding (monostatic) sonars measure the intensity I_{bs} that is scattered back in the direction of the original source of the waves, so an especially useful case of the differential scattering cross section is the **backscattering cross section**:

$$\sigma_{bs} = R^2 \frac{I_{bs}(R)}{I_i} \tag{12}$$

Note again that σ_{bs} has units of m^2. To evaluate the TS of a discrete target in terms of the sonar equation outlined in (8), we would write

$$TS = 10\log_{10}\left[\frac{\sigma_{bs}}{R_{ref}^2}\right] \tag{13}$$

2.3.3 Target strength of extended volume targets

It is often the case that the targets extend throughout a volume defined by the sonar beam and pulse length. For example, if the echo was returned from a large aggregation of fish then TS could be considered as the incoherent sum of the individual echoes from the fish present inside an instantaneously "active" volume, or

$$TS = 10\log_{10}\frac{\sum_{i=1}^{N}\sigma_{bs,i}}{R_{ref}^{2}} \tag{14}$$

where N is the fish number within the beam- and pulse-constrained target volume. This consideration of TS leads to a natural separation between the average scattering cross section per unit volume s_v, referred to as the **volume backscattering coefficient**, and the **insonified volume** B, so that

$$TS = 10\log_{10}(s_v B) = S_v + 10\log_{10} B \tag{15}$$

where the volume backscattering strength S_v is the decibel equivalent of s_v, which has units of m^{-1} (Simmonds and MacLennan, 2005). Similar to the TS for discrete targets, TS is still referenced to m^2 although S_v is in dB re 1 m^{-1}. In this somewhat simple view, the elementary insonified volume (or **resolution cell**) can be calculated using, as a first approximation, the -3 dB beamwidth φ_{3dB} of the system and the system bandwidth or equivalent pulse length τ. For example, the simplest way to calculate the insonified volume for a typical Mills cross multibeam echosounder is

$$B = R^2 \varphi_{3dB-Tx}\varphi_{3dB-Rx}\frac{c\tau}{2} \tag{16}$$

where φ_{3dB-Tx} and θ_{3dB-Rx} refer to the -3 dB beamwidths for the transmitter and receiver, respectively, and $c\tau/2$ is the range resolution.

Equation (16) represents a very simplified view of the insonified volume. Certainly, targets falling outside of the -3 dB beamwidth will contribute to the scattered intensity comprising the echo. To account for this, the insonified volume can be more formally calculated using an integrative measure of the targets throughout the entire directivity pattern. This results in the concept of equivalent beamwidth (Simmonds and MacLennan, 2005) defined as the width of an ideal beam (with a constant response inside the beam and null outside) that would provide the same echo level for an extended target as is actually observed (see Figure 2-2). Using this concept, (16) becomes

$$B = \psi\frac{c\tau}{2} = R^2\frac{c\tau}{2}\int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} H_{Tx}^2(\theta,\phi)H_{Rx}^2(\theta,\phi)\sin\theta\, d\theta\, d\phi \tag{17}$$

where H_{Tx} and H_{Rx} are the directivity functions for the transmitter and receiver, respectively (note that the beam pattern, measured in dB, is equal to $20\log_{10}H$). The difference between the insonified volumes defined in (16) and (17) is often small.

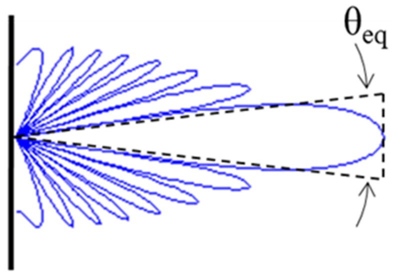

Figure 2-2 The beam pattern for a linear array (blue) and the equivalent beam (aperture φ_{eq}) that has unity amplitude inside its main beam and zero amplitude elsewhere.

2.3.4 Target strength of the seafloor: an extended surface target

Interface scattering strength

The term "scattering cross section" is still used when examining the target strength of the seafloor, but a bit more loosely. The convention in underwater acoustics is to define the scattered intensity from the seafloor as in (Jackson and Richardson, 2007):

$$\langle I_s(R_s)\rangle = \frac{I_i}{R_s^2} A\sigma \qquad (18)$$

where A is the insonified area on the seafloor, R_s is the range at which the scattered intensity was measured, and σ is referred to as a scattering cross section despite the fact that it is dimensionless according to (18). The TS of the seafloor is then

$$TS = 10\log_{10}(\sigma A) = S_b + 10\log_{10} A \qquad (19)$$

where $S_b = 10\log_{10}\sigma$ is the **bottom scattering strength**. The brackets $\langle\ \rangle$ on the scattered intensity in (18) represent an ensemble average, which means that the bottom scattering strength is what we would observe if we collected a large number of independent scattered intensity observations from a seafloor of a given type and averaged the result. The inherent notion in this treatment of the seafloor backscatter cross section is that **the physical process of seafloor scattering is a random process**.

As defined in (19), the bottom scattering strength is independent of the sonar properties (e.g., beamwidth, pulse length) with the exception of frequency, and is also a function of the angle at which the seafloor is insonified. As will be discussed more fully in the following section, S_b is dependent on several seafloor parameters including density, sound speed, interface roughness, and heterogeneities within the sediment volume. It is also worth noting that for most seafloor-mapping echosounders the attenuation is sufficiently high that contributions from the sediment volume can be described as a function of the insonified interface area, A, rather than an insonified volume (hence, we tend not to invoke a *volume* scattering cross section for scatterers within the sediment when considering seafloor backscatter, but rather an equivalent *interface* cross section).

Insonified area: long- and short-pulse regimes

If the sonar beam is oriented orthogonal to the seafloor (i.e., at normal incidence), the insonified area A can be limited by either the beam pattern of the sonar (defined by the -3 dB beamwidth or by the sonar’s equivalent beamwidth) or by the pulse length. The former occurs when the pulse is long enough that it occupies the entirety of the main beam upon reaching the seafloor (**long-pulse regime**). If the pulse is too short for this and only occupies a portion of the main beam, then the insonified area is at first a circle and then an annulus on the seafloor as the pulse propagates out in range (**short-pulse** regime) (Figure 2-3). We can determine whether we are in the long- or short-pulse regime by considering the geometry of the pulse footprint on the seafloor and comparing that with the 3-dB beamwidth of the transducer (Lurton, 2010). It is important to note that because the angle subtended by the pulse intersection with the seafloor is a function of depth, the same sonar can transition from long- to short-pulse regime just by changing water depth. It is also worth noting that for most multibeam sonars, the beams at or near normal incidence are in the long-pulse regime.

For a conical beam, the insonified area in the long-pulse regime is given by

$$A = \pi \left[D \tan(\frac{\varphi_{3dB}}{2}) \right]^2 \approx \pi \left[D \frac{\varphi_{3dB}}{2} \right]^2 \qquad (20)$$

where the approximation holds for narrow beams. In the short-pulse regime the insonified area changes as the pulse propagates through the beam. At the moment that the trailing edge of the pulse reaches the seafloor, it is defined by a circle whose radius is $\sqrt{(D+c\tau/2)^2 - D^2} \cong \sqrt{Dc\tau}$. The insonified disk area is then

$$A = \pi D c\tau \qquad (21)$$

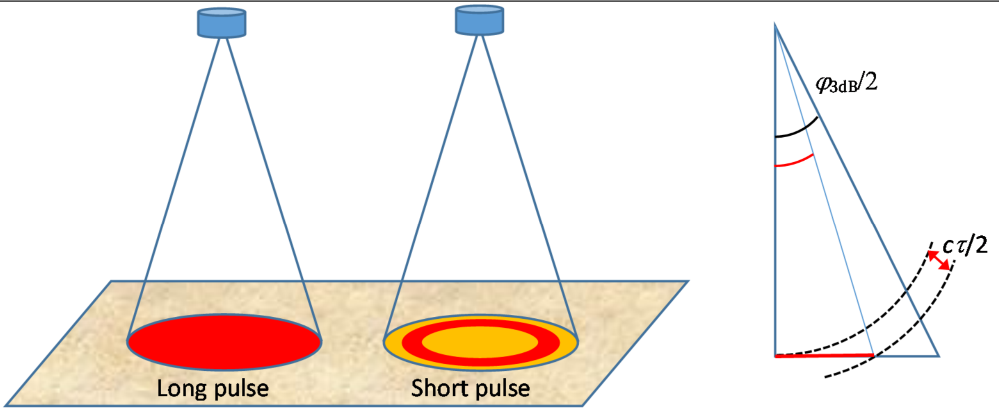

Figure 2-3 Geometry for the long- and short-pulse regimes for a conical beam at normal incidence. In the long pulse regime, the aperture corresponding to the pulse length φ_p is wider than the beam half-aperture $\varphi_{3dB}/2$; the entire beam can be insonified at once. In the short-pulse regime, only an annulus defined by the pulse length can be insonified at once.

The limit between the two regimes is given by the equality of (20) and (21), hence:

$$D_{Lim} = \frac{4c\tau}{\varphi_{3dB}^2} \qquad (22)$$

Regarding MBES, this D_{Lim} value is normally beyond the operating depth due to the narrowness of the beamwidth. For instance, with a 1°-aperture, a 1-ms pulse corresponds to a limit range around 20 km. Hence the long-pulse regime is the general rule for the nadir beam.

In the long-pulse regime, the signal footprint area given by (20) is proportional to the squared range D^2 (and more generally R^2). Combined with a transmission loss in R^{-4}, this results in a target strength proportional to R^{-2}, or -20log$R$ in dB.

Insonified area for a tilted beam

When the sonar beam is obliquely incident on the seafloor, the insonified area is governed by the pulse length (projected onto the seafloor) in one direction (typically athwartship) and by the 3-dB beamwidth $\varphi_{3\mathrm{dB}}$ in the other direction (typically the Tx sector aperture in the alongship direction) (Figure 2.4). Thus, the insonified area is a sector of an annulus, growing smaller with increasing incident angle and increasing proportionally to range, and is given in approximate form by:

$$A \approx R\varphi_{3dB} \frac{c\tau}{2\sin\theta} \tag{23}$$

where θ is the incident angle on the seafloor.

Said otherwise, the footprint is defined by both long-pulse (alongtrack) and short-pulse regime (acrosstrack). The tilt-angle limit for this short-pulse regime is given by the condition

$$D\varphi \frac{\sin\theta}{\cos^2\theta} = \frac{c\tau}{2} \tag{24}$$

Hence (23) is valid for angles beyond the limit angle given by (24). For example, considering an aperture of 1°, the limit is 22° for D = 100 m and τ = 1 ms; or 10° for D = 5000 m and τ = 20 ms.

Around $\theta = 0$ the approximation (23) is not valid anymore, and more detailed expressions have to be developed; however, for MBES with narrow beams, the signal extent on the seafloor is then practically limited by the beam aperture projected on the across-track direction, and the footprint is then given by a long-pulse condition.

The oblique-incidence footprint area A in (23) is then proportional to the oblique range R. Combined with a divergence loss in R^{-4}, this results in a target strength proportional to R^{-3}, or -30log$R$ in dB.

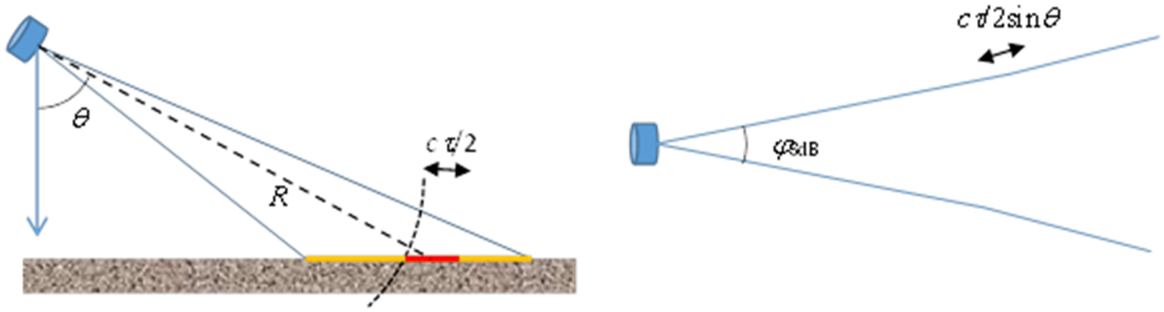

Figure 2-4 Footprint extent in oblique incidence geometry. The vertical cross-cut (left) illustrates the signal footprint extent at a given incidence angle; the horizontal (right) view shows the divergence with oblique range related to the beam horizontal aperture.

It should be noted that, as with the insonified volume for the extended volume targets, the **equivalent beamwidth** should be used rather than the 3-dB beamwidth. For example, (23) can be written as

$$A = \left[\int_{-\pi/2}^{\pi/2} H_t^2(\phi) d\phi \right] R \frac{c\tau}{2\sin\theta} = R\varphi_{eq} \frac{c\tau}{2\sin\theta} \tag{25}$$

For many seafloor mapping systems, the difference between φ_{eq} and $\varphi_{3\mathrm{dB}}$ is small. For example, the difference for uniformly weighted line arrays is around 10%, resulting in about a 1-dB error in the estimate of the TS.

2.4 Physical phenomena in seafloor backscatter

2.4.1 Reflection from a smooth surface

In a first step, we consider a sonar-generated sound wave impinging on a seafloor that would be flat and horizontal on average, but with a rough surface at a small scale. This simplified description neglects both seafloor topography, inner structure of sediments, and presence of heterogeneities (biological, mineral, gas, etc.). It is, however, sufficient for the comprehension of a number of fundamental notions and phenomena.

If the interface is sufficiently smooth, the incident acoustic wave is reflected along an angle symmetrical to the incidence angle and *away* from the direction of the arriving signal: this is the **specular reflection**. The intensity of this reflected signal is then only controlled by the “hardness” of the seafloor and the direction of arrival. Hardness is defined here as the contrast between the characteristic impedance of the water and the seafloor: for a given medium, the acoustical impedance is the product of density and sound speed. For a perfectly smooth interface, the reflected signal is an exact copy of the incident one except for the loss of intensity related to the wave that is transmitted into the seabed, and the interface acts as a mirror (*speculum* in Latin).

Obviously the projector and receiver must be physically separated in order to record this specular echo. This is the “bistatic” configuration used by low-frequency seismic reflections: thanks to the offsets of the receivers along the receiving streamers, the layered seabed can then be investigated according to a wide range of incidence angles (Lurton, 2010). The only exception to this requirement for physical separation is when the beam direction is perpendicular to the seafloor (i.e., at normal incidence), which is the working principle of the classic single beam echosounder. This normal-incidence echo also contributes to the signals recorded by multibeam echosounders, which project and receive sound over a wide range of angles; of a different nature from the oblique backscattered echoes, it raises a number of specific issues (both for bathymetry and reflectivity), especially penalizing in low frequency.

More formally, we can determine how much of the incident acoustic wave is reflected or transmitted by equating boundary conditions at the seafloor (e.g., at the boundary, the sum of the pressures associated with incident and reflected waves must equal the pressure of the transmitted waves - see Kinsler et al. (1999) for details). At normal incidence, the **reflection coefficient** (ratio of reflected to incident pressure) is governed by the contrast between the characteristic impedances $(Z = \rho c)$ of the seawater and the seafloor:

$$V = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} \tag{26}$$

Table 2-1 presents typical values of acoustical quantities (density, sound speed, absorption factor) corresponding to a variety of sediment types.

Table 2-1 Geoacoustical characteristics of typical sediments. Adapted from APL 1994, using the classical Wentworth scale for sediment nomenclature and nominal values for c1 and ρ1 (1500 m/s and 1000 kg/m3, respectively).

	Clay	V. Fine Silt	Fine Silt	Medium Silt	Coarse Silt	V. Fine Sand	Fine Sand	Medium Sand	Coarse Sand
Grain Size Mz(ϕ)	> 8	7-8	6-7	5-6	4-5	3-4	2-3	1-2	0-1
Density (kg/m^3)	1145	1147	1148	1149	1195	1268	1451	1845	2231
Velocity (m/s)	1470	1476	1479	1482	1523	1585	1661	1767	1875
Absorption (dB/λ)	0.08	0.11	0.17	0.37	1.18	1.02	0.87	0.89	0.89
V (0°) (dB)	0.058 (-24.8)	0.060 (-24.4)	0.062 (-24.2)	0.063 (-24.0)	0.096 (-20.3)	0.145 (-16.8)	0.233 (-12.7)	0.370 (-8.6)	0.472 (-6.52)
Critical angle (°) *(intromission angle)*	*(68.6°)*	*(71.2°)*	*(72.5°)*	*(74.0°)*	80.0°	71.2°	64.6°	58.1°	53.1°

According to (24), the higher the impedance contrast, the larger the reflected echo from the seafloor. The reflection coefficient can be either positive or negative, varying between +1 in the case of a perfectly rigid boundary $(\rho_2 c_2 \to \infty)$ and -1 in the case of a pressure release boundary (approximating the water-air interface). In the case of a soft, slow sediment like clay (much of the acoustic pulse is transmitted into the sediment and the reflection coefficient is weak (*V=0.255*). For denser, coarser sediments like coarse sand the reflection coefficient is more than two times higher.

At oblique incidence, application of boundary conditions (expressed for the normal components of the sound field) shows that the reflected wave is directed along the specular direction and the reflection coefficient is angle-dependent:

$$V = \frac{\rho_2 c_2 \cos\theta_i - \rho_1 c_1 \cos\theta_t}{\rho_2 c_2 \cos\theta_i + \rho_1 c_1 \cos\theta_t} \tag{27}$$

where the incident and transmitted angles, θ_i and θ_t respectively, are related by Snell's law

$$\frac{\sin\theta_i}{c_1} = \frac{\sin\theta_t}{c_2} \tag{28}$$

The oblique-incidence reflection coefficient is again dependent on the impedance contrast between the seawater and substrate, but is now dependent on both the incident and transmitted wave angles. Figure 2-5 shows examples of the reflection coefficient for both clay, coarse silt, fine sand, and coarse sand. In the case of the coarse silt and the sands, the reflection coefficient grows with increasing incidence angle until it reaches a **critical angle**, at which point all of the transmitted wave is reflected and only an **evanescent wave** (exponentially decaying) is transmitted into the seafloor. This condition is commonly met since most often the seabed has a sound speed faster than seawater (Table 2-1). For clay, slightly slower than seawater, for a particular high-incidence angle no sound intensity is reflected (**angle of intromission**).

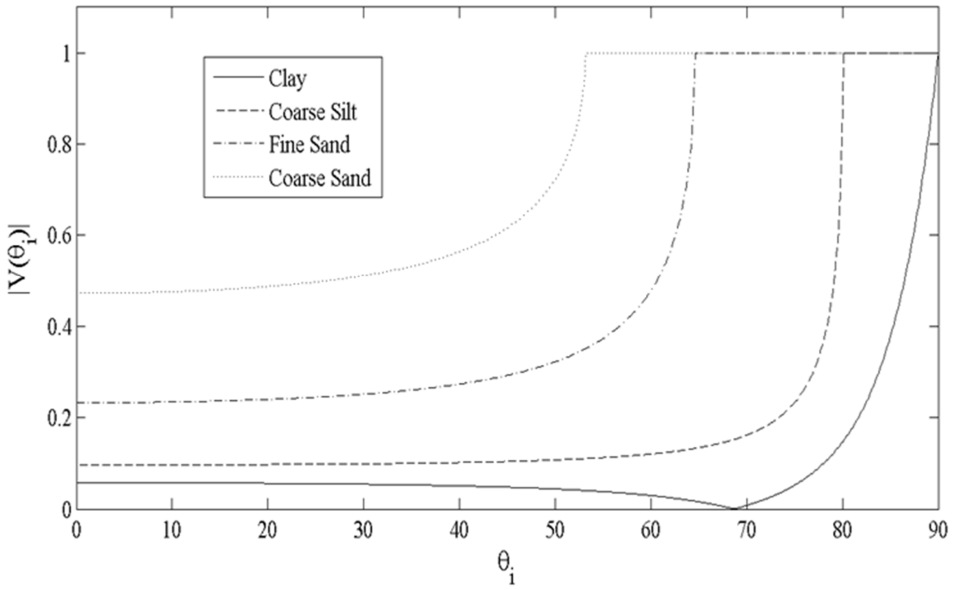

Figure 2-5 Angle-dependent smooth-surface reflection coefficient for clay, coarse silt, fine sand, and coarse sand using the properties from Table 2-1 and equation 2.27.

2.4.2 Seafloor roughness and its impact

In reality the seafloor is never perfectly smooth and the ideal specular reflection does not actually occur. Instead, the acoustic wave arriving at the seafloor is **scattered** around the specular reflection direction by the roughness features, which can heuristically be considered as small (compared to the signal wavelength) targets. The angular spread of this scattered wave (Figure 2-6) depends on the details of the roughness. For low-moderate roughness, most of the scattered wave is still concentrated around the specular direction and a lesser part occurs in the direction that is back toward the projector. Conversely, for high roughness, the incident wave intensity is significantly scattered in all directions, and the specular component vanishes. This **backscatter** gives rise to the acoustic echo and its presence, even at grazing angles, is the fundamental working principle for all swath-sounding systems (multibeam echosounders and side-scan sonars), which have a co-located projector and receiver. Although backscatter is often very low compared to the incident intensity, this returned echo proves to be still detectable and measureable.

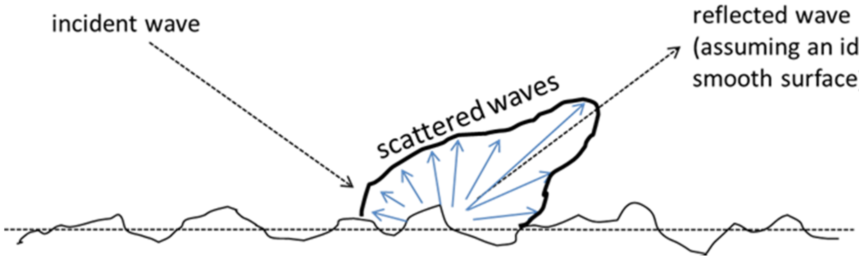

Figure 2-6 The reflected and scattered waves arising from the incidence of an acoustic wave upon a rough surface.

Seen by a sonar system, the interface **roughness** has to be considered in relation to the acoustic wavelength. For multibeam echosounders, wavelengths range from 12 cm (12-kHz deep-water systems) to 0.5 cm (450 kHz used for applications in coastal waters). Acoustic backscatter may be interpreted in terms of the "acoustic roughness", which is defined as the ratio of the geometrical roughness to the acoustic wavelength. If the geometric roughness is expressed as the standard deviation h of the seabed interface elevation, then:

- A **smooth interface** (Fig.2-7 *left*) corresponds to $h < \lambda$: the interface irregularities are much smaller than the wavelength and only slightly perturb the behavior of a perfectly smooth interface. This condition suggests that the specular reflection should be very high, and the scattered field very low.
- A **rough interface** (Fig.2-7 *right*) corresponds to $h > \lambda$: the interface irregularities are much greater than the wavelength and scatter a significant proportion of the incident power. For this condition, the "plane and smooth" character of the seabed interface disappears, the ideal specular reflection is greatly diminished, and more acoustic energy is scattered to all directions.

According to this definition of acoustic roughness, no seafloor is intrinsically rough or smooth – it all depends on the acoustic frequency considered. For seismic investigation using wavelengths ranging from 1 to 100 m, the seafloor (especially layered sediments) is very seldom "rough" compared to a wavelength, and considering mainly the coherent specular reflection from the seabed interface(s) is a valid approach for interpretation. On the other hand, for very high-frequency sonars roughness is significant at the millimeter-scale of sand grains. Here, the specular echo is likely diminished, most of the acoustic field is scattered over a wide range of angles, and interpretation of the echo from the seafloor involves consideration of the roughness.

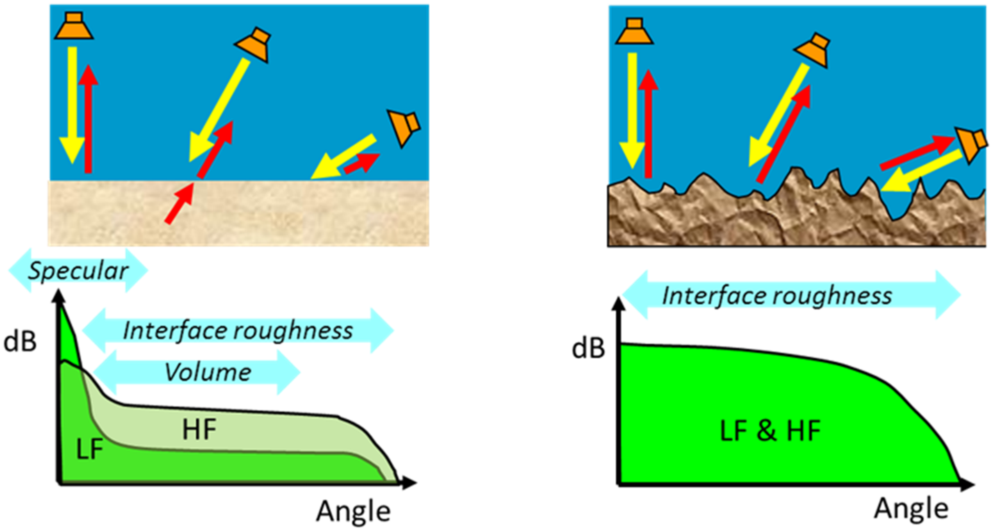

Figure 2-7 Angle dependence of the backscatter level in two typical cases. (Left) On a soft, fluid-like, sediment, a strong and narrow specular component, and a low contribution at oblique angles; this behavior is best marked at low frequencies (LF) compared to high frequencies (HF). (Right) On a rough/hard seafloor, the roughness effect is similar whatever the angle, excepted at low-grazing angle, and the frequency dependence is small.

Statistical description of the interface roughness

To more fully understand rough interface scattering, we need to characterize the roughness. The two common ways of describing a rough seafloor are by using a **probability density function** (pdf) that can be used to calculate central moments (e.g., the variance of the seabed height) or, alternatively, by using a **roughness spectrum**.

The roughness pdf essentially captures the likelihood of finding the seafloor some distance away from the mean (see Fig.2-8). It is usually modeled as a bell-shaped law, with its maximum at the average interface altitude.

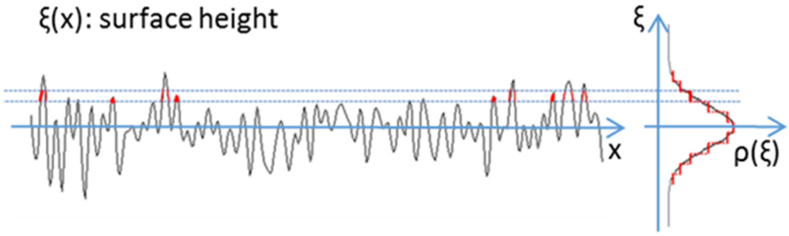

Figure 2-8 Probability density function of the profile of a rough interface characterized at range x by its elevation $\xi(x)$ related to the average depth of the interface. The probability is maximum of finding points around the average elevation, and decreases for extreme elevation values.

Alternatively, the seafloor can be described by using its **roughness spatial spectrum**, which presents the power associated with the various spatial components of the relief – exactly the same way as the well-known frequency spectrum describes the components of an acoustical time signal. The spatial spectrum may be composed either of discrete components (in rare cases of a very well organized harmonic-like relief – rare but not impossible, think of regular sand ripples caused by tidal currents); or of a continuum of frequencies. It is always decreasing for increasing spatial frequency, since the long-wavelength relief (e.g. sand dunes) shows higher amplitude than medium-scale (e.g. sand ripples) and small-scale roughness (e.g. sand grains).

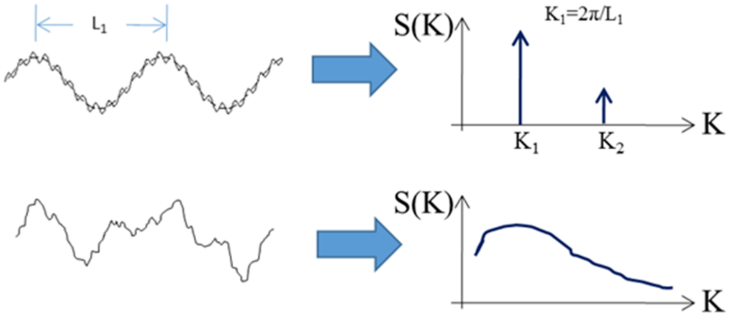

Figure 2-9 Spatial spectrum of a rough surface. The power spectrum, as a function of the spatial wavenumber, may be composed either of discrete lines (is the relief is a summation of a few sine contributions – see upper plot) or a continuum of components in case of a random relief (see lower plot).

In either case, what should be readily apparent is that seafloor roughness is generally considered as random, and so it should be expected that the scattered intensity will also be random. This should be true even if the statistics of the seafloor roughness are spatially stationary (i.e., the central moments do not change spatially), since on any single realization (or ping) we are only examining one configuration of the seafloor.

2.4.3 Coherent reflection coefficient

The presence of seafloor roughness changes the amplitude of the average reflected wave and gives rise to waves scattered in other direction (Figure 2-6). The most intuitive way to see this is in examining the average reflected wave (i.e., the coherent specular reflection), even though this is not actually the measurement we observe at oblique incidence. In comparing the wave reflected either from a randomly rough surface or from a perfectly smooth surface (at the average rough surface depth), we find that there is a difference in path length between the two waves. This difference in path length causes a phase-shift for the scattered wave, and the amount of the phase shift $\Delta\phi$ depends on the wavelength λ of the acoustic wave, the difference in height ξ between the actual (random) surface and the mean surface, and the angle of incidence:

$$\Delta\phi = \frac{2\xi\cos\theta}{\lambda}2\pi = 2k\xi\cos\theta \tag{29}$$

The overall scattered wave includes a large number of these phase-shifted returns: on average these contributions randomly interfere and reduce the mean intensity in the specular direction.

If the underlying distribution of excursions of surface height is known, it is possible to estimate the average observed reflected pressure. Assuming that the excursions are normally distributed about the mean (smooth) surface $\xi = 0$ with standard deviation h, the “coherent reflection coefficient” is equal to the reflection coefficient V that would be used for a smooth surface multiplied by a Gaussian function of the Rayleigh parameter $\eta = 2kh\cos\theta$ (Medwin and Clay, 1998)

$$\langle p \rangle = p_i V e^{-\eta^2/2} \tag{30}$$

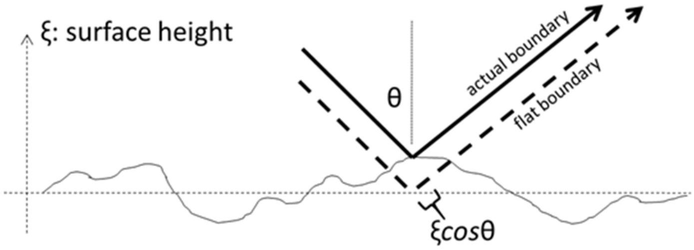

Figure 2-10 A plane wave impinging on a rough interface is reflected by the various points of the interface with differences in the geometrical propagation paths, raising phase shifts between the components of the resulting echo.

The higher the Rayleigh parameter, the smaller the coherent reflection will be and, consequently, the larger the scattered waves in other directions will be. The Rayleigh parameter is large when the surface is rough on scales of the acoustic wavelength (i.e., when kh is large); or, more specifically, on scales of the wavelength projected on the seafloor (i.e., when $kh\cos\theta$ is large). Because of the wavelength dependency, a random surface that appears smooth (i.e., small Rayleigh parameter) at low frequencies may look quite rough (i.e., high Rayleigh parameter) at high frequencies because of the difference in acoustic wavelength.

2.4.4 Basic treatments of rough interface scattering

The coherent reflection coefficient discussed in the previous section describes only the relative amplitude of the wave reflected in the specular direction. However echosounders are primarily concerned by the amplitude of the sound is in the backscatter direction. Modeling of this phenomenon is complex and has been the focus of many theoretical and experimental works (Jackson and Richardson, 2007; Ogilvy, 1987), in electromagnetism as well as in acoustics. In the following we browse the main –and affordable- approaches.

Elementary geometrical laws

The backscattering strength from a rough plane interface shows an intrinsic overall angle-dependence - in $\cos\theta$. This is a simple geometrical effect due to the interception of the incoming wave intensity by the apparent cross section of the reference area. According to this simple approach, a rough interface modeled as a spread of point scatterers radiating isotropically (no angle dependence at the scatterer's scale) and equally distributed over a flat average surface, shows an angle-dependent backscattering strength in (in dB):

$$BS(\theta) = BS_{0LS} + 10\log(\cos\theta) \tag{31}$$

This simple model is well-known in electromagnetism as the **Lommel-Seeliger law** (actually the Lommel-Seeliger model is more about the value of BS_{0LS} as a function of the scatterers characteristics). In underwater acoustics, it is a good description for e.g. coarse-grain seafloors at high frequencies, where the hypothesis of isotropic radiation of scatterers makes sense. The constant BS_{0LS} depends on the "reflectivity" of the interface – it is higher for harder seafloors.

When this hypothesis of isotropic scattering is found to be too simplistic, e.g. for smooth sediment interfaces, the local behavior of scatterers has to be accounted for: for instance, a cosine dependence (maximum backscatter at normal incidence, vanishing at zero grazing angles) shows a good intuitive behavior; combined with the previous cosine, it leads to a dependence in $\cos^2\theta$. This is the famous **Lambert law**, expressed in dB as:

$$BS(\theta) = BS_{0L} + 20\log(\cos\theta) \tag{32}$$

The Lambert's law provides a good approximation of angular backscatter from soft sediments at low frequencies – hence it is a good description for deep-water sediments measured from surface ships. Here again, the constant BS_{0L} depends on the "reflectivity" of the interface – it is higher for harder seafloors.

Actually neither Lommel-Seeliger's nor Lambert's law are expected to fit exactly measured angular responses of actual seafloor backscatter, and intermediate behaviors are to be met. Nevertheless, the $\cos\theta$ dependence, which is strictly geometrical, can be kept as the basic angle dependence: any interface backscatter strength decreases at least by this value. A natural way to go is to fit the experimental BS data with a dependency in $\cos^n\theta$, with $n \geq 1$.

Despite their simplicity (or perhaps because of it!), these power-cosine laws often yield a reasonable fit to data at oblique or grazing incidence. They do less well near normal incidence since they do not account for the specular effect (see, for example, Figure 2-11).

Facets reflection

For randomly rough seafloors at near-normal incidence, a relevant approach is to treat the seafloor as a set of facets (or tangent planes) tilted relative to the average interface plane. Only those facets for which the smooth-surface reflection is pointing in the backscatter direction significantly contribute to the return signal. Developing this idea would lead to a backscatter cross section given by (Brekhovskikh and Lysanov, 1982).

$$\sigma_{bs}(\theta) = \frac{|V(0°)|^2}{8\pi\delta^2 \cos^4\theta} \exp\left(-\frac{\tan^2\theta}{2\delta^2}\right) \tag{33}$$

where δ^2 is the variance in the distribution of facet slopes comprising the seafloor, and $V(0°)$ is the smooth-interface reflection coefficient evaluated at normal incidence.

Although there is a strong angular dependence in the facet model, there is no explicit frequency dependence. More formal developments (e.g., the Kirchhoff approximation, not discussed here) include a frequency dependence that suggests the scattered acoustic waves are much stronger at low incidence angles for low frequency waves, and more evenly distributed across incident angles at high frequencies. This makes some intuitive sense when considering that we have to divide a rough surface into locally planar facets– a condition that is easier to meet at low frequencies with longer wavelengths. At high frequencies, the distribution of facet angles becomes broader, meaning that relatively less energy is scattered back at normal incidence and relatively more energy is scattered at other incidence angles.

Bragg scattering

A more rigorous model can be developed for scattering from rough surfaces by applying boundary conditions at the rough surface, in similar fashion to what was described earlier with the smooth surface reflection coefficient but now expanded in a Taylor series around the average surface height to accommodate the rough surface. Doing so and restricting ourselves to terms that are first-order in quantity $k\xi\cos\theta$ (i.e. small values of the Rayleigh parameter used above) results in the so-called **small perturbation approximation**:

$$\sigma = k^4 \left|A^2\right| S(2k\sin\theta) \tag{34}$$

where S is the roughness power spectrum of the seafloor and is evaluated at the Bragg wavenumber, $2k\sin\theta$. For most seafloors, the roughness spectrum is proportional to the spatial wave number $\mathrm{K} = 2\pi / \Lambda$ raised to the minus 3 or 3.5 power. Because the roughness spectrum is evaluated at the Bragg wavenumber, which is dependent on k, then the overall frequency dependence of σ is somewhere between $f^{0.5}$ and f. This frequency dependence suggests that if the frequency of the echosounder is doubled, we would expect to get something on the order of a 3 dB increase in the target strength of the seafloor (all other parameters remaining equal).

This perturbation approximation method is not well suited to describing backscatter near normal incidence. This is intuitively reasonable if we consider the perturbation expansion that neglected terms that were second order and higher in $k\xi\cos\theta$, a condition that is harder to meet when θ is small near normal incidence. Conversely, the conditions for the facet model (i.e., fitting locally tangent planes to the seafloor that are large enough so that the normal incident reflection coefficient applies) becomes increasingly difficult to meet with larger incidence angles. Fortunately, it is at these angles that the perturbation approximation works best, and so some models blend the two results together. For both models the backscatter strength is dependent on the acoustic impedance contrast between the seawater and the substrate, and both depend on the statistics of the surficial roughness (which may or may not be isotropic).

Sediment Volume scattering

In addition to interface scattering, it is also possible to have scattering contributions from within the **sediment volume** itself. This can occur when there are “objects” placed within the otherwise homogenous sediment (e.g., gas bubbles, benthic animals or their burrows, shell fragments, mineral inclusions), and also when there are heterogeneities in the sediment matrix itself (e.g., slight changes in bulk properties, particularly sound speed or density, caused by stratification). These objects can be “reached” by the incident wave transmitted inside the sediment, and the echo is modified (e.g., it increases in amplitude) according to the impedance contrast of these objects compared to the surrounding sediment.

When considering scattering from within the sediment volume there are several items which we need to deal with including how much sound penetrates the seafloor (based on the transmission coefficient for ideally smooth surfaces and more complicated models for randomly rough interfaces), how far the sound penetrates (in-sediment attenuation varies typically from 0.1 to 1 dB/λ depending on the sediment type, see Table 2-1), the scattering from bubbles, crustaceans, etc., and the propagation back out of the sediment through the seafloor interface and back into the ocean again. The individual intrinsic reflectivity of these buried scatterers increases with frequency; but this effect is compensated by the absorption inside the sediment, whose effect increases also with frequency and hence limits the number of scatterers actually reached by the signal. This sediment volume backscatter is maximal at intermediate oblique incident angles. At steeper angles it is superseded by the specular effect, and at low grazing angles it is negligible due to the difficulty of the incident wave to be transmitted into the sediment volume. The volume effect is potentially **highest for soft sediments**, for which (1) the transmission from water into the seabed substrate is potentially high since the impedance contrast is low; (2) the in-sediment absorption is lower than for coarser-grained materials; (3) chances are that the substrate is colonized by animals or gas; and (4) the typically-low level of roughness-caused backscatter emphasizes, comparatively, the contribution of the sediment volume.

When incorporating volume backscatter into the scattered intensity we might observe, we simply add the volume backscatter cross section to the interface roughness backscatter scatter cross section, assuming that the two are uncorrelated. It is difficult to develop general models for the volume backscatter cross section simply because of the variety of conditions we might expect to encounter and their complexity, but this is still something we must consider when interpreting backscatter observations. In fact, volume scattering can be the dominant contributor to S_b, in particular for soft sediments at oblique incidence and low frequencies where the contribution to surficial roughness (at the wavelength scale) is low and where heterogeneities are prone to exist in the substrate. Further complicating matters are layered seabeds, particularly where a hard (and/or rough) substrate exists below a thin soft layer. Separating all of these potential contributors to seafloor backscatter in order to identify the features of interest for a particular application is a non-trivial undertaking.

2.5 Putting it all together: what we observe from the seafloor

2.5.1 *Combined model*

The various ideas above regarding reflection and scattering from the seafloor can be (and are) incorporated into models that describe the seafloor backscatter strength at all angles. For example, researchers at the Applied Physics Lab at the University of Washington (APL, 1994) have developed a model that uses the Kirchhoff approximation near normal incidence, a composite-roughness model (which can be thought of as applying a perturbation approximation to small-scale roughness with an incidence angle based on a tilted seafloor, thereby accounting for both small- and large-scale roughness) away from normal incidence, summed together with a volume backscatter model. Model inputs include the densities and sound speeds of both seawater and sediment, parameters describing the roughness spectrum (both magnitude and wavenumber dependence, and estimates of how "lossy" and heterogeneous the sediment is). Coupling in the sonar equation the bottom backscattering strength with an estimate of the insonified area, we would write

$$TS = BS + 10\log_{10} A = 10\log_{10}(\sigma_r + \sigma_v) + 10\log_{10} A \tag{35}$$

where σ_r and σ_v are the backscatter cross sections for respectively surficial roughness and te volume (Jackson and Richardson, 2007). The end results for *BS* are predictions such as those shown in Figure 2-11 for a frequency of 100 kHz and for substrates varying from very fine silt (soft bottom with high penetration, low roughness) to rough rock (hard bottom with little penetration, high roughness)[1].

2.5.2 *Angle dependence*

One of the important predictions of these models, which is borne out in experiment, is the strong angle-dependence of the seafloor backscatter. Close to vertical, the specular reflection phenomenon takes over, and this is the direction of the most intense echo level from the seafloor. Seafloors composed of smaller grain-size sediments (e.g., silt and clay) tend to have low roughness, and in these cases the influence of the specular reflection decreases very quickly with increasing incidence angle. The smoother the interface, the more pronounced the specular regime is (i.e., highest level relative to oblique incidence angles, and the narrowest angular sector for the specular region). At oblique incidence angles, the scattering effect dominates because few, if any, facets of the seafloor point back towards the echosounder.

At oblique incidence angles, the angular dependence is generally small. The backscatter level is primarily controlled by the interface hardness (impedance contrast) and roughness; for soft sediments, this is the angle range where volume backscatter is at its highest. This "plateau" regime presents many advantages for seafloor-type mapping, thanks to its stability and to the good separation that is observable between various seabed types.

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[1] It should be noted, regarding this synthetic model (APL, 1994), that (1) the volume contribution finally depends upon a volume parameter which has to be adjusted empirically and (2) the rough seafloors (gravels, pebbles and rocks) are modeled using heuristic fits issued from experimental records, instead of theoretical formulas, and which are parameterized *similarly* to the soft sediments. This illustrates well some of the limitations and paradoxes of today's theoretical models.

At very low grazing angles, the backscatter response of the seafloor collapses as (1) the seafloor intercepts little (per unit area) of the acoustic power available to it; (2) the roughness response decreases; and (3) shadowing effects appear, decreasing the effective backscatter cross section.

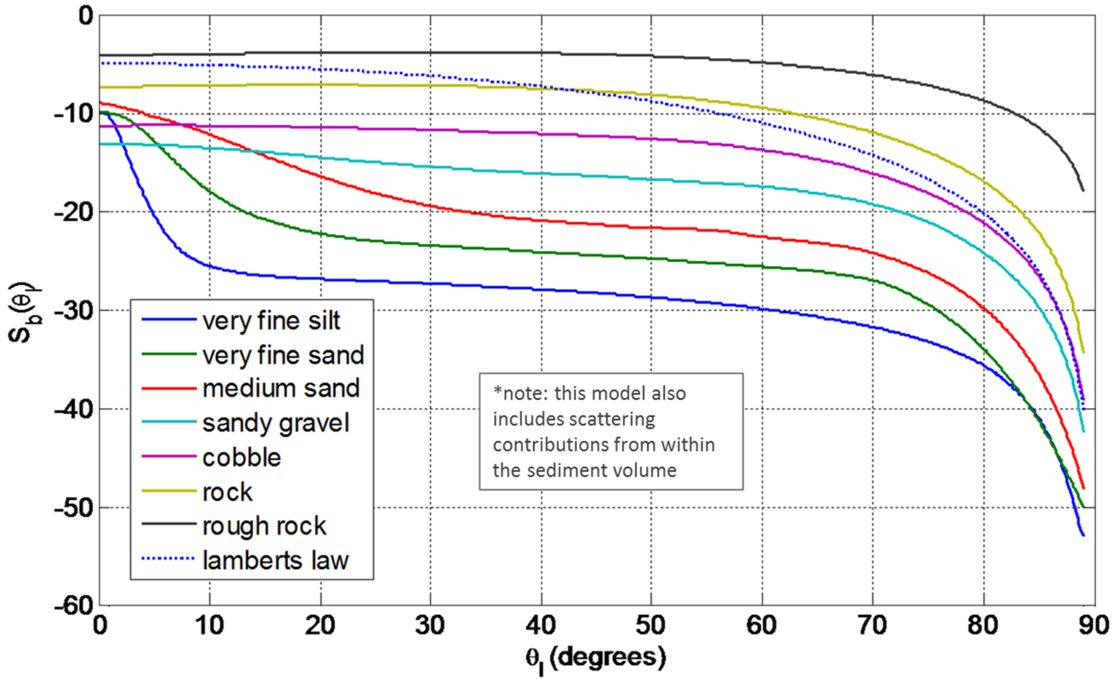

Figure 2-11 Example of angle-dependent backscatter for different substrate types at 100 kHz, based on model results using the APL-UW High-frequency Ocean Environmental Acoustic Models Handbook, APL-UW TR9407 (1994).

The most favorable angle sector for BS measurement appears to be the “plateau” regime. This explains why backscatter mosaics often “normalize” angle-dependent backscatter to a reference value taken within this range of angles: the idea is to replace the slow angle variation of the plateau regime by no variation at all, after an appropriate compensation – and to affect one value measured at a reference angle (40° or 45°). As a result, a geologically homogeneous area will appear with a constant BS (on average) – the way it should have been recorded if the whole swath width would have been insonified at a constant angle.

2.5.3 Frequency dependence

The predictions shown in Figure 2-11 assume a frequency of 100 kHz. It has already been suggested that a smooth surface at low frequencies may look rough at high frequencies. This frequency-dependent behavior is also predictable by models, as shown for a medium-sand seafloor in Figure 2-12. The same surface that looks smooth at 30 kHz, with a high specular reflection and a low oblique incidence scattering (dominated, in this case, by volume scattering), provides a much more uniform (with angle) backscattering strength at 400 kHz where the wavelength is an order of magnitude shorter. Over this decade of frequency, Figure 2-12 suggests that the seabed response should change by as much as 7 dB at oblique incidence, and by nearly 14 dB at normal incidence. These ranges are rough guidelines: the exact frequency dependence should depend on characteristics of the roughness spectrum.

Taken together, the predictions shown in Figure 2-11 and 2-12 suggest some caution must be taken when interpreting seafloor backscatter measurements collected with MBES. Current MBES collect data over a wide range of incidence angles (0°-65° or more) and have the ability to change frequency by an octave or more. These changes in incidence angle and geometry are likely to manifest themselves as changes in seafloor backscattering strength that if left non-accounted for could provide for significant errors in interpretation.

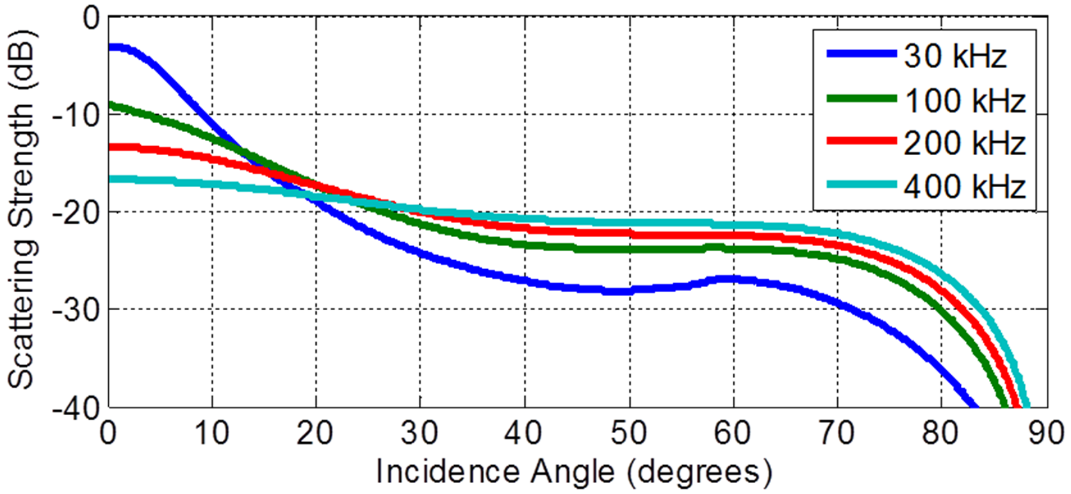

Figure 2-12 Example of angle-dependent backscatter for medium sand at different frequencies, based on model results using the APL-UW High-frequency Ocean Environmental Acoustic Models Handbook, APL-UW TR9407 (1994).

2.5.4 Seafloor-type classification

Beyond the advantageous stability of the plateau regime, predictive models such as those shown in Figure 2-11 suggest that the best separation between sediment types occurs at these intermediate oblique incidence angles. In fact, some sediments that may yield a nearly indistinguishable echo near normal incidence (e.g., very fine silt and medium sand) may be separated by 5-10 dB in oblique incidence. Errors in interpretation observed when comparing data collected over a wide range of incidence angles (including the specular zone) can hence be avoided if the comparison bears only on the oblique incidence area.

Otherwise, both models and field observations show that, at a given angle, the BS values obtained for the variety of possible seafloors may vary over a 20-30 dB range. Hence a classification over a ten of classes is realistically achievable, assuming a spacing of 2-3 dB between classes.

Practically it is then recommended, for optimized results in seafloor classification from BS angular levels, to limit the analysis to angles from 15° to 60°-70°, hence avoiding both:

- the specular zone, with instable values and unclear separation between various seafloor types;
- grazing angles, where the signal/noise decreases, and where the quality of the bathymetry measurements degrade, making uncertain the seafloor slope estimation.

However, if multi-frequency data become available, it could be interesting to exploit the specular response as well; the frequency-dependence of its contrast with the plateau level could be potentially an interesting classifying feature.

An interesting point to mention is that space-borne side-scan radars recording the backscatter from the Earth's surface (Ulaby and Long, 2014) limit their scanning to the angle sector corresponding to the plateau regime: specular and grazing angles are systematically discarded. The averaged BS values are classically normalized by the value at 40° incidence.

2.5.5 Individual echo structure

The model predictions presented here describe the backscattering strength from the seafloor observed *on average*, at a fixed angle and frequency, and for a permanent signal, and also do not fully account for the detailed interaction of the beam on the seafloor. The perception through recorded time signals may be not so straightforward.

Normal incidence

For example, at normal incidence we might get an echo "trace" similar to that shown in Figure 2-13. In this figure, the amplitude of the echo from the seafloor ramps up quickly after the leading edge of the pulse reaches the seafloor, and then becomes constant for a short time under the assumption that the return from the seabed is beam-limited (i.e., in the long-pulse regime). After the trailing edge of the pulse reaches the seafloor the echo amplitude decays quickly and becomes governed by the beam pattern of the transmitting and receiving arrays and by the angular response of the seabed. The return from the seafloor interface (black line in Figure 2-13) is likely to have its amplitude lower than that which would be predicted when considering the smooth surface reflection coefficient alone – this is caused by scattering which redistributes some of the energy to angles way from the specular direction. The amount of energy redistributed in this manner will depend on the roughness – for very smooth surfaces, the reflection coefficient may be nearly realized and for very rough surfaces the difference may be very large. If volume scatterers are present, they might add to the return from the seafloor and could plausibly even lead to a scattered return that was higher than that which would have been predicted by the normal incidence, smooth-surface reflection coefficient. The sophistication of this echo envelope shape makes it a potentially good descriptor for seafloor characterization; it has been actually used in trials of seafloor classification using single-beam echosounders (Pouliquen and Lurton, 1992).

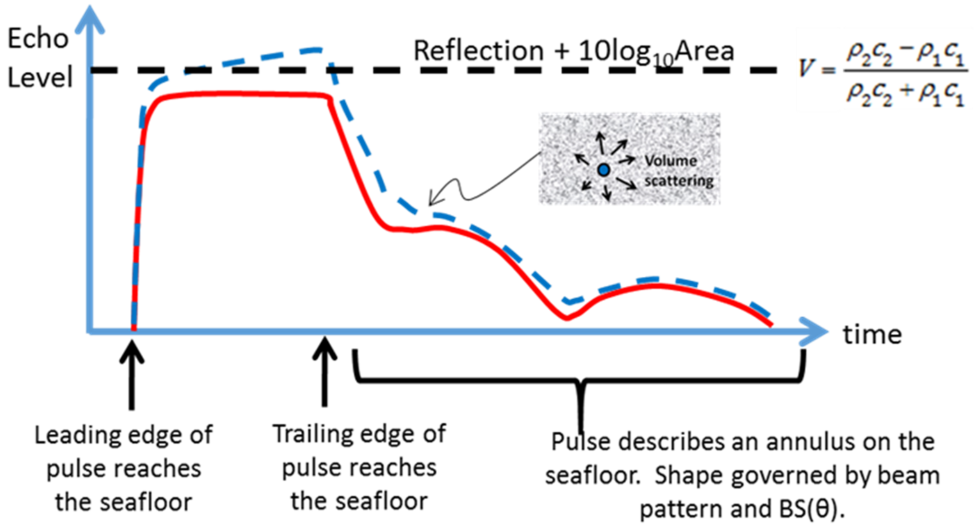

Figure 2-13 A notional echo "trace" corresponding to the return from a nearly flat seabed at normal incidence.

Oblique incidence

At oblique incidence (Fig.2-14), the pulse received inside a beam interacts with the seafloor well before it reaches the beam maximum response axis, and then propagates through the beam in such a fashion that it produces a "scallop" shape. The return from the seafloor tends to be much more extended than it is near normal incidence, and the amplitude of the return is weighted both by the intrinsic scattering properties of the seafloor and by the beam pattern of the receiver (for a typical MBES). The result is an elongated echo from the seafloor, the record of which is often called a "snippet"; MBES use most often phase-differencing techniques to find the range corresponding to the beam steering angle in order to create bottom detection in this regime. One of the features of the data example in Fig.2-14 is that the scattered return from the seafloor appears random. In fact, examination of a large ensemble of independent measurements of backscatter from the seafloor would result in measurements of echo amplitude that span up to 20 dB even at the same location on the beam and even if the seafloor were statistically identical throughout the measurements (Fig.2-15). This is because scattering from the seafloor is an inherently random process: the summation of backscattered contributions from a continuum of surface or volume of elementary point scatterers with random-like phases cause a strongly fluctuating combination (e.g. according to a Rayleigh law, if the scatterer contributions have all similar intensities). This random character helps explain the requirement to average over a region of measurements when generating a crisp-looking seafloor backscatter mosaic.

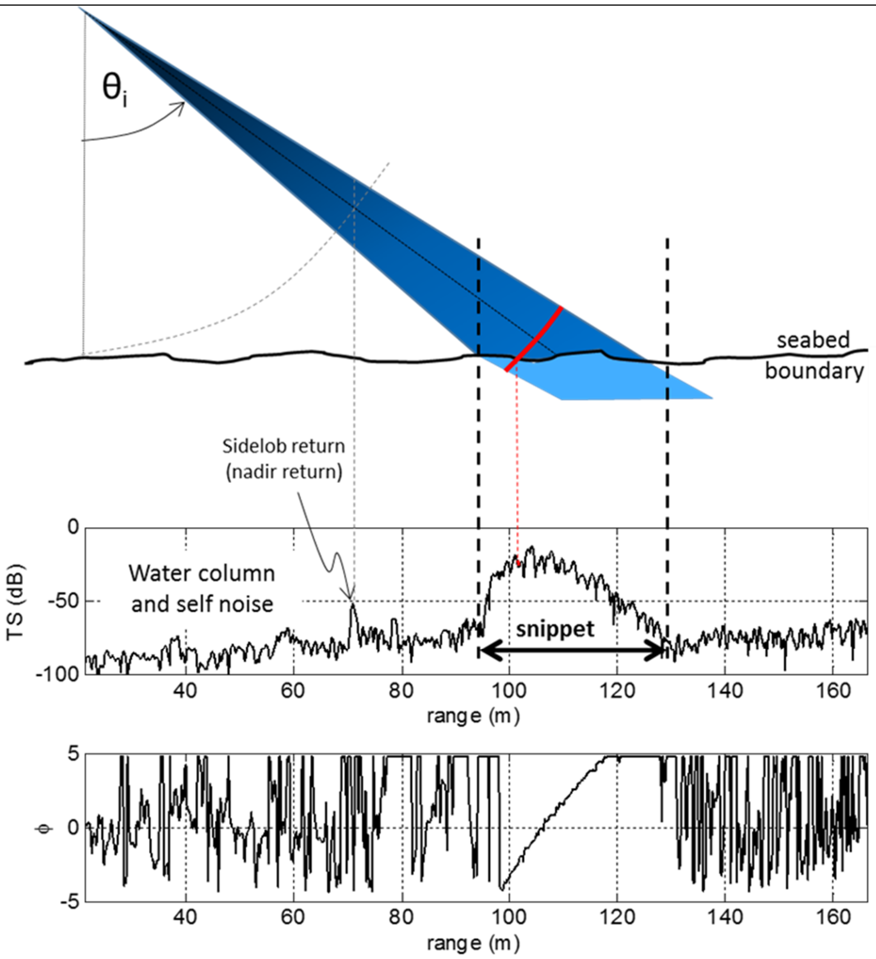

Figure 2-14 An example of the interaction of a pulse at oblique incidence and the generation of a snippet.

2.6 Summary

This chapter has focused on understanding the acoustic processes associated with the measurement of seafloor backscatter. We have employed the sonar equation (2.8) in order to convert a received echo into a seafloor target strength, and recognized the need to further decompose the target strength into an insonified area (delimited by the sonar beam and signal) and a bottom backscattering strength (inherent to the target) per unit area of seafloor. It is the bottom backscattering strength that can be used to characterize the seabed in a way that is the most independent of the system used to make the measurement. Even when recovering the bottom backscattering strength there are still strong dependencies on the angle and frequency of insonification that must be accounted for, particularly when comparing measurements made from different locations and/or sonar systems.

In general, scattering is controlled by the acoustic impedance (hardness or softness) and the surficial roughness of the seafloor and the presence of heterogeneities on or immediately beneath the seabed layer itself including gas bubbles, shell fragments, and living organisms. Many of these characteristics that control the amplitude of the acoustic echo from the seafloor are of interest to those who wish to characterize the seafloor to understand, for example, its efficacy as a habitat for marine organisms: this raises the possibility of inverting the acoustic measurements for relevant seafloor properties, and indeed gives rise to the motivation for the work addressed in this monograph in general. It should be cautioned, however, that some of the influences can become confused: for example, a silty bottom may be predicted to have a high specular reflection and weak oblique incidence backscatter, but if it contains an appreciable amount of gas inclusions it may give an angular response that appears similar to a much rougher substrate. The models and descriptions provided in this chapter should serve to guide a reader’s intuition when analyzing seafloor backscatter, but care must be taken to avoid over-analysis. Ground-truthing backscatter with direct samples or optical sensors is likely to always remain a necessary requirement. Still, few sensing techniques offer the synoptic view afforded by acoustic echosounders.

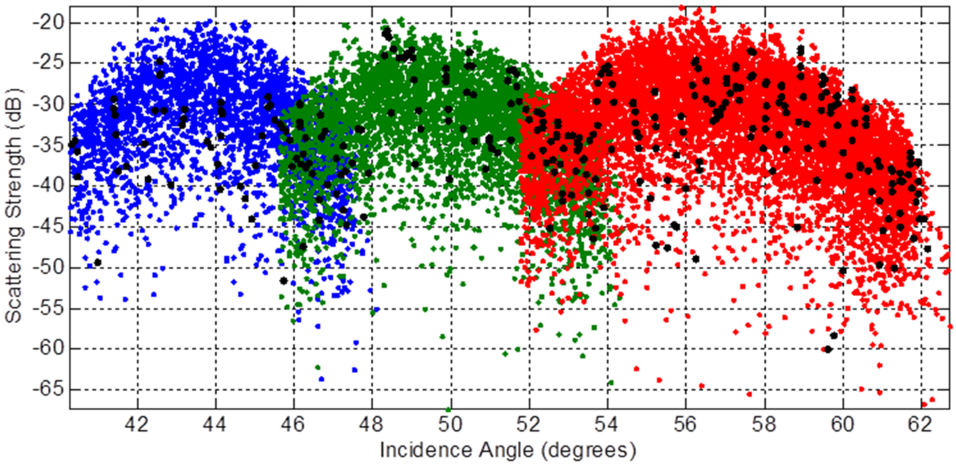

Figure 2-15 An overlay of snippets collected from a featureless, fine-sand seabed in the Eastern Bering Sea. Each color (blue, red, green) shows the snippets collected from a single beam from several 10’s of pings. This type of variability in the seabed echo is expected even for a homogenous seafloor, and is typically removed (by averaging) during the generation of a backscatter mosaic.

Regarding models and their use, a cautionary remark is that most of today's physical theory of seafloor backscatter is designed for a canonical configuration of a limited (although significant) complexity: usually a fluid substrate with an isotropic roughness. However many actual configurations cannot be realistically described under this approximation. Other configurations, although the most frequent especially in shallow water, are approached today at a very different level of sophistication: rough rock relief, pebble spreads, broken shells, coarse gravels, sea weeds, benthic animals… contrasting with the over-detailed models developed for the theory of scattering by a rough interface. Theoretical modeling is extremely useful in the sense that it makes understandable the dominant phenomena and their parameters, and helps to provide orders of magnitude. However, applying theoretical models to inversion processes must be done with the utmost care, since the hypotheses of the model may not fit the reality of the observed physical object - and this cannot be known in advance.

We have examined here seafloor scattering in an ideal sense. In practice, one is most often faced with imperfect knowledge of both the environment (e.g., water column properties) and the systems operated (e.g., sonar sensitivity). This chapter is really about the early stages of the measurement. Chapter 4 will address how our measurement system (the echosounder) necessarily manipulates the acoustic wave into a measurable, and hence recordable, signal. Chapter 5 will show how far we must go in order to do a reasonable job of stripping out the effects of the sonar system and environment in order to recover useable processed results (e.g., a backscatter mosaic).

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CHAPTER 3 SEAFLOOR BACKSCATTER USER NEEDS AND EXPECTATIONS

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Abstract

In this chapter we discuss the needs and expectations that the multibeam community has for backscatter data. The foundation of this chapter is to identify these needs and how MBES backscatter is utilized in the community at present, and the aspirations the community has for the data in the future. This review focuses on the different processing procedures employed to extract useful information from MBES backscatter data and the intentions that the community collects the data for. This discussion is divided into two themes: acoustic signal processing and acoustic image processing. The outcomes of this chapter illustrate the various backscatter output products that are generated from the different processing procedures and how these results are taken up by the diverse disciplines. We summarize the popular ancillary data types that are used to validate the backscatter interpretation and examine the differences between ground truth data and classification validation data. In the conclusions to this chapter we briefly explore some potential common data formats for archiving backscatter based on the data user's diversity of applications and metadata requirements.

3.1 Introduction

The objective of this chapter is to highlight the individual disciplines that utilize MBES backscatter data and the expectations that they have for backscatter end products. This information was sourced from an international survey conducted between May and August 2014 whereby the authors initiated a questionnaire starting with the GeoHab Community (Marine and Geological Habitat Mapping). From this survey ninety seven responses were received and this data forms the foundation to construct the evidence and reference for the challenges and utilization of MBES backscatter within the international community. We explore the 'user communities' different requirements for the data- mapping for discovery (relative level measurements) and mapping for monitoring (calibrated absolute level measurements). We discuss the broad spectrum of traditional and innovative applications backscatter data has utility in and how this influences the processing procedures, signal processing or image processing. We highlight the different output products that the community finds useful for their particular discipline and the limitations that they currently have with backscatter data. To conclude we provide recommendations for metadata requirements to accompany MBES backscatter data for the future, now that much more data is being collected routinely around the world.

3.2 Users of backscatter- the past, the present and the future

In recent years we have continued to see advancement in MBES technology which has further enhanced an already valuable source of seafloor data. These advances have come out of traditional user groups extending the application of the data to meet new requirements and from the motivation of new user groups wanting to employ the technology. This wide ranging and ever growing community of MBES users are adapting and extending the potential of MBES data to address unique applications. MBES users have traditionally included hydrographers, navigators, engineers, marine geologists and military planners; but now we see the extension of the technology to meet the needs of maritime explorers, archaeologists, fisheries biologists, geomorphologists and ecosystem modelers to name a few.

To assess the diversity of the multibeam users and how they employ MBES backscatter data, a user survey was conducted in 2014. The questionnaire (Appendix 4) was advertised through GeoHab and online forums such as “LinkedIn”. The survey was sent to 400 users and a total of 97 responses were received (25 % response rate). Of the community that responded the representation was 41% from the public service (government agencies), 24% from universities, 31% from private companies and the remaining 4% was made up from military and government agencies.

The traditional use of MBES backscatter data has relied essentially on the qualitative interpretation of the backscatter ‘waterfall’ or backscatter ‘mosaic’. Relevant information would have been extracted by hand-drawing lines (digitizing) around features of interest in the MBES backscatter imagery. Qualitative data extraction existed prior to the development of image processing software that was able to deal with the nature of highly textured backscatter imagery (e.g., large artefacts at nadir, intensively speckled images…). The outputs of such analysis would have been single-scale interpreted maps which, although basic, would have still provided a wealth of information regarding the continuous nature of benthic substrates or features of interest. Over the past decade we have seen the refinement of backscatter data and backscatter mosaic images thanks to data acquisition improvement, nadir artefact reduction and image compensation and filtering, the result of both technological advancement in hardware and software. The improvements in backscatter data quality have come from the joint advantages of a) precise co-registration of backscatter with the MBES bathymetry data set, b) improved signal-to-noise ratio compared to conventional imaging sonar; and c) an increased resolution of the physical measurements, leading to a smaller pixel size for the final products. As seafloor backscatter imagery has improved and the scales of features that are able to be defined become smaller and more spatially accurate, we see the user groups expanding in a variety of disciplines; ocean science (geoscience and biology), fisheries research (species distribution modelling), hydrocarbon detection and exploitation; and offshore construction and coastal engineering. This expansion has also coincided with backscatter processing methods becoming quantitative and the classification of MBES backscatter data becoming more robust. This expansion is also related to commercially available backscatter processing software offering greater diversity and more user friendly interfaces whereby “end products” can be easily integrated into mapping projects. The characteristics of these improvements, alongside the variety of digital export formats that the data can now be accessed, have shown how backscatter data has increased to becoming a valuable asset for data users as they seek to image, understand and possibly monitor the undersea environment.

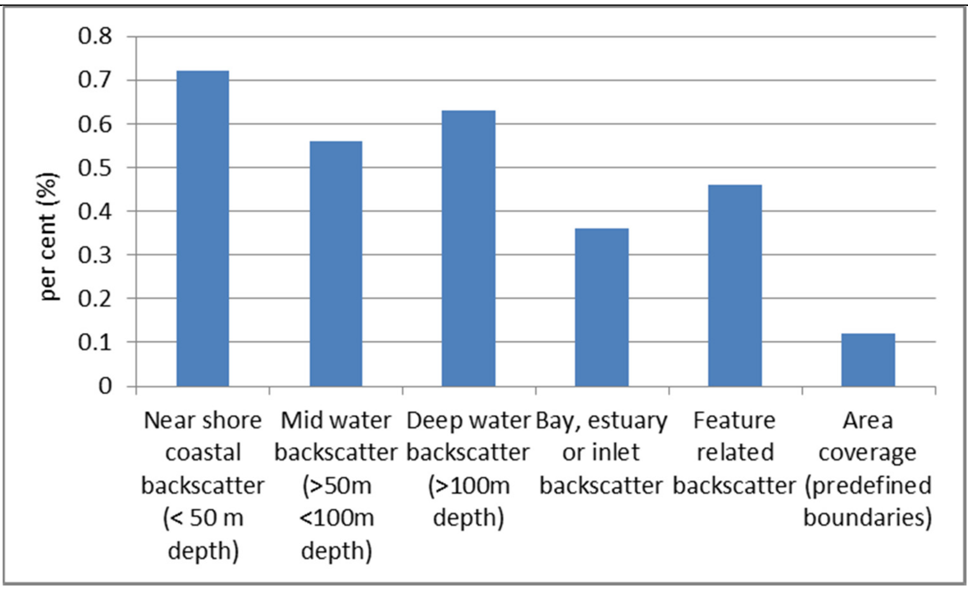

Figure 3-1 Backscatter survey responses to question 3a "What are the marine zones of interest for your work unit with the last five years?"

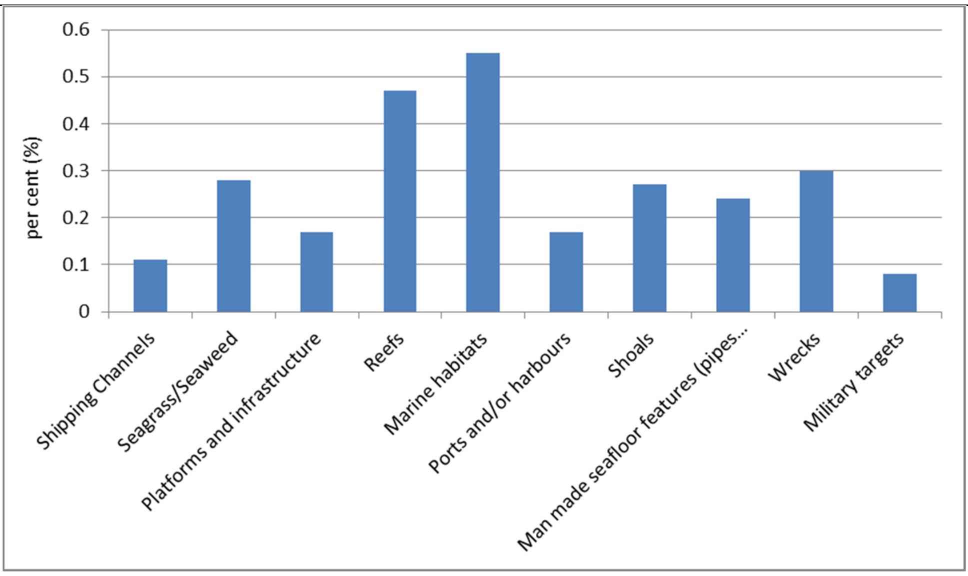

Figure 3-2 Backscatter survey responses to question 3b "What are the main Backscatter features of interest?"

The user needs survey revealed specific details regarding the utility of backscatter within the community (Figures 3-1, 3-2 and 3-3). Within the last five years the marine zones of interest where MBES backscatter data has been the most utilized is the near shore coastal zone (< 50 m water depth) to identify marine habitats (specifically reef systems). Data currency (as to when the data was collected) seemed of less relevance as long as it was collected within the past 10 years (which is likely when the greatest advances in backscatter data collection have developed). The resolution of the gridded data was preferred to be at 1m (likely for coastal research) and 10 m for areas greater than 100 m depth.

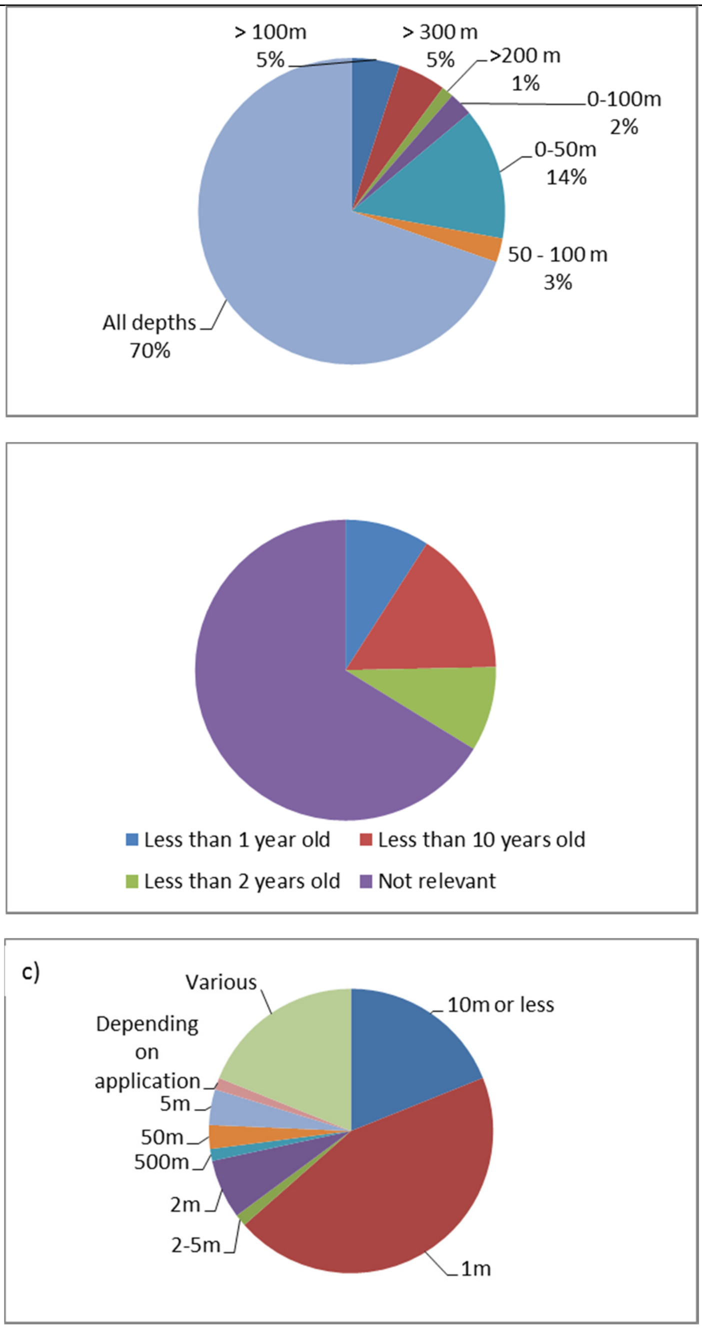

Figure 3-3 Responses to the backscatter survey questions a) 7a 'What is the main bathymetric are of interest"? b) 7c "What data currency important to your surveying application" and c) 7e "When gridded, what resolution of data do you mostly require?".

One of the difficulties for establishing standardizations for operating with multibeam backscatter data if the reference to a wide variety of discipline backgrounds of the user community (Figure 3-3) where the acoustic technical knowledge required for backscatter interpretation varies greatly. Not only is this a product of user training but also user experience with MBES backscatter. Question 2b of the survey asks 'how many years people had been working with backscatter data' with the results showing that majority of users had between 2-5 years of experience (30.5%) followed by 6 -10 years of experience (28%) and 11-20 years of experience (24.4%) and more than 20 years of experience (12.5%) and less than 1 year (4.8%).

3.3 Users' objectives

In this section we address the different user needs and we discuss these relative to ‘mapping for discovery’ (single pass) and ‘mapping for monitoring’ (multiple pass) surveys.

As discussed in Chapter 4, the intensity value (in dB) of the backscatter return will vary depending on the acoustic processing method. In terms of ‘mapping for discovery’ the stability and precision of the backscatter measurement is of a lower demand due to the end-user objectives of only acquiring one time series of data over the survey region. In Figure 3-4 we have identified applications that require only a relative measure of backscatter level against those who require an absolute dB scale, i.e. a value that is calibrated, accurate and stable.

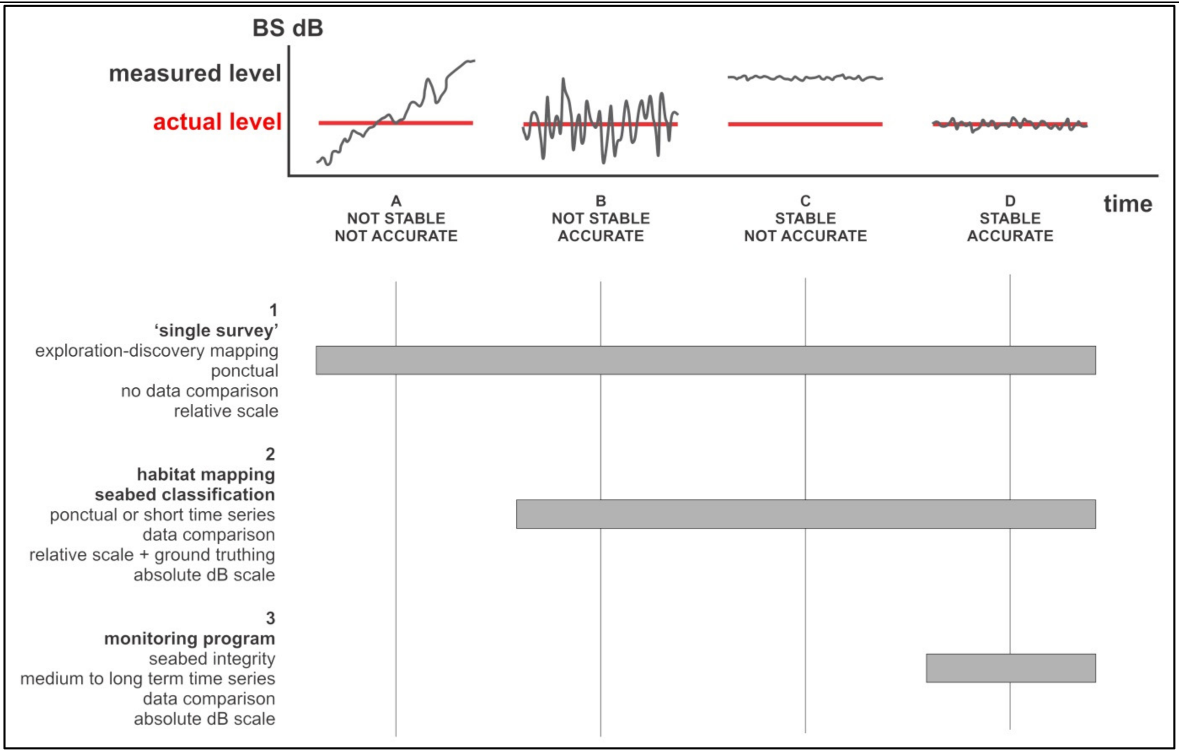

Figure 3-4 Levels of stability and accuracy required for MBES backscatter measurements according to final objectives.

In the first column (Figure 3-4-A) backscatter data are collected from a single survey where there is no planned intention to constitute a long-term time series of data nor to compare them later with data from the same (or different) MBES systems. In this domain (a ‘single pass’ exploration map), users focus primarily on the data processing techniques in order to obtain a high-contrast artefact-free backscatter image that can be used to identify and classify substrate boundaries between different types of seabed and or habitats. The other columns in Figure 3-4 rely on higher degrees of accuracy in the backscatter acquisition and output; they will be discussed in the section for user need requirements in ‘mapping for monitoring’.

Mapping for monitoring objectives require successive measurements of backscatter at the same site under evaluation, in order to observe objectively the sedimentary evolution over time on the medium to long term. The vast majority of users who use backscatter to perform habitat mapping (either coupled with or without data classification at control samples) lies somewhere between the two poles (A) and (D) of Figure 3.4.

3.3.1 Mapping for discovery (relative level- single survey).

Here we refer to 'mapping for discovery' as a single survey of MBES acquisition where the MBES is being employed to map the seafloor, usually for the first time, and where the resolution and scale of the data being generated is inherently maintained to meet the objectives of the survey. In mapping for discovery there is no planned ongoing program to collect data at the same location in the immediate future. In applications for mapping for discovery; the MBES data will form part of the seabed survey and video, sediment grabs/cores, sub-bottom profile information may all be simultaneously collected. These surveys are common to benthic habitat mapping programs that are exploring the seafloor and collecting data on species habitats and facies distribution. In this configuration the MBES backscatter data would be valued for the descriptive image that it gives of the seafloor – alike to side-scan sonar images which provide a high degree of resolution of the surficial sediment composition but a poor geometrical accuracy and intensity control. So the backscatter data recorded in such a context is unlikely to be analyzed as a quantitative reflectivity in dB. Mapping for discovery relies on the cartographic quality requirements of the backscatter (which is indeed insured by MBES), rather than on the accuracy in intensity levels. Within this approach a coarser resolution (meter scale or larger) is sufficient for the mapping purpose.

3.3.2 Mapping for monitoring (calibrated –absolute level)

In this context a strict evaluation of the multiple sources of variation that can affect the mean backscatter level from one measurement to another is mandatory to the application. We refer to Chapter 2 (Background & Fundamentals), Chapter 4 (Backscatter measurement by bathymetric echosounders) and Chapter 5 (Acquisition: best practice guide) where sources of variation in the backscatter are addressed. As surveyors and end-users of backscatter data, it is important to emphasize that some sources of variations can occur and translate into discrepancies in the backscatter image that are not readily apparent by analysis of the sonar equations given in Section 2.2. In order to use backscatter for monitoring changes in the nature of the seabed, potential external sources of variation must first be clarified. A first category of variation can happen on board the vessel and include such causes as aging antennas, antenna surface condition, potential (but not measured) influence of water column (turbidity, bubbles etc.), platform motion, direction of navigation in relation with seabed morphology and biofouling of the transducer head (these external sources of variation are discussed in Chapter 5: Acquisition; a best practice guide). Further variations can be introduced at post-processing time through standardization of procedures relevant for the monitoring task – consistency in post-processing software and workflows.

Users of 'mapping for monitoring' specifically need to address:

- Stability of the dB values: monitoring and control of variability and sources causing discrepancy;
- Repeatability: quantitative comparison between different surveys over for example a reference surface (patch test);
- Accuracy: estimation of the measured level of uncertainty with which to provide the ability to detect changes in the seabed environment over that of mapping uncertainty.

For geoscientists (geologists, geographers and biologists) the impact of poor accuracy and stability constraints in the backscatter measurements depends on their specific objectives and applications. The requirement to compare data acquired by a MBES over time at one specific location by the same sensor will be determined by the particular application. There is great advantage for scientists to work with calibrated MBES systems especially as more data is collected and a need arises that these data be merged to generate large geographic coverage. Calibrated and stable data in dB values allows for data comparison, data merging and the ability to use these data to detect natural or human-caused effects and changes on the seabed. Generating calibrated dB values implies that a number of 'best practices' in acquisition must first be implemented (*see* Chapter 5).

From a quantitative point of view, a key issue for all MBES users is the accuracy of the backscatter strength (BS) measurements. Currently, there is no formal quality level scale (such as those IHO standards that exists for bathymetry) for the BS and consequently no standardization in reliability for the dB values. However, the evaluation of the variance associated with the average level measured with a MBES on a given area may be addressed by a series of successive measurements during a short period of time. Figure 3-5 illustrates this type of testing for a given system. In this configuration, the variance between the average levels of BS measured in the same area during a tidal cycle of 12 h is practically negligible (std dev. ≈ 0.1 dB) meaning that over a short period of time the average level of BS is fully stable.

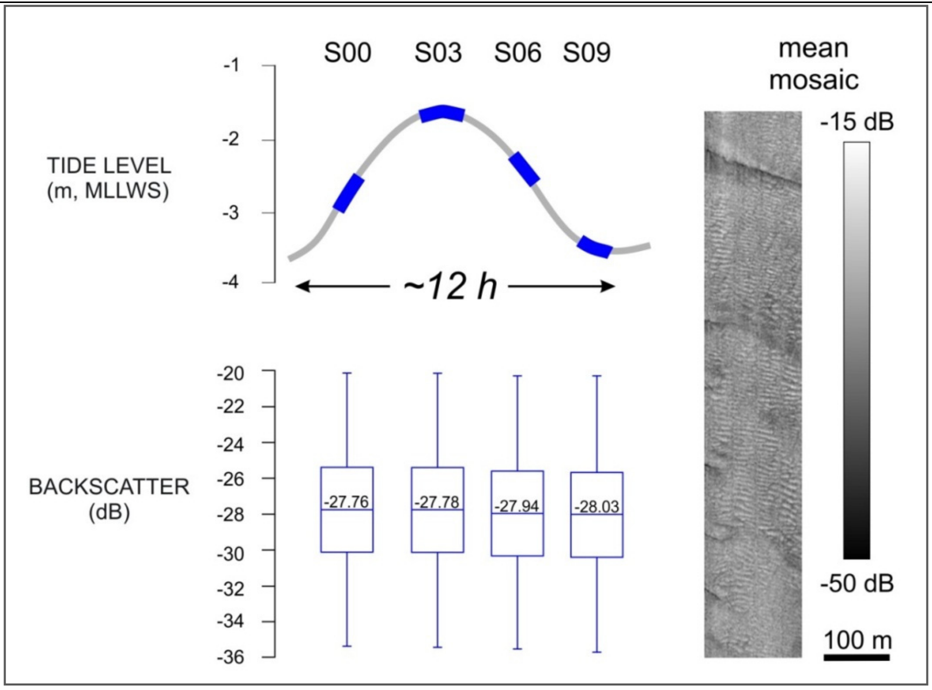

Figure 3-5 Evaluation of Backscatter Strength (BS) variance from successive measurements during a tide cycle (~12h); 4 surveys of the same area with constant input and runtime parameters; boxplots of the BS data with mean values; for the four data sets, the statistics are calculated from each mosaics values (resolution = 1x1m) on the common rectangular area presented in the figure; very low dispersion of the 4 mean values: standard deviation = 0.1 dB; data from Kongsberg EM1002 MBES on RV Belgica.

The magnitude of the required accuracy of BS measured by MBES with the aim to discriminate sediment classes can be appraised from the known Applied Physics Laboratory (APL) model which "employs a mixture of theory and data fitting and use the same set of bottom parameters" (APL, 1994). For an acoustic system at 100 kHz, the APL model shows the relationship between the BS level and the grazing angle for different sediment types (assuming a flat seabed) (Figure 3-6). For each sediment type, the strong angular dependence of BS causes a very high dispersion of measurements around the mean values with an average standard deviation of 13 dB. The average difference between the mean BS levels of the different sediment types is 2 dB for the entire angular range and 3 dB for the most discriminating angular part, from 30° to 60 ° grazing angle (plateau of the curves, the

"MBES BS paradise"). In terms of accuracy, it may be considered that 1 dB (half of the mean difference) is in the order of magnitude of the accuracy necessary to discriminate the classes of sediments on the basis of their mean BS response in the grazing angle angular sector of 30° to 60°. Such 1 dB level of accuracy should always be ensured and certified in the technical specification of a MBES system and perhaps in the future, within the metadata of MBES output products.

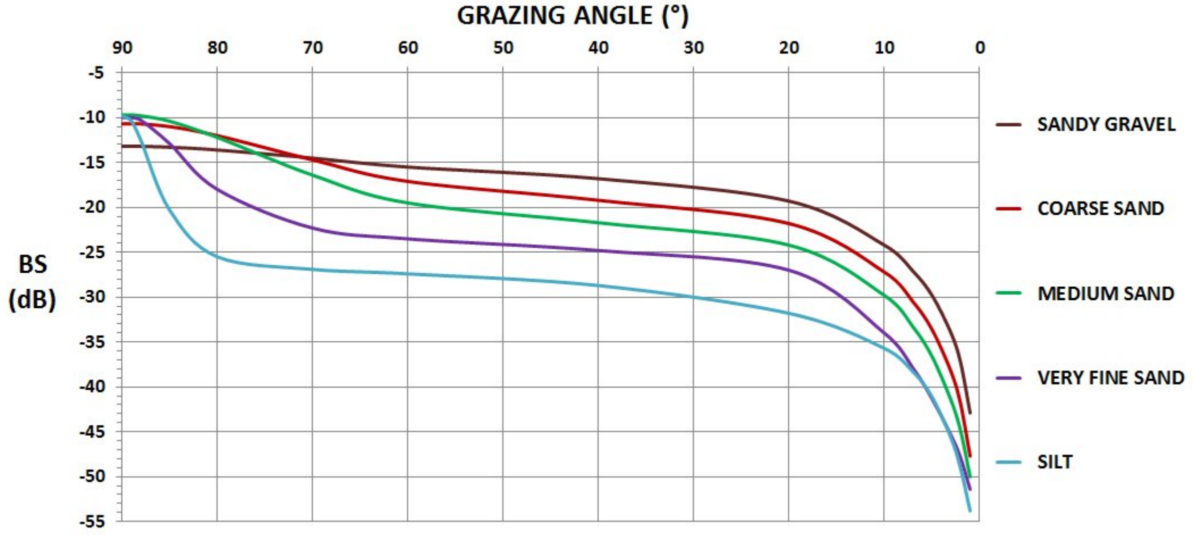

Figure 3-6 Backscatter Strength (BS) versus grazing angle for different classes of sediment at 100 kHz. Data from: University of Washington Applied Physics Laboratory, high-frequency ocean environmental acoustic models, APL-UW TR 9407-AEAS 9501, October 1994.

Processing software may be a significant source of variation in dB levels. As shown in Figure 3-7, using the same set of data, different processing software can generate radically different dB values. The difference of dB levels between the software is not a simple bias: its magnitude varies with the seabed type, up to 10 dB (= 5 times the average difference between the mean BS levels of the different types of sediment at 100 kHz). It should also be mentioned that for the same software different methods and settings used for the mosaic calculation can also generate substantial changes in the dB values. In particular, mosaics generated from the same data, but calculated from beam time series or beam averaged values show differences in mean levels that can exceed 2 dB. Standardization of processing algorithms is a real challenge today for using the backscatter to monitor seabed sediment variations. High variations between data from various processing software seriously hamper the possibilities of exchange and comparison of backscatter data among geoscientists. This has important consequences for users responsible for long-term monitoring programs. These results provide a clear example of the need to standardize the processing protocols so that when using the same software the data are uniformly and consistently processed. With currently available software and the absence of standardized processing protocols backscatter data must be systematically processed according to the same procedure with the same software to maintain internal consistency.

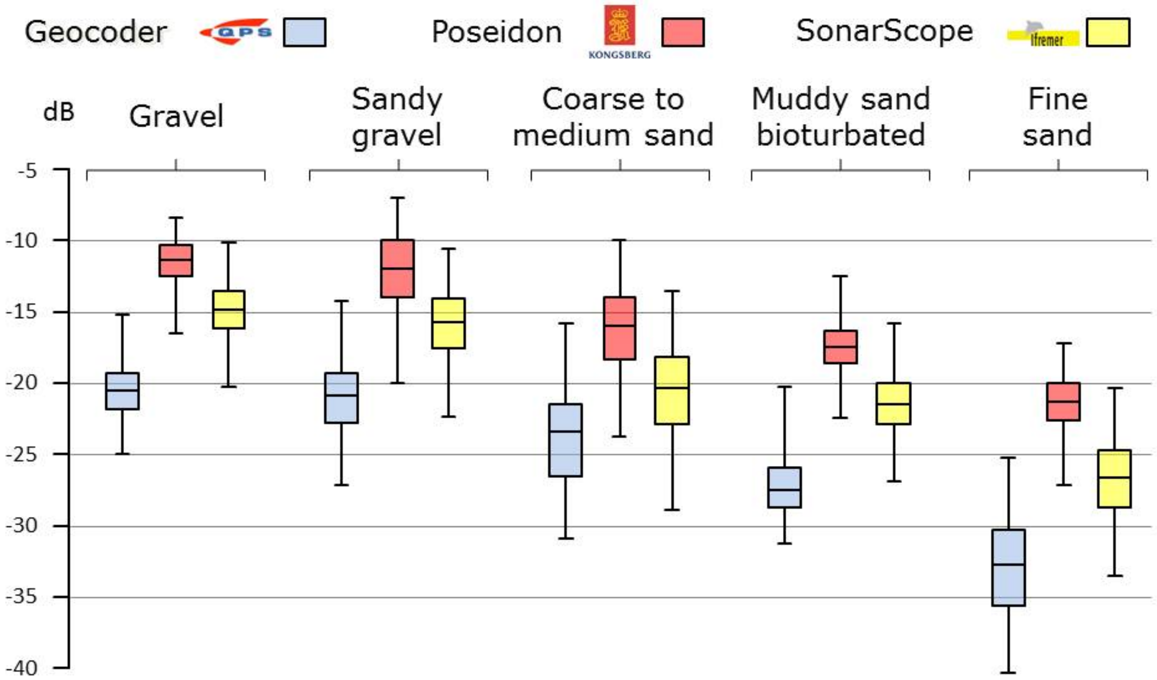

Figure 3-7 Comparison of 3 processing software; same dataset surveyed on different type of seabed on the Flemish sandbanks area; Kongsberg EM3002D MBES on RV Belgica; Data from campaign 0906 – 26/02/2009; Processing: Geocoder: 1x1m mosaic using beam time series and defaults settings (Tx/Rx power gain correction, beam pattern correction, calibrated backscatter range and AVG correction); Kongsberg Maritime Poseidon: 1x1m mosaic using beam averaged BS, 2D interpolating filter set on 3, footprint size set on 50%, histogram correction 100%; SonarScope: 1x1m mosaic using beam averaged backscatter, global compensation using BS versus Tx angle mean curve; boxplots computed for each mosaic (same area for each sediment type).

Water column properties (bubbles and turbidity) will affect the backscatter values at the interface recorded by a MBES system (even with a calibrated MBES). This remains a major issue in coastal areas as well as in deep waters. For monitoring programs it is absolutely necessary to answer the question: how does the mean backscatter amplitude variation, from one survey to another, reflect the significant changes in the seabed properties and are not a result of changes in the conditions of the water column (increase turbidity during changing currents near the seafloor, migration biology, increased occurrence of micro bubbles in the sea surface due to wind, ...)? Repeated surveys with a multidisciplinary approach combining MBES and ADCP measurements, optical measurements of sediment load near the seabed, turbidity sensor chains rising into the water column and water samples should be organized in the future in order to assess the influence of the water column on the backscatter at a given location and time.

For monitoring applications it should be mandatory that an absolute calibration be followed by regular control of the stability of the mean BS level. This should be completed and recorded on a reference site with the multiple sources of variation that can affect the mean BS level from one measurement to another (see chapter 5, 5.2.2.2 Relative calibration).

3.3.3 Spatial resolution

For MBES backscatter users, a proper understanding of the significance of backscatter values in terms of spatial resolution is needed to take full advantage of backscatter data. Controlled by the acoustic signal itself (wavelength and bandwidth) and the beam geometry, the intrinsic spatial resolution of a MBES is not constant. Inside each beam, the backscatter time series corresponds to the successive echo intensities returned from a finite area of the seafloor inside the beam footprint, function of the pulse length, the beam width along and across track and the slant range (see chapter 4 for details).

Several criteria can be used to define the spatial resolution of the final backscatter mosaic. A rule of thumb is to consider that the average resolution of the mosaic must, as far as possible, reflect the actual average spatial resolution as defined by the along and across dimensions of the footprint. The artificial increase of the resolution during the mosaicking process can create a misleading impression of extreme resolution to end users and stakeholders. However, in shallow waters, backscatter raw data from modern MBES, large numbers of narrow beams and very high ping rate, can be used to generate mosaics of increasingly fine resolution, up to tens of centimeters. Such ultra-high resolutions allow a precise characterization of biological and sedimentary facies but are traditionally used for local explorations and monitoring programs.

A useful approach for the next generation of backscatter processing software would be to adjust the mosaic resolution accordingly with the actual raw backscatter spatial resolution with the ultimate goal to vary pixel sizes across the georeferenced backscatter grid.

Some of the most important issues that users should address with regards to their MBES backscatter data include:

- What is the finest resolution that can be expected from the backscatter data considering the specific parameters of the system and environment (e.g., depth)? It is important to keep in mind that it is not principally the size of the footprint (beam width + depth) that determines the optimal spatial resolution, but that other factors come into account.
- The output grid resolution will depend on the need for the scale or resolution of the intent of the survey. For example, with a scale of 1:10000 (standard for geological maps), 1 mm on paper = 10 m on the ground. Since the human eye can perceiving around ½ mm, a resolution of 5m is sufficient in this case, and it is not necessary to compute mosaics with finer resolutions even if the initial data allows it. Yet, despite this evidence there seem to be a real push for obtaining the highest possible resolution from many users even though it does not fit the survey purposes.
- Statistical comparisons show that the average level in dB does not depend on mosaic resolution. When considering the BS mean level (e.g., for a monitoring program), it is unnecessary to compute mosaics of very fine resolution (e.g. 0.5 x 0.5 m).
- These expectation compare to radar data where satellites operate both SAR (with meter-resolution for very detailed imaging) and scatterometer (with kilometer-resolution, for averaged backscatter)

3.4 Processing procedures

A host of seafloor studies have used seafloor backscatter data in different and complementary ways. Although it is difficult to include representative studies from every different backscatter application, some of the well-known methods used for backscatter seafloor discrimination (based on the level of BS), are compiled in Table 1. Processing procedures can be broadly divided into signal processing and image processing methods. Signal processing focuses on data represented in angular or time space where the raw amplitude of returned signals is preserved. With image processing methods the backscatter signals are modified (flattened) to produce smooth looking image mosaics. Backscatter processing procedures applied for signal and image processing are detailed in Chapter 6 (Processing Backscatter Data: From Datagrams to Angular Responses and Mosaics). Here we describe the common ‘users’ concerns with products from either of the two processing procedures.

Table 3-1 A synopsis of the different ways seafloor Backscatter Strength (BS) has been used

Measure of MBES BS	Computed from	Studies that have used this method
Angular response [signal processing]	Averaging N pings over the swath and comparing with theoretical models	Fonseca et al., 2005 Jackson et al., 1986
Angular response after segmentation based on mosaics [signal processing]	Angular range analysis extracts features from mean BS angular curves and compares with theoretical models	Fonseca and Mayer, 2007 Fonseca et al., 2009
Statistical analysis of angular curves [signal processing]	Linear discriminate analysis /Principal component analysis/ clustering	Parnum, 2007 Hamilton and Parnum, 2011
Angular response characteristics within nº of angular curve [signal processing]	Mean intensity, BS mean slope, second derivative,	Hughes Clarke et al., 1997
BS fluctuations as a function of incidence angle [signal processing]	Shape factor of K-distribution	Hellequin and Boucher, 2003 Le Chenadec and Boucher, 2007
Mosaic analysis / Thematic clustering [signal processing]	Averaging NxN grid cells obtained after normalizing at a particular angle and segmenting areas with similar mean BS	Dartnell and Gardner, 2004 Lamarche et al., 2011
Power spectral methods [signal processing]	Power spectral classification works specifically along the ping azimuth, deliberately avoiding high grazing angle data and can be used to attempt to classify multiple sediment types within a single swath.	Pace and Gao, 1988 Tamsett, 1993 Lurton et al., 1994
Textural methods such as Gray-Level co-occurrence matrices (GLCM) [image processing]	Image segmentation of changes in textural values from the derived BS image.	Pace and Dyer, 1979 Reed and Hussong, 1989 Imen et al., 2005 Lucieer & Lamarche, 2011 Lucieer et al., 2013
Mosaic: Bayesian approach [image processing]	Analysis of distribution of the BS	Simons and Snellen, 2009
Fractal analysis [image processing]	Analysis for modeling topographic relief based on 2-D spatial spectrum analysis that confines the variety of modeling spectra within a single class of fractal spectra. The shape of a fractal spectrum is defined by only two parameters, which are a fractal dimension, and a cut-off wavenumber that determines the roughness correlation length. In the general case of an anisotropic surface, the cut-off wavenumber is different along X and Y directions.	Linnett et al., 1991 Carmichael et al., 1996
Probability density function (PDF) [image processing]	Used as a posteriori for outlier detection.	Stanton, 1984 de Moustier, 1986 Alexandrou et al., 1992
Hybrid techniques [image and signal processing]	Using a combination of the above techniques along with the features extracted from the seafloor bathymetric data e.g. slope, roughness	Foster, 2014

3.4.1 Signal processing

Signal processing uses the parameters (shape, amplitude, angular variations etc.) of the seafloor returned echo. The output of signal processing may be backscatter presented in the time domain or the angular domain. Time domain signal processing has been widely used in single beam echo sounders where amplitude of the first and second return from the seafloor (E1 and E2) is used to characterize the seafloor. Time domain signal processing of the multibeam has not gained popularity. Instead the majority of users rely on angular dependent variations of the backscatter. The variations in the backscatter with angle (incidence angle at the seafloor) are an inherent property of the backscatter that can be exploited to differentiate between the seafloor types. The angular curve can be corrupted if appropriate geometric and radiometric corrections are not applied (Figure 3.8). Significant changes in the amplitude or the shape of the angular curve can be the result due to incorrect corrections related to TVG, seafloor slope correction, transmission losses and adjustments for transmit and receive characteristics of the sonar used. To generate a stable backscatter angular curve, several swaths (or pings) are averaged together although care has to be exercised to avoid averaging angular curves that are collected over more than one seafloor type. Segmented areas of backscatter mosaics can be used as an aid in the selection of the swaths or parts of the angular curve that are to be used in the averaging process thus avoiding contamination of the backscatter from different seafloor types. The correction of the backscatter angular response overall (Figure 3.9) or in sectors (Figure 3.10) will drastically reduce the strong along track artefacts.

Once the angular response curves have been obtained, these can be compared to modelled seafloor surfaces or to classified ground truth data to characterize the seafloor into various classes (Figure 3-6). Further processing may be required to simplify this procedure by extracting features that can be used more easily as an input to inversion models. For example Fonseca et al. (2009) divided backscatter angular response into near, far and outer response (Figure 3-11).

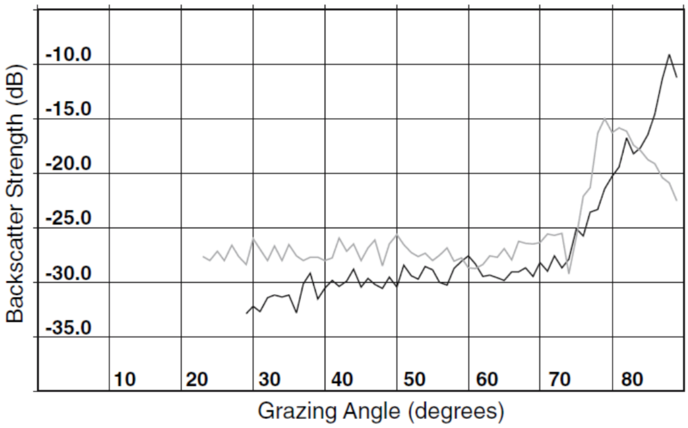

Figure 3-8 Backscatter Strength (BS) angular response of a small patch on the seafloor, acquired by a Simrad EM3000 multibeam sonar. The gray line shows the original observation and the black solid line the BS angular response after all the geometric and radiometric corrections were applied. Note that the seafloor had a considerable slope, so that the maximum BS in the original observation was not at nadir but at a grazing angle of 80. (Figure from Fonseca and Mayer, 2007).

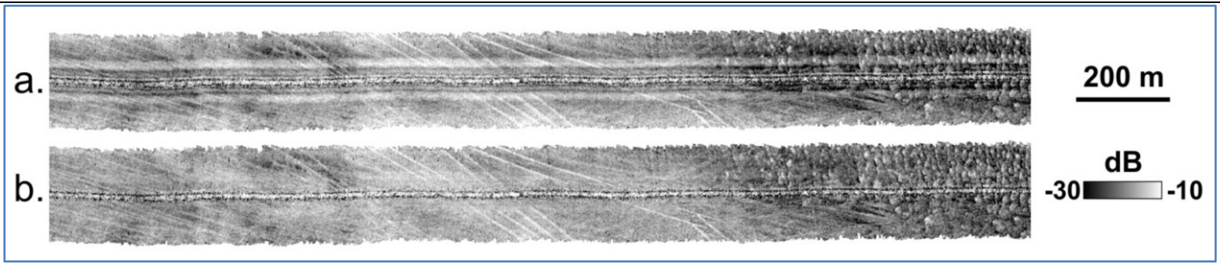

Figure 3-9 Correction of backscatter angular response and beam pattern. a: Raw data as delivered by the manufacturer note the along track clear strips around 55°. b: After correction using an average intensity versus transmit angle; note the good overall quality of the compensation. Light across track lineaments correspond to trawl marks. Data from EM3002d of RV Belgica, backscatter processed with Ifremer SonarScope software.

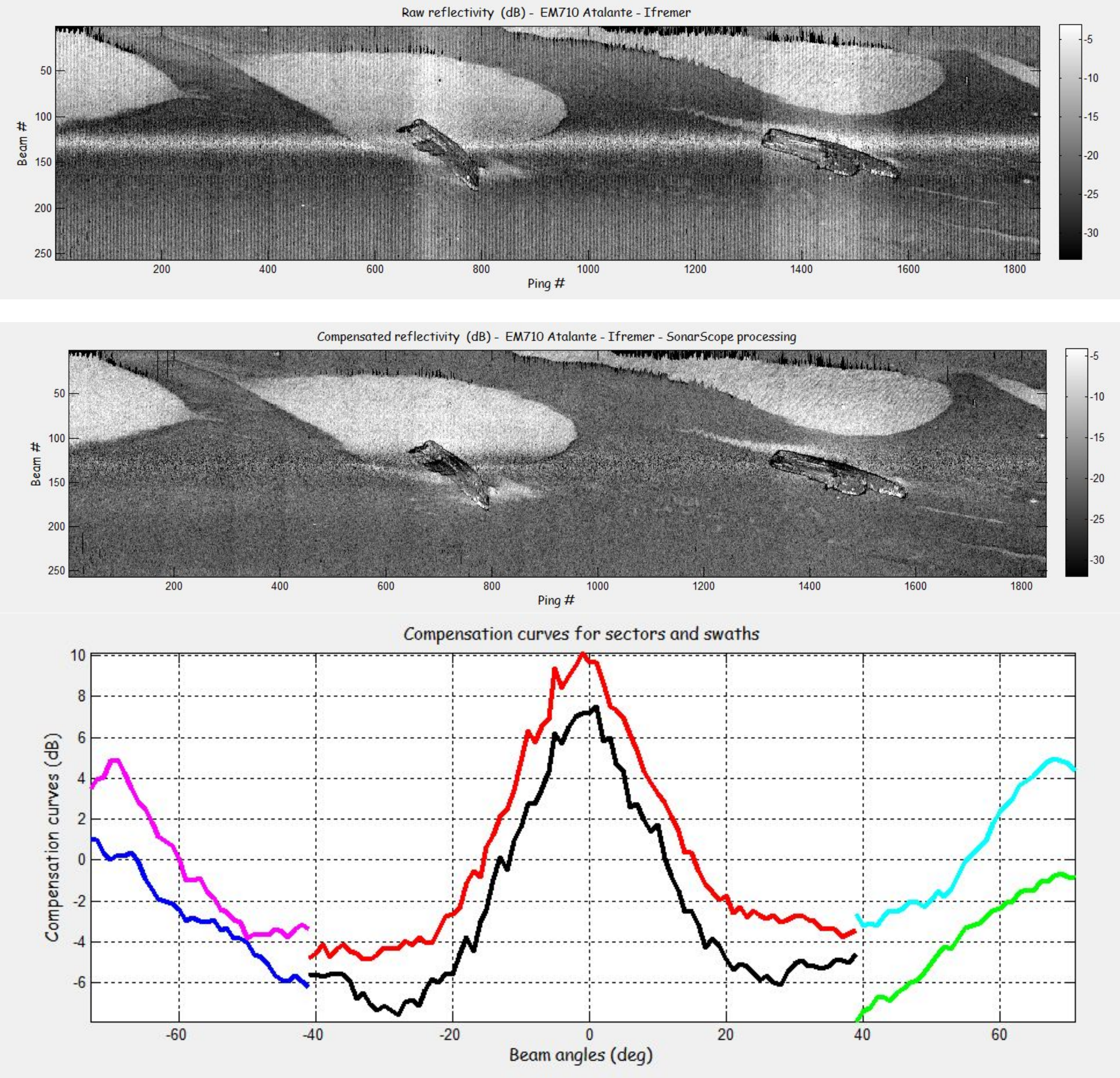

Figure 3-10 Correction of backscatter angular response and beam pattern. Above: raw data; Middle: after correction; Bottom: applied compensation for the different sectors. Data from EM710 of RV Atalante (Ifremer), backscatter processed with Ifremer SonarScope software (from Jean-Marie Augustin, unpublished).

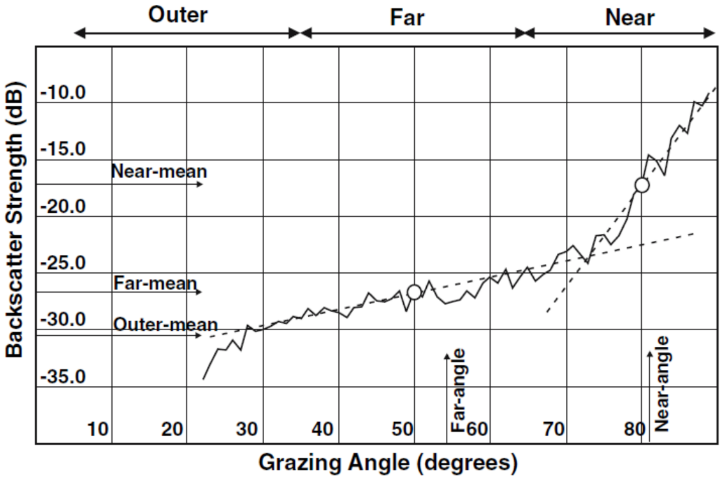

Figure 3-11 An example of extraction of parameters for use in inversion processing (from Fonseca and Mayer, 2007). The dashed line at the near range defines the near-slope and the near intercept (white circle). Similarly, the dashed line at the far range defines the far-slope and the white circle the far-intercept. The arrows on the left side of the graph show the calculated dB levels for the near-mean, far-mean and outer mean, and the arrows on the bottom the near-angle and the far-angle.

3.4.2 Image processing

Image processing refers to any form of signal processing for which the input is an image, such as a MBES backscatter grid with cell values in dB. The output of image processing may be either a classified map or a set of characteristics or parameters related to the image. Most image-processing techniques process the image as a two-dimensional signal and apply standard signal-processing techniques to it. These signal processing algorithms are utilized to extract features of interest from the image such as geological facies, geomorphological topographies or patterns and textures representing different habitat types.

A MBES backscatter image defined by geographic coordinates is considered to be a function of two real variables, for example, $a(x,y)$ with a as the amplitude (e.g dB at a particular angle of incidence) of the image at the real coordinate position (x,y). A backscatter image may be considered to contain sub-images sometimes referred to as regions-of-interest (ROI), or simply regions. This concept reflects the fact that images frequently contain collections of objects each of which can be the basis for a region. In a sophisticated image processing systems it should be possible to apply specific image processing operations to selected regions. This has been reported on in the literature and is a novel advancement in acoustic backscatter processing (Figure 3-12) (Lucieer, 2007, Lucieer and Lamarche, 2011, Lucieer, et al., 2013).

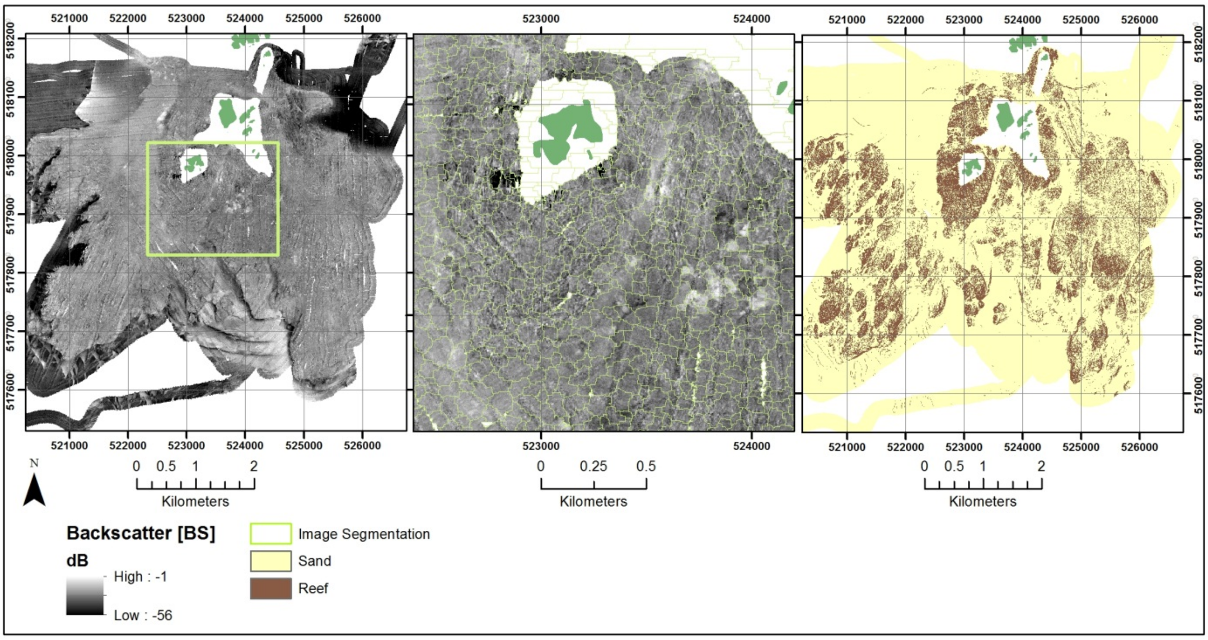

Figure 3-12 An example of image segmentation of multibeam backscatter. A) Multibeam backscatter image B) Image segmentation shown by green outlines C) Image classification of segments based on object textural and spatial parameters (slope, rugosity etc).

3.5 Applications

3.5.1 What do we want to achieve from the different backscatter processing procedures?

The backscatter users' survey provided a synopsis of the diversity of current applications of backscatter. The top three current applications from this survey (Q2) were seafloor type mapping (16%), marine habitat mapping (14%) and data acquisition/collection only (no further analysis) (10%). The anticipated future application (Q8) also mimicked these results. In section 3.5.2 (discipline requirements) the top two applications: seafloor type mapping (geology) and marine habitat mapping are discussed.

Although the survey did not poll the users about which processing *procedure* they used, the answers to question 2c: '*Please list the software packages your work unit has used for its backscatter applications*' and question 2d: '*How does your work unit interact with backscatter in its current applications?*' provide some insights about how backscatter data is processed. The majority of users use Sonarscope, QPS Fledermaus, ArcGIS, CARIS and MB Systems (Figure 3-13). In this list only Sonarscope, QPS Fledermaus, CARIS and MB systems provide some level of backscatter data processing while ArcGIS provides image analysis once backscatter image has been produced by the earlier listed software tools. Amongst all the three backscatter processing tools, users can apply backscatter corrections and produce mosaics (image processing) with varying level of signal processing available. The question 2d results showed that backscatter data are used in a variety of ways by users including visualization for distribution maps (image processing), analysis for boundaries (image / signal processing) and as input to sediment and habitat classification map (signal processing). The relative demand of image processing vs. signal processing cannot be ascertained from the user survey.

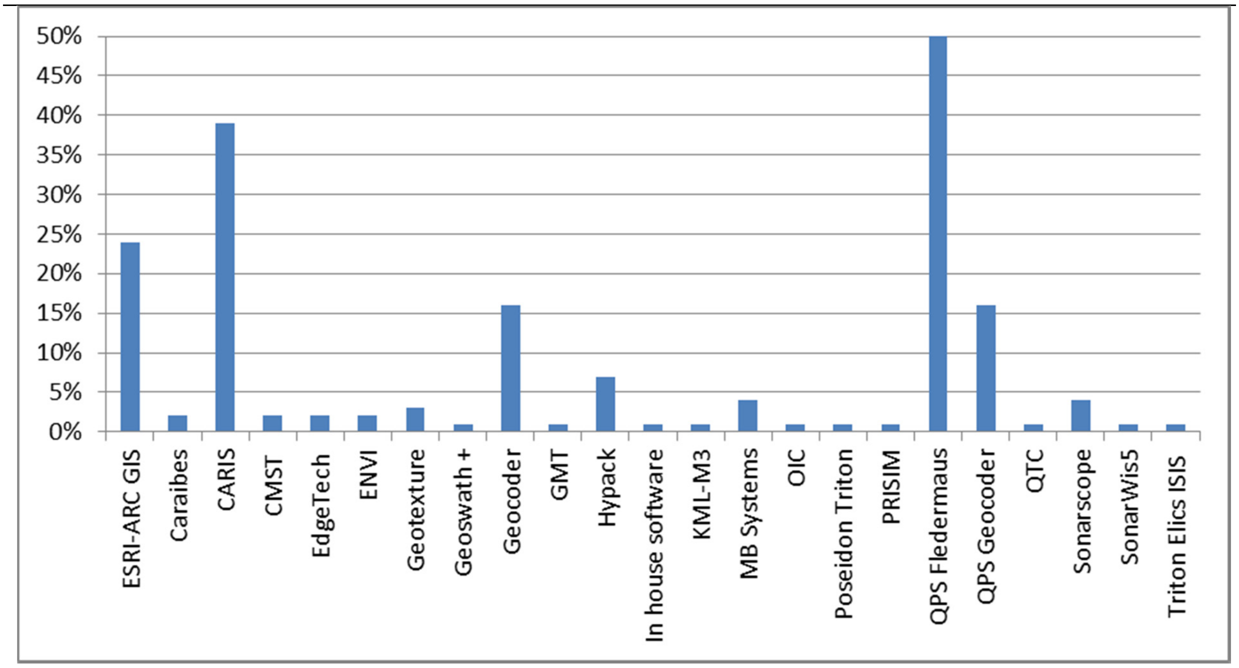

Figure 3-13 Survey question 2c - software packages utilized for backscatter applications- results shown as percentage of responses.

As a large majority of users indicated backscatter primarily as ‘scientific interest’ (Q10) compared to business requirements or policy requirements, it can be inferred that perhaps backscatter users currently feel the field of backscatter processing is still undergoing transitional development. Although we suspect that most of the users are using image processing to extract useful information from the backscatter mosaics. The utility of signal processing is predicted to expand in the future with the implementation of signal processing tools and procedures in commercially available software and with it the realization that signal processing can provide quantitative characterization of the seafloor.

3.5.2 Discipline requirements

Relative and absolute data accuracy has been discussed in section 3.2. It is the spatial and radiometric resolution of the backscatter data that will ultimately define the utility and the value of the data for both seafloor type mapping (geology) and marine habitat mapping. The ability to use processing methods (3.4.1 and 3.4.2) to discriminate between different seafloors at a specific spatial resolution in addition to a high degree of accuracy is the main focus of these two disciplines. If the question was reversed into “which radiometric resolution is needed by scientists for their particular applications?” then we would require a definition about the significant differences in the mean BS (0.5 dB, 1 dB, 2 dB or some other value). From the survey we learnt that the scientific applications of multibeam backscatter are many and varied. Figure 3-14 demonstrates the scope of backscatter applications with the largest sectors belonging to surveying and mapping, research education and expert advice and marine and coastal conservation.

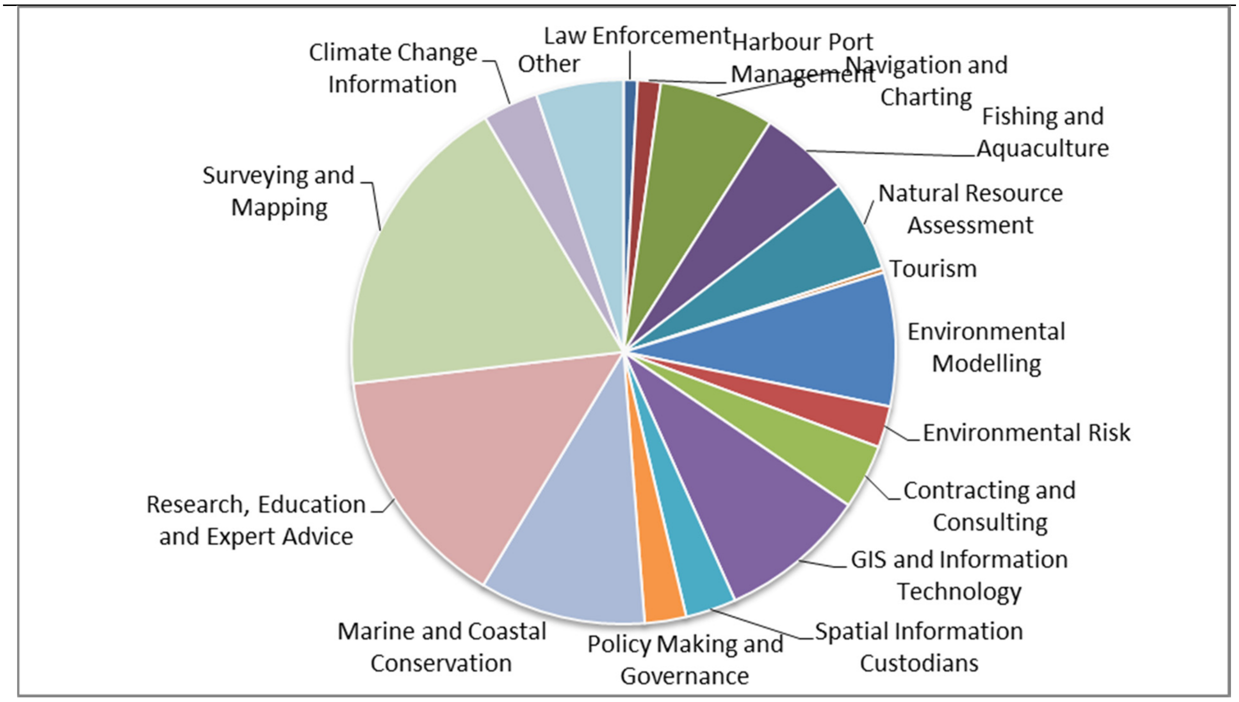

Figure 3-14 Survey responses to question 2a- What are the primary roles of your work unit?

Within these three primary roles backscatter was utilized in seafloor type mapping, marine habitat mapping, '*just acquired with no particular intention*' and part of marine survey (with the potential of the data to be assessed at a later date). Figure 3-15 illustrates the further detail of uses for backscatter data from the respondents.

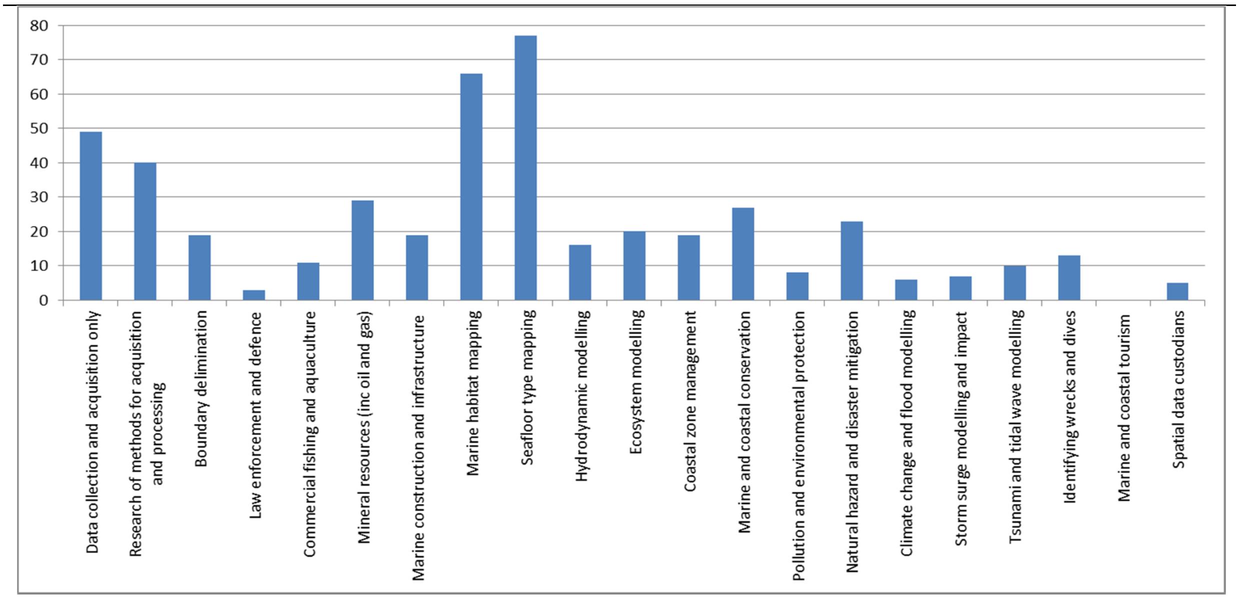

Figure 3-15 What is the current application of backscatter within your work unit?

As we continue collecting more MBES data at an international level, it will become imperative to apply standardizations to backscatter data in order to calibrate their dB levels. As users develop skills and new processing methods become available, a new approach that will require standardization of methods ranging from sensor control, through to acquisition processes to processing software will no doubt become available. The issue of standardization of backscatter data will become ever more relevant to a wider range of data users once time series of backscatter data are compiled. Apart from the 'cosmetic' desire to be able to display all available backscatter data from one area on a single map, there is also a very real demand among various user groups for standardized backscatter values/signal properties between surveys conducted using different multibeam systems/survey platforms/acquisition and processing software. This expectation is sometimes driven in reverse when a calibrated system and technique were not previously employed in the initial surveys.

So, what are the general requirements from some of the common users within the community?

a) Marine Geology

Marine geologists typically use backscatter data to aid in the interpretation of surficial seabed sediments. Traditionally this has been done using only the amplitude information from backscatter mosaics, together with expert interpretation. The interpretation of the backscatter was also guided by available ground truth information (video, sediment grabs) and any other available information on the geology of the area (Figure 3.16). Using this traditional workflow the expert was often able to accommodate variation in backscatter data quality, and/or differences between backscatter dB levels between surveys covering the particular study area. Where several frequencies of MBES have been used, it was important that the geologist was aware of the differences in penetration and scattering mechanisms arising from e.g. shallow water and deep water echosounders, since these will not necessarily affect the dB levels, but will be very important to the interpretation.

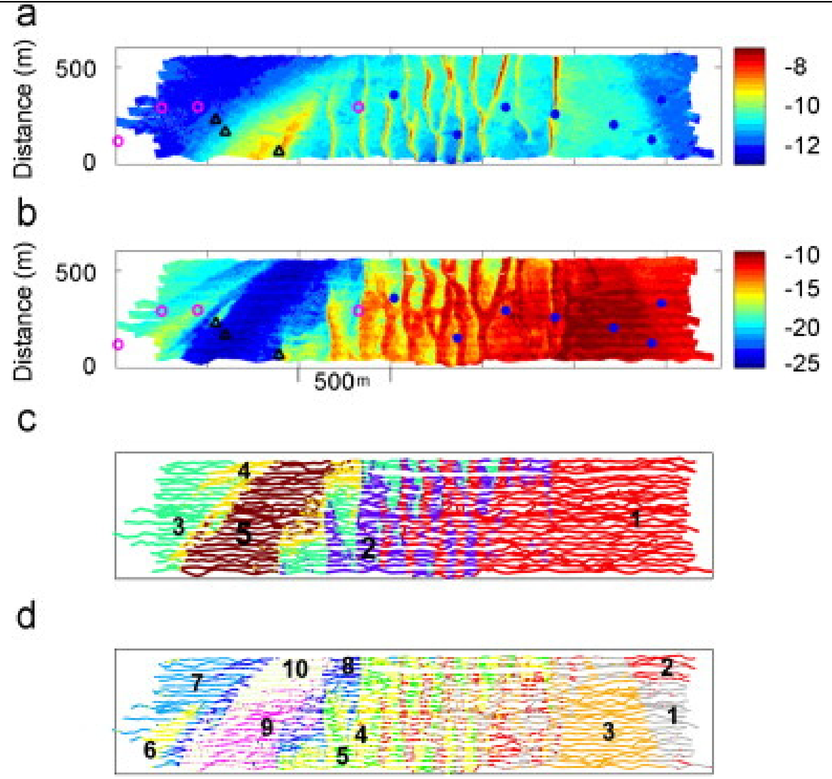

Figure 3-16 Keppel Bay multibeam data (from Hamilton and Parnum, 2011). (a) Bathymetry with sediment sample locations, blue circles are coarse sand and shell debris, mauve circles are muddy sand, and triangles are mud or sandy mud. (b) Mean Backscatter Strength (dB) averaged over 40–60°. (c) Mapping of five acoustic classes from a direct clustering of BS curves and (d) mapping of 10 acoustic classes from a direct clustering of BS curves.

As larger areas of the seabed are being processed and interpreted, issues of standardization in backscatter dB levels between surveys becomes more important. While this is the case to a certain extent for traditional expert interpretation, it is more so for automated classification and extraction of quantitative descriptors of the backscatter amplitude, or signal properties that may be used as an aid to interpretation/classification e.g. texture measures, and estimates of geotechnical properties.

b) *Benthic Habitat Mapping*

Benthic habitat mapping, i.e. mapping that integrates the biological properties of the seabed with the seabed facies, tends to rely even more on automated methods than sediment interpretation. This is due to the fact that it is not possible to collect biological data at the same vast expanse that MBES data can be surveyed; and inference and extrapolation are required from a very small and well understood area of seabed. Many applications of habitat mapping make use of some form of classification or modelling and will often integrate backscatter data directly or indirectly in this process. Standardized data is essential for this workflow. Data quality and signal levels/properties that differ between surveys within a same study area lead to poor classification/modelling results and weaken the usefulness of backscatter data for habitat mapping.

3.6 Ancillary data

In the backscatter user needs survey we specifically asked “what other data sets do you use in conjunction with backscatter data (Question 9- Figure 3-16)”. Overwhelmingly the response was ‘bathymetric data’ followed by seismic, sub bottom, lidar, imagery (aerial/satellite) and sediment samples. When the users were asked ‘what were the fundamental limitations they faced when trying to utilize backscatter data with other data sets’ the responses were primary related to: a) integrating the data processing of backscatter into the workflow of other data sets and b) matching the data resolution of backscatter data with other datasets (Question 9B Figure 3-17).

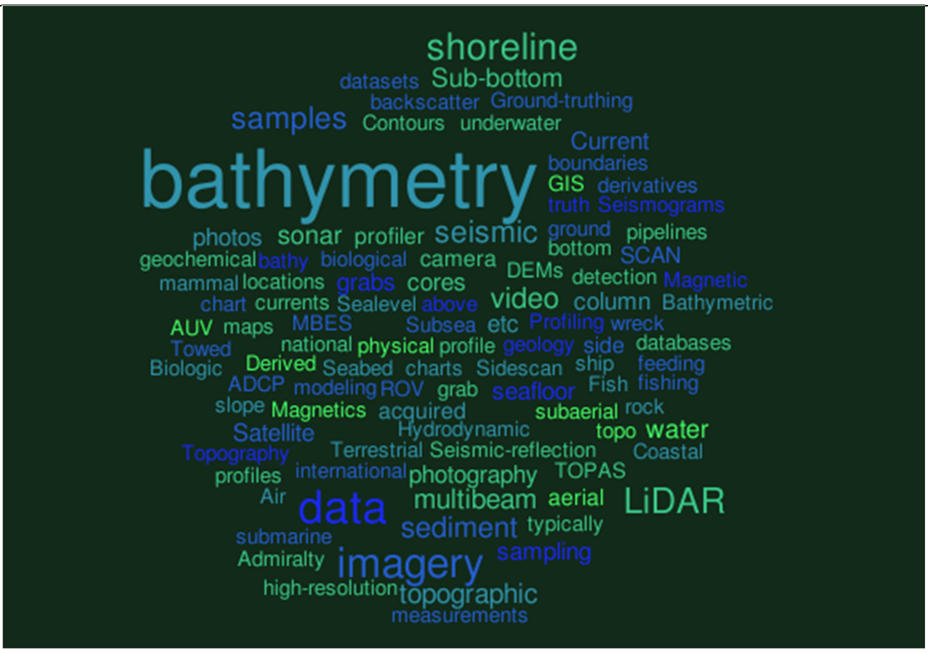

Figure 3-17 Word cloud of responses to question 9 – “What other data sets do you use in conjunction with backscatter?”

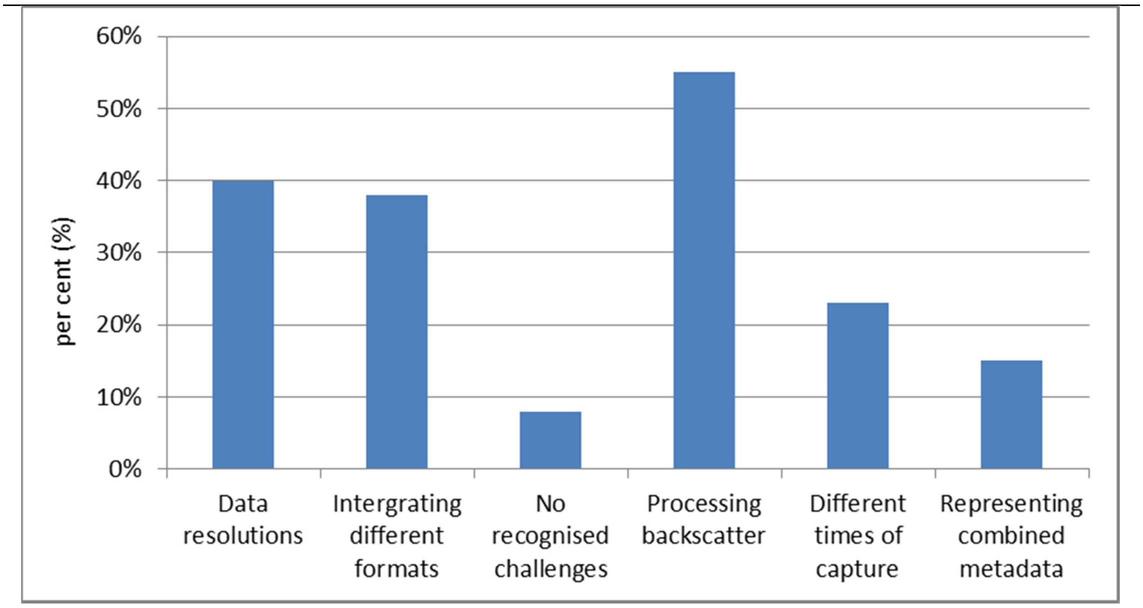

Figure 3-18 Figure showing responses to the question "What challenges has your work place had with integrating backscatter with other datasets?"

3.6.1 Data types

The following answers were received to the question "What types of ancillary data sets are used by backscatter users?"

- Environmental data including sound speed and absorption coefficient profiles, weather conditions;
- Host of ancillary data required for MBES operation vessel attitude, accurate positional information;
- Bathymetric data for computation of slope: the scale and resolution of the bathymetric data required for co-registration of the bathymetry and backscatter data;
- Vessel characteristics: noise levels and hull shape to document the potential effect of bubble sweep down;
- Sonar characteristics: Receive and transmit characteristics of the sonar if absolute BS is desired (More details can be referenced in other chapters).

3.6.2 Ground truthing data

The following answers were received to the question "What are appropriate ground truthing data / other environmental data needed for data processing and data interpretation?"

- Video, photographs, sediment grabs and real-time observations of seafloor geology and biological cover recorded from a towed camera sled help develop and verify derivative products based on backscatter data. The seafloor backscatter data provides the geo-acoustical properties of the seafloor and traditional ground truthing data may not provide explanation for the variations in the seafloor backscatter. In-situ ground truthing in terms of sediment acoustic properties have been proposed (Kraft et al., 2004) but so far these ground truthing methods have not gained widespread acceptance mostly due to the fact that users are more interested in the geophysical properties that they can infer from the geoacoustical observations (i.e. seafloor backscatter). The linkages between the geoacoustical and geophysical properties is an active field of research and beyond the scope of this paper but it is important to realize that seafloor backscatter is not capable of providing all the geophysical properties that a user may want to obtain and therefore combination of ground truthing data and seafloor backscatter should be dealt with due caution to avoid over interpretation of the seafloor backscatter data.

- Seismic profiling.

3.6.3 Water column data

- ADCP intensity profiles, or optical observations, in order to evaluate the turbidity, the amount of sediment in suspension near the bottom to evaluate the impact of the water column condition on the seabed backscatter.
- Water column amplitudes as provided by most modern MBES; data that can be merged with the backscatter mosaic.

3.7 Data formats

3.7.1 Common data format for archiving

What is the common data format for archiving backscatter data and do we need to standardize the data format?

Backscatter data can be stored in several formats. The most common one is as a raster mosaic of the backscatter amplitude value. These rasters can be stored in many data formats, usually dependent on the processing software employed or the data formats in common use within the user's institute. Some of these formats are now largely outdated and it would seem desirable today that in the interests of data compatibility backscatter data are removed from the restrictions of any proprietary data format. For example ArcGIS grid format has been in widespread use for data integration among the scientific community; however more flexible formats such as ascii may be a favorable standard for the future. For data exchange there will no doubt also be a long term demand for simple text files giving position coordinates and backscatter value (xyz files).

- To answer the non-standardized processing problem (discussed in 3.3 and 3.4) a data format that allows to erase all previous corrections and to revert to the raw unprocessed signal would be appropriate. All processing steps need to be described in this format. Currently the only way to be able to return to the raw backscatter values is to maintain the original data backup: for KM systems, the .all format, which combines all recorded data (including backscatter) with the survey parameters. Which format can preserve all the corrections – Format that enables recovery of raw data: that will mean host of ancillary data set to enable corrections. Analogous to depth data what are the things most required for backscatter data.

3.7.2 Metadata requirements

Currently, there are no accepted standards of how backscatter data are reported. This is due to the fact that the reporting of backscatter results will vary from manufacturer to manufacturer and even for a particular sonar manufacturer several processing options will be available to users. The details of different data acquisition and processing methodologies are provided in chapters 4, 5 & 6. From a user's point of view, various available backscatter data that have been processed and acquired in different ways, pose challenges for further exploitation and consistency for processing methods. Therefore, the foremost need of users is the ability to quickly verify what corrections have been applied (or not) and what do the backscatter data values reported by the sonar manufacturer represent. A well planned metadata report that is available with the raw data may help answer these questions. Most often, users need derived products from the raw backscatter data (Section 3.3) for analysis and interpretation; therefore each product, will need to be accompanied by additional metadata fields defining how the backscatter data have been processed. The problem of data consistency is not unique to backscatter data and other remote sensing fields (notably satellite radar and imagery) who have adopted consistent standards to define what the data (raw or derived product) mean; this could be a source of inspiration for future evolutions. We feel that having by developing a consistent terminology to quickly define what corrections have or have not been applied to the data is an extremely useful first step in this process.

Other technologies have explored establishing a metadata standard such as for radar (radiometric measurement data). The following three levels establish the basis for their metadata input dialogue (MTPE EOS -Reference Handbook; 1995 edition) and have been adapted as an example for backscatter processing:

Level 0

Unprocessed and manufacturer provided backscatter data at full resolution; there may be more than one type of level 0 data in which case, the levels can be expanded to include 0a, 0b. The example of Level 0 data would be raw data files obtained from sonar.

Metadata requirements: How were the data acquired?; was any internal processing completed?; what do the backscatter values represents (for example if the data are instantaneous backscatter samples in arbitrary units) or some processing has been conducted (for example averaging over any interval); which corrections have been applied (for example how (if any) corrections for insonified area, transmission loss, beam pattern, etc. have been applied etc.

Level 1

This level would include backscatter at full resolution that has been processed to correct for radiometric and geometric corrections. The resolution of this level is the same as Level 0. The only difference is that all the corrections have been applied to the data.

Metadata requirements: How were the radiometric and geometric corrections applied?

Level 2

This level would describe the derived backscatter such as the mean dB value taken over a period of time or space interval for example: backscatter mosaics.

Metadata requirements: How the mean value of backscatter computed?

3.8 Current needs

The backscatter user needs survey comprehensively summarized the current challenges that backscatter users experience. These challenges are discussed under the following headings:

a) *Data Storage and processing speed.*

Many of the users commented that one of the major challenges with backscatter data are the costs associated with the 'acquisition storage' and 'backup storage' required for the large volume datasets that backscatter data will generate throughout a survey. One of the major problems that this creates for future reference is that there is a real challenge that it is not possible to archive the corrected backscatter data with the sounding values. When the data is retrieved there can be a lack of understanding of the influence of the acquisition settings from the original data. It was acknowledged by some users that the changes to the NetCDF support in the mosaic data set could significantly help in overcoming this limitation. At present it was noted that current IT technology and infrastructure is not ready to handle the large data volumes of raw and processed data from water column backscatter and seafloor backscatter in a user friendly manner. This severely affected processing speed and ability to perform even basic analyses on such large data sets.

b) Skills and Expertise

One of the limitations of backscatter utility has been identified as being hampered by contractors and processing staff not being properly trained in processing backscatter and that a lot of training courses (from various companies) focus more on bathymetric processing in the MBES training courses. This lack of expertise has compounding issues in the field as poor training of surveyors can lead to surveyors' constantly adjusting sonar settings, during under acquisition, which can severely affect the quality of the backscatter measurements at post-processing time. There are very few researchers or surveyors that fully understand the implications of the sensitivities of backscatter data and therefore little is being communicated for uptake by the industry. Many of the image processing experts (for example those analyzing the data in ESRI software) have little acoustic experience with which to interpret the data.

c) Software

Commonly in the Backscatter Users Group survey individual responses mentioned software evolution and software compatibility undergoing a significant development at the current moment. The limitation regarding software was mentioned in both acquisition software packages and processing software packages and that sometimes the data formats between the different platforms were not compatible. The costs of processing software both to purchase and to maintain – for some users was a severe limitation to their abilities to improve backscatter processing within their industry.

Some users mentioned that there was a lack of "platform independent" solutions to handling backscatter processing issues. This was identified by a number of users and an example was given that some software packages do not provide navigation correction where others do, and that few software packages were able to quantitatively handle navigation correction. That in some instance there were problems with file compatibility between the software and the sonar output files so that navigation issues could not be corrected.

In many instances user responses in the questionnaire said that the software documentation for both acquisition and processing packages was very poor in relation to backscatter data handling. This was noted in addition to "inappropriate or missing specifications of technical details from manufacturers".

d) Processing

Many of the backscatter questionnaire participants said that the software parameters in relation to automated backscatter processing were not properly 'tuned' by users which resulted in less than ideal corrections being applied and therefore unsatisfactory results. There was little confidence in the automated backscatter processing algorithms provided by software companies in that the results were deemed unstable or "still in beta testing mode" although they were commercially available. Many of the users commented on the need for "human intervention" at all stages of the automatic processing workflows where ‘adjustments’ were often required and that other steps appeared to be a ‘black box’.

Many of the users noted that although the limitations for acquiring, processing and analyzing backscatter data were going through a period of great transition that recent advances especially made by CARIS and Fledermaus have made the process a little simpler especially with regard to cleaning artefacts from the data (nadir) and navigational uncertainties (e.g. towed sidescan).

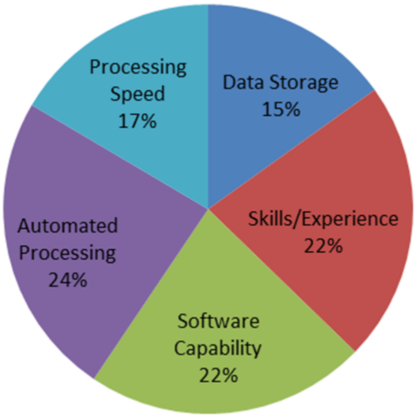

Figure 3-19 Summary of responses from backscatter questionnaire of challenges using backscatter data.

In summary, the largest issues to still be addressed that were identified as causing the greatest concern to the backscatter community was the lack of calibration required for optimizing backscatter data, the lack of standardization methods available for referencing and the ongoing struggles with the large data volumes (relevant to both data storage and time required for processing) (Question 5a, Figure 3-18).

In terms of future direction for backscatter data 98% of the respondents saw an ongoing need and utility for backscatter data and recognized it as a developing area that would reveal of wealth of information to their research programs. As 84.3 % of respondents had the means to acquire their own backscatter data there is already substantive investment in the community to support the ongoing improvement of this data source.

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CHAPTER 4 BACKSCATTER MEASUREMENT BY BATHYMETRIC ECHO SOUNDERS

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4.1 Objectives

The purpose of this chapter is to describe what is applied inside a sonar measuring backscatter, from the physical echo at the receiving (Rx) array input to the reflectivity datagram. This overview aims to provide operators some knowledge of the stages involved, how things can go awry, and to provide a common understanding for a discussion of practical steps that can be taken to correct them – namely the innovative operation of echosounder calibration. Importantly, it is hoped that end-users and manufacturers may become more mindful of each other's requirements, for instance with regards to important issues such as sonar calibration. Section §4.4 includes information provided by sonar manufacturers and specific to particular sonar systems. There is no emphasis on any particular approaches or protocols of acquiring backscatter data. The objectives of this chapter are:

- Explain how backscatter is measured by bathymetric echosounders (i.e. MBES and PMBS) in general.
- Understand how backscatter is measured by the different bathymetric echosounders available in the market – including calibration.
- Understand how much of the processing performed over the raw signal is necessary for the particular use of the backscatter data.
- Understand whether it is possible and, if so, how the raw signal (or a specific processing stage) can be retrieved from the datagrams.
- Provide an overview of the types of calibration that can be performed to enable calibrated backscatter measurements of the seafloor.
- Provide design wish list for sonar manufacturers.

4.2 Backscatter measurement: today's MBES state of the art

4.2.1 What is measured?

To understand how to derive a backscatter measurement from an acoustic measurement made by an echosounder, it is helpful to understand what is being measured by the sonar, and what processing steps are usually being undertaken at the acquisition stage. The description of this complex process also provides opportunities to show where the quantitative acoustic values can be altered or even lost, how to retrieve them, and how to better design sonar systems to retain them.

The active sonar equation (expressed in decibels) was introduced thus in §2.2.1

$$EL = SL - 2TL + TS \tag{36}$$

where the received Echo Level (RL) is a simple function of the source level (SL), transmission loss (TL) and the target strength (TS).

Although the backscatter measurement is derived directly from TS, it is the received level RL that is actually measured. The terms in this expression are acoustic quantities. That is, although expressed in decibels, they represent acoustic intensity having units of watts per square meter. Therefore one seeks to retain (or regain in post-processing) these proper units through the measurement process (Figure 4-1).

For bathymetric sonar systems, after the transmission or "ping", a time series of acoustic measurements is made along each beam (this is also the case for multibeam sonars with multiple beams, and phase-measuring sidescan systems with 2 beams). Seafloor backscatter is derived from the acoustic measurements, associated with seafloor detections. The calculation of seafloor backscatter requires exact knowledge of the acoustic energy impinging on the seafloor, the amount returned to the sonar and the area of the seafloor that was insonified. The details of how this is done are described in the following sections. For now we consider the intersection of the beam and the seafloor and the extent of the seafloor that is characterized by each measurement (Figure 4-1).

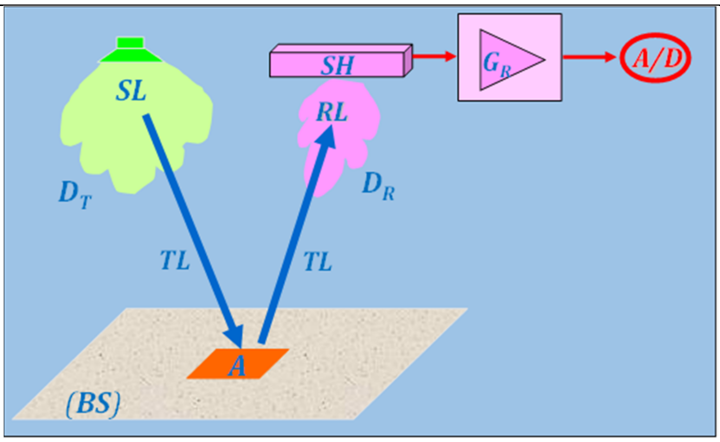

Figure 4-1 The Backscatter process parameters. RL: Received echo Level; SL: Transmitted source level; DT: Transmitter directivity pattern; TL: Transmission loss; A: Insonified area; BS: Backscattering Strength; DR: Receiver directivity pattern; SH: Receiver sensitivity; GR: Receiver gain; A/D: Analog to Digital converter.

The measurement area differs depending on the geometry of the beam and the seafloor (Figure 4-2). In case of Multibeam Echosounders (MBES), for beams intersecting the seafloor at near normal incidence, the seafloor within the whole of the beam is insonified nearly instantaneously and the resolution of the measurement is determined by the along-track and across-track extent of the beam. In this case we say the measured area is “beam limited”. For beams intersecting the seafloor at oblique incidence, the transmitted signal insonifies only portions of the intersection of the beam and the seafloor at each instant. In this case the resolution is usually said to be given by the along-track extent of the beam defined by the along track beam width, in the along-track direction, and half the projection of the effective transmit pulse length onto the seafloor, in the across-track direction. The effective transmit pulse length is approximately one over the bandwidth of the signal. For beams intersecting the seafloor at oblique incidence we say the resolution is “pulse-limited”. For Phase Measuring Bathymetric Sonars (PMBS) systems, the large across-track width of the receive beam provides a pulse-limited case in all circumstances. See Chapter 2 for more detailed modeling of these insonification regimes.

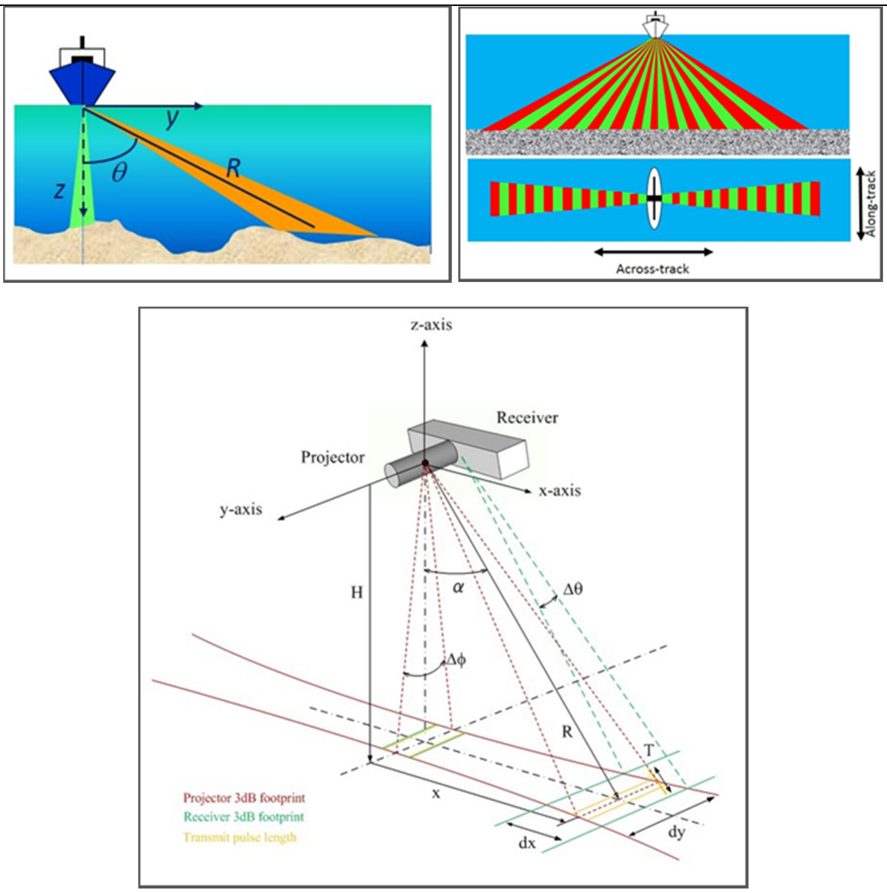

Figure 4-2 Sketched (upper) and detailed (lower) Illustrations of measurement areas depending on the geometry of the beam and the seafloor. The illustration highlights the difference between beams intersecting the seafloor at near normal incidence, compared with beams intersecting the seafloor at oblique incidence.

4.2.2 How is it measured (sensed, processed and logged)?

Most bathymetric sonar systems undertake a number of major distinct stages for measuring the Received Level of an active sonar return from which a backscatter measurement is ultimately derived (see section 2 equation 3). This section provides a step-by-step overview of these various stages, providing operators with some knowledge of this process. Importantly, it is hoped that end-users and manufacturers may become more mindful of each other’s requirements, for instance with regards to important issues such as sonar calibration (see Chapters 5 & 6).

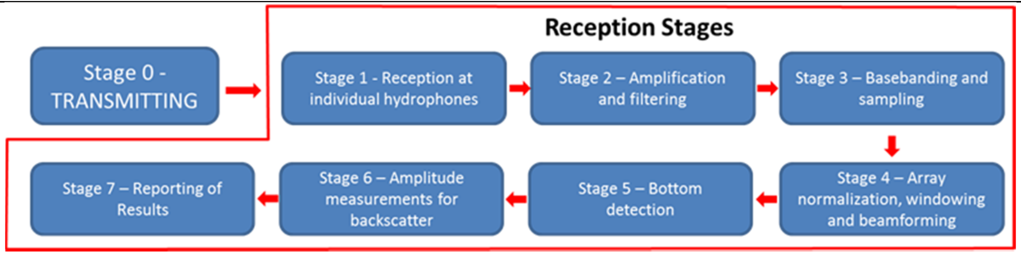

Figure 4-3 An outline of the different stages of backscatter measurement by bathymetric multibeam systems. These stages are generalized somewhat as many differing strategies are employed by different manufacturers (see Section 4.4 for more details).

Stage 0 – Transmitting

The sonar transmit pulse interacts in two ways with the reception process. First, it defines the band-pass filter in which the reception process is normally done; a mismatch between the transmitted signal’s bandwidth and the receiving filter may lead either to an underestimation of the received intensity (too narrow a filter), or to an insufficient elimination of noise (too wide a filter). Second, it controls the extent of the backscattering footprint at a given instant, and has to be accounted for in the compensation of the footprint area. Hence a full understanding of the transmitted pulse is integral to calculation of acoustic backscatter. Recalling from the sonar equation (§2.2.1 and eq.(4.1)), the source level of the transmitted signal is required to calculate the seafloor target strength. To subsequently convert target strength to backscatter one must correct for the insonified area, which for obliquely oriented beams in a MBES system and any measurement in a PMBS system is a function of the transmitted bandwidth (or, equivalently, duration) in across-track and transmitted along-track beamwidth in along-track direction. Additionally, the transmitted beam may be divided into different frequency sectors. Therefore, the source level (Hammerstad, 2005), transmitted beam pattern, and transmitted bandwidth are important characteristics of the transmitted pulse and are needed for correct estimation of the backscatter during the reception cycle. See Chapter 1 & 6 for details regarding these calculations.

Two types of signals are commonly used in bathymetric sonar systems, namely, **continuous wave** (**CW**) and **frequency modulated** (**FM**). CW signals consist of a single frequency (sinusoid) whose transmit duration defines the signal bandwidth. Shorter transmit durations produce a wider band of frequencies around the center frequency while longer transmit durations produce a smaller band of frequencies around the center frequency. Examples of 30 µS and 50 µS pulses at 500 kHz and their frequency content is shown in Figure 4-4.

Frequency modulated pulses consist of a pulse whose center frequency is not constant, often varying linearly over the pulse duration. Unlikely CW pulses, the frequency content of an FM pulse is determined by the frequencies of the transmitted signal rather than the duration of the transmitted pulse. An example of two FM pulses is shown in Figure 4-4 (*right*). Each pulse is 120µS in duration; however one signal sweeps from 485 kHz to 515 kHz (30 kHz bandwidth) while the other sweeps from 450 kHz to 550 kHz (100 kHz bandwidth). The frequency content of each is also shown illustrating that a wider bandwidth signal is created in the second pulse independent of the duration of the transmitted pulse.

Which signal resolution? Bathymetry vs Backscatter

Defined as the equivalent spatial length of the signal duration, the **resolution** can be defined as the level of details that can be distinguished in the recorded echoes. It is, in the radial direction, the counterpart of the Tx sector width which determines rather the along-track size of the footprint. For instance, in sidescan sonars used to image seafloor scenes, it is desirable to get as high a resolution as possible, and very short signals are transmitted inside very narrow Tx sectors. For MBES used for bathymetry mapping, the trend is also to improve the resolution; today's systems are evolving toward narrower Tx and Rx beamwidths (0.5° beamwidths are not uncommon now), and signal duration is normally set as short as possible, in the limits of an affordable SNR upon reflection.

However, for BS mapping, the requirements may be different. Backscatter users are rather interested in getting averaged reflectivity over areas whose typical extent is one magnitude larger than the details expected from bathymetry charts. Hence getting a high resolution is not so useful, and hence long pulses may be sufficient; even they may be better since their use improves the SNR and lowers the speckle. However maintaining the high resolution for bathymetry is still preferable. Hence the trade-off between expectations of bathymetry and backscatter measured at once by one same instrument is not straightforward. What could be considered is that while it is always possible to degrade the measurement resolution (by spatial averaging of the data) the inverse cannot be done. When one single instrument is used for acquiring collocated bathymetry and reflectivity, it is therefore likely that the maximalist requirements (here bathymetry) will be prevalent.

An interesting parallel is to be done here with satellite-borne radars mapping the Earth's surface: a "scatterometer" is a system different from the imaging SAR (Synthetic Aperture Radar, very-high resolution – meter to decameter) used for both imaging and topography mapping: much simpler, the scatterometer provides a poorer resolution in angle and range (kilometer) relevant for its purpose of large-scale mapping.

To increase the resolution of a system operating with a CW pulse, one must shorten the transmitted pulse length, for example, from 50 µS to 30 µS as shown in Figure 4-4 (*left*), and this increases the occupied bandwidth. Because the duration of the transmitted signal is less, the transmitted energy is also decreased, reducing the signal to noise ratio of the returned signal.

To increase the resolution of a system operating with an FM pulse, again, one must increase the bandwidth as well, by increasing the modulation frequency band over which the sonar transmits. But lengthening their transmit duration increases their available energy and hence the SNR, while leaving intact their time resolution, controlled by the modulation bandwidth. Because the bandwidth is independent of the pulse length, bandwidth may be increased without a commensurate reduction in signal to noise ratio. Here lies the main advantage of FM over the CW: rather than providing a significantly improved range resolution, they improve the reception performance through the SNR increase.

Amplitude of both type of pulses is usually shaded (weighting window applied along the pulse envelope, hence decreasing the *effective* pulse length) in order to lower frequency leakage and temporal sidelobes after reception processing, that affect their achieved range measurement capability. Manufacturers should make explicit, and provide the equivalent effective pulse duration, for an optimal setting of the post-processing operations (see §6.6.2). This is valid as well for FM signals: the effective pulse duration **after** pulse compression should be announced clearly to users.

While FM signals offer serious advantages for bathymetry (thanks to their good performance in presence of noise, they do significantly increase the effective swath width), CW may be preferred for backscatter measurements since their simpler reception process limits the risks of level biasing compared to FM adapted filtering. However, when correctly applied and processed, and operated under good conditions, FM signals can theoretically provide reliable estimates of backscatter. This can be observed for example in recent Kongsberg systems where practically no level difference can be made between different Tx-sectors transmitting either CW or FM pulses.

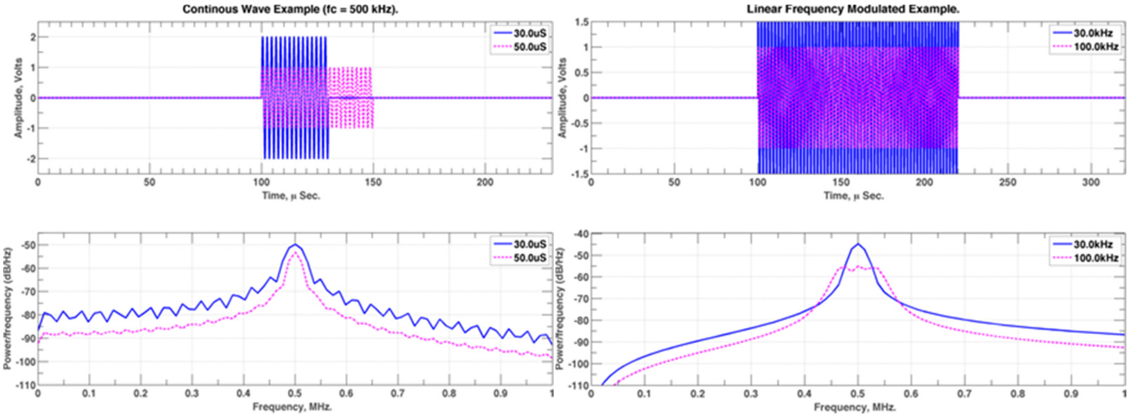

Figure 4-4 Examples of transmit pulses in the time domain (upper) and as frequency spectrum (lower): (left) continuous-wave (CW) signals; (right) frequency-modulated (FM) signals.

Stage 1 – Reception at individual hydrophones

Individual hydrophones receive the acoustic pressure fluctuations from the transmitted pulses backscattered from the seafloor and convert them into analog voltages on a wire. The amplitude of the electrical signal is proportional to the received pressure.

Since the hydrophone's function is to convert acoustical pressure signals to electrical signals, the unit of the output analog signal is Volts, with a scaling for correspondence with the input acoustical pressure. However, until the electrical signal is sampled (digitized), it cannot be converted to an acoustic quantity. In any case the conversion is usually done at a much later step (after amplification, filtering, digitizing and beamforming). To convert them to Received Level at this point, one must know the receive sensitivity of the individual hydrophones.

The receiving sensitivity of individual transducers is normally well-controlled by constructors, and constrained upon production inside strict tolerance limits regarding the characteristics of ceramics constituting the arrays. Normally the nominal resulting sensitivity of an array should hence be well known; ideally it should be individually calibrated in factory, and the results provided to customers, and integrated as parameters of the processing operations. However sensitivity can be subject, in the field, to various modifications, including:

- drift with aging of the ceramics;
- impact of temperature and hydrostatic pressure (the latter maybe an issue for deep-sea vehicle sonars - unfortunately this point is very difficult to evaluate experimentally;
- modification of the coating material characteristics, either on the short-term (biofouling) or on the long term (chemical action of seawater).

Little literature is available to the public on these matters. However, a good way to control their impact is to conduct calibration operations with a sufficient periodicity (see Section 4.3 below).

Stage 2 – Amplification and filtering

The analog signal from each receiver hydrophone is typically filtered at this stage to attenuate noise, and is amplified using a static gain. It may optionally be amplified by applying either a time-varying gain (TVG) or an automatic gain control (AGC). TVG or AGC attempt to compensate for the decrease in signal intensity along the reception time, due to transmission loss (spherical spreading and acoustic absorption). TVG is based on a predictive estimate of the signal decrease with time; while AGC automatically adapts to the fluctuations of the received level. This allows the system to measure over a larger range of values than the sampling hardware would otherwise allow.

Some newer systems do not apply an analog time varying gain. Instead, they sample the digital signal using A/D hardware with sufficient dynamic range to digitize the largest amplitudes (usually the specular return) down to the noise floor of the system. However it is common for systems to apply a digital TVG or AGC to their amplitude measurements after sampling, largely for aesthetic reasons, equalizing the measurements across the swath.

Ideally, the type of compensation and its details should raise no particular issue as long as they can be compensated for in post-processing for retrieving the original signal magnitudes. However, this idealized suffers practical limitations:

- Post-compensation implies that the parameters of the correction laws applied by the sonar have been carefully and exhaustively recorded in the datagrams;
- The actual physical filtering applied to the signal in these compensation operations may be different of their ideal values, because the filters are analog, although digitally commanded. So detrimental phenomena such as amplifier non-linearity, saturation, clipping, response time delay etc. may happen. (Greenaway and Weber, 2010). As a consequence, the post-processing compensation of TVG risks being as imperfect as the filters themselves.

N.B. In post-processing (see Chapter 6), the TVG can be refined in order to account for more accurate corrections than the ones needed for the real-time processing. It is also completed by an angle-varying gain (AVG) whose purpose is to equalize the physical processes depending on incidence angle.

Stage 3 - Basebanding and Sampling

Any of several methods may be used to digitally sample the signal. The following paragraph will be familiar to sonar engineers without being too obscure to less familiar users. Details are not essential for most users although some discussion is warranted.

Traditionally the analog signal from each element is first mixed with quadrature components (sine and cosine signals) at the operating frequency of the sonar and the result is low pass filtered to *baseband* the signal. Basebanding allows sampling at the Nyquist frequency for the transmit bandwidth rather than that of the much higher carrier frequency by shifting the signal to a frequency band centered on the zero-Hz frequency (Figure 4-5). Another strategy is to notch-filter the signal around the carrier frequency and quadrature sample, at a rate to capture the transmit bandwidth.

Increasingly, thanks to the progress in ADC technology, modern systems are opting to omit analog basebanding and sample at the full Nyquist frequency of the carrier frequency. The series of numbers is then digitally basebanded and decimated. In any case, the final effective sampling rate should be at the Nyquist frequency for the transmit bandwidth at a minimum, and as such produces a sample with each resolution cell of the transmit signal (e.g. half the pulse length for a CW transmit pulse).

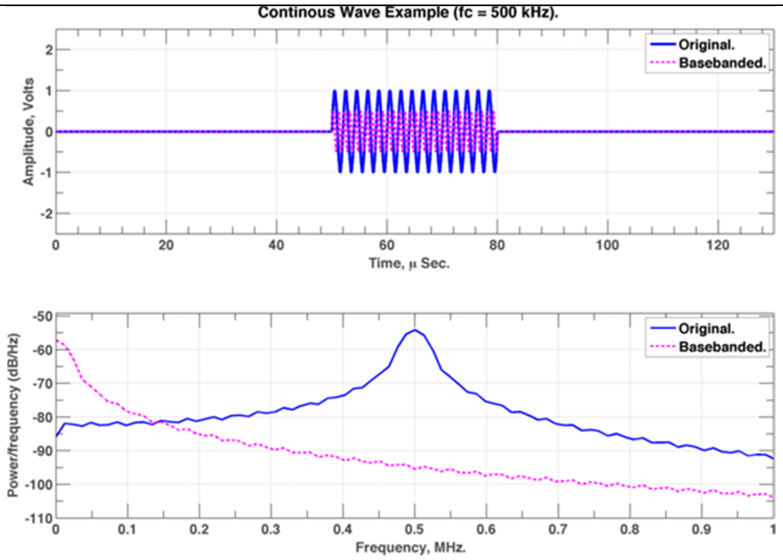

Figure 4-5 Illustration of basebanding. The original CW signal at 500 kHz is multiplied by a similar signal at 500 kHz producing signals whose frequency content is centered on the sum (1 MHz) and difference (0 kHz). The high frequency component is filtered out leaving a low-frequency signal whose information content is identical to that of the original signal. Hence this signal may be sampled at a lower rate, decreasing hardware requirements and associated manufacturing costs.

When applied properly, the basebanding and sampling process produces complex-valued quantities (a real and imaginary part) whose magnitude represents a direct measure of the amplitude of the voltage sampled (i.e. the acoustic signal of interest plus any gains applied). For this reason, the units of the complex digital values are the same as those of step 2, namely Volts (again with a scaling for correspondence with the input physical level of the incoming signal).

A nuance regarding the digitization process warrants comment as it affects some older sidescan systems. One key characteristic of Analog to Digital Converters (ADC) is the number of bits they used to store digital value. This number indicates the number of steps and hence the step size between adjacent digital values for a given measurement range. In addition, ADCs require reference input voltages which provide the measurement range of the system. For example, a 12-bit ADC, operated from -1 V to +1V can produce 2^{11} or 2048 digital values between 0 V and +1 V. ADCs generally do not report decimal digital numbers in units of Volts directly, but rather, integer values (i.e. 0-4096 in this example), leaving the scaling of these values to the system integrator. Some sonar manufacturers have chosen to report integer values directly representing the magnitude of the complex basebanded signal, rather than floating point values. When this is the case, the units of the resulting value become ADC Counts * Gain, and an additional scaling factor is required to make quantitative measurements.

While generally beyond the scope of this document, it is worth noting that stages 1-3 do not come without chance for error - although normally a good part of these uncertainties could (and should) be controlled by technical refinements designed by the constructor (self-calibration of the Rx channels; control of saturation etc.). Among other causes, biases in the measurement may result from drifting sensitivity of the receive elements, misbehaving gain stages or clipping of signals. See Chapter 5 with regard to the control of system settings for acquisition.

Stage 4 - Array normalization, windowing and beamforming

The next stage for MBES systems involves beamforming using the received signals of individual hydrophones. This step is generally not required for PMBS systems, although there are exceptions.

Beamforming is a processing operation aimed at creating a directivity pattern from the individual signals received (or transmitted) by elements along an array (assumed as a straight line, for simplicity). The primary purpose of beamforming is to get a spatial directivity thanks to the creation of a narrow directivity lobe inherent to the array length for a given frequency; the achievable lobe width is approximately (in rad) the ratio of the wavelength to the array length. Thanks to the independence of the individual signals, beamforming makes it possible to steer the directivity lobe in whatever direction, just depending on delays (or phase shifts) applied to the array elements. Thanks to digital signal processing capabilities, beamforming can be applied to create at once a very high number of beams to be processed simultaneously, with steering angles able to adapt (for instance to the physical motion of the platform) in a very agile way. High values of steering angles are possible (typically up to 75°) although the steered beams are less performing than the well-pointed ones (because the apparent array length is shorter). Finally the digital nature of the beamforming computation makes it possible to apply at will array weighting functions in order to optimize the shape of the directivity pattern: the near-field effect can be compensated by applying an adaptive focusing law, while the sidelobe level can be improved (i.e. decreased) by applying an optimized shading law along the array.

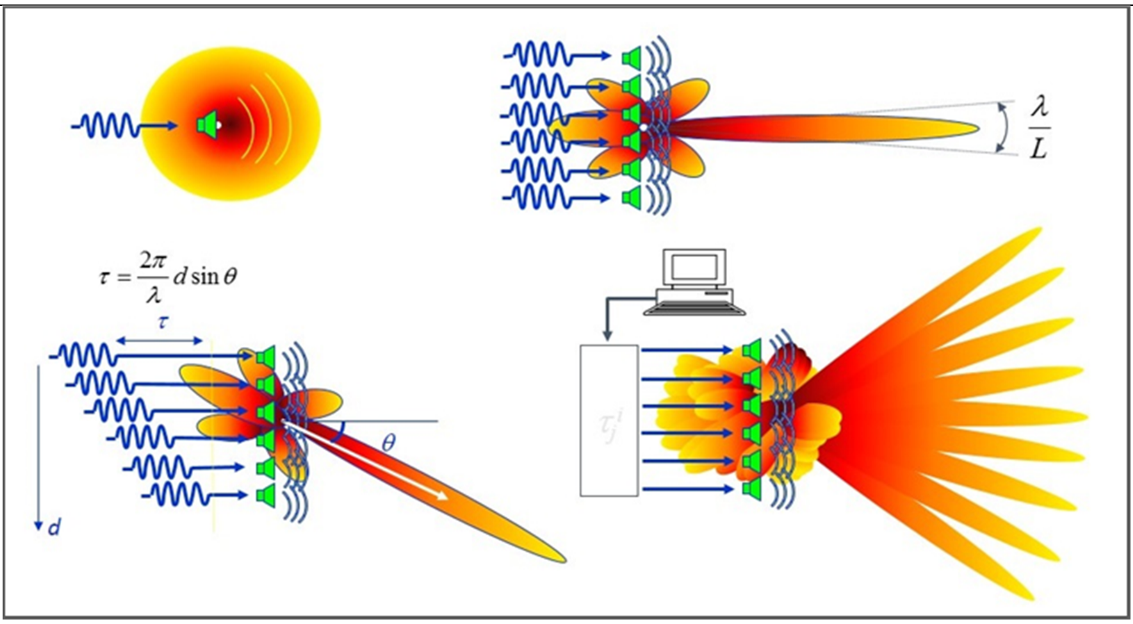

Figure 4-6 Array directivity and beamforming. The summation of signals to (or from) several transducers forming an array of length L creates a directivity pattern with a lobe of width λ/L. Proper delaying of the signals along the array makes if possible to steer the beam at will; in reception, a high number of beams can be formed simultaneously.

Before beamforming, two steps are commonly undertaken to mitigate the sensitivity of sidelobes, through which unwanted signals may corrupt the desired signals from the central part of the beam. Sidelobes are inherent to the beam forming process and can cause unwanted signals to corrupt those from the preferential direction of listening.

Some systems will first apply a normalization factor to each receive element (hydrophone) sample to level the mean signal measured across the receive array, compensating for differences in transducer hydrophone sensitivity and electronics (particularly phase response) in each channel. This process is applied in Reson Seabat systems as the "*CalTone*" functionality.

In addition, systems apply at beamforming a windowing (or array shading) function to the receive element measurements along the array; roughly its purpose is to decrease the contributions of the external array elements. A windowing function selectively attenuates some transducer signals relative to the others and by doing so helps to reduce the receive sensitivity of the array in directions outside intended listening direction of the main lobe. Particularly common is the Dolph-Chebychev window which reduces beamforming sidelobes to a constant level relative to the main lobe in all directions. While windowing functions have the desirable effect of reducing sidelobes they have the generally undesirable effect of slightly increasing the width of the main lobe (this undesirable effect is theoretically minimized by the Dolph-Chebyshev windowing), by a factor typically 1.2 to 1.4 depending on the windowing details.

After normalization and windowing, beamforming is accomplished by summing signals across the array after applying a time-delay (or more or less equivalently a phase shift). The time delay to be applied is computed based on the sound speed at the sonar head and therefore the sound speed accuracy at the sonar head affects the beamforming process. Different time-delays are applied to each hydrophone in the array to synthetically steer the array toward any desired beam direction. The process is repeated to create as many beams as desired (Figure 4-6).

In many systems a single set of time delays or phase shifts are applied across the receive array for all measurement ranges for a given beam. Other systems conduct "dynamically focused" beamforming in which changing sets of time delays (or phase shifts) are applied at each range step, allowing the array to be focused at each range step along the main axis of the beam. The advantage of dynamically-focused beamforming comes in both reduced sidelobe levels and compensation for complicated receive array interference patterns that result in the so-called **near-field** of the transducer. The effect of the near-field on unfocused systems is discussed further in Step 6. As an intermediate mitigation of the near-field effect, certain systems (Kongsberg) artificially shorten the active length of the Tx and Rx array, in order to decrease the limit range between near- and far-field, in accordance with the local measurement range – the counterpart being a wider beam lobe due to a shorter array.

Signals that begin as complex valued time series from each element become complex valued time series along each beam axis after beamforming. As might be expected during each of these steps, normalization, windowing and beamforming change the amplitude levels of the received signals. For example, application of a window to reduce sidelobe levels requires normalization of the amplitude by the square root of the sum of the squares of the window values. Additionally, the process of beamforming, whether phase or time-delay, may require for certain systems calculation of Fourier transforms (FFTs), which must be normalized by the square root of the number of points (minus any zero-padding) in the FFT.

When the effects of normalization, windowing and beam-forming are compensated for, the units of the resulting time series along each beam are again Volts, with a scaling for correspondence with the input physical level of the incoming signal. All changes in magnitude resulting from these various operations must have been recorded accurately, so that retrieving the original physical magnitudes remains possible.

Failure to normalize for windowing or the FFT calculation typically results in a constant step offset in the reported signal amplitude and because these operations are statically hard-wired into the system, operators do not readily notice their omission.

Stage 5 - Bottom detection

Although its details are not critical to the reflectivity measurement, the bottom detection impacts the backscatter data:

- It ultimately determines where the backscatter measurement is taken from within each beam time series.
- The bathymetry quality affects the interpretation of the data since the BS is grazing angle-dependent.
- Finally the sounding quality may be an indicator of the BS quality: a poor SNR will result in a poor accuracy of both bathymetry and reflectivity.

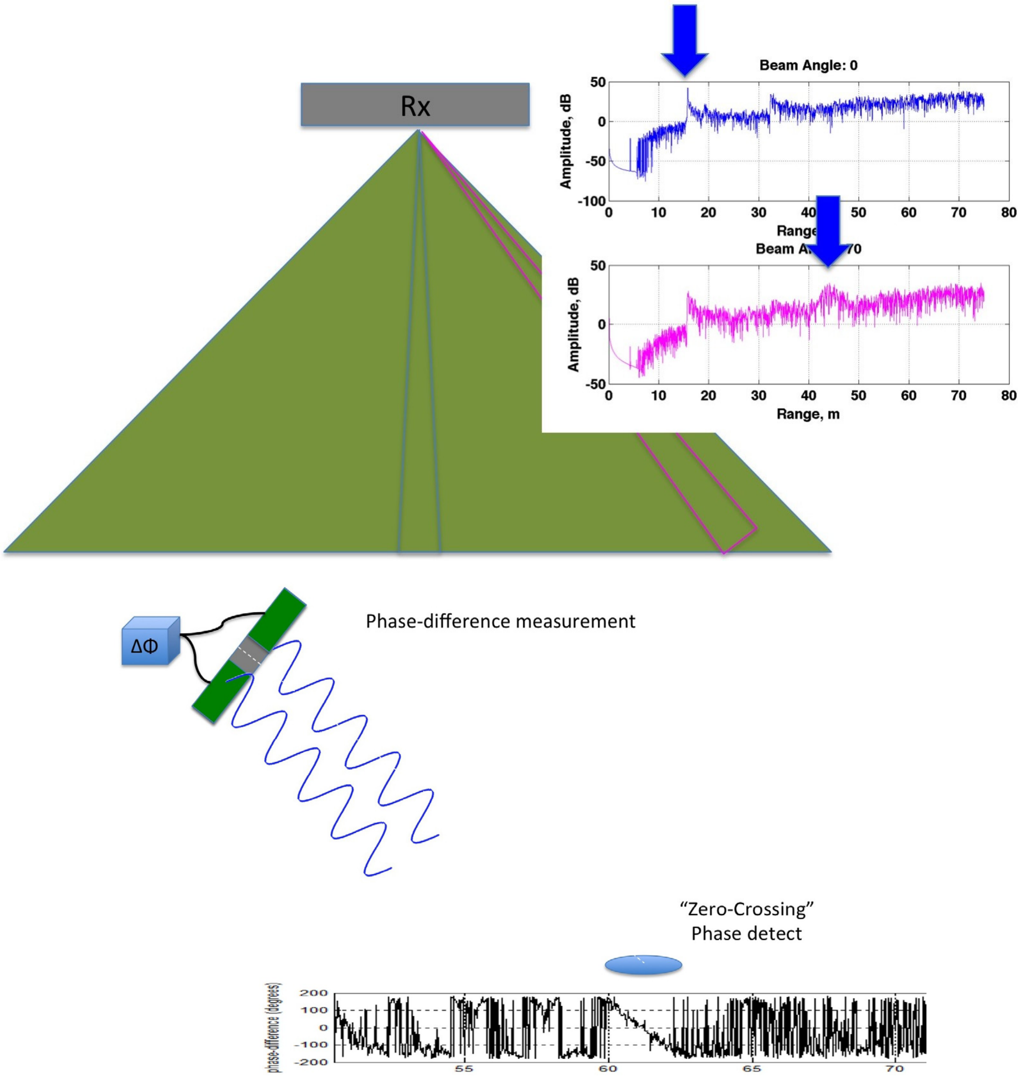

Figure 4-7 Examples of amplitude (a) and differential phase zero-crossing detections (b). Beam amplitude time series for near-nadir beams (blue) and oblique beams (magenta). The bottom produces a sharp peak in the former from which an accurate detection is possible in the near-nadir beams and a broad peak from which an accurate detection is not possible in the oblique beams. Hence amplitude detects alone are used for near-nadir beams. For oblique beams, the steered receive array is split into sub-apertures from which the differential phase of the received signal is measured. When the pulse passes the intersection of the beam and the seafloor a characteristic phase-ramp is produced in the differential phase time series. The zero-crossing of this phase ramp is used to mark the two-way travel time of the pulse along this beam.

It is useful to recall that MBES systems fundamentally measure bathymetry from two-way travel times at known beam angles, while PMBS systems measure receive angles from known two-way travel times. In either case, a two-way travel time from which a range can be determined and an angle relative to the sonar are required.

For MBES systems, common bottom detection methods include amplitude weighted mean detects, for near-nadir beams, and sub-aperture phase difference zero-crossing detects for oblique incidence beams (Figure 4-7). These methods produce a single two-way travel time for each beam. Some systems produce multiple bottom detections from the sub-aperture phase difference measurements within a single beam in addition to the zero-crossing detect. This process is similar to the interferometry process used by PMBS systems producing a receive angle measurement with each time step as the pulse travels across the seafloor within the beam.

While many of the details (Lurton, 2010) are omitted from this discussion, it is sufficient to know that any of these methods for either system may produce a bottom detection derived from multiple measurements in time and space. Moreover, the resulting detect may not be an integer number of samples and hence may not have a single amplitude measurement associated with it. Determining which amplitude measurement (or measurements) should be attributed to each bottom detection is discussed in Stage 6.

Stage 6 - Amplitude measurements for Backscatter

Several methods are commonly used to determine which amplitude measurements of seafloor reflectivity should be reported with the associated bottom detect.

MBES beam bottom- detect amplitude

Some systems report a single amplitude measurement within each beam and do so by picking the amplitude in the beam time series that falls closest in time to the bottom detection or some blending/averaging of the two closest measurements. Because each sample is complex, the amplitude is the magnitude of that complex sample (i.e., the square root of the sum of the real and imaginary components). Any blending of measurements should be done with the squared magnitude such that the blending occurs on values proportional to acoustic intensity.

MBES Beam average amplitude

Alternatively, some systems (this has been the case for long with the Simrad/Kongsberg MBES) select a subset of the amplitude samples near the bottom detection time and combine them into a single beam-average amplitude measurement. How samples are selected varies from system to system; one method being to select those samples that would fall within +/- half a beam width assuming a flat seafloor. Here, because beams invariably overlap, adjacent beam average backscatter values are not statistically independent.

PMBS Binned Data amplitude

PMBS systems may bin their bathymetric data (by across-track range, receive angle or some other method) and often produce an associated amplitude value with each bin. This practice is common for Edgetech systems (4600 and 6205) in which the RMS value (in linear units) is taken.

As mentioned above, any method of averaging should be calculated on the square of the magnitude of complex samples such that values proportional to acoustic intensity are averaged rather than amplitudes (see Chapter 2).

MBES / PMBS beam time series amplitudes (snippets)

A majority of systems report a time series of amplitude values across the beam along with each beam's bottom detect. This is the case for MBES reporting "snippets" and PMBS systems in general. For MBES systems, the method by which these are selected varies from system to system. Selecting those samples falling within +/- half a beamwidth of the bottom detect assuming a flat seafloor would not be unreasonable, although some of the sonar systems only report the values to achieve full bottom coverage removing the spatially overlapping samples.

If the criterion of +/- half a beamwidth of the bottom detect is used, systems may report redundant information in overlapping sections leaving post-processing software to sort out the redundant measurements, or they may stitch measurements together such that only a single amplitude measurement is reported for each portion of seafloor.

Beam time series amplitude measurements such as these are modulated by the receiver sensitivity (beam pattern) of the synthesized (MBES) or static (PMBS) beam. For MBES that extract amplitude measurements from beam edge to beam edge, where the beam edge is defined as –3dB down from the maximum sensitivity, the modulation across the beam varies by 3 dB commensurately. However for PMBS systems, it is not uncommon to measure well beyond the nominal beam width causing much larger modulations in the signal level. Although phase-difference measurements (available in either system type) provide an indication of where in the beam the measurement was made, few systems utilize this information to correct the amplitude time series for the received beam pattern.

Great attention must be given at this stage to ensure that beam, beam-average and beam times-series amplitude measurements are still proportional to acoustic received level as it was for previous steps. First, the method by which the measurements are selected and averaged must be considered to ensure biases are not incorporated into reported values; this is of the constructor's responsibility, however the principles practically applied for it should be accessible to users. Second, measurements from beam-formed data are now heavily dependent on the angle from which the acoustic signal was received (the beam pattern) and must be corrected for that variation. Because both MBES and PMBS systems measure the received signal's angle with respect to the beam center, these systems may correct for these effects – possibly in real-time, and in any case at post-processing. To do so requires careful bookkeeping of amplitude values along with careful knowledge of the receive array beam pattern. However, because beam patterns can change with installation, subsequent aging of a system, and with dynamic steering to account for the vessel motion even these values may not be sufficient. Instead, some manufacturers do not attempt to correct for the receive array beam pattern prior to reporting amplitude levels, leaving results uncalibrated and requiring some external calibration method. Ideally a preliminary calibration should be performed by the constructor, in factory and upon installation; then the evolutions from this nominal status should be tracked by the sonar's users, applying calibration procedures.

An additional comment is warranted regarding beam pattern corrections for both MBES and PMBS systems and their operation in the "near field" with static or unfocused beam forming. At distances nominally less than L^2/λ, where L is the length of the array and λ is the wavelength of the sonar's operating frequency, the sonar is said to operate in the near field. At these ranges, a complex interference pattern occurs in a transducer beam pattern (for both transmit and receive transducer arrays) when they are not dynamically focused to each measurement range. This interference pattern is heavily angle- and range-dependent, rather than simply angle-dependent as it is for operation beyond the near field / far field transition. A near-field empirical calibration of the receive array would require beam patterns through both all angles and all ranges of operation. The complexity of such a calibration and its application generally makes an empirical calibration untenable. Alternatively, the near-field response may be modeled as a function of both range and angle, but deviations in manufacturing and installation from ideal can complicate the modeling process. In general, operation outside the near-field is recommended for statically beamformed sonars.

To mitigate the effects of near-field operation, some systems dynamically focus the receive array. In addition, some also transmit several pings at a time, in which each transmission is focused into different angular sector at the expected range of the seafloor. The addition of transmit focusing is rare as it requires a sizable increase in hardware, complexity and cost. A pre-focused Tx array is, by definition, focused at only one range (for one transmitted ping). Nothing such as dynamic focusing continuously varying with time (applied for Rx) is then possible – the only way to go is to focus at some intermediate acceptable range. While it is more common to only address the receive array through focusing, this necessarily leaves the effects of near-field operation on the transmit signal unaccounted for.

Stage 7: Reporting of results

The last stage is the reporting of the results in the sonar data. At this point, the amplitude measurement (or measurements in the case of time-series backscatter) associated with a bottom detection consists of a complex number whose modulus reflects the magnitude of the acoustic received signal, any static or time-varying gains applied by the system and variations due to the direction of measurement resulting from the sonar’s receive sensitivity beam pattern. Recall that this acoustic amplitude is not yet acoustic backscatter, as it still requires corrections for transmission loss and the insonified area or volume as appropriate.

To calculate the received acoustic amplitude one need to scale the value, removing the applied gains, receive sensitivity of the array and angular effects of the beam pattern. However for many reasons, some practical, other historic, any number of things may be reported instead.

The acoustic return intensity from nadir to the swath edge may cover many orders of magnitude. As described in Stage 2, static and time-varying gains are applied, in part, to counter the effects of two-way transmission loss. This process (Stage 2), aside from the seafloor itself, is often the cause of much of this across track variation. By leveling the signal, the resulting amplitude data is more aesthetically pleasing (and indeed practically usable) for the purposes of mosaicing allowing users to more easily identify differences in the seafloor. For this reason, rather than report true acoustic received signal levels from which backscatter may be more readily derived, it is not uncommon for systems to leave static and time-varying gains uncorrected in their reporting of acoustic amplitude measurements.

In addition, for most systems beam pattern modulation of the signal is unknown and its correction cannot be not applied – at least not without a dedicated calibration operation.

The nadir specular return may be many orders of magnitude greater than returns from adjacent portions of seafloor in which the return is dominated by scattering. For this reason some systems apply a digital time varying gain, attenuating signals near nadir and further amplifying signals near the swath edge before reporting acoustic amplitude values. This may come in complement to the TVG applied at the receiver’s input: in e.g. Kongsberg MBES, propagation and angle effects are all mixed in a TVG law accounting for transmission loss, footprint extent, and the angle response of the seafloor – all expressed as a function of time (Hammerstad, 2000). Such complex TVG laws have to be computed digitally, but are applied as an analog amplification to input electrical signals prior to their digitization; although the amplifier gain is digitally-controlled, its actual response is imperfect and may not reflect the ideal control parameters values that are recorded in the datagrams. In recent high-dynamics MBES where TVG is not strictly needed any more, the propagation and angle compensation is applied on the digitized data.

In the absence of these corrections, and because the amplitude of the acoustic received level measurements can vary over several orders of magnitude, some systems report acoustic amplitude values as “uncalibrated decibels” (dB = 20*log10(A), where A is the magnitude of measured amplitude) rather than linear value.

Finally we note blunders that may occur. The reported magnitude may contain biases due to being unaccounted for effects described above in stages 5 and 6, namely, element sensitivity, element level normalization, windowing, FFT normalization, and averaging of data. When these effects produce a constant bias for a given system or configuration, they may go unnoticed and, indeed, when a system is externally calibrated they may be removed. Effects such as FFT normalization whose amplitude may be dependent on the number of beams, or element level normalization which may be conducted automatically by the system at regular intervals will not be quantified during external calibrations. This produces variations in received amplitude level with each survey confounding any effort to produce data comparable between surveys and other systems.

4.3 Intensity calibration of bathymetric echosounders

To be quantitatively and rigorously usable, backscatter measurement needs to be a function of system frequency, angle of incidence at the seafloor and seafloor characteristics (see Chapter 2) - and not a function of a particular sonar system (See Chapter 3). The sensor influence therefore needs to be removed from the backscatter measurement. The main system characteristics that influence the backscatter measurement have been summarized in §4.2. These sensor-related corrections are either applied during the data acquisition by the sonar manufacturer, or they may need to be corrected during post-acquisition by data users; see Chapter 6, where processing techniques to correct for several of these system specific adjustments are discussed. In either case, the corrections for these factors are a fundamental part of the backscatter measurement. The primary requirement for such processing is the knowledge about the measurement sonar characteristics. The identification and quantification of the sonar characteristics is the aim of several of the techniques and processes collectively known as “Calibration”.

In a general sense, the process of calibration is to check, adjust, or determine by comparison with a standard, that an instrument is performing satisfactorily and is capable of collecting data within some reasonable expectations (usually in terms of measurement accuracy, according to user needs and/or to meet agreed upon specifications), in a repeatable fashion, and coherently with some verifiable reference. Calibration of echosounders is not a new concept, regarding the bathymetric sounding measurements. A historical example of a calibration method for a single beam echosounder (SBES) is the “bar check” method: a plate which is lowered under the narrow-beam SBES to check and adjust the depth measurements of system ensuring that all variable parameters of the measurement sensor are included in the calibration. Today, with the advent of MBES and PMBS, the bathymetric calibration is conducted with help of reference surfaces where several sonars are tested against a stable seafloor, and/or by collecting data in varying environment and directions (e.g. patch test, dynamic heave test etc. - Gueriot et al., 2000) to calibrate the sensor angular mounting, squat etc.

The problem of MBES bathymetric measurement calibration is relatively constrained as compared to the backscatter measurement calibration. The seafloor depth, as a physical quantity, depends only on the location of the seafloor and implies a simple geometrical description, which can be objectively measured - including by non-acoustical methods. This is quite straightforward compared to the seafloor backscatter which is a function of the angle of incidence and the “type” of the seafloor (which may include a number of different features). The time and spatial scales at which the depth and backscatter of the seafloor may change also differ considerably (with depth not changing within time scales less than tidal cycle vs. backscatter changing possibly at time scales of less than a few minutes due to organic activity, ambient noise levels etc.). Miscalibrated or poorly known device characteristics (e.g. source level or transmitted pulse length) may not affect the bathymetric measurement severely as compared to the backscatter measurement. Therefore, generally, it is not possible for the backscatter users to rely on methods like bathymetric calibration which assume a static seafloor during calibration and are only focused on calibrating a small subset of device characteristics.

Another important aspect of backscatter calibration is the highly dynamic nature of the MBES components that influence backscatter measurement. The dynamic focusing to mitigate near field effects have been addressed earlier. In case of the dynamically-steered beam (both transmit and receive) to compensate for the vessel motion and to maintain a uniform sounding density on the seafloor, the beams are dynamically steered according to motion at the time of the measurement. The yaw-, pitch- and roll-compensated beams therefore are expected to induce some pattern changes as compared to non-motion compensated beams. This, in turn, implies that the beam pattern characteristics of these beams will need to be calibrated at various levels of vessel motion. Empirical verification of beam pattern at various motion levels is non-trivial. However, information provided about the elemental spacing, sensitivity and details of the beam forming process are known, theoretical prediction of these dynamically changing characteristics can be modeled (other examples may include changes in sound speed at sonar head, received band width fluctuations due to Doppler effects caused by vessel motion).

It is important to recognize that the calibration of individual constituting elements of MBES is an engineering approach that only sonar manufacturers, and only a minority of users, are able to perform. In-field calibration methods, such as the use of reference target areas (see section 4.3.2 below), are the preferable and only practical solution for backscatter calibration for most users.

4.3.1 Echosounder components to be calibrated?

With detailed description of the measurement process outlined in Section 4.2., it is sufficient to focus in this section on various components of the echosounders, whose calibration is critical for the backscatter measurement. Table 4-1 below summarizes the echosounder components desired to be calibrated at each stage of measurement along with the calibration result desired for meaningful utilization of the backscatter results.

Two methods of calibration are mentioned in Table 4-1. Empirical calibrations involve checking and verifying the performance of various MBES components. Generally, users have limited information about how data are processed internally at each measurement stage. The empirical calibration is therefore analogous to understanding a “black box”, where only the box input and/or output are controllable. To break into the black box, either the input of the system is controlled in which case calibrated external transducers are used to produce echoes which are then recorded by MBES/PMBS units. The input to and the output from the measurement unit are then known and their comparison can shed some light on the internal working of the measurement sensor. In another approach, the return from a calibrated reference target (either a sphere or an extended target) can be used. The use of a normalized sphere (derived from fisheries acoustics) has been successfully applied on MBES

(Lanzoni and Weber, 2010), however, the extended target calibration (although appealing for multibeam measurements) has seen only limited use mostly due to difficulties in maintaining an artificial extended target free of gas bubbles and other in-water homogeneities (Heaton et al., 2013; Heaton et al., 2014).

Another calibration approach proposed here is the method of extracting information about the MBES/PMBS components based on theoretical modeling. This approach is desirable to get to the calibration of the components which are hard or impossible to be calibrated using empirical approach either by user or sonar manufacturer. This can provide badly needed information to process the backscatter with a little more certainty as compared to the status quo where no information is available for the particular component. Examples of good candidates for this kind of calibration can include: effects of motion on the dynamically steered transmit and receive beam pattern; effect of different basebanding methods; and reporting of the different measures of backscatter.

Table 4-1 Calibration of MBES and PMBS components desired to achieve absolute level of backscatter.

Measurement stage	Calibration component	Calibration result desired	Method of Empirical calibration	Achievable through modeling? *	Occurrence of calibration
Transmission	Transmit Source Level	Absolute level of transmit power in dB ref 1 µPa at 1 m – as a function of system's power level setting. Influence of ambient conditions (temperature, pressure?)	Tank measurement using calibrated hydrophone, and level measurement device. Impedance measurements of transducers (as a control, at least)	No (although approximate values can be available from constructors)	At system's commissioning (for reference) then periodically – aging and biological fouling may cause level to decrease.
	Transmit beam Pattern	Directivity pattern of the array at a convenient angle step (magnitude 1°) according to user-configurable settings	Tank measurement	**Yes (using Sensitivity of Tx transducers – provided that directivity of individual elements is known)	According to sensitivity calibration of array's individual sensors
	Transmit band width and Pulse Length	Effective pulse length and bandwidth according to user-configurable settings	Tank and at-sea measurement	No (Yes for determining the effective value from measured ones)	At system's commissioning (for reference); not critical afterwards
Amplification and filtering	Rx Hydrophone sensitivity and individual elemental beam pattern	Receive sensitivity and directivity of individual elements – at different temperatures -and pressure?	**Tank measurement (Access to elemental data)	**Yes (provided that sensitivity and directivity of individual elements is known)	At system's commissioning (for reference) then periodically – aging and biological fouling may cause sensitivity to decrease. Directivity non critical
	Gain (Fixed, TVG)	Absolute values of gain used at different user configuration settings to test linearity and saturation	Tank measurement, using an external hydrophone; or at sea upon stable echo (reference target), or stable noise of sufficient level	No - The actual response has to be measured and checked. Some theoretical modeling may be needed though, for result analysis.	At system's commissioning (for reference); not very useful afterwards
	ADC (Analog to digital converter)	Saturation levels and dynamic range achieved	Tank measurement, data over different bottoms. Possibly in lab.	**Yes (provided detailed characteristics of ADC known)	Once – or could be relied upon independent trials of these components.
	Self-noise	Vessel- and self-noise at various operating conditions	Independent noise measurements. Hopefully through dedicated self-test functionalities	No	As often as possible (1) along the platform + sonar lifecycle (2) according to local/instantaneous conditions

Basebanding and sampling	Digital signal constitution	Absolute value coded in the digital signal w/ref to the analog physical input	Left to constructors	Yes – for most of it. The details of methods and algorithms are constructor's property.	To be checked once – and possibly at new releases of system's versions
Array Normalization, Windowing, beam forming	Receive beam pattern	Measurement of actual beamwidth & sidelobe levels of the array	Tank measurement using calibrated Tx-hydrophone as source or using calibration spheres	Yes – for most of it (detailed algorithms used for these operations). Direct measurements are very difficult – and unlikely to be done.	According to inspection of Rx channels sensitivity. Not useful otherwise.
	Window coefficient	Exact (as applied) detailed window form	Left to constructors	No	Once if ever
	Array normalization	Exact (as applied) detailed normalization form	Left to constructors	No	Once if ever
Bottom detection	Not effecting backscatter directly. Anomalous backscatter samples would be reported associated with anomalous bottom detects.				
Amplitude measurement	Method of amplitude measurement	Methodology to obtain backscatter results	Left to constructors As a check, collection and processing of data with different amplitude measurement	Yes (using detailed information from manufacturer)	To be checked once – and possibly at new releases of system's versions
Reporting of results	Content and units of results reported in datagrams	Which corrections have been applied? How to get absolute backscatter from results?	Left to constructors As a check, comparison against other calibrated MBES	Yes (using Detailed information from manufacturer)	To be checked once – and possibly at new releases of system's versions

* If yes - information needed

** Will be affected by internal processing / algorithm used inside sonar component which may or may not be available depending on the system.

4.3.2 Types of Calibrations

Different calibration strategies can be used, depending on the echosounder component that is to be calibrated (see Table 4-2 - Calibration of MBES and PMBS components desired to achieve absolute level of backscatter), which supposes various degrees of knowledge on the system's other components, to be able to propagate calibration results to backscatter measurement. The approach will depend also on the system characteristics: i.e. frequency, far field distance, type of output data available (water column, stave data, across-track/along-track phase etc.), fixed on-board vessel or mobile device etc. Finally it depends as well on the practical availability and usability of measurement facilities: test tanks, docks, reference seafloor areas etc.

Reference Sphere

In the case of the water-column backscatter, use of reference spheres to calibrate SBES (and more recently MBES), in tank or at sea, is commonly applied to fishery echosounders and has been well documented (e.g. Simmonds and McLennan, 2006; ICES, 2015). Water Column output of the SBES/MBES, formatted to correspond to single target TS, is then calibrated towards the theoretical reference sphere TS value.

The first requirement is of course to have water column data available as quantitative referenced digital values, and to have enough information on echosounder data processing to be able to relate water column output data to Target Strength value on one side, and to bottom backscatter output on the other side.

A particular challenge for bathymetric echosounders is then the accurate angular positioning of the sphere within the transmission and the reception beams, along the narrow axis of both, since sphere echo level must be compensated for beam shape to retrieve Target Strength. Interferometric phase information can be used if available, but is rarely possible, if ever, in the along-track direction. An alternative positioning device can help, such as a split-beam fishery echosounder; and an accurate mounting and moving device is compulsory both for the echosounder or the sphere (Lanzoni and Weber, 2011, 2012; Lurton et al., 2013). Another way to cope with it, if the sphere echoes can be logged densely enough along its motion within echosounder swath in along- and across-track directions (at steps of a fraction of beamwidth), is to take into account only the maximum echo received from the sphere in each reception beam, and to consider this to correspond to beam axis maximum response. The precision of the result will be related to the beam attenuation corresponding to the maximum position error toward axis.

The sphere echo evolution during such a calibration procedure enables also to retrieve the two-way beam pattern (combination of transmit and receive response, potentially in both across-track and along-track dimensions), which is an important component of the echosounder range/swath capability and pulse insonified area assessment.

This type of experiment can be conducted in a tank or at sea (the latter is possible but unpractical when not impossible), according to equipment characteristics (far-field constraints, target mobility and stability, target motion control device etc.). Part of the reception far-field constraint can be mitigated if stave data (not yet beamformed) are available, provided sphere echo SNR remains acceptable and information is sufficient to relate stave data to echosounder water column or backscatter output values.

Artificial Extended Target

The use of a reference sphere for intensity calibration requires theoretical modeling to relate single target echo to extended bottom backscatter measurement, which is the MBES normal target configuration. Using a reference extended target instead of a sphere, enables to calibrate directly the echosounder backscatter output obtained on a surficial target. The assumptions used in the computation, such as the insonified area, are then included in the calibration process, and the need of accurate localization of a single target is discarded.

Different characteristics are desired for such an artificial target. It should be: 1) of a known and homogeneous surface backscatter index; 2) independent on insonified area location, with a sufficiently random structure so as to avoid interference phenomena; 3) preferably omnidirectional or with a controlled directivity diagram, and avoiding volume contribution. This is a relatively new approach, and recent investigations have been conducted with a “curtain” of irregularly oriented chain links, animated with small agitation, that achieved good results for in-tank calibration of high-frequency echosounders (Heaton et al., 2013; Heaton et al., 2014).

Reference Area

From an operational perspective, a very appealing way to proceed and control echosounder calibration, is to survey an area of known backscatter, in order to correct the equipment measurement output (Mopin et al., 2012; Welton et al., 2013). Here again, such a reference area must exhibit specific characteristics. Absolute backscatter level and directivity must have been measured with an alternative calibrated echosounder, at an adequate frequency. A calibrated SBES (calibrated in the fisheries way) can be used for this, with various tilt angles. A reference area must be flat and its backscatter as homogeneous as possible and independent of line orientation (a detrimental polarization being easily induced by organized roughness, such as small bottom ripples caused by tides or currents). Depth must be compatible with sonar’s far-field distance. Area backscatter must be stable over time, with sedimentary, biological and bathymetric permanency. Finally, attention should be paid to the area location, so as to enable regular acquisition with minimal ship’s transit time.

Inter-calibration

A simple way to calibrate an echosounder is to use a complementary calibrated equipment (commonly a calibrated SBES), with similar frequency, and to adjust their backscatter measurement results. Constraints on the choice of the surveyed area are then relaxed (although flat regular areas remain preferable for simplicity), the compatibility of depth with far-field distance remaining.

If the reference echosounder is a SBES, it should be preferably tilted, so as to avoid the normal incidence case, with specular effect and more complex considerations with insonified area computation and impact (Lanzoni and Weber, 2011, 2012; Lurton et al, 2013). Calibration will be obtained only for the MBES beams covered by the tilted SBES (several tilt angles can be tried, according to mounting device capability).

System component calibration

The calibration procedures above are empirical ones, where echosounder output is directly compared to a standard given by a reference target, artificial or natural. A more analytical procedure is possible, calibrating each equipment component described in Table 4-2, starting from the manufacturer’s initial information, completing it by tank measurements (signal level, pulse length and shape, hydrophones transmission and reception sensitivity and directivity etc.), and modeling the processing chain down to the backscatter data output. This calibration approach can be applied to more complex equipment behavior, such as dynamic focusing or stabilization, or change of beamforming modes without specific calibration, but obviously requires an in-depth knowledge of echosounder internal processing, which is rarely fully available. Implying dedicated training and equipment, this approach is normally to be reserved to constructors and a few specialized engineering labs.

Nevertheless, this analytical modeling approach remains necessary to understand potential shortcomings of empirical calibration procedures, since backscatter output necessarily relies on embedded acoustic model that can be more or less adequate to effective phenomena (absorption, propagation losses, acoustic ray bending, incidence angle, insonified area etc.). This can limit the scope of validity of the calibration result.

Internal Calibration

Some systems offer internal calibration functionalities, enabling calibration or monitoring of echosounder components, such as:

- Transducer impedance measurements;
- Transmission/reception current and voltage monitoring (amplitude and phase) for each individual transducer channel;
- Noise level measurement;
- Stimulation of the reception chain with a controlled electrical signal to check the data output.

These procedures do not provide complete calibration capability for absolute backscatter measurement, but their operation is strongly recommended to alert the operator to any shift in echosounder behavior and performance.

Calibration result implementation

According to equipment, calibration corrections can be specified to the echosounder so as to get direct calibrated measurements. Otherwise post-processing tools have to include a corresponding correction facility. In all cases, a clear and accurate logging of the calibration results must be ensured; **a calibration effort can be wasted if no usable track is kept of its results**.

4.4 Catalogue of processing applicable in sonar systems

4.4.1 *What do current bathymetric sonars measure?*

In this section, information is provided specific to each of the swath echosounders most commonly used (Table 4-2), with a synopsis of the systems and manufacturers listed and described below in alphabetical order. These descriptions are not meant to be exhaustive in detail. The reader is directed to the manufacturer for more information.

- Kongsberg GeoAcoustics GeoSwath Plus (henceforth *GeoSwath*) is a Phase Measuring Bathymetric Sonar (PMBS) existing in normal, AUV/ROV and compact setup and three frequency versions: 125, 250 and 500 kHz. All models share the same data representation.
- Kongsberg Maritime EM-Series (henceforth *Kongsberg*) is a line of Multibeam Echosounders (MBES) performing traditional beamforming. It consists of various models differing in frequency for different depth ranges. Current models, ordered by increasing frequency, are EM 122, EM 302, EM 710 and EM 2040, but older models are still widely used: EM120, EM

300, EM1002, EM 3000, EM 3002, etc. Each model has a different array configuration and therefore different beam patterns. Recent models use new datagram formats (Kongsberg, 2013). The data representation for newer models differs from that of older models.

- R2Sonic Sonic series (henceforth R2Sonic) is a line of MBES performing frequency domain beamforming. It consists of four models differing only in the aperture of their transmitter and/or receiver: Sonic 2020, Sonic 2022, Sonic 2024 and Sonic 2026. All four models can operate over a frequency band of 200 kHz to 400 kHz, with a high-resolution 700-kHz mode also being available on 2022 and 2024, and a 100-kHz option on the 2026. All models share the same data representation.
- Teledyne RESON SeaBat series (henceforth Reson) is a line of MBES performing traditional beamforming. Current models make up the 7k-series, ordered by increasing frequency: 7150, 7160, 7111, 7101, 7128 and 7125. A new model, T20P, has recently been added to the product line. Older models (8k series) are still widely in use: 8125, 8101, 8111, 8160, etc. Data representations differ between the newer and older model series but are otherwise common across the model range.

Note that PMBS and MBES are different technological approaches to achieve swathe bathymetry measurements. MBES implement a beamforming algorithm on the received signal to electronically steer the array in hundreds of different receiving directions. The signal in each direction is then processed to produce one or several soundings and one or several backscatter data values. In comparison, PMBS is based on the sidescan sonar technology in that it does not produce directional beams but rather records backscatter data as one single time-series of samples stretching from nadir all the way to the outer swath. The soundings are obtained by processing the phase signal of that single receive beam. Both systems produce backscatter data and the bathymetry needed to georeference the backscatter samples. More information on these technologies and their main differences can be found in Lurton (2010).

Table 4-2 Internal conversion of the received echo at receiver array to the results reported in the datagram at each acquisition stages.

System	Stage 0: transmit	Stage 1: Receiving	Stage 2: Amplification	Stage 3: Sampling (after basebanding)	Stage 4: Array normalization, windowing & beamforming	Stage 5: Bottom detect.	Stage 6: Amplitude measurement	Stage 7: Reporting of Results
GeoSwath	Both source level and pulse length can be modified at any time. These values are reported in the datagram	Low-noise filtering around the sonar frequency	Base gain and TVG (~20logR)	The signal in the channel (stave) used for backscatter is rectified, low-pass filtered (envelope) and sampled	N/A	N/A	The actual time series after stage 3	Acquisition settings (source power and pulse length and base gain) are reported in the datagrams.
Kongsberg EM 3002	Fixed HV voltage. Three frequencies and pulse lengths available.	Band-pass filtering	TVG and ADC or High resolution ADC at high sampling rate (for sonar head serial numbers > 700)	Band-pass filtering per sector tuned to TX bandwidth	Amplitude shading, Time delay beamforming	Yes	Correction of SL, Receiver sensitivity, all gains, RX and TX beam pattern, absorption profile etc.	Datagram format published at Kongsberg.com
Kongsberg EM 1002	SL updated by measured HV voltage. Different beamwidhs, frequencies and pulse lengths available. Optional mechanical pitch stab.	Band-pass filtering	TVG amplifier	ADC at high sampling rate	Amplitude shading, phase shift/time delay beamforming Band-pass filtering per sector tuned to TX bandwidth Roll stab.	yes	Correction of SL, Receiver sensitivity, all gains, RX and TX beam pattern, absorption profile etc.	Datagram format published at Kongsberg.com
Kongsberg EM 120/300	SL updated by measured HV voltage. Many beamwidths and sectors with different frequencies and pulse lengths available. Roll, pitch and yaw stab,	Band-pass filtering	TVG amplifier	ADC at high sampling rate	Amplitude shading, phase shift/time delay beamforming Band-pass filtering per sector tuned to TX bandwidth Roll stab.	yes	Correction of SL, Receiver sensitivity, all gains, RX and TX beam pattern, absorption profile etc.	Datagram format published at Kongsberg.com

Kongsberg EM 122/ 302/710/2040	SL updated by measured HV voltage. Many frequencies, beamwidths and sectors with different frequencies and pulse lengths available. Roll, pitch and yaw stab, Shaped pulses. Near field focus per sector	Band-pass filtering	Fixed gain	High resolution ADC at high sampling rate	Amplitude shading, Time delay beamforming Band-pass filtering per sector tuned to TX bandwidth Roll stab.	yes	Correction of SL, Receiver sensitivity, all gains, RX and TX beam pattern, absorption profile etc.	Datagram format published at Kongsberg.com
R2Sonic	SL, frequency and pulse lengths are user set-able and pitch stabilized on 2026	Buffering, amplification and filtering	Fixed and/or Time variable gain with user set-able parameters	Oversampled high resolution ADC	Variable aperture, frequency domain split aperture beamforming with dynamic focusing and roll compensation	yes	At bottom detection point or time series	R2Sonic published format
Teledyne RESON 7125, T-20	SL controlled by voltage and pulse width modulation Different pulse length and frequencies available	Band-pass filtering	TVG amplification	ADC at high sampling rate	Channel equalization, time-delay / phase-shift beamforming with array shading for sidelobe control Roll stabilization Dynamic focusing	Yes	Amplitude time series after stage 4 or 5	Various imagery records with all sonar settings recorded Data Format is published
Teledyne RESON 7160, 7150	SL controlled by voltage Different pulse lengths available Pitch stabilized	Band-pass filtering	TVG amplification	ADC at high sampling rate	Channel equalization, time-delay / phase-shift beamforming with array shading for sidelobe control Roll stabilization Dynamic focusing	Yes	Amplitude time series after stage 4 or 5	Various imagery records with all sonar settings recorded Data Format is published
Teledyne RESON 7111	SL controlled by voltage Different pulse length available Pitch stabilized	Band-pass filtering	TVG amplification	ADC at high sampling rate	Channel equalization, time-delay / phase-shift beamforming with array shading for sidelobe control Dynamic focusing	Yes	Amplitude time series after stage 4 or 5	Various imagery records with all sonar settings recorded Data Format is published

4.5 Recommendations

4.5.1 *Sonar Manufacturer signal processing*

In order to make quantitative acoustic measurements suitable for calculation of acoustic backscatter, we recommend that the following point should be taken by sonar manufacturers. Operators and users should be able to retrieve easily the following information, made available in an exhaustive and clear form, either in the sonar documentation (generic or individual) or in the recorded datagrams:

- Nominal values of the main parameter settings (Source Level, Pulse Length… and also directivity patterns, gains…), clearly expressed and easily available (in datagrams) for further compensation operations in post-processing;
- Content and units of the reported values: what is being reported, received level, target strength or backscatter; amplitude or intensity, in linear units or in decibel;
- Gains applied during the measurements: analog static and time-varying, digital conversion;
- Possible application of corrections and their detailed characteristics: removal of static and time-varying gains; correction for transmission loss and insonified area;
- Corrections applied for beam patterns and receive sensitivity; biases that might result from element level normalization, windowing, application of FFTs and other effects.
- Calibration results for individual systems, measured during the manufacturing process: transmit and receive patterns (for transducer elements and array); source level; pulse length; TVG curves.
- Backscatter value estimation: result of a single measurement or a blending (to be described) of multiple measurements over successive samples?
- Location of the seafloor at the measurement and associated mode of bottom detection. (In addition to locating the measurement for display, location is required for proper correction due to the insonified area, which is in turn dependent on the angle of arrival of the acoustic signal relative to the seafloor local slope.)
- If the reported value is meant to be backscatter rather than received level, corrections applied for the transmitted source level the two-way transmission loss, and the footprint extent. Details about the transmission loss model (spreading and absorption) and the insonified area computation.

4.5.2 *Design of future sonars*

The following are a number of recommendations to sonar manufacturers, which are of general relevance and not dependent on particular system specifications or application:

- Generalize the use of high-dynamics ADC (floating dynamics) in order to avoid TVG ASAP. The purpose is to decrease the uncertainty linked to the practical realization and response of analog TVG, whose *a posteriori* compensation is always imperfect;
- Generalize in-lab measurements and tests of transducer sensitivity and directivity characteristics; electronic channels response etc. ;
- Improve the availability and clarity of technical information about the system characteristics useful for backscatter, already detailed in §4.5.1 (Tx and Rx sensitivities and directivity patterns, source levels, values for gain and compensations applied, compensations applied for TS or BS estimation etc.);

- Provide specific dedicated functionalities for implementation of calibration results inside systems for compensation: both at the system input (for real-time application) or when logging datagrams (export for post-processing);
- Implement automated functionalities for self-test of various characteristics of the system: impedance of Tx and Rx element transducers; scan of the transducer arrays; sensitivity and response of the electronics channels (via reference voltages);
- Make available self-noise measurement functionalities at reception on the sonar receive channels;
- Apply a common and normalized nomenclature to the recorded data, synthetizing the stages of signal processing applied. From the raw physical data acquisition down to the BS datagram.

From a more prospective point of view, it is felt that an effort should be done by constructors in order to simplify the design and functionalities of seafloor-mapping sonars, at least regarding the backscatter-measurement capabilities: the high level of sophistication desirable (and achieved today) for bathymetry applications may be detrimental to a reliable measurement of backscatter, in that it multiplies the risks of uncertainties in the processing involving compensation of the various stages of the sonar operation from transmission to reception and processing. This could go, for currently existing sonars, through the definition of simplified operational “backscatter-orientated” modes maximizing the reflectivity measurement accuracy and stability. For future systems, this could imply the definition of intermingled modes (devoting certain ping cycles to backscatter rather than bathymetry, although it is not clear whether this goes really in the sense of simplification); or even define specific sonar systems optimizing the backscatter measurement at the expense of a lower quality in bathymetry – for configurations where meeting hydrography standards may be unnecessary.

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CHAPTER 5 ACQUISITION: BEST PRACTICE GUIDE

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5.1 Objectives

The objective for this chapter is to provide a practical framework to guide acquisition of seafloor acoustic backscatter. Each backscatter mapping project will be different and will generally have different objectives, different requirements, and different operational parameters. For example, a one day survey of an oyster reef will likely have very different operational considerations than a multi-year campaign to survey and delineate the surficial coastal resources of a coastal state. The common objective is gathering sufficient amounts of quality seafloor and environmental information to create products depicting the seafloor that are devoid of measurement system or measurement time specific effects or artifacts.

In recognition that different requirements will dictate different approaches, we have structured this chapter around a series of statements we recommend the surveyor considers well before the equipment is selected and data acquired. The resultant decision tree (Figure 5-1) is a guide into specific considerations and procedures (such as full or partial calibration). Other repercussions for these considerations, such as details related to costs or time required to overcome some of the described barriers to backscatter quality, are not discussed in detail as they vary widely depending on the specific survey. This approach is built on backscatter as a physical measurement rather than as a simple imagery product.

We will consider environmental conditions that may be of more concern in some areas than others. For example, biological fouling may be of particular concern for a proposed survey in a tropical estuary while a survey in an industrial northern harbor may have a more pressing need to understand the background noise characteristics.

We then look at the specific design of the proposed survey and consider the impact of different coverage and acquisition strategies. This includes the layout of the survey with thoughts to subjects such as optimal line spacing, patterns, and orientation; cross lines and other checks; and considerations on data rates and file sizes. All this information is quite general, and we hope will be useful to anyone considering a backscatter survey campaign.

The final section details several sonar systems in use today. This is meant as neither an endorsement nor a criticism of these systems and will unfortunately become outdated as the specific equipment changes. This section will help to understand how the design and implementation of these systems affect the decisions required by the surveyor.

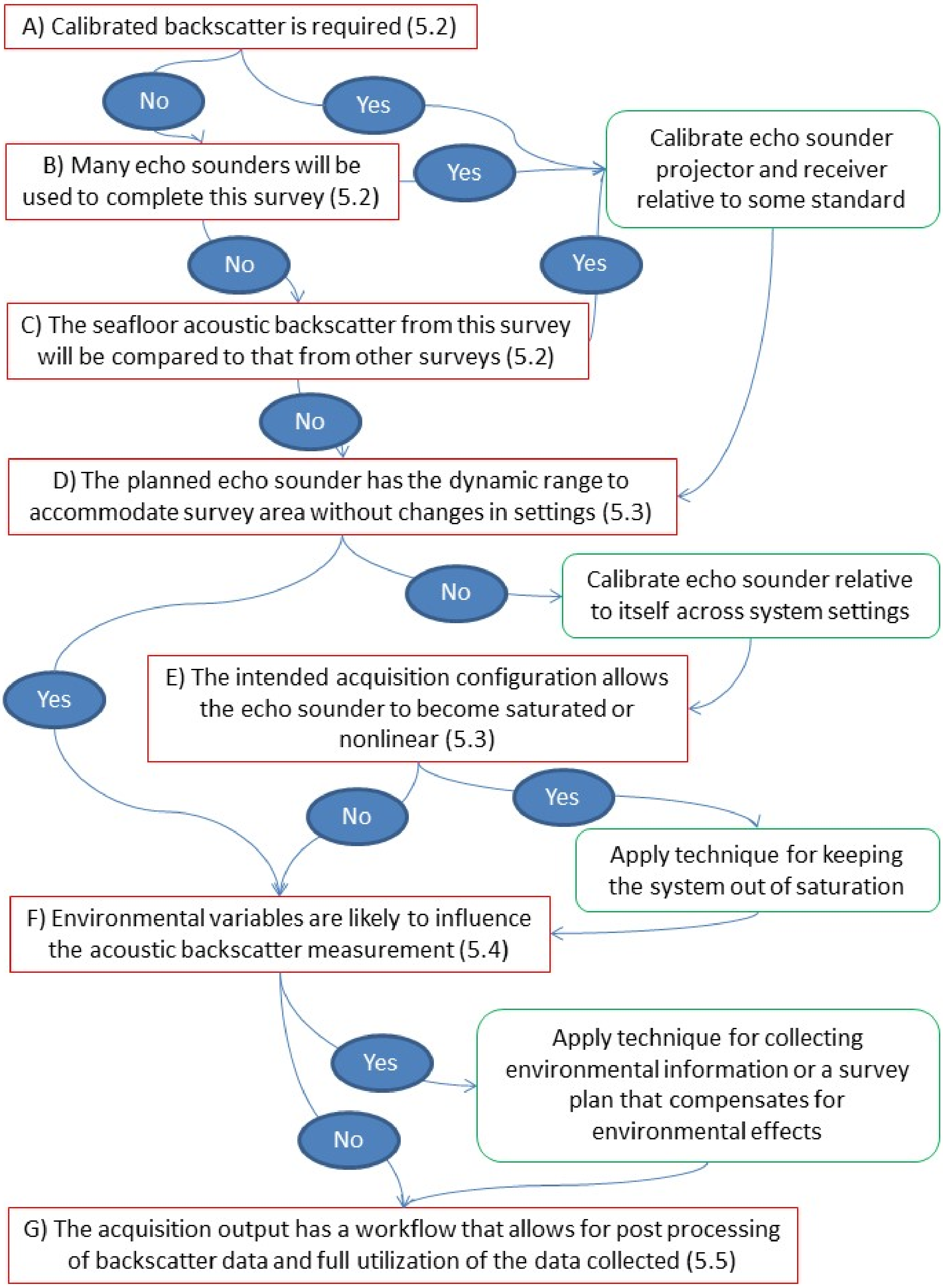


Figure 5-1 A decision tree approach to planning a backscatter survey. The red boxes are statements to be answered as either 'Yes' or 'No' to guide how a surveyor plans for a backscatter survey according to the survey requirements, and are labeled with a letter for simple reference. Each statement also lists the section in which the technical details are addressed. The green boxes are provided for context between questions for how each answer impacts additional requirements. The goal should be to arrive at the base of the decision tree by the simplest route possible.

5.2 Calibration of bathymetric echosounders for field operations

5.2.1 Why calibrate

Commonly surveys consist of many measurements, and comparing measurements requires a common reference. Whether independent measurements are combined from the same instrument or from many instruments, a consistent and meaningful product depends on the combination of comparable data. For example, hydrographic surveyors use a vertical datum such that depth measurements taken at different times are comparable through a common vertical reference. For backscatter the echosounder needs to be calibrated against some standard to obtain comparable backscatter levels (see Chapter 4). What defines "comparable" is a function of the survey specifications. A surveyor needs to understand the requirements for the backscatter products before conducting the survey in order to make the right decision about which echosounder to use and whether or not to calibrate. For surveys requiring some measurement of absolute or "true" backscatter, e.g. for inversion of models, an absolute level calibration (§5.2.2.1) should be applied. If only a consistent product between different vessels or different surveys is required, then relative calibration (§5.2.2.2) may be appropriate (Hughes-Clarke et al, 2008). In all cases the calibration should be objective (quantifiable and verifiable) and duly documented. Repeating calibration over the operating life of a given systems helps to ensure consistency of measurements over space and time. Such repeated operations will safeguard against potential changes arising from degradations of the sensitivity of the echosounder's acoustic elements or the health of system electronics over time, which may significantly impact the backscatter measurement. Changes in the vessel mounting configuration may also impact backscatter measurements.

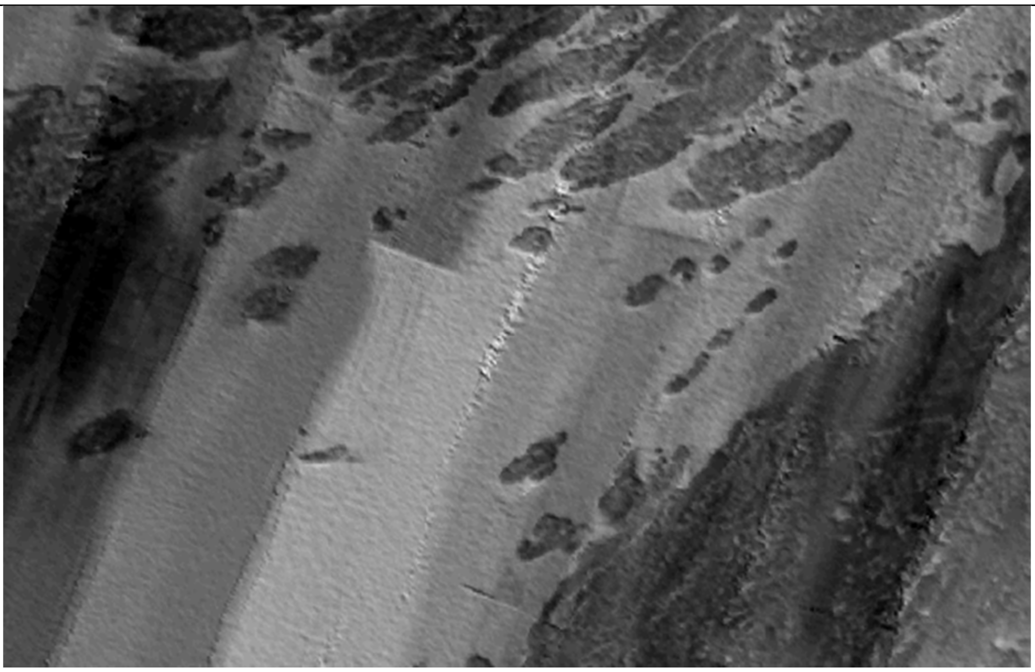


Figure 5-2 A small section of a 400 kHz seafloor acoustic backscatter mosaic as collected in approximately 60 meters of water by NOAA Ship Ferdinand R. Hassler. Both rocky outcroppings and sandy seafloor are depicted, but with overprinted and distracting survey line dependent measurement artifacts and offsets.

Perhaps just as important as knowing when to calibrate for backscatter is knowing when not to calibrate. It may be that instabilities in the echosounder electronics caused by changes in temperature make the calibration process not worthwhile. This is not to say that the final backscatter product will be useless, but the accuracy expected from these systems should be tempered. Alternately, a processing approach to backscatter may be specifically designed to be independent of absolute or even relative calibration values (Gavrilov and Parnum, 2010).

5.2.2 Types of calibration

Here we differentiate between absolute and relative calibration, and briefly describe the available techniques.

5.2.2.1 Absolute calibration

Absolute calibration can be undertaken using the different approaches detailed in Chapter 4. Appropriate levels of expertise and of additional equipment or facilities necessary to process the calibration are important to consider before attempting an absolute calibration.

A convenient object with a known target strength can be used as a reference object for calibration. Standardized metal sphere commonly used in fisheries acoustics for this purpose offer a number of advantages: isotropic directivity pattern minimizing measurement constraints, simplicity and reliability of the predicted TS, ease and precision of the manufacturing. This kind of approach is simpler in a confined tank environment, where the target position can be accurately known and if far-field conditions can be met. Some steps have been made to use split beam echosounders to position a target sphere relative to a separate multibeam echosounder that is to be calibrated (Lanzoni, 2011). Artificial extended-area targets (Heaton et al. 2014) may also help solve the target positioning problem since they are large enough to cover a whole beam and even to extend over several beams at the same time, so that the surface backscattering strength can be directly measured at various angles; unfortunately these approaches are not currently developed sufficiently for field use.

Relative calibration techniques (§5.2.2.2) can be used for absolute calibration if the reference target backscatter can be established using a calibrated echosounder. In this approach the measurements of the calibrated echosounder are used to determine the offset by grazing angle for the system to be calibrated.

5.2.2.2 Relative calibration

A relative calibration is different from absolute calibration in that the reference target backscatter strength is unknown and can only be used for the purpose of comparison. This method is used for comparing different acoustic systems on different vessels or to ensure consistency of a single system with different settings. When employing a relative calibration only appropriately similar physical measurements should be compared, and avoid the use of significantly different frequencies (see 5.3.2).

Using a seafloor area as a relative calibration target is the most straightforward approach when in the field. This is because the seafloor is readily available and the calibration is performed with the entire measurement system, including the supporting sensors and vessel mounting. This all inclusive approach makes sense in an operational context since mounting configurations can have an effect on backscatter. As described in Chapter 4, the choice of the seafloor area is important as a number of factors can affect the quality of the calibration. A reference area should be flat, level, and of a homogeneous seafloor type so processing assumptions, such as projected beam foot print estimates, will minimally bias the results. The area should also be deep enough to be in the far field of the echosounder for a consistent beam pattern. It is important to weight the assumption of seafloor statistical stationarity and isotropy against the accuracy requirements of the backscatter measurement.

The relative backscatter response between two systems can be compared by recording a series of lines and computing the backscatter average values as a function of transmission angle, beams number and across track distance. Hundreds of separate pings over a flat, homogeneous seafloor should be collected to best support the desired statistics. These statistics are then used to assess the consistency of the backscatter and to compute a backscatter bias (Augustin and Lurton, 2005).

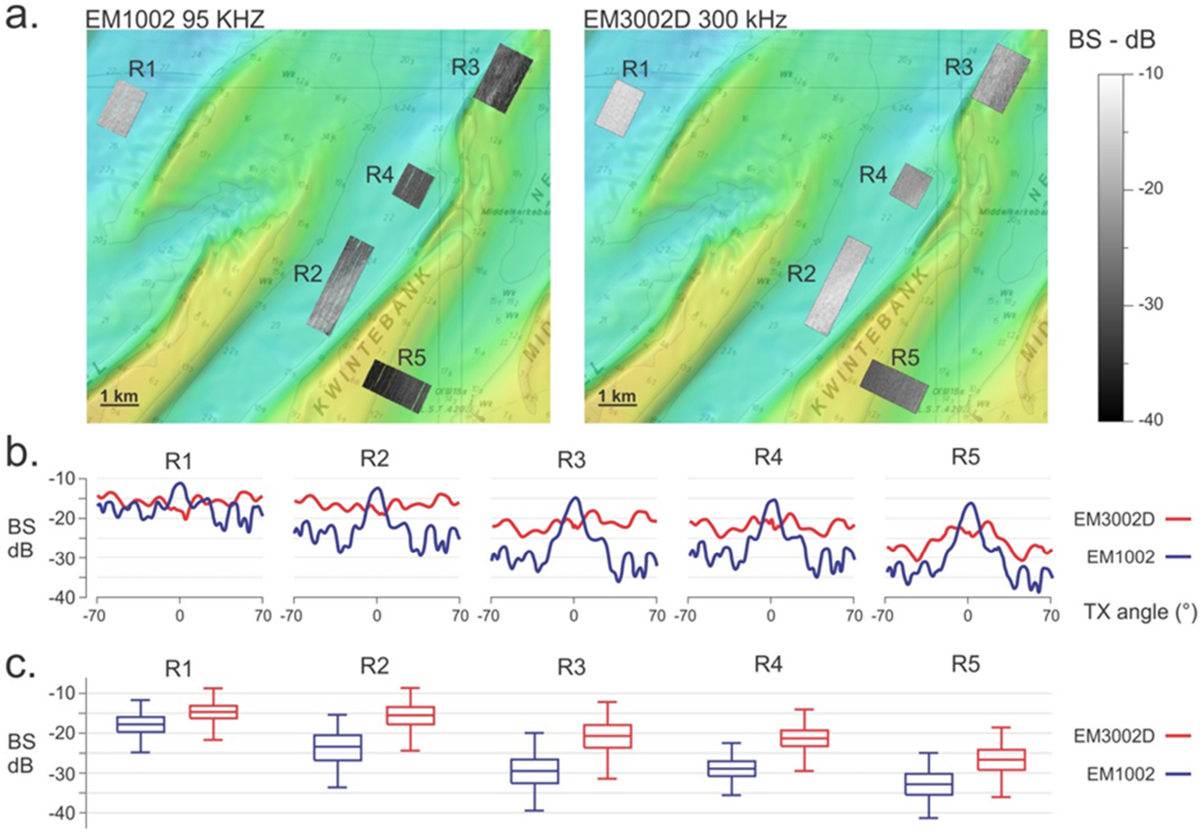


Figure 5-3 Comparison of two different MBESs (Kongsberg EM1002 95 kHz and EM3002D 300 kHz) installed on the same vessel (RV Belgica) on an area featuring different types of seafloor; R1 = coarse gravel, R2 = gravel and sandy gravel, R3 = coarse to medium sand, R4 = fine to medium sand highly bioturbated, R5 = fine sand. Data from both MBESs were acquired simultaneously; A.: backscatter maps of the 5 areas for each MBES presented with the same grayscale; B.: mean backscatter versus TX angle curves for each area and for each MBES. Note the high difference of the curves patterns of the 2 MBESs especially for the coarser sediment areas (R1 to R3); C. Summary statistics by box plots for each zone and each MBES; Differences between the MBESs fluctuate from 3 to 8 dB depending on the type of sediment; unlike the EM1002, due to its high frequency the EM3002D makes no difference between R1 and R2 zones, both zones have the same roughness for a 0.5 cm wavelength signal.

The backscatter reflects (beyond the impedance contrast at the interface) the “acoustical roughness” defined as the ratio of the geometrical roughness to the acoustical wavelength (see chapter 2). A relative comparison of different echosounders must take into account the differences in system settings, such as pulse length, between the echosounders considered. For echosounders operating with a substantial difference in frequency (e.g. 100-300 kHz), the relative “acoustic roughness” will lead to large differences in levels of backscatter (see Hughes Clarke et al., 2008). An example showing a comparison of two different MBES working at 95 and 300 kHz and installed on the same vessel is presented in Figure 5-3.

Dual-head echosounders, such as dual-head MBESs and PMBS, combine two synchronized systems but oriented differently to cover either side of the vessel. The different transducers and receive electronics in each "head" need a relative inter-calibration to combine the output of the two separate systems. An example of relative calibration and inter comparison of a same model of dual-head MBES installed on two research vessels is presented in Figure 5-4. Care must be taken that the sonar heads are accurately aligned. This is usually done using the classical bathymetry calibration steps (Gueriot et al., 2000).

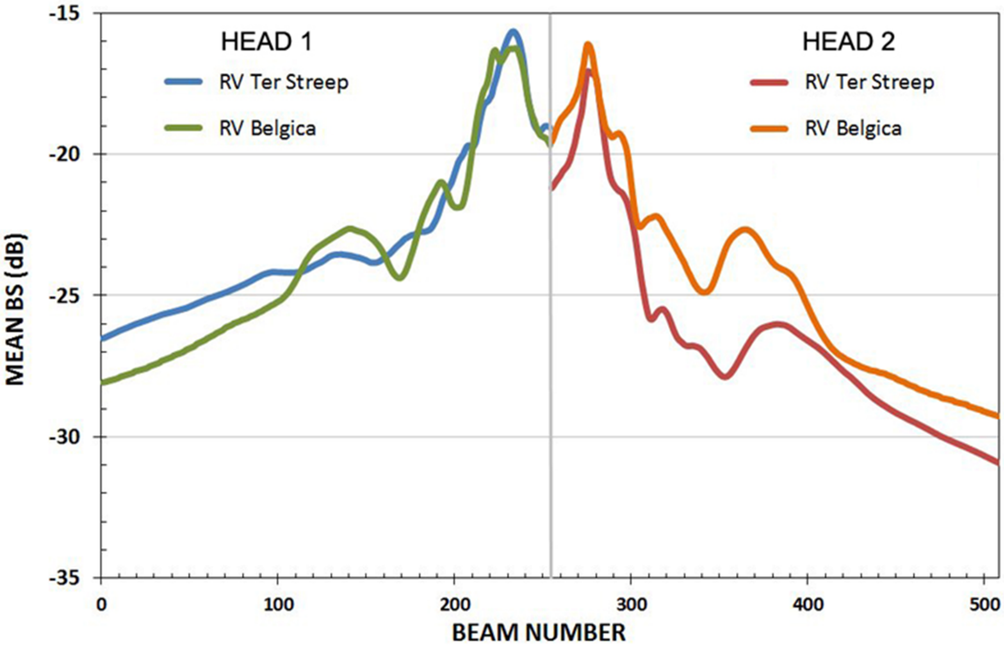


Figure 5-4 Mean backscatter (dB) versus beam number for identical dual-head Kongsberg EM3002D's, installed on two research vessels (RV Belgica and RV Ter Streep). RV Ter Streep EM3002D's data shows a mean bias of 3 dB between the two heads with a strong difference of angular response requiring a post-processing geometric correction. RV Belgica EM3002D data have no vertical bias and excellent symmetry of the two heads curves. (Data of the RV Ter Streep from Flemish Hydrography).

A relative calibration can also be used for internal setting comparison to ensure consistency within a single system's electronics. By comparing backscatter with different system settings, such as transmit power or receiver gain, the user can ensure that changing these settings during survey will not affect the final product beyond survey specifications (see §5.3).

In coastal areas it is often difficult to meet all the criteria for a good relative calibration seafloor area in a single location. In practice it may be necessary to weigh the relevance of each criterion for how a candidate area will be used. The expectations for using the area should be adjusted accordingly.

Other environmental parameters, such as the water column physical characteristics or weather conditions, should also be carefully considered before conducting a field calibration. A changing or complicated water mass requires good water column monitoring to ensure minimal influence on the calibration. Since there is no guarantee that this monitoring effort would be successful, or that all the complications will be handled correctly in post-processing, it may be simpler to find a different area for calibration. Micro-bubbles in the water column, resulting from wave action or 'bubble sweep-down' under the hull, or additional noise from heavy weather, can also interfere with calibration and should be avoided.

5.2.2.3 Application of calibration information

Some manufacturers have developed distinct approaches to backscatter where adjustments are applied during acquisition to improve the real time backscatter (see §5.6). Properly adjusted backscatter can be useful during acquisition and thus these techniques are valuable. But blunders or poor assumptions made during acquisition can be detrimental to the final products if they cannot be properly accounted for in post-processing. All real time adjustments should be recorded alongside the recorded backscatter so that the data may be easily returned to an unprocessed state in post-processing where improved techniques may be applied.

Please refer to §5.6 for more vendor specific information on approaches to calibration where they exist.

5.2.3 When to calibrate

Some of the reasons to calibrate include:

1. Installation of an echosounder;
2. On a periodic basis (such as yearly) to observe system health and general changes to sensitivity;
3. At the beginning of any large surveys for which backscatter measurement is of particular importance;
4. When using multiple echosounders to ensure consistency and mutual congruence;
5. In case of unfamiliar oceanographic conditions, such as large changes in temperature, to check changes in system sensitivity.

Calibration schedules should also be a function of stability of the measurement system. For example, echosounders with significant analog components may vary in sensitivity with factors that are difficult to meaningfully track, such as internal temperature, making a calibration inconsequential. Information concerning the stability of the measurement system over time, measurement stability between restarts to the echosounder, and the impact of biofouling over time should all be of particular concern to operators interested in recording comparable data over several different sessions in the same area. Despite an increasing use of backscatter for monitoring of the seabed, it is difficult to quantify the impact of the aging of the electronic components and the antifouling on the transducer faces on the average measured level of backscatter (see Case Study 5-1).

Case study 5-1 – Measurement system sensitivity variation over time

A five-year time series is used to illustrate how potentially important time-dependent backscatter sensitivity is for monitoring studies. Five of the six described zones in Figure 5.5 were monitored with EM3002D MBES. These areas are distinct in water depth, geomorphology and hydrodynamic conditions, but a similar trend affecting the mean backscatter in all regions was observed. demonstrates that some of the short term drift correlates to the vessel maintenance history. Strong biofouling (barnacles with few oysters) on the transducers was observed during both dry docks, requiring thorough cleaning and new antifouling coating on underwater components. The long term trend presents a statistically significant slight decrease of the mean backscatter levels, approximately 2 dB over five years, which may indicate aging of the MBES in addition to biofouling concerns.

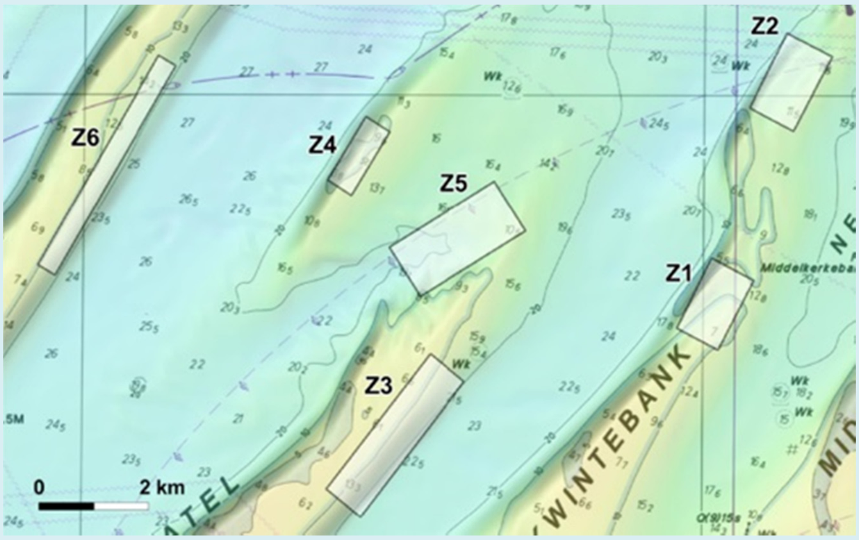


Figure 5-5 MBES (Kongsberg EM3002D on R/V Belgica) backscatter survey areas during a five year study, varying from fine to coarse sand.

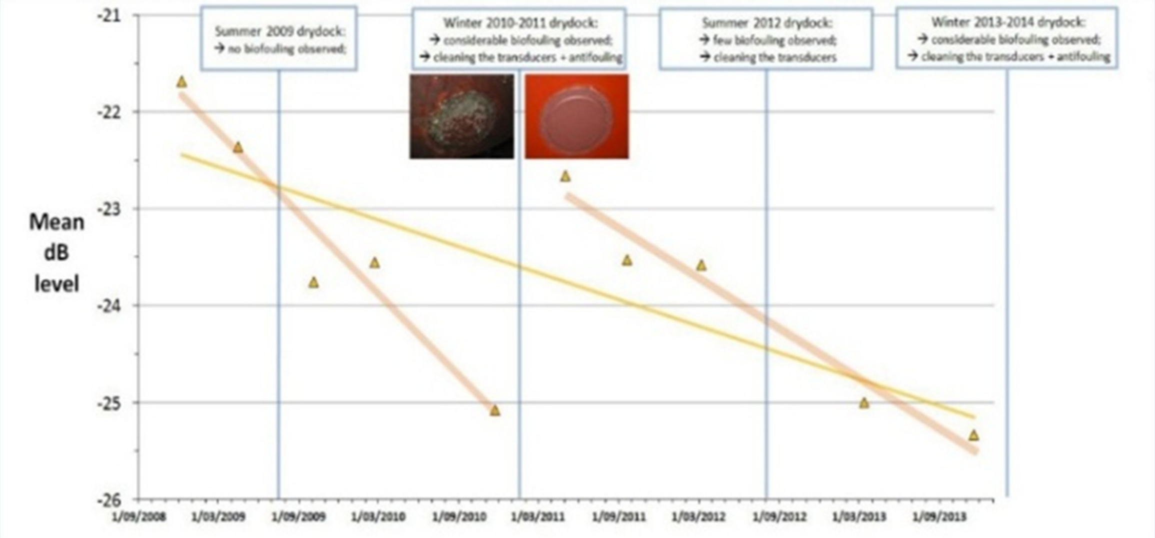


Figure 5-6 Detail on the Z6 backscatter time series with observations reported from the dry-dock history of the R/V Belgica.

Case Study 5-2 - Effect of aging of MBES

The effect of aging of MBES components on measured backscatter level is complex and varies from one MBES to another. A prior time series of the EM1002 MBES on the same vessel in two nearby areas (Figure 5-7) shows an initial small positive drift of 1dB/year. This trend during the first two years of measurement is followed by five years of measurement during which the average level of backscatter is relatively stable. Taking into account the geomorphology and sedimentology contexts of both areas, this equal positive trend cannot be attributed to an identical increase of the average sediment grain size in both areas. Rather, this trend suggests a drift of the measuring system with an increase in sensitivity that could be hypothetically related to a change in the transducer coating during the first two years.

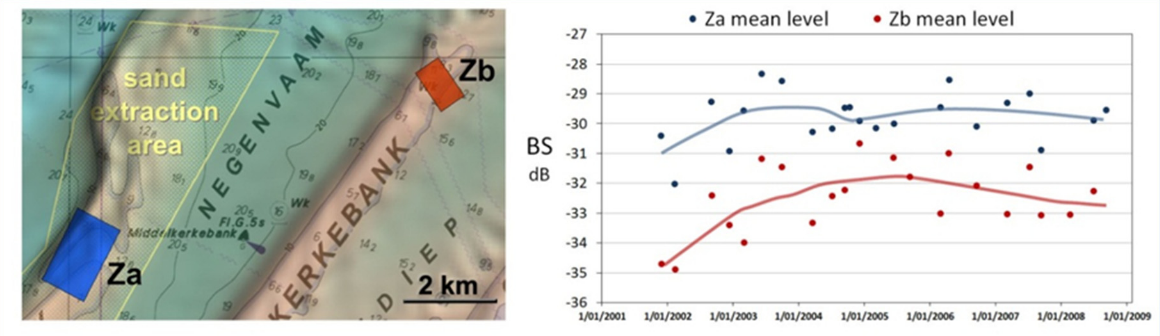


Figure 5-7 MBES (Kongsberg EM1002 on RV Belgica) backscatter time series acquired over a period of seven years on two reference areas of the Flemish sandbanks (Belgian part of the North Sea). Za area located in a large sand extraction area is intensely dredged and dominated by medium sand; Zb area is located outside the extraction area and is dominated by fine sand.

5.3 Echosounder settings and changes during survey

5.3.1 *Dynamic range and saturation*

Chapter 4 discusses the different echosounder system settings and Chapter 6 describes how they are accounted for in post-processing. Ideally these settings would have minimal to no impact on the final product, but imperfections or compromises in the real world mean the backscatter surveyor should understand how to minimize measurement system impact on the final product.

If an echosounder has sufficient dynamic range, which is to say the sensitivity range to accommodate both the weakest and strongest echoes (Figure 5-8), then system settings may be kept constant throughout a survey thus avoiding the internal calibration steps discussed in §5.2. But this one set of settings must provide good bottom detections throughout the survey area, for all depths and all seafloor substrates, and it is difficult to impossible to determine this before the survey. Only the system settings used during the survey need to be calibrated to meet the backscatter accuracy requirements of the survey. Much of the time, however, the depth range and seafloor types for a survey area either vary widely or may not be known *a priori*. In this situation the power, gain, or pulse length may need to be modified and adapted during the survey to ensure good bottom detections across the entire swath. Whether they are automatic or manual, these changes in system settings may lead to offsets in the final product if not cross calibrated.

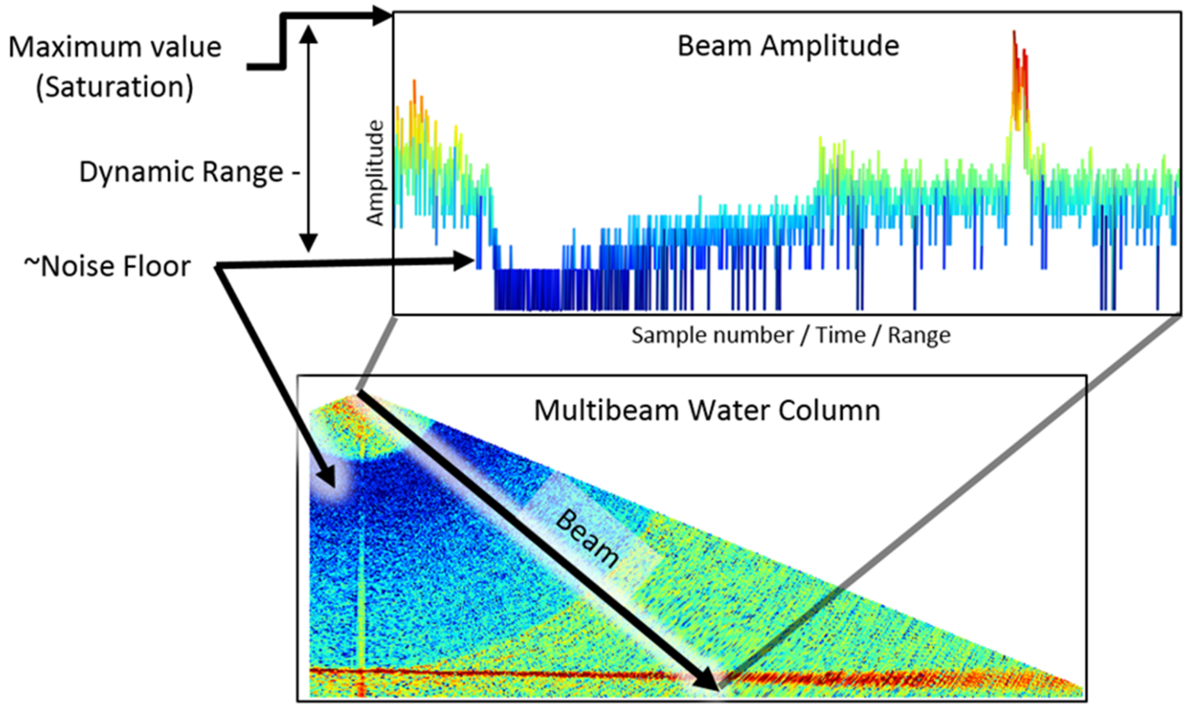


Figure 5-8 The concept of dynamic range as illustrated within a single MBES swath. The lower plot depicts the water column and seafloor backscatter as blue (low backscatter) to red (high backscatter). The upper plot is a backscatter amplitude series over a particular beam. Backscatter above the maximum value has saturated the receiver and will limit the usefulness of the data.

When an echosounder is operating near the lower limit of its dynamic range the backscatter level comes close to the noise floor. In this situation the signal-to-noise ratio becomes poor, and bottom detection quality is degraded. This situation has a clear negative effect on the bathymetry, signaling the sonar operator to make a change to the system settings (increasing time varying gain or the power, or changing the operating modes).

Conversely, when the received signal exceeds the dynamic range of the system, the signal is clipped or otherwise distorted in a non-linear fashion, leading to an irrevocable loss of some backscatter information (Greenaway, 2010). Unfortunately, it may not be obvious to the operator when the system is running near the upper limit of its dynamic range. Many systems can obtain satisfactory bottom detections from clipped or otherwise disordered signals. This situation makes it difficult for a sonar operator to know when to change system settings to avoid saturating the receiver. The situation can be further complicated by the dependence of the saturation point upon the echosounders' settings, making it even more difficult for the sonar operator to know how to control the system. Specific tools may need to be provided by the echosounder manufacturer to guide the operator and avoid a saturated state.

While the effect of non-linear behavior on backscatter may not be clear in real time, in post-processing adjustments made according to the echosounder settings may make the problem more obvious. The effect of saturation is more evident when echosounder changes are made while in a saturated state. This can create obvious artefacts that coincide with the settings changes, making adjusting settings less desirable if the operator cannot monitor for echosounder saturation.

Cascading complications can arise when trying to meet high quality backscatter requirements with low dynamic range systems. If the survey area includes a broad range of depths and seafloor types, but an echosounder with low dynamic range is used, system settings would need to be changed frequently to maintain the return within the dynamic range of the system. An internal calibration across the range of such settings should be conducted to avoid artefacts due to the changes in system settings. A way to monitor for non-linear behavior may also need to be developed if one does not exist for the particular echosounder type. If more than one vessel is to be used they should at least undergo a relative calibration to avoid artefacts due to sensitivity offset between the different echosounders. But, if an echosounder with high dynamic range or if a less dynamic seafloor is expected, the entire survey may be conducted with one set of system settings. How these different situations are best dealt with is a function of the survey area and the echosounder in use, as well as the experience of the echosounder operator and the backscatter requirements. It should be clear, however, that an echosounder with high dynamic range affords the backscatter surveyor more flexibility.

Understanding the echosounder dynamic range and the need for setting changes, all in the context of backscatter accuracy requirements, is an important part of planning for a backscatter survey. If setting changes will be frequent then at least a relative internal calibration and monitoring for saturation may be necessary. See §5.6 for more specific discussion regarding vendor and model specific considerations.

5.3.2 Echosounder frequency and backscatter

Seafloor backscatter is dependent on the frequency of the echosounder in use (Jackson et al., 1986). Investigating the varying response of the seafloor to different frequencies may be the purpose of a backscatter survey and provide more insight into the properties of the seafloor, but care should be taken when a single survey has been covered by various frequencies. Combining different frequencies on adjacent areas into a single product without clearly describing and delineating the product may be deceiving to the end user. Since many currently available echosounders are capable of changing frequency during survey, the backscatter surveyor should be careful to control this aspect of the echosounder operation. Ideally an area should be characterized with one frequency. If a different frequency is required for optimal operation, such as when working at a different depth, the data should be explicitly separated.

The pulse type may be an additional setting choice related to the frequency. Frequency-modulated (FM) pulses, as opposed to single-frequency continuous wave (CW) pulses, are now available in some echosounders. While a given seafloor should produce the same backscatter from an FM- or a CW-pulse of the same bandwidth, CW processing is simpler, hence less prone to instrumental uncertainties and therefore preferentially recommended. Longer CW pulses may further reduce the used bandwidth in some echosounders, narrowing the seafloor frequency response around the carrier frequency and reducing ambiguity to the conditions of the backscatter, while also spatially averaging the local seafloor response. In the long run, broadband systems may allow for a promising multi-frequency view of the seafloor (Hughes Clarke, 2015); however the frequency range necessary for such an approach (several octaves) raises technological constraints which are not yet fully solved in current commercially available multibeam echosounders.

5.3.3 Additional considerations when changing settings

For some echosounders there may be a small delay between when changes in system settings are commanded and actually altered. This can result in a discrepancy between what is reported for echosounder settings and what was actually applied. For example, when an echosounder operator reduces the transmit power, for some systems it can take several pings for the power to actually come down to the commanded level. The recorded level may not reflect what was actually transmitted while the power comes down, so a transient artefact may exist in the post-processed product. Note that such delays, quite common with analog electronics, are less common with strictly digital operations (such as receiver filter changes in the post-ADC modules). This is one more argument in favor of a minimization of the sonar parameter changes during field acquisition.

5.4 Environmental and geometric factors to consider

5.4.1 Different factors to consider

Up until this point this chapter has focused on the measurement system itself, namely calibration of the echosounder. However, environmental factors affect or degrade the quality of backscatter measurements and must also be considered. Just like accounting for the effects of the echosounder, the energy lost to the water column or lost to a different direction must also be quantified to ensure the highest quality backscatter product. Minimizing interference of desired seafloor backscatter with other sources, such as vessel noise or other echosounders, is important for a quality backscatter measurement. While it is not possible to predict the seafloor response, ensuring high data density and consistent survey direction helps support the statistical result. Finally, the geometry of a swath system means there is likely to be a region of specular return from the seafloor where the measurements are difficult to normalize properly relative to the rest of the swath. Designing a survey to best overcome each of these challenges starts with understanding how each might degrade the backscatter measurement.

5.4.2 Water column characteristics

Acquiring good backscatter data starts with collecting correct bathymetry, which implies that sound speed profiles (SSP) accurately reflect the water mass during survey time to support ray tracing. SSP can be provided by direct sound speed measurements, but absorption profiles are also important for backscatter surveys for compensation of signal attenuation. Measuring the salinity and temperature as a function of depth is the appropriate way to obtain the frequency-dependent absorption profile, although estimates can be obtained from a sound speed or temperature profile combined with an average salinity for the entire water column. If a full profile cannot be inferred from local measurements it is important to use absorption estimates representative of the surveyed water depth rather than just extrapolating the surface absorption for the whole water column. Particularly in deep water assuming surface salinity for the entire profile could lead to gross misestimates of signal attenuation in the water column. Finally, the frequency dependence of the absorption coefficient needs to be considered as well, since it may cause shifts between transmit sectors working slightly different frequencies.

Water mass chemistry is not the only source of signal loss. Suspended sediment (Richards et al., 2003), biology (Simmonds and McLennan, 2005) and bubbles (Lurton, 2010) all absorb or redirect part of the acoustic signal, and if not accounted for in post-processing can have detrimental effects on the final product quality (see Case Study 5-2). These sources are essentially transient and hard to quantify, but may be evident in the full water column backscatter with proper display settings. Unfortunately, there currently is no solution for estimating and compensating the impact of water column absorption other than the effects of ideal seawater. This does not dispense with taking note of such conditions, and documenting the recorded backscatter data with these observations. The best strategy is to avoid surveying in conditions or at times where these interferences may be present. Increased sediment transport may occur near the mouth of rivers after heavy rain fall, and bubbles can be introduced from breaking waves, vessel traffic, or even a survey vessels own wake. The surveyor should be mindful of these points which impact on the backscatter measurements.

5.4.3 Noise sources

The noise floor of the measurement system is an important lower bound for acoustic measurements, but in many cases environmental noise may exceed the internal system noise and further limit the effective dynamic range of the system. Susceptibility to environmental noise is a function of the working frequency and bandwidth of the system, and also the quality of the signal processing for removing out-of-band signals. Avoiding these external sources of interference can improve backscatter by removing distracting transient signals in the final product or by increasing the dynamic range of the system by lowering the effective noise floor. Depending on the frequency of the echosounder, rain and waves may increase the background noise. Survey vessel machinery and other echosounders (e.g. fathometers traditionally at 50 and 200 kHz), including that from other vessels transiting the area, may interfere with the backscatter measurement system. Waves and survey vessel machinery are unavoidable hazards, but how much they affect the backscatter measurement system should be considered and weighed against the requirements of the final product. Changing vessel speed may reduce mechanical noise and improve the backscatter. Changing the direction of survey may reduce vessel motion that creates bubble sweep down noise. Transient events may affect the bathymetry, in which case the resulting interference can be filtered out. If the bathymetry remains unaffected it may be difficult to understand these sources of interfering noise. Many of these noise sources can be quantified with suitable time and test conditions using either vendor supplied noise test or passive water column statistics.

5.4.4 Biological influence

Biology can influence backscatter, whether from within the sediment volume, from the seafloor surface, or from within the water column. In some cases the biological signature may be the purpose for collecting backscatter, and in other situations it may be a time varying distraction. A backscatter surveyor may want to plan a survey around when there is minimal influence from benthic biota. For high frequency systems this may be primarily from epifauna, and for lower frequency systems this may also include the infauna.

5.4.5 Complex Bathymetry

For the backscatter surveyor it is important to consider the spatial scale of important features. Accounting for seafloor slope is a key step in backscatter processing (see Chapter 6), and the slope of the seafloor is only appropriately defined on a particular scale given the measurement system and survey design. Seafloor relief that is smaller than the resolution of the slope correction may contribute to backscatter as a form of roughness. Anisotropy in the backscatter measurement may be an indicator of complex bathymetry with a directional dependence smaller than the slope correction resolution. The directional nature of the seafloor may be evident in the bathymetry, but it could also be due to directionality in the sediment volume rather than the seafloor surface.

Depending on the purpose of the backscatter survey, complex bathymetry can be useful or detrimental to the derived product. Features that are recognized to be smaller than the slope scale may be accentuated in backscatter products. But bathymetry may be complex in relief or in composition, and it may be difficult or impossible to discern which is responsible for a particular effect on the resulting product.

5.4.6 Seafloor incidence angle

As discussed in Chapter 2, the specular region is the area where the incidence angle is near zero. This is also generally the most powerful part of the echo and has the highest signal to noise ratio (SNR). Normalization routines may not function as well in the specular region, possibly due to receiver saturation, and thus plotting it together with other normalized backscatter can decrease the value of the final product. The backscatter surveyor may find the best strategy is to discard the specular echo, optimally maintaining data between 15 and 60 degrees incidence, and plan to cover this region with adjacent swaths as outlined in §5.5. This problem is especially serious at low frequencies and over flat smooth seafloors, and may be less of an issue with high frequency systems over coarse seafloors.

The bathymetry data in the specular region are problematic as well. The coherent-reflected component causes a very specific bias of circular shape at the center of the swath (the infamous "Erik's horns"). The intrinsic accuracy of the sounding detection (done on the echo amplitude envelope) may be less than the interferometric one at oblique angles, despite a better SNR.

Case Study 5-3 - Impact of sea conditions on backscatter measurements

Conditions impacting the acoustic properties of the water column will affect the measured echo level. In a time series of MBES data of a same area, the data acquired during rough weather presents a clear negative offset of up to 3 dB of the mean dB levels relative to the overall average while measurements in calm weather are much more stable. Air bubbles and turbidity caused by rough sea state have a large negative qualitative and quantitative impact on resulting backscatter data. Seabed images issued from MBES data acquired under rough weather may present a shift in backscatter level associated with transmission and reception loss caused by bubble interference (Figure 5-9). The effect of sea state on the quality of backscatter data is complex and depends largely on the specific characteristics of the vessel and the sonar system. The surveyor must assess conditions and suspend operations when there is significant impact to the backscatter quality.

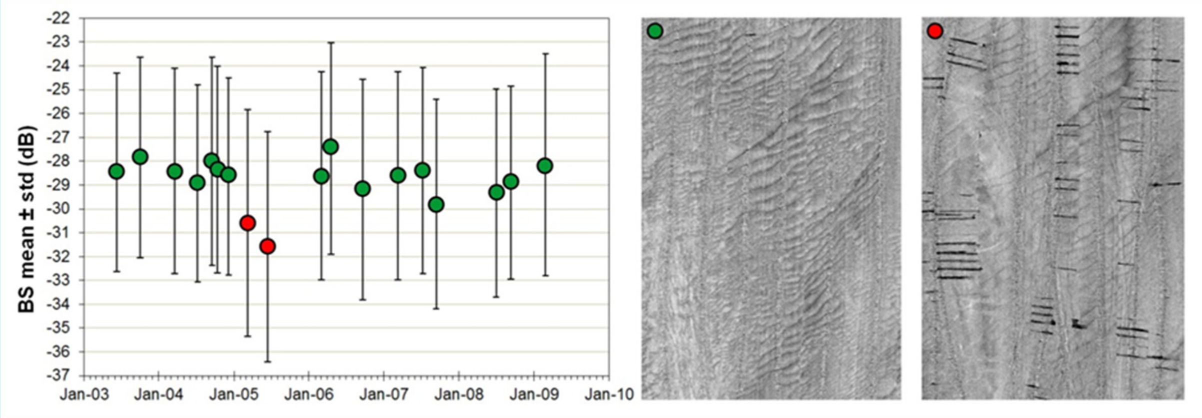


Figure 5-9 MBES (Kongsberg EM1002 on RV Belgica) backscatter time series on a sandbank area covered by very large dunes. Backscatter is plotted as mean value ± std.dev. versus time. Green dots = surveys under calm sea conditions. Red dots = surveys under rough sea conditions, causing a decrease of about 3 dB of the average measured backscatter.

5.5 Survey techniques for maximizing backscatter quality

A backscatter survey is a complex combination of decisions based on hardware, software, environmental conditions, and operational procedures, all geared toward a specified product. Acquisition hardware and software, as well as file types and sizes, all need to integrate seamlessly into an efficient workflow. Survey methods need to be designed to take advantage of hardware features while avoiding potential pitfalls and accounting for environmental factors. The surveyor should carefully consider the goals of the backscatter survey before setting out to design it. The requirements of a specialized backscatter survey, such as to investigate the angular response characteristic of a seabed area, may be significantly different from the simple addition of a backscatter mosaic to a previously planned bathymetric survey. A good backscatter surveyor should know when accuracy can be sacrificed for efficiency.

5.5.1 Coverage overlap between adjacent swath

Backscatter is a statistical estimate based on seafloor acoustic samples and the statistics associated with seafloor backscatter improve with many measurements. Overlap between adjacent swaths can help provide additional measurements for comparison. Frequently hydrographic survey lines are spaced for minimal overlap to allow for efficient coverage (Figure 5-10), but the highest quality backscatter is often considered to be between 15° and 60° in incidence angle.

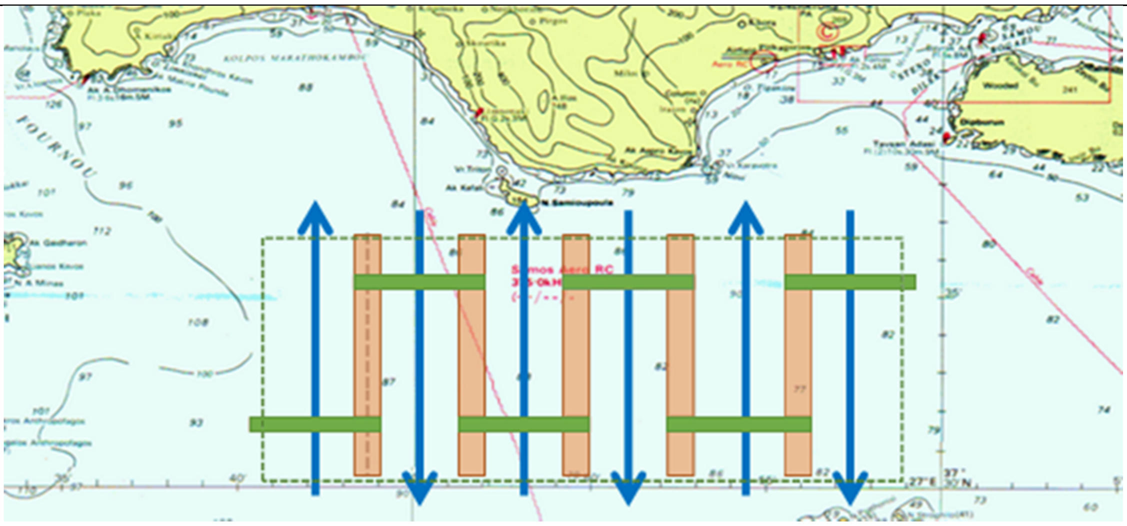


Figure 5-10 Survey lines preplaned and surveyed with minimal overlap between swaths. Green areas represent the swath width along each line, and the orange areas are where the swaths overlap.

Depending on the backscatter quality required and the echosounder in use, the survey line spacing may need to be adjusted to maximize the data in the highest quality angle region. This can result in highly redundant data and makes the exclusion of backscatter in the specular region (less than ~15°) possible. See Figure 5-11.

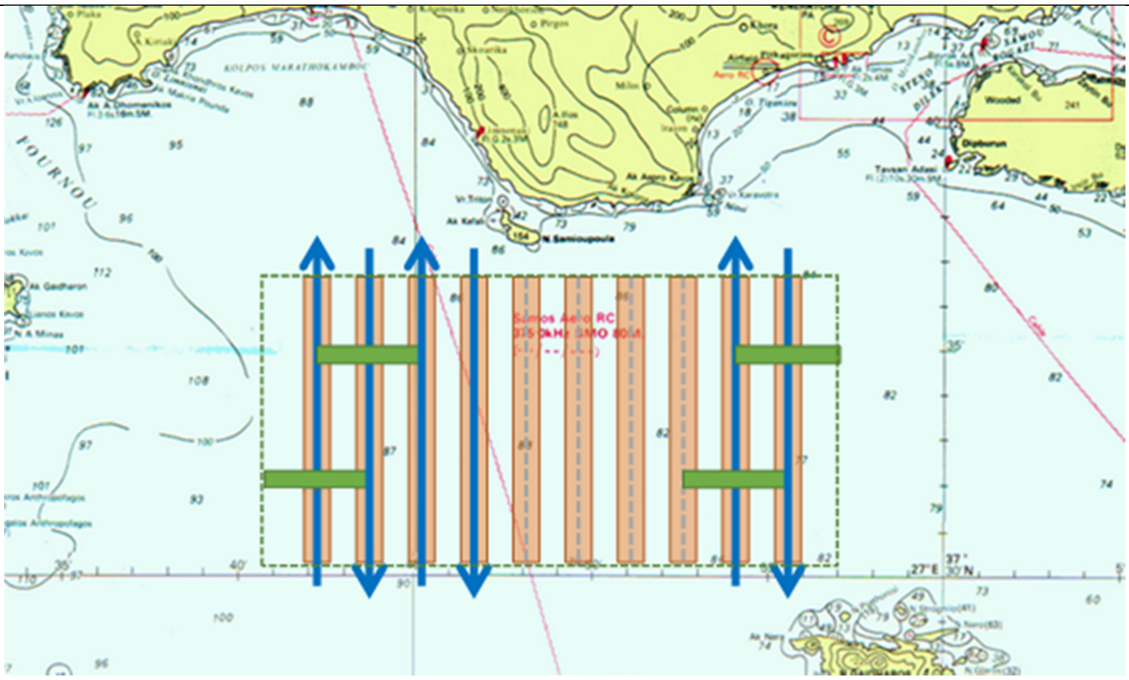
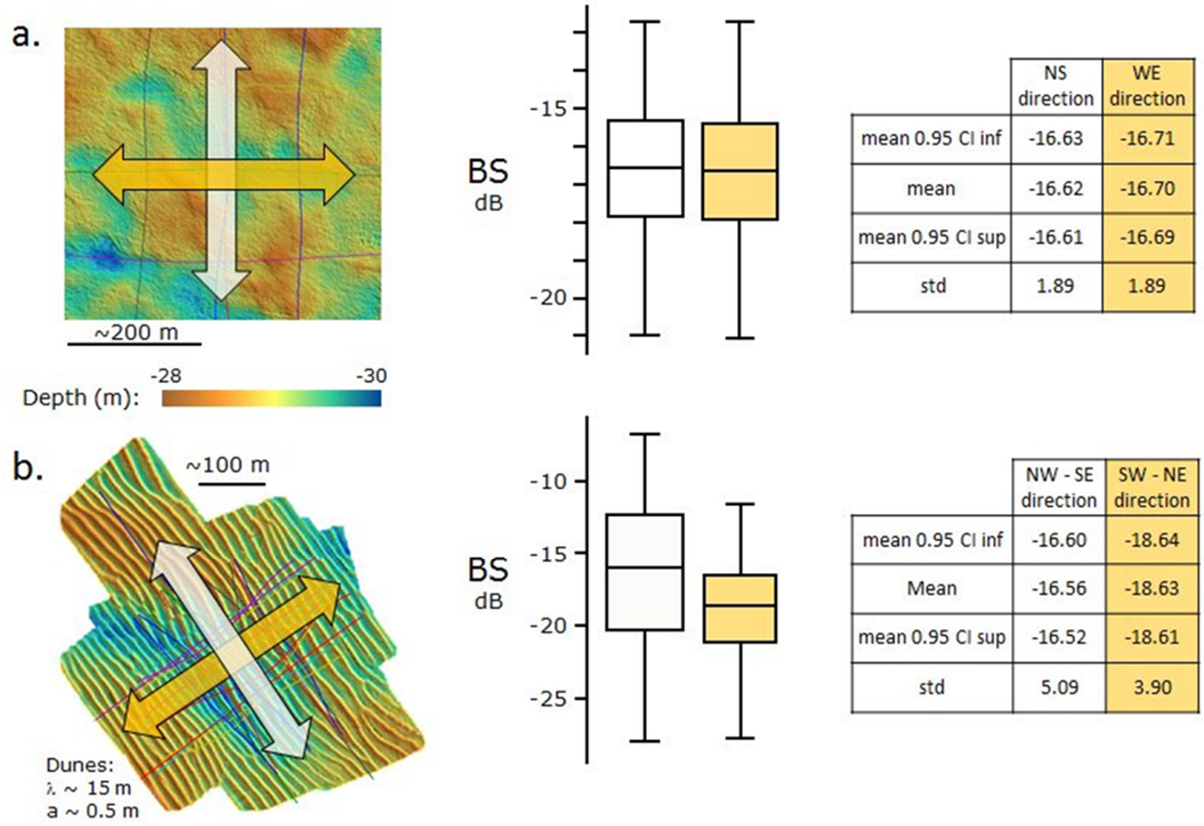


Figure 5-11 Survey lines preplanned and surveyed with significant overlap between adjacent swaths. The green areas represent the swath coverage for each line, demonstrating coverage of the nadir regions on the adjacent lines.

Beyond the statistical benefits of redundant data, seafloor backscatter is expected to be angle dependent and this redundancy can provide further information for downstream users that are interested in looking at the angle dependent response of the seafloor. The benefits of adjacent data overlap need to be weighed against efficiency concerns, as in any hydrographic survey, since this doubles the time required to cover a survey area.

5.5.2 Direction of navigation

The impact of vessel heading on the backscatter measurement should be considered when designing a survey, particularly in areas of complex bathymetry (§5.4.5). In an isotropic area (with flat topography and uniform sediment coverage) the impact of survey direction should have minimal impact (Figure 5-12a). Conversely, on an anisotropic area, the direction of sailing has a strong influence on the backscatter levels (Figure 5-12b). Insufficient accuracy in the adjustment of backscatter slope correction may explain this difference. Optimally, surveys on areas of complex bathymetry should be navigated unidirectionally.



	NS direction	WE direction
mean 0.95 CI inf	-16.63	-16.71
mean	-16.62	-16.70
mean 0.95 CI sup	-16.61	-16.69
std	1.89	1.89

	NW - SE direction	SW - NE direction
mean 0.95 CI inf	-16.60	-18.64
Mean	-16.56	-18.63
mean 0.95 CI sup	-16.52	-18.61
std	5.09	3.90

Figure 5-12 Effect of the direction of navigation on MBES (Kongsberg EM3002D on RV Belgica) backscatter levels on isotropic and anisotropic seabed. a: 2 successive datasets: 3 lines N-S, 3 lines W-E on a flat sandy gravel area. b: 2 successive datasets: 9 lines NW-SE, 9 lines SW-NE on a sand dune area . For all datasets: backscatter mosaics (1x1 m) for TX ∊ [20°-70°].

5.5.3 Line steering

Traditionally acoustic surveys are conducted with preplanned lines for navigation to ensure even coverage of the seafloor. Some contemporary surveys use a real-time display of swath coverage to adjust the vessel route and optimize overlap with previous data. While real-time coverage navigation can improve survey efficiency, rapid turning while collecting data can produce sparse data coverage and/or poor backscatter quality. If real-time coverage navigation is used, turns should be kept slow and with a large curvature to reduce these effects. Sharp turning also exposes the seafloor to insonification from different angles, and can result in the expression of anisotropic effects in the backscatter data.

5.5.4 Cross lines

Cross lines are commonly collected in bathymetric surveys to estimate the consistency of depth measurements and to check for blunders. Cross lines are usually collected at nearly orthogonal angles to the primary survey direction (known as main scheme lines) to ensure that any across swath bias does not systematically effect the comparison. As described previously, this is a good situation to discover anisotropic seafloor effects. While including cross lines in the final product can be detrimental to overall consistency, discovering areas with different backscatter is often the purpose for collecting backscatter to begin with. Cross lines should be collected as part of a backscatter survey to establish variability in the seafloor (see §5.5.2), but they may be excluded from the final product for consistency depending on the survey specifications.

5.5.5 Dealing with poorly calibrated systems

In cases where the seafloor does not have significant benthic relief or variability in composition it may be simpler to avoid changing system settings on uncalibrated systems. When this is not possible one approach to dealing with artifacts created by changing acquisition settings attempts to provide redundant data to help blend the change in backscatter. This requires repeating the affected line twice. This repetition, while inefficient for the coverage strategy, is important as it provides data that can be used for consistency-check at post-processing. The methodology is as follows:

- 1st run: if acquisition parameter changes are required during run, note position and finish line with no changes;
- During the turn, adjust the acquisition parameters and find new optimal values;
- 2nd run, repeat the same line in the opposite direction. Start the line with new optimal acquisition settings and continue to end of line with the same settings.

On the next line, both sets of parameters ("old" for the beginning of the line and "new" for the second portion of the line) may produce optimal data with minimal changes (Figure 5-13).

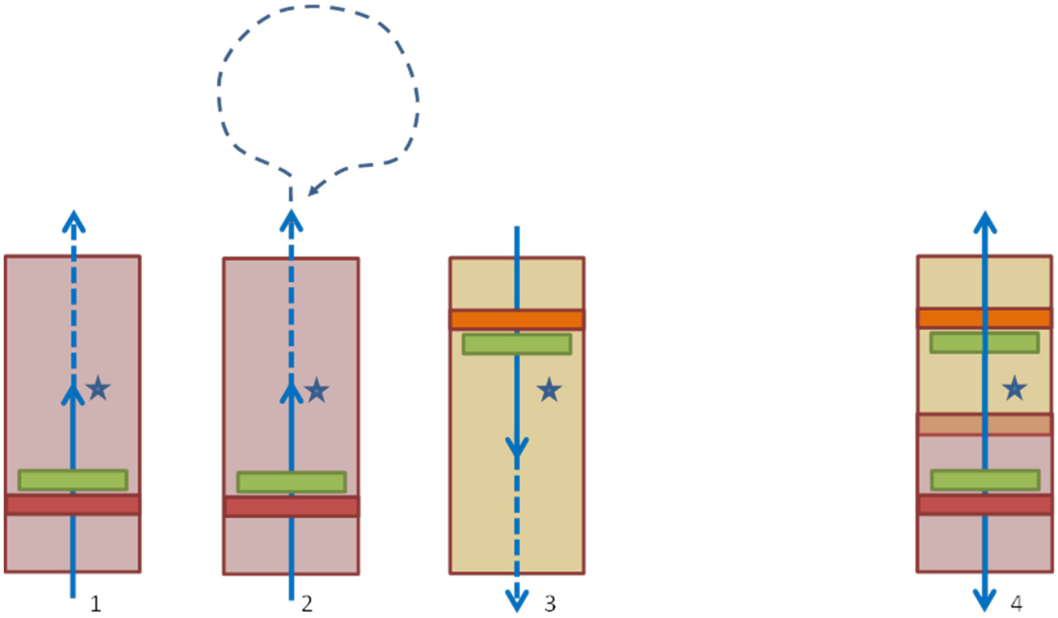


Figure 5-13 Dealing with changing acquisition settings on systems with uncalibrated settings (1) First run: the star flags the point where current acquisition parameters are not optimal. (2) Turn: where new optimal acquisition settings must be found out and set. (3) Second run: over the same track as 1, but in opposite direction with new optimal settings. (4) The result is the full line covered with optimal parameters for backscatter and some overlap in the central area.

5.5.6 Files sizes

Backscatter surveys can require significant storage space due to the size of backscatter data. File sizes can become so large that it can take a long time to move data from disk to disk, or even become impossible to process the data with current software. This can have serious operational and workflow repercussions for the backscatter surveyor. To overcome extremely large file sizes the surveyor may need to understand the particulars of echosounder configuration or the tradeoffs between different record types of backscatter data. Care must be taken when averaging backscatter values for space compression however, as the statistics are irrevocably altered. For echosounders with high sampling rates it is particularly important to store only the acoustic samples associated with the seafloor, and not a large number of samples from above or below. In general it is helpful for the downstream user if the acquisition team keeps in mind the processing time and storage requirements associated with large files. Segmenting files while on a line can make individual files a more manageable size, but this can also lead to dropped pings between files and thus may need to be avoided. Running shorter lines so they are segmented more frequently without a break in the middle of a continuous section may be the best approach.

5.5.7 Data in paired (separate) files or single files.

Because of the file size considerations discussed in 5.5.6, at times the acquisition team may choose to acquire with a method that separates backscatter records into a separate file. Depending on the downstream workflow this can be beneficial if most users are only interested in the bathymetry associated with a survey, thereby decreasing the size of files to move, process, and store. However, if a high percentage of the downstream users are interested in backscatter keeping all the data in one file is beneficial. File management becomes simpler with a single file, and the pairing of files in post processing is less likely to run into difficulties when merging the data sources, matching time stamps, and avoids differing pings that exist in one file verses another.

5.5.8 Changing echosounder settings

There have been several previous discussions on changing echosounders settings in the context of relative calibration (§5.2.2.2), and also in dynamic range and saturation (§5.3). In practice these are all tied together for how the backscatter surveyor decides to run a survey. While a section on “survey approaches for maximizing backscatter quality” would not be complete without addressing changing echosounder settings, it is important to conduct this discussion in the context of the specific manufacturer and model. Please see §5.6 for further details on system setting optimization.

5.5.9 Biofouling

When biological growth impedes the measurement system, such as over the echosounder transducers, it changes the backscatter measurement. This biofouling should be removed frequently as a form of preventative maintenance. This includes the sensors used for estimating the surface sound speed.

5.6 Echosounder specific background

Each echosounder manufacturer has approached backscatter acquisition differently. Some systems are made to provide users with manual control of many system settings, while other systems are more automated and do not allow the user much control at all. The backscatter surveyor needs to understand how to best operate their echosounder to meet the backscatter accuracy requirements of their survey. The purpose of this section is to provide the backscatter surveyor with some background on different systems, helping them to ask the right questions to meet their survey requirements. Despite the overview provided here, follow up questions should be asked of the manufacturer as echosounders continue to develop rapidly and much of the information provided here is based on dialog and experience with little documentation for reference.

5.6.1 Multibeam Echosounders

5.6.1.1 Kongsberg Maritime multibeam echosounder

Kongsberg Maritime (KM) relies on their Seafloor Information System (SIS) graphical user interface for operating their series of multibeam echosounders for bathymetric use. For system settings, such as pulse length and type, transmit power, and gain, SIS generally groups settings into “modes”, such as "Shallow", "Deep", etc. The exception to the mode based approach is the EM2040, which allows for the frequency and pulse length and pulse type to be changed directly by the user and does not have the same system of grouping system settings by mode. In general new KM systems have a high dynamic range such that the mode does not change often, improving general consistency since many artefact are simply due to changing settings that are not properly reported.

KM performs a number of processing steps to the backscatter data in real time (Hammerstad, 2000). This includes compensation for applied gains and beam patterns, and accounts for transmit pulse and power level. A flat seafloor is assumed for beam foot print and angle dependent backscatter adjustments. The appropriateness of this assumption may result in artefact in the real time backscatter. Some adjustments are available for optimizing the angle dependent backscatter, specifically the transition angle from Lambert’s law to specular refection. These user adjustments are recorded such that these real time assumptions can be removed in post processing (Chapter 6).

One user setting that results in unrecoverable real time backscatter adjustments and should be carefully avoided is “sector tracking” as found in the Runtime Parameters / Filter and Gains. This functionality normalizes the backscatter between sectors and improves the imagery during acquisition. While potentially helpful in real time, this normalization process is not recorded, and the logged data are irrevocably altered. In general this across-swath normalization should be avoided.

For proper normalization between sectors, recent versions of SIS (4.1.5 and later) provide a user interface for defining a simplified directivity model. This functionality exists for the EM122, EM302, EM710. The models are saved by mode in a *BSCorr* file which contain offsets as a function of angle and swath number (for dual ping systems and modes). Upon system delivery, the *BSCorr* file is populated with default KM values which may be adjusted during installation and sea trials (SAT). These values are then applied automatically in the sounder computations. The resulting quality depends on the skills of the processor as no standard software is provided for determining the model to apply. Fine tuning of the *BSCorr* file requires expert knowledge. The contents of this file are supplied in a KM datagram so the applied calibration offset can be undone. Since the sounder response is generally stable the parameter tuning process does not have to be repeated often. A proper coefficient estimation results in hardly visible residual angle modulation, which is easily removed at post-processing. It should be noted that the time to collect the supporting data for this process can be considerable as it must be completed for each mode, frequency, and swath. While is it is possible to normalize between all sectors and modes using *BSCorr*, the user should carefully consider the appropriateness of this normalization as different frequencies may actually produce different backscatter values.

KM MBES integrate environmental information to optimize automated system operation and to provide a semi-processed solution. For backscatter an important environmental influence is the absorption profile used to estimate the transmission loss in the water column. The absorption profile can either be provided from a CTD cast or be estimated from a sound speed cast and mean salinity estimate. If the method for providing the absorption profile is through a sound speed profile and a manually entered salinity estimate, it is important that this estimate be a mean value for the water column and not a value just from a surface measurement (see §5.4.2).

5.6.1.2 R2Sonic multibeam echosounder

R2Sonic provides a much more manual user interface than the previously described set of echosounders. System settings, such as transmit power, gain, TVG slope, pulse length, frequency, etc. are all accessible to the user. While this allows the operator to drive the system out of its dynamic range, either into the noise floor or into saturation, R2Sonic provides the user with an interface to observe saturation as a function of the system settings. The operator manually manages the dynamic range by maintaining good bottom detection quality, essentially ensuring good signal to noise, and also observing the backscatter in the provided tools to avoid saturation. Depending on the backscatter accuracy requirements of the survey, it may be necessary to perform a calibration of the echosounder, including the system settings, since setting changes may be common.

Because it is up to the user to manually balance the backscatter within the system's dynamic range it is important to recall how each of the system settings will affect the backscatter measurement. Power and pulse length will boost the backscatter level (thanks to the signal intensity and the footprint extent) and improve the signal-to-noise ratio. Gain affects the signal level in the RX channels hence does amplify both backscatter and noise. The logical conclusion is to increase the power and reduce the gain, but the dynamic range of the system is larger with higher gain. Accounting for this additional factor, the operator should try to maintain a reasonable amount of gain to maximize the dynamic range of the echosounder, keep the power low enough to stay out of saturation but high enough to maintain good signal to noise and bottom detections across the swath. Using the manufacturer provided saturation monitor will help develop a more intuitive understanding of how saturation and system settings relate.

Another important factor to balancing the gain for R2Sonic systems is the TVG curve, which changes as a function of the “absorption” and “spreading” settings. The absorption and spreading values are terms in the equation for the applied TVG curve, and are named for how this curve compensates for the physical absorption and spreading of acoustic energy in the water column. The result of applying this curve is an equalization of the acoustic energy as a function of range, essentially scaling for the expected signal loss to best utilize the available dynamic range. But the physical absorption and spreading are not the only causes for change in signal strength as the change in backscatter strength with changing incidence angle also decreases across the swath. It may be valuable for the operator to maximize use of the TVG ramp across the swath rather than throughout the entire water column if bathymetric backscatter is a priority over water column backscatter. In shallow water this may mean using high gain because the TVG curve does not change much over short time periods. In deeper water the operator may choose to turn down the gain, but increase the absorption and spreading system settings to maximize the TVG ramp across the bottom detection range.

Manually manipulating these settings over dynamic seafloor depths and types can be challenging. Depending on the requirements for backscatter accuracy it may be simpler to allow the echosounder to saturate rather than deal with the potential loss of bottom detections from poor system settings.

5.6.1.3 Reson multibeam echosounder

Reson echosounders have the option for automated setting control or manual setting control. While this option is convenient, neither takes into account saturation of the echosounder receiver. The automated setting control attempts to acquire high quality bathymetry, but possibly at the expense of the backscatter. Strategies for monitoring the backscatter relative to the available dynamic range may change depending on the Reson MBES.

The latest Reson MBES, the T20-P, saturates at the maximum obtainable digital value (rather than some internal hardware limit) and thus the dynamic range is not a function of the system settings. As a result it is possible to monitor for saturation using the maximum recorded intensity values. Keep in mind that the water column color map provided in the user interface wedge display is not tied to actual values and should not be used to indicate saturation. The brightness and contrast display settings can be adjusted to scale the display relative to the reported backscatter. The 7000 series MBES, such as the 7125, have a varying dynamic range as a function of gain. Reson does not currently provide a tool to monitor for when the MBES dynamic range is exceeded and thus a tool must be developed by the user if this is of concern for satisfying the survey backscatter requirements. Previous 8000 series MBES had relatively low dynamic range compared to current systems and were prone to saturation if not left in automatic gain control.

Reson systems use a TVG to fit backscatter into the available dynamic range. As described in the previous section, absorption and spreading system settings are used to control the shape of the TVG curve and users should apply the same approaches (see 5.6.1.2) to optimize for seafloor backscatter.

For the 7125 series MBES there are additional complicating factors regarding the transmission power. The power and pulse length settings should be carefully considered before setting and/or changing. Older 7125s, such as the SV1 and ROV1 systems, had an inconsistent power output for settings bellow 190. The new SV2 systems do not allow power outputs at these lower levels, so this is not a concern with more current system. However, the SV2 projectors may have a non-linear output that should be calibrated to meet stringent backscatter requirements. If the seafloor is generally unremarkable in depth or composition changes then keeping the power at the same value may keep the backscatter more consistent without performing a calibration. For all 7125 series systems, the pulse length actually generated only changes in steps of 10 µs, (e.g. 80, 90, 100, etc.), so the finer scale changes available below 100 µs should not be used. Using intermediary values (e.g. 55, 56, 57 µs) results in reported and logged values misrepresenting what was physically created.

The recorded gain settings have generally been observed to reflect what gain was applied in real time, but some exceptions with specific MBES units have been found. If extensive changes in systems settings are expected for the survey area and the backscatter survey requirements are stringent the surveyor should consider a calibration of all the system settings, including gain and TVG.

It is worth noting that there is a calibration routine on 7k series and newer Reson MBES systems. This routine is meant to equalize receiver array elements so they are properly balanced for beam forming. Recent versions of the Seabat software run the normalization routine automatically upon startup, and Reson encourages running this routine to ensure optimum beam forming. This routine does not ensure that the sum of the element’s sensitivity is the same both pre and post normalization however, which effectively changes the sensitivity of the receiver array. Running this normalization routine has been shown to cause backscatter offsets, and so it may be in the best interest of the backscatter surveyor to avoid running this routine. Contact Reson for directions on how to disable the routine if it is run automatically, and for which versions of the firmware this is of concern.

Modern Reson echosounders, 7000 series and later, can have either a static or a dynamic backscatter number of samples per beam depending on the settings and records used. If the sample number is set too large file sizes can be three to ten times the needed size. If this number is set too small there will be backscatter gaps in the resulting product. Thus a detailed understanding of the echosounder operation for optimal selection of record types and record setup can be very important to avoiding extremely large file sizes.

5.6.2 Phase Measuring Bathymetric Sonar

Phase Measuring Bathymetric Sonar (PMBS) echosounders are only considered here in the context of survey planning and are not broken out by individual manufacturer for survey settings or other considerations. This is due to limited input from individuals with experience with the different PMBS currently on the market. We recommend contacting the manufacturer for setting recommendations and for customer referrals.

PMBS echosounders do not form directional beams, but instead determine the sonar relative angle of arrival of all echoes. Previous discussed calibration and environmental considerations are still relevant with these echosounders. Because the transducer mounting strategy is optimized for angles away from vertical, these systems are often considered to collect good information for relatively wide swaths, even in shallow water. But the bathymetry data from PMBS are limited by the same refraction and motion concerns as limit MBES swath widths. For this reason, PMBS swaths are sometimes consider to have two sections, a portion for good bathymetry and a portion for seafloor backscatter. If a flat seafloor assumption is appropriate for the survey area then only the backscatter swath width may be considered for line spacing during survey planning. For example, in Figure 5-14 survey lines could be spaced 50 m, which would provide full coverage for bathymetry with overlapping backscatter. However the range could be set to 80 m if the seafloor could be assumed to be relatively flat and interpolation between the swaths reasonable.

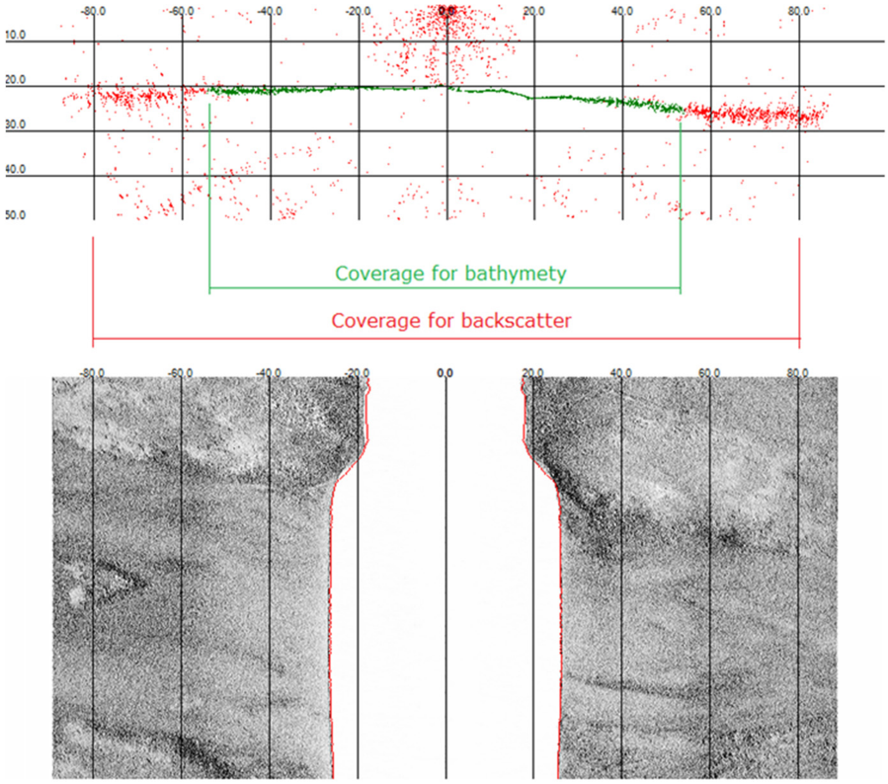


Figure 5-14 Data example from a PMBS, illustrating the difference between effective swath width for bathymetry (green) and backscatter (red).

Because PMBS do not form beams the range scale effectively determines the recorded swath width. If a wide swath is used, the resulting change in ping rate from working with longer range scales should be considered as it effects along track coverage or survey speed.

Another suggested survey pattern, used in side scan sonar search surveys, it is a recursive 75%-25% overlap between adjacent lines (or 60%-40%, as shown in Figure 5-15).

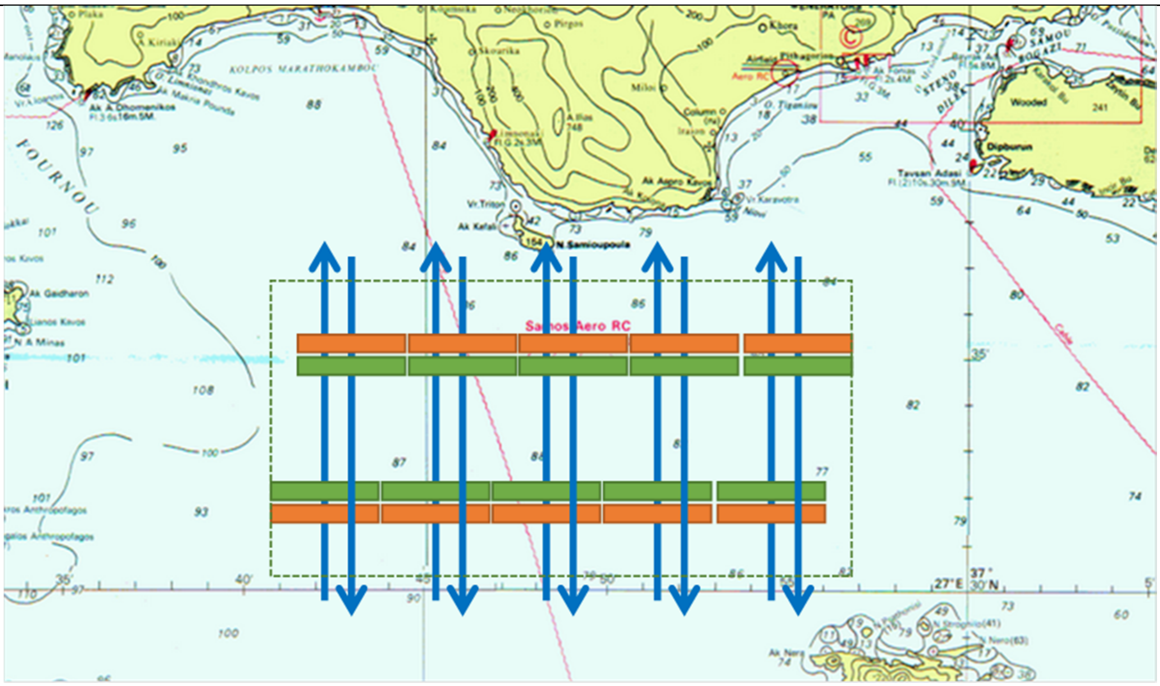


Figure 5-15 For phase measuring systems, green area with full bathymetry coverage. The nadir of every line is also covered by the adjacent line, which improved the data density of that area as well as it allows sensing the angular backscatter response of the seafloor at two different angles.

5.7 Concluding thoughts and recommendations

It is our first recommendation that surveyors understand the final product requirements before conducting a backscatter survey. Depending on the backscatter product specifications, preparation and equipment may significantly shift the amount of time and cost when compared to a classical survey designed only for bathymetric purposes. Ideally, backscatter survey products only depend on the angle-dependent response of the seafloor to the echosounder acoustic frequency because proper adjustments have been made for measurement system and environmental effects. The effort required to reach such a state for all surveys may be beyond the capabilities of the measurement system, the survey team, or reasonable expectations for mastering the environmental conditions; so practical compromises need to be made based on the backscatter requirements.

Because we have focused solely on backscatter, the methods for acquiring good-quality high-resolution bathymetry have not been addressed here; they are well-known, and may be found in an abundant literature dedicated to hydrography and MBES (NOAA, 2014). If backscatter is considered as a property of the seafloor rather than simply imagery from the measurement system's perspective, good bathymetry is also important for the backscatter surveyor. The resolution and consistency of the bathymetric product will impact the resulting backscatter products, especially if small features or rapid changes in slope are present. Requirements for acquiring bathymetry

The backscatter surveyor is impaired by some particulars that need to be addressed through research or by manufacturers. Further work is needed to understand aging of the acoustic array for example. Other aspects of the measurement system, such as beam patterns or misreported settings, should be addressed by the manufacturer. Some environmental effects, such as bubbles in the water column, currently have no compensation techniques and will result in the appearance of changes in the bathymetry and/or backscatter. These considerations deserve attention to continue to improve the seafloor backscatter product.

As a parting recommendation, we provide a list of approaches for two types of surveys at different parts of the quality spectrum. We recognize that all surveys do not fit into these categories, but leave it to the backscatter surveyor to decide which parts of which approach are appropriate to their specific requirements. The criteria are tied to the statements in Figure 5.1 by the corresponding question reference letter in the figure.

Basic Survey: A survey intended for complete coverage with a single echosounder. There is no intention of comparing the backscatter from this survey to another survey of the same area. The resolution and scale of the data being generated is inherently maintained to meet the objectives of the survey.

1. Based on the information provided, Figure 5.1 F statements A, B and C are all ‘No’ and a backscatter calibration is not required. Prepare the echosounder and supporting equipment as for most hydrographic surveys, such as integrating the positioning system and motion sensor, as well as any sound speed instrumentation.
2. Since no information is given about the survey area or the echosounder to be used, simplicity and recognition that this is a basic survey leads to the assumption that Figure 5.1 D is ‘Yes’. Minimal changes should be made to echosounder settings during the survey, which means establishing the best settings for maintaining the swath width for the depth range and seafloor type for the survey area before beginning main scheme data acquisition (§5.3).
3. It is rare that environmental conditions would not be a concern, thus Figure 5.1 F is ‘Yes’. Monitor the environmental variables (sound velocity and absorption coefficient derived from water column temperature and salinity) with regular measurements during the survey (§5.4). Cease survey operations when the sea conditions are such that significant ping series are lost or bubbles are observed in the water column (§5.4.2).
4. While this is a basic survey, the following are good general rules of thumb when considering Figure 5.1 G. Collect data with closely spaced and parallel lines (§5.5.1) while minimizing the vessel rate of turn (§5.5.3). Ideally the line spacing would allow for sufficient overlap so as to allow for the exclusion of the specular return. If cross lines are collected, separate from main scheme to keep the primary product consistent (§5.5.4). Set the survey speed to balance along track data density, vessel noise characteristics, and survey efficiency.

Mapping for monitoring: A survey intended for comparison to other surveys in which other echosounders may be used over the same area with the objective of observing the evolution of seafloor acoustic backscatter over time. Settings will need to be changed within the survey area to maintain good depth measurements. Under these conditions some changes need to be adjusted from the basic survey approach for achieving success.

1. While answers to Figure 5.1 A and B are unclear from the information provided, C is ‘Yes’ and D is ‘No’. Any echosounders of similar frequencies which are to be used for the survey area should be cross calibrated against one another. Each echosounder should also undergo an internal calibration for the settings to be used during the survey (§5.2).

2. Since settings will be changed but the answer to Figure 5.1 E is unknown, the surveyor should use any tools available to avoid driving the echosounder receiver out of its dynamic range (§5.3) if there is cause for concern.
3. As part of Figure 5.1 G, clean the transducers regularly to avoid biofouling (§5.5.9) to ensure the most comparable results as it is the stated purpose of the survey.

The simplest strategy for good backscatter is to minimize changes where possible such that the consistency of the final backscatter product is maximized. The risk of residual echosounder effects as a result of changes need to be weighed against optimizing settings for the immediate survey area. If a choice is possible, a smaller number of different echosounders or transmit sectors is to be preferred to minimize the need for cross-normalization. Of course some trade-off must be found with regard to the other constraints of the survey.

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CHAPTER 6 PROCESSING BACKSCATTER DATA: FROM DATAGRAMS TO ANGULAR RESPONSES AND MOSAICS

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6.1 Objectives

6.1.1 Introduction

Several software suites (for either research or production) have been developed in the past decade to process backscatter data from swath echosounders into two different outputs: **backscatter mosaics** and **angular response** (Figure 6-1). Backscatter mosaic is the common term for a georeferenced, grey-scale image of seabed reflectivity in which tone and texture are representative of the nature and geomorphology of the seafloor; angular response is the common term describing **Backscatter Strength** (BS) as a function of the angle of incidence at the seafloor (θ).

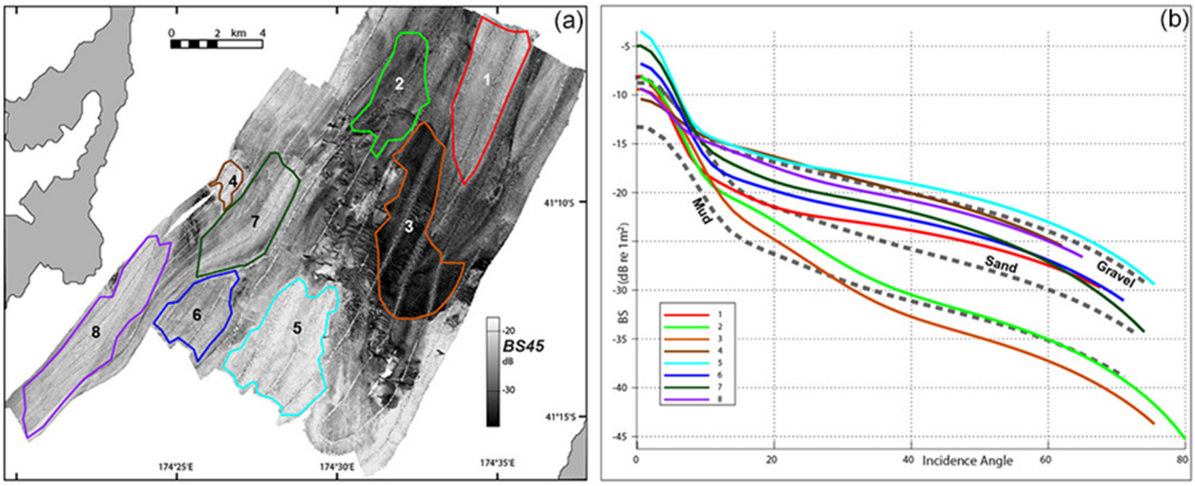

Figure 6-1 Examples of a backscatter mosaic (a) and angular response (b). Data shown are a subset of an EM300 dataset acquired in the Narrows Basin, Cook Strait, New Zealand, and processed using SonarScope. The mean angular response curves were computed from the color-corresponding polygons shown on the backscatter mosaic. Angular response curves in dashed lines are modelled BS angular profiles for some seabed types (figures modified from Lamarche et al., 2011).

The backscatter mosaic and the angular response are obtained through a series of processing stages, the details of which may differ between sonar models and data processing software suites[2]. This chapter aims at (1) reviewing this process in order to identify the sources of inconsistency in backscatter data products and (2) providing a number of recommendations to manufacturers (of both sonar and data processing software) and backscatter data users in order to reduce this inconsistency in the future.

Figure 6.2 presents an overview of the backscatter data processing chain. To accommodate various levels of understanding from various readers, the processing sequence is reviewed here at three levels of details:

- The next section (§6.1.2) presents an overview of the process;
- The main body of the chapter presents a more detailed description organized by sonar model and software suite (§6.2 to §6.13 , with individual steps indicated on Figure 6.2);

In this introductory section, the review of the processing chain (§6.1.2) is completed with general considerations about angular response and backscatter mosaics (§6.1.3).

This chapter concludes with recommendations for backscatter processing (§6.14).

6.1.2 Processing chain overview

The processing chain starts with decoding the raw data (§6.2 and A.6.1. This is straightforward and done using information provided by manufacturers in user manuals. The next steps are corrections dependent on the system’s hardware and firmware (Figure 6-2):

- Compensation of static gains, time-varying gains and manufacturer corrections (§6.3);
- Correction for source level and transmit/receive beam patterns (§6.4).

Different sonar models imply different raw data decoding and system-specific corrections. In this chapter, the corresponding sections are organized in sub-sections according to the most commonly used swath echosounders:

- Kongsberg GeoAcoustics GeoSwath Plus (henceforth *GeoSwath*),
- Kongsberg Maritime EM-Series (henceforth *Kongsberg*),
- R2Sonic Sonic series (henceforth *R2Sonic*), and
- Teledyne-Reson SeaBat series (henceforth *Reson*).

The accuracy of system-specific corrections is dependent upon the degree of knowledge of the system operated. The information in this chapter is provided here “to the best of our current knowledge”. It was obtained from the systems manuals, from personal communication with manufacturers or from user observations and calibration, with sources sometimes conflicting with others. Due care was taken to specify the source of the information. However, we advise the readers to obtain their own information from the manufacturer of their system. Section §6.14 contains recommendations about the needed information expected from manufacturers in order to achieve consistent and accurate system-dependent corrections.

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[2] Note that most software suites are designed to produce backscatter mosaics but not necessarily angular response.

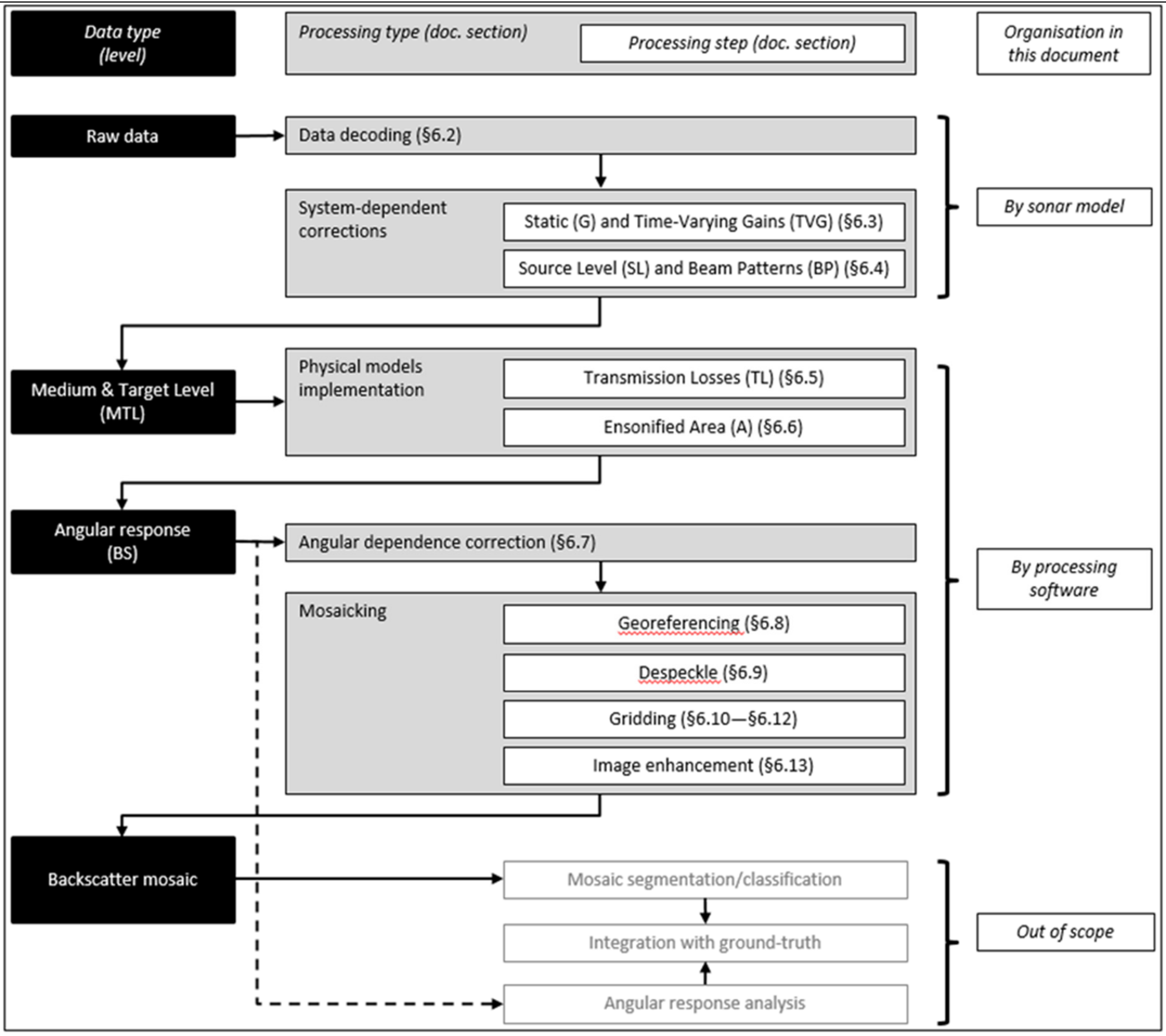


Figure 6-2 Backscatter processing chain. Section numbers are mentioned for reference to the main body of this chapter.

Compensating the system-specific corrections results in the intensity difference between the level transmitted at 1 m from the transducer and the level at the receiving antenna. This difference is due to energy losses occurring as the signal interacts with the water medium and the seafloor; it is noted in this chapter Medium and Target Level (MTL, see Figure 6-2). Although this is not a standard notation, it is used here for convenience because this difference is independent of the system's hardware and firmware (although the physical phenomena responsible for this level are dependent on some acoustic parameters of the system such as frequency, beamwidth, pulse length, etc.).

The next stages of the quantitative signal-processing chain are designed to compensate MTL for the physical interaction of sounds with the underwater medium, namely:

- Correction for transmission losses in the water column (§6.5);
- Correction for insonified area extent on the seafloor (§6.6).

The accuracy of these corrections is dependent on the suitability and level of detail of the physical models implemented. These physical models are only discussed briefly in this chapter, insofar as they are relevant to an understanding of signal corrections. See Chapter 3 for more detail on the definitions and the relations (sonar equation) linking source level and directivity, transmission losses, receiver characteristics, target characteristics and received signal.

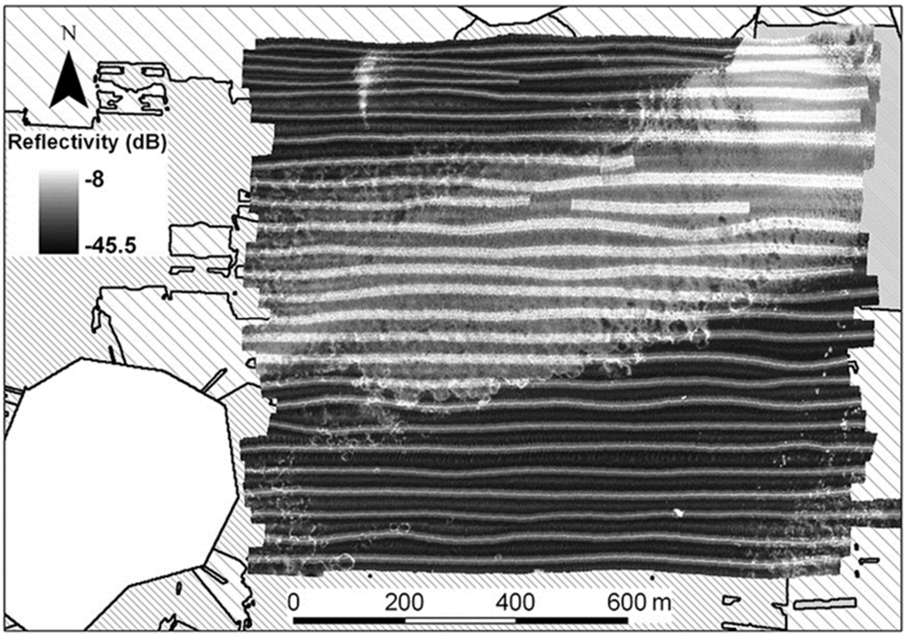


Figure 6-3 Example of georeferenced and mosaicked BS without correction for angular dependence (from Schimel et al., 2010). The variation of BS with angle of incidence is visible as a strong along-track banding artefact (oriented East-West in this case). Note that the banding artefact depends on seafloor type, as illustrated by its different width between strongly reflective and weakly reflective seabed types (respectively in light and dark tones).

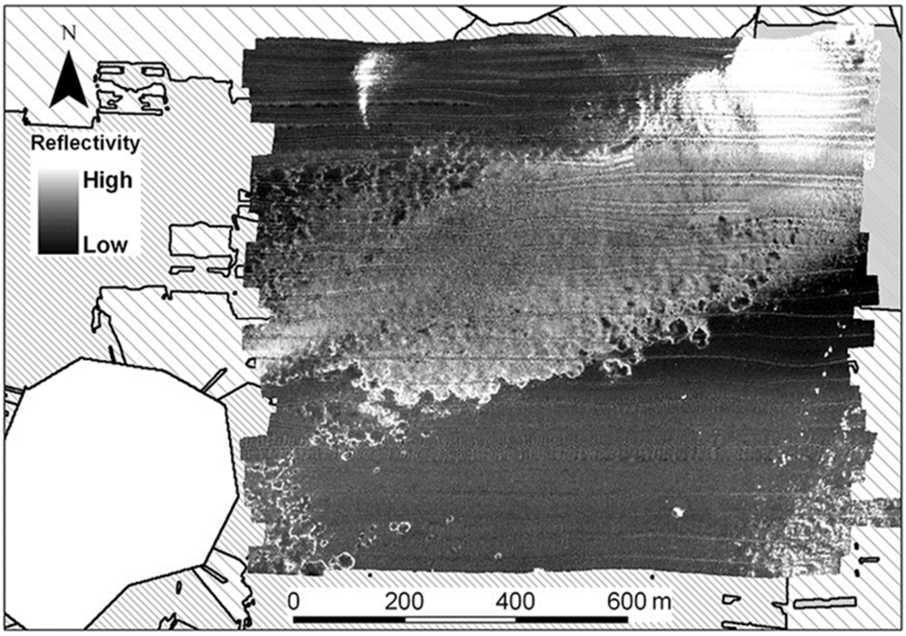


Figure 6-4 Example of georeferenced BS with correction for angular dependence (i.e. backscatter mosaic, from Schimel et al., 2010). The compensation required assumptions to be made on the spatial homogeneity of seafloor type. Where invalid, the assumptions resulted in residual artefacts.

In theory, the signal level after corrections for transmission loss and insonified area is the physically meaningful *BS*. Since the calculation of insonified area involves estimating the angle of incidence, the angular response $BS(\theta)$ can be directly retrieved at the end of this step (Figure 6-2).

The seafloor backscattering strength BS is intrinsically dependent on the angle of incidence θ (see Chapter 3). The consequence of this dependence is that a georeferenced representation of BS displays a strong along-track banding that hinders both visual interpretation and image processing algorithms (Figure 6-3). A compensation for angular dependence (§6.7) is therefore necessary to make a usable geographical representation of BS (Figure 6-4).

The last processing stages consist of a series of level corrections, data geo-referencing and data management that lead to the creation of a backscatter mosaic. They include:

- Georeferencing / slant range correction (§6.8);
- De-speckling and anti-aliasing (§6.9);
- Gridding (§6.10 through to §6.12);
- Image enhancement (§6.13).

This sequence concludes the processing by producing the backscatter mosaic that is typically exported in a format convenient for GIS display or further image processing.

The physical model corrections, the angular dependence correction and the mosaicking methodology are more or less arbitrary choices, so that processing software suites tend to differ in their implementation of these stages. In these sections, we provide general descriptions of the possible algorithms and illustrate their implementation in the main software suites available today:

- ***Geocoder*** (Fonseca and Calder, 2006; Fonseca and Mayer, 2007; Fonseca et al., 2009; Rzhanov et al., 2012; http://ccom.unh.edu/theme/data-processing/geocoder); a software originally developed at the Center for Coastal and Ocean Mapping (CCOM) at the University of New Hampshire (UNH) and now individually developed for proprietary implementation in a number of commercial software suites. One of such commercial developments is *FMGT* (*Fledermaus Geocoder Toolbox*), a module of the commercial *Fledermaus* software from QPS, and which will be considered in the following. To our knowledge, other versions (either the CCOM original, or post-developed) have been also implemented by Caris, Triton, Hypack, Reson, Fugro, and Chesapeake Technology;
- ***MB-Process*** (Gavrilov et al., 2005; Parnum, 2007; Hamilton and Parnum, 2011; Parnum and Gravilov, 2011a, 2011b); a research software developed at the Centre for Marine Science and Technology (CMST) of Curtin University and Geoscience Australia.
- ***MB-System*** (http://www.ldeo.columbia.edu/res/pi/MB-System/); an open-source software package developed by the Monterey Bay Aquarium Research Institute (MBARI) and the Lamont-Doherty Earth Observatory of Columbia University (L-DEO).
- ***PRISM*** (http://noc.ac.uk/science-technology/research-groups/mg/seafloor-habitat-mapping/mapping-technology-techniques), developed at the National Oceanography Centre.
- ***SonarScope*** (Augustin and Lurton, 2005) http://flotte.ifremer.fr/fleet/Presentation-of-the-fleet/On-board-software/SonarScope); a commercial software developed at the French Research Institute for Exploitation of the Sea (Ifremer);
- ***SwathEd*** (Beaudoin et al., 2002; http://www.omg.unb.ca/~jhc/SwathEd.html); a research software developed at the Ocean Mapping Group of the University of New Brunswick.

Methodologies for analyzing the angular response for seabed characterization, segmenting and classifying the backscatter mosaic, or integrating with ground-truth, are out of the scope of this document (Figure 6-2). Their variants are many and currently a field for innovation and experimentation rather than routine activities prone to standard procedures. However, a few notes are provided in the following sections.

6.1.3 Notes on angular response and mosaics

Geophysical vs empirical angular response analysis

The variation of BS with angle θ at a given frequency is dependent on the type of seafloor and therefore potentially allows seafloor classification and characterization (Lurton, 2010). As previously described (see Ch. 4 and 5), obtaining $BS(\theta)$ from the recorded signal implies knowledge –and careful removing— of a number of terms dependent on the sonar geometry, electronic hardware, characteristics of the water-column and geometry of the seafloor at the sounding's location. Once all data samples have been reduced to Backscattering Strength and associated incidence angle, the pairs of values (BS, θ) can be compiled over an area that is both (1) of assumed homogenous seafloor-type and (2) large enough to compile as many samples as possible for each angle over the widest angular range possible. The distribution of samples, or more commonly the mean BS value per angle, can then be analyzed for seafloor characterization by fitting physical models of seafloor backscattering to the data (e.g. Fonseca and Mayer, 2007). Such an approach can be referred to as an *angular response geophysical analysis.*

The main issue with this approach is that in most Backscattering Strength theoretical models (see Ch.3), the number of seafloor parameters is too large to invert the models efficiently and unambiguously. A more pragmatic approach consists in fitting simpler empirical models to the angular response with the more modest objective of identifying differences between seafloor types using empirical parameters (e.g. Lamarche et al., 2011). Such an approach can be referred to as an *angular response empirical analysis*.

An interesting advantage of empirical analyses over geophysical ones is that some of their descriptors are insensitive to systematic biases in the $BS(\theta)$ estimates that occur, for example, from poorly calibrated systems. In order to distinguish two different seafloor types on the basis of their angular responses, the *absolute* level of these responses does not matter as much as the fact that its *variation* with incidence angle is dependent on seafloor characteristics only. Therefore, empirical analyses are applicable even in the very common event that the constant parts of the system-dependent information needed for accurate reduction to BS (static gain, source level and directivity indices) are missing.

Mosaic artefacts arising from angular dependence compensation

The processing path to a backscatter mosaic continues where the path to angular response leaves off. The first step is to normalize the angular response to a reference nominal angle, which in theory makes the resulting signal independent from any other factor but the nature of the seafloor at the origin of the echo. However, since the variation of BS with θ is itself dependent on the type of seafloor responsible for the backscattering and since seafloor type is a piece of information that is unknown *a priori*, strong assumptions of local seafloor spatial homogeneity must be made to implement a suitable angular compensation. The invalidity of these assumptions is the source of residual artefacts commonly found in backscatter mosaics (Figure 6-4). For example, drawing one single angle-compensation curve from one particular local seabed configuration and using it on the entire survey will successfully compensate all areas that have the same seabed configuration and lead to artefacts everywhere else. Using *adaptive* compensations (i.e. drawing an angle-compensation curve from the same area as the data to be corrected) reduce the number of artefacts in large areas of seafloor displaying the same seafloor configuration but will not prevent them at areas of transitions between seafloor types.

There is today no standard methodology for angular dependence compensation—this chapter presents a number of them (§6.7). Most backscatter processing software suites implement their own algorithm, based on different assumptions of local seafloor spatial homogeneity. Different compensations will lead to different mosaics showing different artefacts.

Reference incidence angle

BS as recorded from multiple angles of incidence is not usable graphically (on a reflectivity map) since its inherent angle-dependent variations mask the seafloor-dependent local differences (Figure 6.3**Error! Reference source not found.**). As explained above, it is the whole point of the angular dependence compensation to remove this effect. However, the result of this compensation is that the mosaic level is not the measured BS any more, but the 'measured BS normalized to a reference incidence angle of X degrees (or a reference angular interval of X-Y degrees)'. We encourage the mosaic producers to report their backscatter level accordingly as BS_X (or BS_{X-Y} in case of a reference angular interval). The issue remains as to whether such BS_X map can be considered a quantitative product given that two different software implementing different processing methodologies on the same dataset can produce two different maps both claiming to represent the same BS_X. However, if everything has been conducted ideally using calibrated signals and adaptive angular dependence compensations that truly represented the local seafloor configurations, the angle-compensated BS_X mosaic will represent what should be the BS of the seafloor insonified at a constant angle X all over the scene.

Absolute backscatter level or mosaic visual quality?

If the user's main objective is an artefact-free mosaic, the merit of an angular compensation methodology will be judged by the visual quality of the resulting mosaic, that is, the contrast between seafloor types and the relative absence of remaining artefacts, irrespectively of the mosaic absolute level. Most of the processing steps that follow angular dependence compensation have the same purpose of improving the readability of the mosaic and its suitability for interpretation: this aim guides the selection of methodological choices for gridding the data samples, blending overlapping lines and post-mosaicking corrections such as de-speckling, anti-aliasing or low-pass filters.

The importance of the objective of artefact-free, seafloor-dependent variations in tone and texture in the mosaic over the objective of an absolute level has also a practical advantage: it implies that the final processing sequence can be applied to a signal level that is not necessarily the physically meaningful BS level. The software program can be designed to simplify or omit many of the steps usually required to retrieve the BS level and still produce a visually appealing, useful backscatter mosaic. Since the information required to retrieve the BS level is often scarce or ambiguous, such simplification and omissions are indeed common. Such processing methodology results in a backscatter mosaic that can be considered as a *qualitative* product. We encourage users following that path to illustrate this qualitative character by using qualitative terms in the legend of backscatter mosaics (e.g. "high" and "low" reflectivity as in Figure 6-4) instead of quantitative, but possibly meaningless, dB values.

However, other users might instead focus on the objective of producing a mosaic presenting a correct absolute level. Indeed, even if imperfect, its evaluation is of primary importance in seabed classification or characterization. Such objective requires the information about gains, source level, beam patterns to be known and taken into account in the processing. The result of such a processing can be considered a *quantitative* product and users might use a quantitative legend - but they must also remember that the displayed result is referenced to a certain angle (or angular interval, see previous section), and that the level thus displayed is still dependent on the choice of methodology, particularly the angular dependence compensation.

Physical vs Geological convention in mosaic color scale

A last point of interest on the subject of backscatter mosaics is the choice of the color scale used to represent the data. Although not necessarily followed in all cases (e.g. Hill et al., 2014), the common practice is to use a grayscale color bar (i.e. shades of grey ranging from black to white). There is debate however, as to the direction of the scale; that is whether low backscatter/reflectivity should be represented in black and high backscatter/reflectivity should be represented in white, as in Figure 6-4, or the other way around.

The decision to represent increasing reflectivity in increasingly white tones is supported by the fact that higher reflectivity indicates higher energy, which translates for example in low-energy acoustic shadows in the lee of a significant feature on the seafloor to be shown dark as in our visual perception of the shadow of objects in the sun light. This *physical convention* is often favored by acousticians, or GIS/imagery specialists. The opposite decision to represent increasing reflectivity in increasingly dark tones is supported by the fact that (1) the original seafloor-backscatter-imaging devices (analogue sidescan sonars) would print sonar images on thermal papers, which darken when exposed to heat, and that (2) rocks are more reflective than soft sediments and would therefore appear darker than sand on a sonar image, as on a regular photography, and help for interpretation. This *geological convention* is often favored by geologists and older sidescan users. Since the decision ultimately remains the privilege of the person in charge with processing and presenting the data, we simply recommend that the convention used in any particular map product be made clear in legend and/or caption.

6.2 Decoding of raw measurement units

The unit of the “backscatter” data recorded in the data files is often dictated by limitations in numeric types available for writing binary files. A decoding of the manufacturer’s preferred unit is therefore required to transform the measurements to units that are both physically meaningful (dB) and allowing system inter-comparison.

This decoding is fairly straightforward as the necessary information is small and usually provided by manufacturers in manuals. However, the lack of standards implies that backscatter data representation has continuously evolved with hardware and software updates. In particular for historical manufacturers (Kongsberg and Reson), backscatter data now exist in several data types and the representation of each type may be dependent on the version of the acquisition software.

6.2.1 GeoSwath

The GeoSwath system natively generates raw data files (with “.rdf” extension, henceforth *RDF files*) containing range, receive angle and amplitude triplets for each travel-time measurement step, along with vessel navigation and other ancillary sensor data, and sonar operating parameters. Raw data format information is provided in Kongsberg Geoacoustics (2012). Backscatter amplitudes in RDF files are the direct output of the Analog-to-Digital Converter (ADC) for one stave of the multi-stave ensemble on each side (i.e. port and starboard).

6.2.2 Kongsberg

Kongsberg systems generate raw data files with ".all" extension with an option for water-column data to be recorded in a separate file with ".wcd" extension. Kongsberg systems have traditionally produced two backscatter data types, recently completed by a third format for water-column-capable systems:

- "*Beam Intensity*": currently representing the average signal level over a given beam's footprint.
- "*Seabed Image*": containing a time-series of samples for each beam. The samples recorded are picked from the full beam amplitude signal "in such a way that fitted together the total array of samples represent a continuous set along the bottom" (Hammerstad, 2000).
- "*Water-column*".

All Kongsberg data types are stored in scaled units of dB within different datagrams, with newer versions of datagrams implementing a finer-grained scaling factor for improved radiometric resolution (Kongsberg, 2013). The processing of Kongsberg backscatter data is dependent on the data type and the version of the datagram they were taken from.

6.2.3 R2Sonic

R2Sonic systems generate raw data files (with ".R2S" extension) containing backscatter data in four different representations that are consistent across all models (R2Sonic, 2013):

- "*Bathy Intensity*": a single-value of backscatter intensity per beam. Currently representing the return level at the bottom detect point;
- "*Snippets*": time-series of data samples per beam;
- "*TruePix*": a sidescan-like single time-series of triplets (intensity, range, angle) for port and starboard sides. Sample range distance is roughly the pulse length of the transmitted signal; For each side, TruePix reports the magnitude of the strongest echo for each range, and accurately measures the angle of the return;
- "*Water Column*": reports magnitude and/or phase time series for all beams.

6.2.4 Reson

The newer generation of Reson systems (i.e. Seabat 7k-series and T20-P) store a variety of data types (with .s7k extension) with several datagram versions existing for each type (Reson, 2011):

- "Beam magnitude" in datagrams 7006 and 7027; the 32-bit float value is the magnitude of the beam time series at the sample closest to the bottom detection location. Note 7006 datagram collected with software version prior to Feature Pack 1.3.2 are not useable.
- "Foot-print time series" ("Snippet") in datagrams 7008 (obsolete) and 7028 are 16-bit amplitude time series centered on bottom detection. Initially selectable fixed length for all beams are now of variable sizes, ensuring 200% seabed coverage in most cases.
- "Sidescan" in datagram 7007; port and starboard variable bit depth magnitude time series. Each sample value is the maximum magnitude across all beams on one side after across-beam low pass filtering.
- "Water column" in datagram 7008 (obsolete) and 7018: 16 bits magnitude time series.

Older Reson SeaBat systems (i.e. Seabat 8-k series) allowed for recording data (with .sns or .raw extensions) of water-column, snippet, per-beam intensity and sidescan modes with all formats using an unsigned 16-bit integer for storage with values being proportional to linear pressure.

However these systems could output water column only at a dramatically reduced ping rate due to the limited data transmission rates associated with the serial and/or 10BaseT output interfaces.

6.3 Correction for static gains, time-varying gains and manufacturer corrections

Most systems implement a number of gains both before and after the ADC stage. Detailed information on how and why these gains are implemented can be found in Chapter 4.

Gains applied before the ADC can be usually separated in a static gain and a time-varying gain (TVG) applied in real-time in order to overcome the decaying of signal strength with range and keep the signal level within the ADC dynamic range. The TVG is therefore a form of correction for transmission losses (see section §6.5) and is thus a desirable compensation. As an analogue process, however, it comes with a number of limitations and uncertainties and often does not accurately represent the true signal decay. Therefore, it is often desirable to remove the TVG implemented in the sonar hardware and re-introduce a better correction for transmission loss in post-processing.

Gains applied after the ADC can also be separated into static and dynamic components, with dynamic ones varying with range, depth or other parameters. These gains are usually meant to be desirable compensations for some of the physical processes represented in the sonar equation terms such as insonified area or angular dependence. As previously, a better estimate for the compensation of these terms is almost always available in post-processing; an illustration of this is given in Figure 6-5.

If these manufacturer gains are removed successfully, the resulting corrected level is the level received at the transducer face prior to application of gain, commonly referred to as Received Level (*RL*, see sonar equation in Chapter 2).

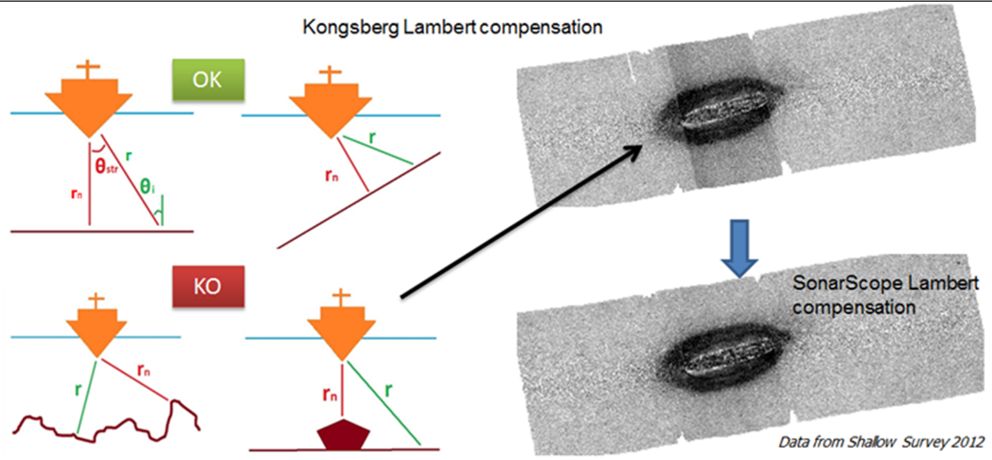


Figure 6-5 Example of artefact induced by sonar hardware gains and compensated in post-processing. Here, the dynamic gain implemented in a Kongsberg system fails to account for the complex bathymetry induced by a shipwreck lying on a flat seafloor. The removal of this gain followed by a more appropriate compensation of insonified area in post-processing allows correcting the artefact (Augustin, 2013, data courtesy of Shallow Survey 2012, processed with SonarScope).

6.3.1 GeoSwath

GeoSwath systems apply three gains, all of them applied prior to the ADC:

- A built-in static gain (G_0) applied during pre-amplification and filtering;
- A user-variable static gain (G_i);
- A time-varying gain (TVG_{GS}).

Since the stored signal amplitudes in GeoSwath data files are simply the value reported by the ADC, these gains must be corrected in post-processing.

6.3.2 Kongsberg

Kongsberg systems implement a user-configurable static gain termed "system gain offset"—noted GO_1—used to adjust the signal level within an allowable range of -10 dB to +10 dB. It is applied consistently to all Kongsberg backscatter data types. In a dual-head system, the gain for the second head is noted GO_2. This system gain offset cannot be changed while the system is pinging. It is therefore not designed to manually adjust the system level during acquisition but rather to normalize the signal level to some desired level, perhaps with respect to another system or to a seafloor of known backscattering properties.

In an attempt at producing backscatter data that are reduced to Backscattering Strength, Kongsberg systems apply a complex dynamic gain that includes:

- A compensation for frequency-dependent attenuation of the signal in the water column;
- A correction for spherical spreading;
- A compensation for the insonified area;
- A compensation for the level variation with angle of incidence at the seafloor.

Unfortunately, the simple models implemented in these gains may result in artefacts when assumptions are not met (see e.g. Figure 6-5). Kongsberg has issued a technical document (Hammerstad, 2000) describing this dynamic gain to allow users to remove it.

6.3.3 R2Sonic

R2Sonic systems apply a user-settable fixed gain and TVG implementing a traditional transmission loss model. The user can specify the spreading and absorption parameters in real-time. Thus these parameters may vary through a file on a ping-by-ping basis.

6.3.4 Reson

The new T20-P system applies a simple TVG law.

Reson 7k and 8k systems apply a non-standard and proprietary TVG function whose details are not publicly available. However, the manufacturer has provided this information to some users willing to sign a non-disclosure agreement. The following information was obtained from personal communication within the bounds of this agreement.

By non-standard, it is meant that the TVG parameters identified as Spreading and Absorption coefficients in Reson documentation are not applied in the standard manner prescribed by the sonar equation to overcome expected transmission losses. The Spreading and Absorption parameters of the Reson TVG equations are perhaps better described as the logarithmic and linear scaling factors. In Reson approach, the primary role of the TVG is to maintain the signal level within the dynamic range of the receiver hardware and electronics, rather than to describe accurately physical phenomena.

The algorithms used by the manufacturer can vary with model number and generation (i.e., the 7000 series versus the 8000 series). The 7125, 7111, 7160 and 7150 share the same TVG equations, with the temporal resolution of the equations being rescaled for the 7150 to accommodate the longer travel times associated with the deeper water depths in which it is used. The 7101 uses the original TVG model used by the 8000 series systems (discussed below) and the T20P has a unique TVG that differs from the 7K series system. There is no documentation for the TVG used by the 8K systems, however, it is known that a non-standard TVG is applied much like that of the 7K systems. Since 8K systems use a non-standard curve and the curve that is used is not known, it is not possible to fully correct imagery for 8K systems to arrive at seafloor backscattering strength. The 7101 system is a hybrid generation system in that the wet side acoustic and electronic components are from an 8101 but the top side components features the modern processing and control interface of 7K systems. As a result, the 7101 uses the original 8K series TVG and is subject to the same limitations as the earlier generation systems.

The user can specify the Spreading and Absorption parameters in real-time, thus these parameters can vary throughout the file on a ping-by-ping basis. With 8K series systems, operators are strongly encouraged to fix the Spreading and Absorption values during acquisition to avoid introducing artefacts in the imagery. The newer 7K series systems, with the exception of the 7101, can be reasonably compensated in post-processing for TVG parameter variations, providing that the user is able to monitor the signal level in real-time to avoid signal saturation.

6.4 Correction for source level and transmit/receive beam patterns

Corrections for Source Level (*SL*), Transmit Beam Pattern (*TxBP*) and Receive Beam Pattern (*RxBP*) remain at present the main obstacle to a fully-quantitative processing chain as most of this information is often unknown to the users.

Some manufacturers provide a generic value for *SL* and generic beam patterns obtained from the testing of a prototype in a tank. However, individual systems may vary from these generic values as their construction, housing, and electronic components may differ from the model design. In addition, system components experience degradation through time, which can affect these levels significantly. Ideally, each system should be calibrated before first use, and regularly through their life cycle but the logistical difficulty of a controlled laboratory calibration and the lack of a standard procedure for field calibration to date implies that this is rarely done, if ever.

Practically, the situation is quite confusing for users and operators. Manufacturers may record (or not) the *SL* or beam patterns in the data files, and may (or not) automatically correct the data. Most processing software can read the *SL* data that have been recorded in the files or can use generic data or data obtained from manufacturers. Some processing software implement models of beam patterns, and/or propose calibration functionalities to retrieve empirical *SL* and beam patterns.

6.4.1 GeoSwath

Source level in GeoSwath can be set during acquisition as a “Power” option, using an index value (1-10 in the acquisition interface, 0-9 in the RDF data files). The reported amplitude data are not corrected for source level and must therefore be compensated during post-processing.

No corrections are made for transmission or reception beam patterns in the raw data files.

6.4.2 Kongsberg

Data acquisition software for Kongsberg systems allow for SL reduction by -10 dB or -20 dB. The EM 710, EM 302 and EM 122 also have a “Mammal Protection Mode” with a “Soft Startup” option, in which the system starts with a low SL and increases it gradually over a user-specified time span. In both cases, the reduction in SL is stored in the Runtime Parameters datagram as the “Transmit Power re maximum” field. These variations in SL are compensated for in all backscatter data types and no further corrections are necessary in post-processing.

Source levels vary between different transmission modes (Shallow, Medium, Deep, etc.) and Transmit sectors. These are corrected for in real-time using a series of modeled parameterized source level and beam pattern corrections whose parameters are stored in a configuration file stored in the sonar Transmission/Reception Unit (TRU) named BSCorr.txt.

BSCorr.txt can be retrieved and possibly modified through FTP connection. Alternatively, a standalone program in SIS (valid for EM 122, EM 302 and EM 710, but not for EM 2040) can be started to allow the user to edit the correction values and update the file in the TRU. Note that the BScorr.txt file does not adjust the actual source level; it is only used in the receiving process to correct output imagery data. The beam pattern correction uses three descriptors (stored in BSCorr.txt file) summarizing the angular correction for each transmit sector:

- Source level
- Transmission lobe athwartship pointing angle
- Transmission lobe 3-dB aperture angle

This simple description (assuming a classical lobe shape for the beam pattern) is completed by polynomial fits for certain configurations where a wide unfocused central beam is formed.

For more recent EM sounders (such as the EM710), the 3-parameter model of radiation pattern implicit in the BScorr.txt file is now replaced by a lookup table of levels vs angles (at a sampling step better than 10°), which is spline-interpolated to retrieve the complete beam pattern curve.

The corrections applied by the configuration file have not historically been preserved in the raw multibeam data output by the sounder. Users interested in adjusting these corrections in post-processing must retrieve the configuration file from the TRU via FTP. However, as of Revision Q of the EM datagram format descriptor (Kongsberg, 2013), a new "ExtraParameters" datagram including the beam pattern corrections is now stored systematically (datagram ID: 33h/51d/3).

The absolute accuracy of the default SL corrections in each system's configuration file is unknown – although supposed to be set at reasonable values. It is advised that a system be at least relatively calibrated to update the configuration file with appropriate values that reflect the natural variation of the echosounder's output in various mode and sector configurations. Procedures documenting this type of effort are discussed in Beaudoin et al. (2012).

Offsets between systems of the same model are likely best addressed through the use of the GO1 and GO2 parameters.

6.4.3 R2Sonic

Transmit power in R2Sonic models can be adjusted by the operator. However, these adjustments are not being compensated in the imagery output and must therefore be corrected in post-processing.

The SL is recorded in the header of both the imagery and bathymetry datagrams. The absolute accuracy of the reported SL is unknown, however, the relative variation between SL settings on a given system appears to be consistent thus imagery can be corrected for source level variations for the most part as long as the received signal level is not saturated. Firmware updates available in August 2014 allow for the recording of an additional SL corrector that captures the deviation from the nominal source level with these variations being associated with (1) lag of SL reduction when the operator reduces the setting, and (2) low level (1-2 dB) ping-to-ping fluctuations in power at low source levels.

No corrections are made for transmission or reception beam patterns. The manufacturer has measurement results available and may be willing to share this information upon request.

6.4.4 Reson

The source level used by Reson systems can be adjusted by the operator. This information is stored in the Sonar Settings datagram (ID=7000). These adjustments are automatically compensated for in the imagery output for some models (7150, 7111) if the “Calibrated Backscatter” option is purchased, but not in others. Compensation for transmit power in models that do not implement it must be performed in post-processing and is usually done by normalizing the receive intensity by the transmit power. The absolute accuracy of the reported *SL* is unknown, however, the relative variation between *SL* settings on a given system appears to be consistent thus imagery can be corrected for source level variations for the most part.

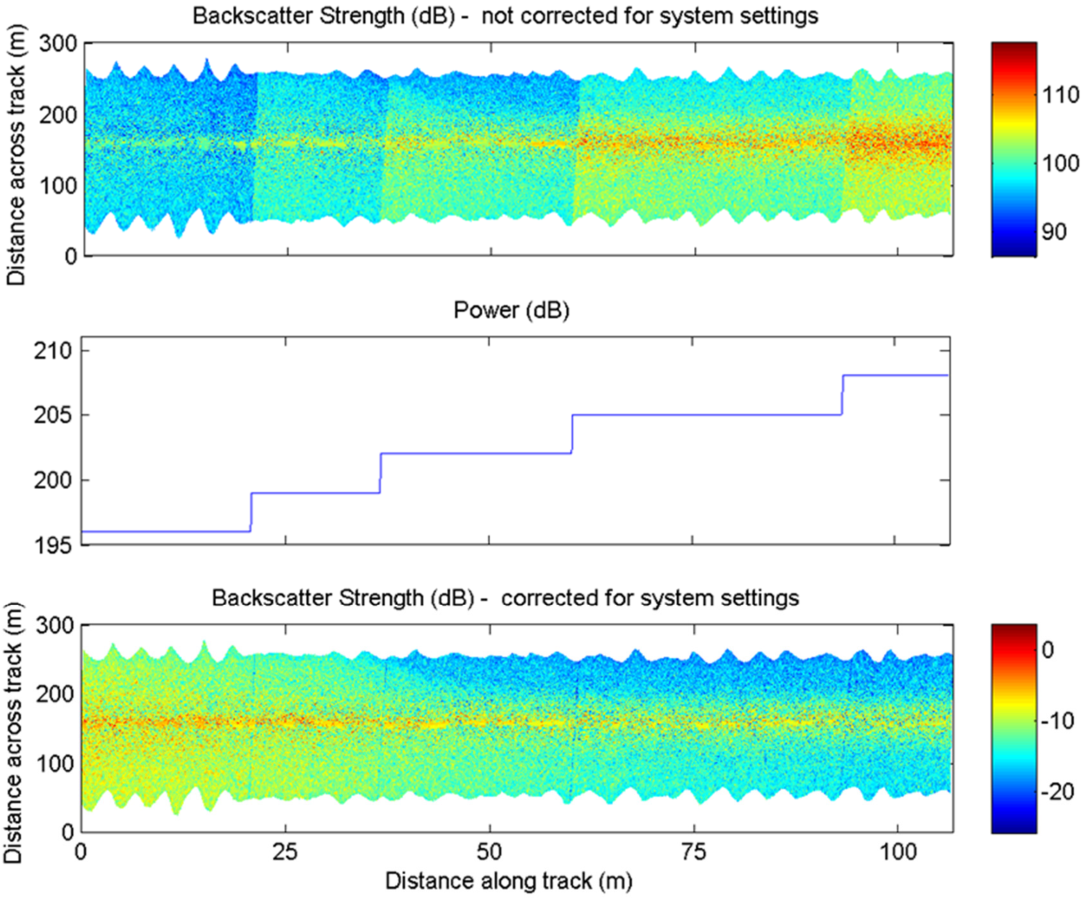


Figure 6-6 Backscatter data from a Reson Seabat 8125, not corrected (top) and corrected (bottom) for changes in power (middle). (from Parnum, 2007). Note that the dB scale of the non-compensated data is arbitrarily referenced.

While power settings are logged in the data files, allowing for their removal in post-processing, it has been observed that corrections leave artefacts for data recorded near the settings change in at least 8101 (Beaudoin et al., 2002) and 8125 (Parnum, 2007; see Figure 6-6 in this document) models, suggesting that the time at which changes in power settings are effective are not accurately registered by the 8k-series systems, possibly due to some delay for the modification to be fully effective in the analogue electronics.

The manufacturer measures beam patterns and receive sensitivity of all sonars in test tank after manufacturing. They store this information in their own database, but do not correct the data for these measurements and do not provide these values to the user by default. However, they may be willing to share this information upon customer's request.

6.5 Correction for transmission losses

At this stage of the processing chain, all sensor-specific peculiarities should have been removed. The retrieved level is thus the Medium and Target Level (*MTL*, see Figure 6.2) a combination of Transmission Losses and Target Strength. The goal is then to compensate *MTL* with the best approximation of the true transmission loss *TL* as possible to retrieve the target strength *TS* (see the definition of Target Strength in Chapter 2). A simple approach takes the classical model for the two-way transmission loss:

$$2TL = 40\log_{10}(R) + 2.\frac{\alpha}{1000}.R \qquad \text{(eq.37)}$$

where:

- *R* is the range in meters associated with a given imagery sample;
- α is the frequency-dependent absorption coefficient in dB/km.

α is not only dependent on frequency, but also on temperature, salinity, pressure and pH, all of which vary with depth. However, the simple equation above is often implemented by assuming an average value of α over the water depth of interest.

Many modern MBES implement variable operating frequencies, with the operator often being able to change this setting between different files or pings and the system generating slightly different frequencies inside different transmit sectors. Absorption coefficients should be adapted to this frequency agility. Further, CTD measurements or ocean databases could be used to compute depth-profiles of absorption coefficients varying with temperature and salinity, which offers the possibility to adjust the absorption coefficient with depth; an alternative is to use the current SVP to retrieve a rough profile of temperature, an approximation sufficient for the absorption estimation. The depth-dependent absorption coefficient can be then applied to compute the cumulative absorption over the ray paths. To our knowledge, this complete set of operations is applied today only in Kongsberg MBES (with the applied absorption coefficient values per sector stored in the *Raw Range* datagrams).

Improved estimates of *TL* may therefore be possible by computing the cumulative absorption over the ray path using a variable absorption coefficient. Further improvement could be obtained by integrating the true spreading loss over refracted ray paths. Studies should be dedicated to the question of whether these improvements bring significantly different *TL* estimates than those from the simplistic spherical spreading and constant absorption assumptions.

6.5.1 Software implementations

In FMGT, the classical TL model is used. Technical notes direct users to a set of absorption coefficient calculators provided by the National Physical Laboratory (NPL) to assist in determining a reasonable absorption coefficient.

MB Process implements the correction for transmission loss as above, but in the linear domain. The absorption coefficient is calculated using an empirical formula based on the system frequency, temperature, salinity and depth with the last three fixed to 20° C, 35 ppt and 0 m.

MB-System does not apply transmission loss corrections.

In PRISM, the transmission losses can be compensated by several methods. The simplest method is to measure the average received intensities over the complete swath of ranges from a large number of pings. These range values can show a proxy for the transmission losses assuming that the imagery features are equally spaced over the imagery and the bathymetric variation is not significant. The curve of range values against average intensity often requires smoothing. The output intensities are therefore relative intensity values rather than calibrated decibel losses. The advantage is that quick results are produced without the need for water column absorption coefficients.

In SonarScope, the TL applied by the manufacturer (as part of the TVG) can be compensated for (according to the specific formulas and local parameters) with Kongsberg and GeoSwath systems; the extension to Reson systems is under progress. SonarScope applies a transmission loss based on (1) a geometrical divergence based on 20log of the curvilinear length (instead of spherical range) and (2) an absorption profile averaged over the water depth.

In SwathEd, the classical model is used to treat Reson and R2Sonic data. Recent work has allowed for frequency dependent corrections for Kongsberg systems with CTD profiles providing the necessary oceanographic information to support the cumulative absorption calculation along a given ray path.

6.6 Correction for insonified area

Correction for insonified area transforms the Target Strength (TS) into Backscattering Strength (BS). As in the estimation of transmission loss, different approximations of insonified area can be computed resulting in a trade-off between realism (and therefore artefacts) and complexity.

Chapter 4 describes the physical models of insonified area that are most commonly implemented. These models are mostly a function of the transmit and receive beamwidths in the cases of near-normal incidence, and of pulse width in the case of low incident angles.

The first and most common approximation is to consider a flat seafloor, neglect refraction in the water column and assume that the sonar transmits exactly at nadir and receives exactly in the across-track plane. These assumptions allow for insonified area estimates that are fast to compute but may be grossly unrealistic, especially as they misrepresent the actual angle of incidence at seafloor. In particular, the flat seafloor assumption will result in the imagery retaining all topographic related modulations in signal strength due to slope effects in both the across-track and along-track directions. The computation ease made this assumption very popular in early multibeam hardware processing units and early software.

A second and most commonly used approximation consists in taking into account water-column refraction and seafloor slope for the calculations inside the across-track plane. This approximation still assumes that the sonar transmits exactly at nadir and receives exactly in the across-track plane, and neglects the along-track slope of the seafloor.

The third and most realistic approximation consists in taking into account pitch and transmit steering angle to define radial and tangential directions to be used for widths computations instead of the along-track and across-track directions. The radial direction is defined by the line on which both the echosounder and the sounding footprint lie. This plane can be referred as the ray-path plane. The angle of incidence in the ray-path plane can be used to provide the incidence angle in the across-track insonified area calculations described earlier. The tangential direction is orthogonal to the ray-path plane and the seafloor slope in this direction defines entirely the incidence angle used in the along-track insonified area equations.

6.6.1 Beam Width considerations

The beamwidth is a critical parameter in estimating the area insonified near nadir. However, most systems report a generic beamwidth value. The user must be aware of a number of subtleties.

First, the reported beamwidth is typically for beams orthogonal to the array face. A beam electronically steered by an angle θ has its main lobe widened by a factor $1/\cos\theta$. For example, a steering angle of 25° relative to the acoustic axis will increase the beam width by 10% (i.e. about 0.4 dB for the target strength). Fortunately, this effect becomes significant only at large steering angles for which the insonified area on the seafloor is usually limited by the pulse width and not the beamwidth.

Second, the beamwidth varies with frequency and this effect is often not taken into account by manufacturers.

For example, R2Sonic systems' beamwidths change by a factor of two over the frequency range allowed by their systems while the beamwidths reported in the bathymetry and imagery header do not change between models or when adjusting frequencies.

Kongsberg systems implement various transmit sectors using different frequencies. This implies that along-track Tx-beamwidths vary with sectors (not confirmed by the constructor). The effect might be small since the frequency separation between transmission sectors typically only spans less than ±10% of the nominal carrier frequencies. At fixed array length, the beamwidth varies inversely proportionally to frequency, hence a change of 10% in frequency leads to a 0.4 dB difference of the estimated BS level. It is unknown whether the manufacturer hardware or processing software takes into account this variation.

As more systems increase their bandwidth and frequency operational agility, it will become increasingly important to better understand whether or not manufacturers are reporting nominal or actual beamwidths and which of these two, if any, are used in real-time corrections. Post-processing software also need to take this into account and report if this is done or not.

6.6.2 Pulse Width considerations

The pulse width is a critical parameter in estimating the area insonified away from nadir. Again, manufacturers report a nominal value and it may be unclear whether this value takes into account pulse tapering, which makes smaller the effective width to be accounted for in footprint estimate.

Current GeoSwath models (2009) apply no pulse tapering.

Kongsberg MBES apply pulse envelope tapering (100% for CW signals, i.e. the bell-shape encompasses the complete pulse duration). The total pulse length is given in the Raw range datagram; the effective pulse length is given in the Runtime datagram as $1/B$.

Reson 7k and T20-P systems typically apply a 10% Tukey tapering. The exact pulse shaping parameters are reported in datagram 7000.

R2Sonic pulse lengths are reported in the datagram. A trapezoid envelope is applied to suppress spectral leakage.

Note that if the pulse width was below the Nyquist frequency, which was possible with older systems and operators wanting to "maximise" bathymetry resolution, the peak and width end up under-sampled and so may cause incorrect resulting *BS* values.

Specific issues arise for pulse length associated with Frequency Modulated (FM) waveforms supported in some multibeam echosounders on the market (Kongsberg and Reson). The advantage of FM waveforms is their ability to use long pulse widths together with a large bandwidth, increasing the signal-to-noise ratio while simultaneously preserving range resolution capabilities through the use of a matched filter ("pulse compression"). At the receiver output, the effective pulse width τ_{eff} (in s) to be used for insonified area corrections is given by the inverse of the bandwidth BW (in Hz) of the FM signal:

$$\tau_{eff} \sim \frac{1}{BW} \qquad \text{(eq.38)}$$

and the increase in *SNR* (in dB) is:

$$PG \sim 10\log(BW.T) \qquad \text{(eq.39)}$$

where T is the transmit duration (in s) of the physical signal. Practically, a FM signal can be thought of as an equivalent CW signal of duration τ_{eff} and source level increased by PG. The amplitude shift associated with the matched filter operation should be accounted for in backscatter post-processing; this has to be done by the manufacturer, since it involves the details of the algorithms.

Kongsberg systems appear to automatically apply such corrections as no significant level offset is observed between transmission sectors using traditional CW waveforms and outer sectors using FM waveforms. The *BW* and *T* parameters for each transmission sector are provided in the raw range and beam angle datagram.

To date, Reson systems using FM signals apply a compensation to compensate for the gain associated with pulse compression. However, the present design of this processing is not fully validated and is still prone to evolve.

6.6.3 Software implementations

In *FMGT*, nominal beamwidths are corrected for frequency dependence when possible for R2Sonic systems, otherwise the nominal beamwidths are used for all other makes and models. The nominal pulse width reported by the echosounder is used for all makes and models. For systems where the pulse length varies with transmit sector, e.g. Kongsberg systems, the transmit specific pulse length is used as opposed to the nominal value reported in the run time datagram. For each beam, the insonified area calculation assesses whether or not the insonified area is pulse width limited (away from nadir) or beam width limited (near nadir). If the user provides a terrain model, the local topography is used to improve the estimation of the incidence angle with the seafloor in both the along track and across track directions. No allowance is made for the effect of refraction on the incidence angle.

MB Process computes the surface scattering coefficient for the peak and energy (or pulse average) values within the beam time series. The peak intensity is normalized by the area insonified instantaneously by the sonar transmit array and observed within each receive beam. The energy is derived from the integral intensity; it is normalized by the transmit pulse width and the footprint area defined as the intersection of the transmit and receive beam incident on the seafloor.

MB-System does not correct for insonified area.

In *PRISM*, the exact definition of the insonified area is defined by an estimated beamwidth cut-off value and pulse width. *PRISM* simplifies these corrections by assuming it is included it in the transmission losses correction. If pulse width is changed the transmission losses curve is recalculated and normalized to match previous curves.

In *SonarScope*, the beamwidth considered along-track is the nominal one. It is not compensated for the frequency in case of multi-swath or multi-sector. The beamwidth across-track is considered only close to the vertical, in the “long pulse” regime; no correction of the nominal aperture is applied either. The pulse duration considered is the nominal one given by the manufacturer. It is assumed that the manufacturer’s value is the effective duration, hence needing no further correction. The effect of the incidence angle upon the insonified footprint accounts for several physical phenomena. The angles provided by the echosounder are replaced by computed “true” incidence angles accounting for (1) the refraction effect along the ray path from the sonar to the seafloor, and (2) the local slope of the seafloor (computed along- and across-track from the smoothed local Digital Terrain Map).

In *SwathEd*, nominal beamwidths are corrected for frequency dependence when possible for R2Sonic systems, otherwise the nominal beamwidths are used for all other makes and models. The nominal pulse width reported by the echosounder is used for all makes and models. For each beam, the insonified area calculation assesses whether or not the insonified area is pulse width limited (away from nadir) or beam width limited (near nadir). If the user provides a terrain model, the local topography is used to improve the estimation of the incidence angle with the seafloor in both the along track and across track directions. As an alternative, the topography in the locale of a given beam is determined by fitting a plane to the beam and its neighboring beams in the fore-aft direction and the across-track direction, the main advantage of this approach being that construction of a terrain model is not required. No allowance is made for the effect of refraction on the incidence angle.

6.7 Angular dependence correction

Angular dependence correction is aimed at compensating for the across-track variation of *BS* due to the physical dependence of the seafloor response with the incidence angle. At the end of this angular equalization, the *BS* measurements are normalized across the swath to a standard value, namely the *BS* value at a reference angle. This correction is typically only required if further processing includes mosaicking, whereas analysis techniques that take advantage of the angular variation in seafloor response—for example response inversion by fitting a model—will obviously not apply this correction (Figure 6-2).

Note that “angular dependence correction” is not a standard terminology. “Angular normalization” is sometimes used. A common acronym used is AVG, standing for “angle-varying gain”, probably because early implementations of this correction were done at the hardware-processing level and therefore implemented as an electronic gain in a similar manner as time-varying gain (TVG) was implemented to compensate for transmission loss. Although this terminology can lead to confusion, its usage is widespread in software so we will use this acronym.

AVG requires each data sample to be associated with its corresponding angle of incidence at the seafloor, which has usually been calculated during the previous processing step (correction for insonified area). It then finds the appropriate corrective term in a lookup table organized by angle. Actual AVG compensations differ on how the lookup table is created in the first place.

Generic angular responses measured for typical seafloor types or generated from canonical physical models such as Jackson’s (APL, 1994, 2000) are possible approaches to create the look-up table.

However, in most field data, both the seafloor type and its spatial variability are *a-priori* unknown, making this approach inapplicable.

Most often AVG is therefore an empirical approach in that the lookup table is created from the data themselves. The most common lookup table is created using the following sequence:

1. Select a subset of data to calculate the lookup table from;
2. Bin all signal samples from that data subset into angular bins, typically 1°-wide;
3. Compute the average signal level per angle bin;
4. Calculate a "reference level" as the average value either at a conventional angle (for example, 45°) or over a wider angle interval (be it wide, for example 20°-60° in Fonseca et al., 2009 or narrow for example 43°-47° as in Lamarche et al., 2011);
5. Create the lookup table as the difference of the average angular response and the *BS* level at the reference angle.

The choice of the data subset is a paramount step, and controls the final results of the process. A single subset can be chosen as the entire dataset (Preston, 2009) or data from one trackline covering an area of seafloor showing little backscatter variation (Beaudoin et al., 2002). More often, the subset can be selected dependent on the data to correct, for example as the entire line containing the samples to be corrected (Schimel et al., 2010), or the data within a number of pings before and after the samples to be corrected. This last option (often called a "sliding window") is probably the most common (e.g. Fonseca and Calder, 2006; Gavrilov et al., 2005; Kloser et al., 2010; Parnum and Gravilov, 2011) and its size should be set by the operator. It can be reduced further to a half a swath in order to process the two sides independently.

In this manner, the AVG consists, for each data sample, in subtracting the average level for the sample's corresponding angle calculated over a wider area and adding the average level for the angle taken as reference. Hence the local *BS* values are replaced by a value corresponding to the reference angle. The result is expected to represent the *BS* over the scene had it been insonified at a constant conventional angle (say, 45°).

A more advanced version of such an approach (Parnum, 2007; Preston, 2009) consists in correcting not only for the average level corresponding to each angle, but also its standard deviation, since the level standard deviation also varies with incidence angle (Figure 6-7).

Two parameters critically impact the result of the correction in the approach to construct the lookup table described above: the subset and the reference angle (or angular interval). The larger the subset, the more likely it is to overcome the data statistical variation and thus smooth out across-track variations, but the more likely it is to overlap several different seafloor types and to mix up their typical angular responses, creating along-track artefacts, particularly at transition between seafloor types. Conversely, smaller subsets create less along-track artefacts and more across-track ones. The choice of the reference angle will affect the overall aspect and of the reflectivity level mosaic.

Figure 6-7 illustrates how different corrections affect the resulting mosaic. The effect of the subset size selection (the whole track or a reduced number of pings surrounding the samples to be corrected; see Figure 6-7 *b* versus *d*, or *c* versus *e*) on creating along-track or across-track artefacts is obvious. Compensating (or not) for the standard deviation affects the overall aspect of the mosaic as different seafloor types present different standard deviation (Figure 6-7 *b* versus 6-7 *c*).

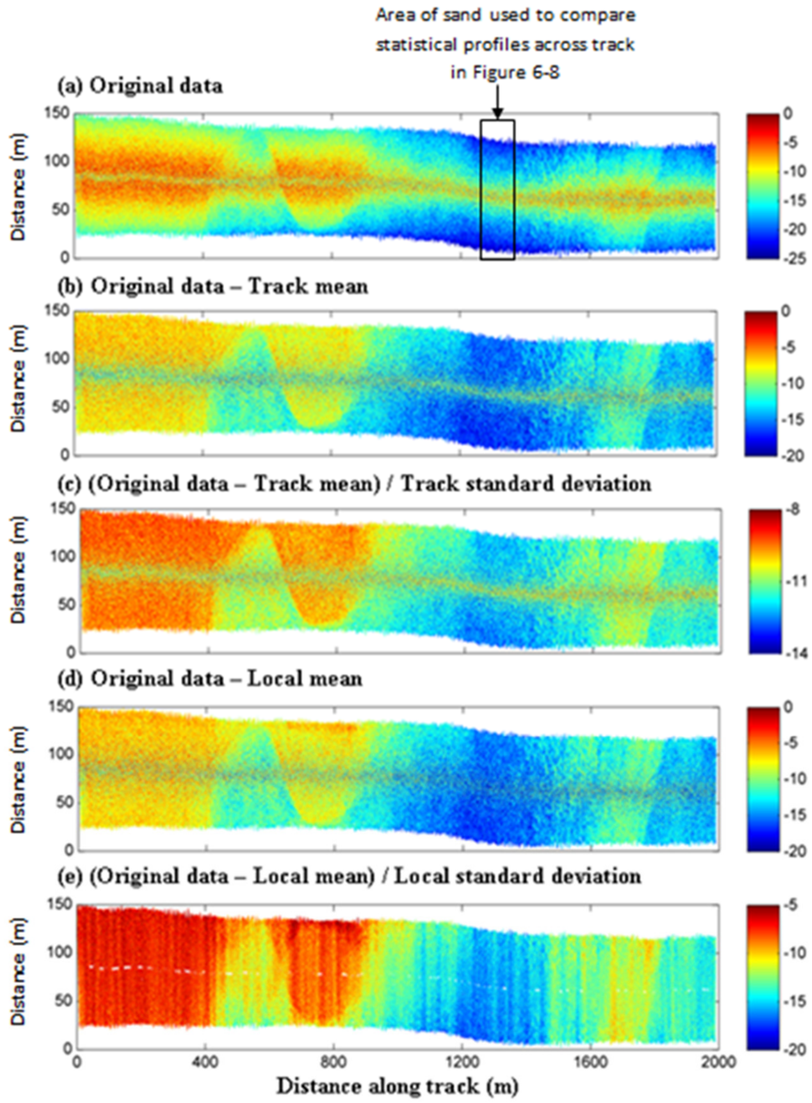
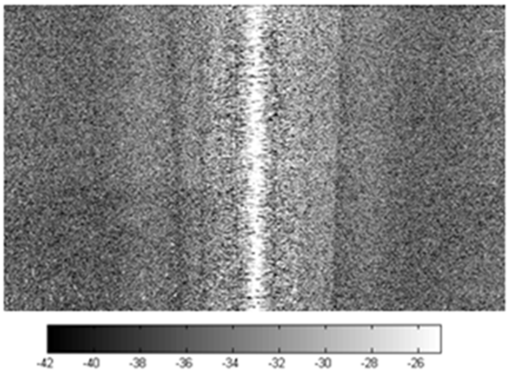


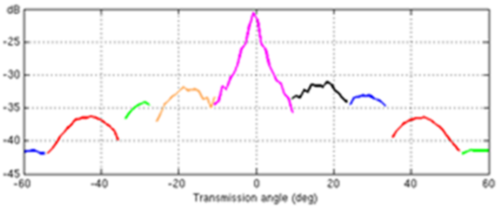
Figure 6-7 Backscatter strength (dB) from a single transect of data from a Reson SeaBat 8125 MBES acquired in Esperance Bay (Western Australia) before (panel a) after (panels b-e) application of various corrections for angular dependence. The various corrections include (b) the removal of the mean angular response calculated over the whole track and addition of the mean BS level at 30°, (c) the same but including a correction for standard deviation, (d) using the mean angular response calculated over a sliding window of pings, and (e) the same but including a correction for standard deviation. Image from Parnum (2007). Data processed with MB-Process.

Instead of building the lookup table directly from the average angular response over a data subset (step #5 in the sequence above), one can use the result of fitting the angular response to a generic *BS* model with a limited number of parameters (e.g. the Lambert's Law; or a more sophisticated model such as in Augustin and Lurton (2005) or Lamarche et al. (2011)). The interest of this approach (Figure 6-8) is to identify separately the respective angular responses of the seafloor and the MBES; the latter is the residual between the original data and the model, checked for consistency between several different seafloor types. The method gives access to the seafloor *BS* corrected from the residual modulation by the MBES directivity pattern.

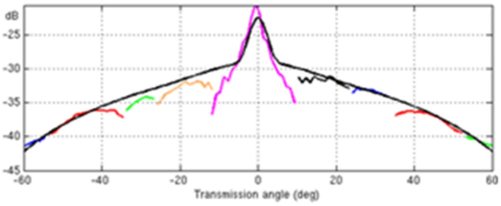


A : "Raw" sonar image (dB) of an homogeneous sea-floor from an EM300. Water depth 1050 m; displayed swath width 3400 m. (N.B. Any manufacturer compensation removed).

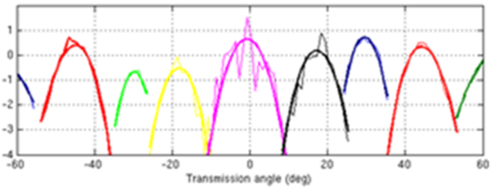
B : Insonified areas corresponding to the transmission sectors of the MBES.



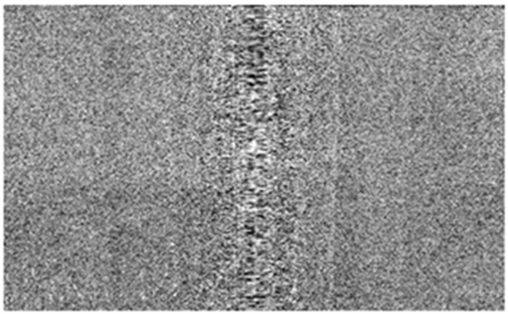
C: Averaged amplitudes of image A, displayed *vs* angle according to the transmission sectors of the MBES. This curve is the sum of BS and emission sectors beam pattern.



D: a conventional model of BS, including a specular effect and a generalised Lambert's law variation, is fitted to the data from C.



E: Fitting of the emission sectors directivity patterns model, on averaged signal values minus BS estimation obtained from D.



F : Final image compensated from beam pattern estimation(E) and BS estimation (D). some very slight artefacts are still visible at the limits between the transmission sectors

Figure 6-8 Example of a correction sequence of angular dependence. From EM300 backscatter data (A) and transmit sector extent (B), the average angular BS for each sector is calculated (C). A physical model is fitted to the entire angular range (D) followed by individual transmit sector beam patter models (E). The resulting corrected data are free from angular dependence on transmit beam patterns variations across the swath (F). From Augustin and Lurton, 2005. Data processed with SonarScope.

6.7.1 Software implementations

In *FMGT*, AVG curves are estimated on a line-by-line basis using the corrected backscatter, i.e. measurements where all possible radiometric and geometric correctors have been applied. The backscatter data are averaged into angular bins with the angle being derived from a particular data point's depth and across-track offset. These same backscatter points are retained for seafloor characterization analysis (ARA), but the AVG filtered data are used for mosaics. If the user has not applied a beam pattern correction during the backscatter correction stage, the AVG filter will remove the effect of the beam pattern if the beam pattern is roll-stabilized.

In *Sonarscope*, angle modulations brought in by both the echosounder (beam patterns) and the seafloor are processed together (Figure 6-8). Regarding the sonar influence, the directivity patterns are estimated from field data recorded on a flat seafloor, using a backscatter strength that is either already known (reference calibration area) or more often assumed (according to a generic model). The angle-dependent modulations caused by the arrays are then identified: first the correction applied by the manufacturer is removed (according to the *BSCorr.txt* configuration file in Kongsberg systems) and more accurate pattern shapes are fit to the data instead, optimizing the angle equalization. The seafloor BS in *SonarScope* can be processed and displayed in several ways. If a physical investigation of BS is planned, no attempt is done for smoothing out the angular backscatter. Conversely, for mosaicking, angular equalization is applied. The “global mean angular trend” is the only option available at present. The reference value associated to the equalized swath can be either the average BS value computed over the training zone; or a conventional angle value such as 45°. More sophisticated approaches can be applied however, taking benefit of the “toolbox” character of *SonarScope*. They imply that segmentation is first applied; then the angular backscatter is compensated for inside each segmented area, accounting for the average angular response computed locally.

MB Process has an empirical correction for the angular dependence that removes the mean angular trend using a sliding window along each line and then restores the mean value at 30° from within the sliding window. The length of the sliding window is chosen by the user. Future implementations will allow the user to select the reference angle and removal of the mean and standard deviation trends (Figure 6-7).

In *MB-System*, the subprogram *mbbackangle* calculates tables of angular response over the data. It has numerous options to allow customizing of the binning. The program *mbprocess* can use the angular response tables to remove the angular response relative to a reference angle, either symmetrically or asymmetrically.

In *PRISM*, angular dependence is handled similarly to transmission losses by normalizing the across-track backscatter signature. This assumes a homogeneous seafloor-backscatter signature and combines the values of transmission angle from the transducer and the incidence angle on the seafloor into a single correction.

In *SwathEd*, initial corrections followed the methods described in Beaudoin et al., (2002) with the addition of a rolling average correction that allowed for adaptation of the angular response correction to changing seafloors encountered along a survey line. More recent work provide for beam-pattern corrections for multi-ping and multi-sectors systems as those designed by Kongsberg.

6.8 Georeferencing / Slant range correction

Georeferencing is the step consisting in determining the horizontal (geographical) location of each data sample. This step will be different depending on the data type being processed.

6.8.1 Single value per beam

Data types consisting of one single backscatter value per beam (i.e. “Beam Intensity” in Kongsberg, “Bathy Intensity” in R2Sonic, “Beam magnitude” in Reson) can be directly associated with the horizontal location of the beam’s sounding point.

6.8.2 Half-Swath Time-Series

Data types consisting of a single time-series of samples on each side of the swath (i.e. “Sidescan” in Reson) can be georeferenced (in first approximation) using the same type of slant-range corrections as is commonly used for sidescan imagery. However the bathymetry data provided by each beam (sounding point coordinates) makes it possible to improve significantly on the basic slant-range correction procedure (applied in non-bathymetric side-scan sonars) by precisely locating the trace on the ground all along the swath (Beaudoin et al., 2002).

6.8.3 Beam Time-Series

Data types consisting in time-series of backscatter samples for each beam (i.e. “Seabed Image” in Kongsberg, “Snippets” in R2Sonic and Reson) are more challenging to georeference as the position of each sample must be located between the known beam footprint centroid positions.

One approach is to interpolate the bathymetry data between neighboring beams, from the detected sounding points (at the beam center) to all the time samples. Another approach consists in transforming these data to make them similar to half-swath time-series, taking into account the beam position and signal resolution and apply the corresponding georeferencing method in the previous section (i.e. slant-range correction). This method is straightforward for beam time-series that have been formed specifically as to create a continuous trace along the seafloor when concatenated. Beam time-series that have been formed specifically to cover the beam footprint may need some simple methodology to form a continuous trace (for example averaging samples between beams with overlapping footprint).

6.8.4 Amplitude/Angle Time-Series

A time-series of amplitudes and angles is the native output of phase-measuring bathymetric sidescan sonars (therefore applicable to Geoswath data).

Phase-measuring bathymetric sonars produce amplitude and angle measurements vs time (or equivalently slant range). Traditionally, relatively rudimentary forms of sidescan mosaic have been available that omit the bathymetry information with the exception of the nadir return, disregard refraction, remove the water column, place measurements across-track assuming a flat seafloor, and perform image blending of the resulting waterfall data, perhaps after first removing along-track artefacts. Since no data is omitted this method requires no consideration for flagged measurements or interpolation.

Designed for the R2Sonic MBES, the TruePix imaging geometry provides time-series of angles and amplitudes; however it is not the same as with PMBS. TruePix locates the peak return across the beams on port and starboard for every range, and accurately measures the angle to the peak return and reports the range, magnitude and angle of that point. This process is totally independent from the bottom detect, and is thus more robust than snippets, and coverage of the water column with a data volume a couple of magnitudes less than water column data.

More sophisticated approaches of this data type are possible; a recommended strategy is as follows:

1. Process bathymetry independently from backscatter by first flagging low SNR measurements and outliers, binning and averaging data in the across-track direction and generating a DTM. Care must be taken to ensure the binning and DTM creation process produces an artefact free surface such that estimates of local slope are not unduly biased.
2. Returning to the full (i.e. non-binned) but flagged amplitude data set, fully georeference and ray-trace each measurement.
3. From the angle of incidence, along-track and across track seafloor slopes at each measurement location, correct for the pulse-limited insonified area, calculating DTM slopes from points surrounding the measurement location.
4. Make other corrections (source level, beam pattern, gains, etc.) to obtain acoustic BS.
5. Assemble mosaic from these XYZ-dB values.

6.8.5 Binned amplitude/angle time-series

The result of binning and averaging a time-series of amplitudes and angles. Binning may be done in any of several ways, including across-track distance, angle or other dynamic methods. The binning process is generally advantageous only for bathymetry and it is generally preferable to NOT average amplitude values, reporting instead the amplitude value of the measurement closest to the bin centre; when done, averaging for amplitudes should always be RMS averaging of linear quantities, not of dB values. This is a common derivative data set of phase measuring bathymetric sidescans.

With phase-measuring bathymetric sidescan systems, the range and angle for each sample is known and the georeferencing of each sample is considerably simpler, however there are additional concerns regarding the angular information as it is unfiltered and thus noisy relative to the bathymetry information from traditional beam formed multibeam systems.

Here where angle measurements and their associated amplitudes have been binned and averaged the process should proceed as with non-binned data with care taken in correction for the insonified area. Calculation of the insonified area should reflect the method by which amplitude values are generated for each bin. For example, if the reported amplitude for the bin reflects the RMS amplitude of measurements contributing to the bin, the insonified area should ideally be calculated as the average insonified area from the individual measurements. Note that the insonified area in this case is not the full area of the bin; hence computing the mean insonified area ideally implies to calculate and sum the insonified areas for each point contributing to the bin. This information may have been lost in the binning process leaving only other less accurate methods.

6.8.6 Software implementations

In *FMGT*, “Single value per beam” and “Footprint time series” are supported and use the bathymetric solutions for each beam to assemble records at the correct location on the seafloor. Basic techniques are described in Beaudoin et al., (2002) and are recapped in the Appendix A-6.

MB Process uses the “single value per beam” data type and therefore simply geolocates the backscatter values using the bathymetry solutions for each beam.

MB-System geolocates each value using either the beam value or interpolation between beam values using a flat seafloor hypothesis.

PRISM has several different methods for geometric corrections such as slant-range and georeferencing which can be tailored by the user according to the data quality and availability. The simplest slant-range correction is to assume a flat seafloor and use the central beam altitude in a simple Pythagoras calculation. This is useful when the bathymetry is noisy, corrupt or not present. A true slant range correction is also possible using a bathymetry grid. An advantage of using a previously made bathymetry grid is that the data may have been cleaned. The georeferencing of swaths is done individually using the position and azimuth of the vehicle. As *PRISM* was designed originally for towed vehicles in the deep ocean such as GLORIA (Searle et al., 1990) and TOBI (Le Bas et al., 1995) the positional data was always of low resolution. Therefore attitude information was rarely used in refining the location of the central beam and hence the backscatter imagery. Production of mosaics in *PRISM* is often prone to small pixel gaps where pixels in the final mosaic are not filled by pixels from any specific swath but fall in between two pings. PRISM has two ways to fill these small gaps/individual pixels: along track beam spreading can be included to fill the gaps by replication, or by interpolation. It has been found that interpolation can give a smoothed and distorted texture to the imagery and thus the interpolation is given some "noise" scaled on the local variance. This hides the interpolation pixels and provides the user a better image for interpretation.

SonarScope processes both geometries “Single Value per beam” (straightforward) and “Footprint time series” (the time samples are located along tilted segments joining neighboring sounding points). The “Amplitude time series” is possible under a flat-seafloor hypothesis. Note that other geometries are possible for data analysis, e.g. “ping/beams” very convenient for a large number of applications.

In *SwathEd*, “Single value per beam”, “Footprint time series” and “Amplitude time series” are all supported and use the bathymetric solutions for each beam to assemble records at the correct location on the seafloor. Basic techniques are described in Beaudoin et al., (2002) and are recapped in the Appendix A-6.

6.9 Despeckling and anti-aliasing

Given the noisy nature of acoustic signals, it is usually desirable to de-speckle the data to improve the output imagery. This process can be applied before or after mosaicking and will usually consists in the application of a noise-reduction low-pass filter such as a median filter. Prior to mosaicking, the process can be applied in the across-track dimension (1D) or in the across-track versus along-track dimension (2D). After mosaicking, the process can be applied to the 2D mosaic organized in the Easting and Northing dimensions.

If the slant-range corrected imagery is of a much higher resolution than the mosaic map that it will be contributing to, it is advisable to down-sample the slant-range corrected imagery prior to mosaicking. For example, slant-range corrected imagery may be computed at 0.05 m resolution but the final map product will be prepared at 0.50 m resolution. A simple approach is to create an additional slant-range corrected set of line imagery at the desired resolution and to compute the mean signal BS of all contributing samples from the higher-resolution source imagery samples that fall within a particular bin in the down-sampled imagery.

6.9.1 Software implementations

The *UNH Geocoder* software and presumably its commercial implementations apply a selective 2-D median filter in the across-track and along-track direction to the slant-range corrected imagery prior to mosaicking. The default configuration allows for consideration of the swath before and after the current swath and for up to two samples in the across-track direction for a given sample, resulting in an asymmetric 3x5 filter window. The median of the 15 samples is then calculated. The sample at the centre of the filter is replaced by the median value if its level falls below the 37th percentile or above the 63rd percentile of the 15 sample set. *UNH Geocoder* implements the approach of gridding individual lines at the desired resolution as described above to solve the discrepancy between imagery resolution and final grid resolution.

MB Process computes the median value when gridding data.

In *MB-System*, the subprogram *mbfilter* can apply a number of different low pass and high pass filters across the data on a ping by beam basis. The mosaicking program *mbmosaic* can use either the original or filtered values.

In *PRISM*, imagery de-blurring can be done to remove far range horizontal beam spreading. A model point spread function (PSF) is created and then applied using a constrained iterative application. This restoration algorithm is known as the Jansson-van Cittert method (Jansson et al., 1970). The imagery can be de-speckled using a small 3 by 3 median filter but limited to pixels outside the two standard deviation threshold.

The *SonarScope* toolkit offers a predefined list of de-speckling filters that can be parameterized by the user. They can be applied on pre- or post-mosaic dataset – although better results are obtained after the mosaicking is completed. Besides the classical median filter, an adaptive Wiener filter (described in Lim (1990) equations 9.26, 9.27 and 9.29, p 548) provides particularly good results.

SwathEd supports de-speckling during the anti-aliasing operation by computing the median signal level instead of the mean. At this stage, the median filter only operates in the across-track direction. At a later processing stage (but prior to mosaicking), a 2D median filter can be applied to slant-range corrected imagery with user-configurable along-track and across-track filter widths. Contrary to the *UNH Geocoder* approach, the median filter always replaces the center sample with the median. *SwathEd* implements the approach of gridding individual lines at the desired resolution as described above to solve the discrepancy between imagery resolution and final grid resolution.

6.10 Grid size definition

The grid resolution used to construct the mosaic will be based on the data density of the points produced from the processing. Not all data collected will be used, as some will be ”bad picks” and removed as part of the QC process. The backscatter data density is affected by many parameters including footprint extent (beam and/or signal), backscatter sampling method, depth, swath width, vessel speed, slant range used during collection, sound velocity, ping rate and the amount of overlap between adjacent lines.

The backscatter sampling method will determine the maximum number of points per ping. For instance, if a ‘one value per beam’ approach is used then the maximum number of points in one ping will be limited to the number of beams formed by the system. In contrast, if a time series is constructed, either from a sidescan record or from the beam time series, then the maximum number of points in one ping will be determined by the swath width (i.e. maximum range) and sampling frequency. The swath width distance across-track will increase with water depth, so if there is a fixed number of points (as with one value per beam) then the data density will decrease with depth.

6.11 Gridding strategy and lines overlap

Several methods are possible for numerical determination of the value affected to each grid cell:

- Mean or weighted mean in linear units. This process is mathematically correct for taking the average in linear units; however this averaging is applied to intensity values, hence it is rather to be considered as an RMS summation. It is sensitive to outliers.
- Mean in logarithmic units: the averaging operation is applied to the dB-values. As a result the average of orders of magnitude is not equivalent to the true mean value in natural linear units. It is less sensitive to outliers than a “natural value” averaging.
- A Median or Mode determination can be applied equivalently to either natural of logarithmic values. It is insensitive to outliers.
- Minimum or Maximum value (Brightest return). This straightforward operation is not well-adapted to a statistically significant analysis, since it always finds outliers and skews results towards the upper end of distribution. It may however be useful for target detection or to create imagery that is similar to sidescan.

In case of overlapping lines, when grid cells have been insonified from various survey tracks, several strategies are possible:

- Purely and simply ignore the issue: each sample is taken into account in the grid cell calculation independently from its line of origin. As a consequence, data taken at different incidence angles will be averaged locally; also samples with inhomogeneous levels of quality (e.g. in terms of SNR) will be processed indistinctly.
- Avoid blending between adjacent lines. The values entering the cell calculations are taken from the closest line. A seam naturally occurs at equidistance from two parallel lines.
- Avoid blending, but by defining the frontier from considerations on the incident angle rather than across-track range. This is equivalent to taking the closest line for a flat horizontal seafloor, but is presumably more relevant if non-flat topography.
- Apply a controlled blending of the lines. This implies to apply a weighting operation to the samples, according to some criterion (of angle, or of SNR).

6.11.1 Software implementations

Geocoder implements a three-layer grid structure. Each cell in a layer holds a backscatter value and a source file index, up to three files can contribute to a single location. It is unsure how preference is given to lines when more than 3 contribute to a given cell. The final mosaic blends the three values. There are options to force one line to have preference over another.

MB Process grids the median value of each grid cell, the size of which is specified by the user.

In *MB-System*, the subprogram *mbmosaic* supports both highest priority per pixel and weighted linear means, with priorities/weights determined by beam angle, preferred look angle and preferred heading. Missing pixel values can be interpolated from surrounding pixels.

In *PRISM*, backscatter imagery is not calibrated and thus overlapping swaths cannot be averaged. Two options exist for overlapping data: a user-defined line delineating the cut from one swath to another, or a defined line calculated as an equidistant point from two navigation lines. This latter method works well for parallel lines on a standard survey protocol. If the lines are less ordered or have cross-lines *PRISM* will calculate the area's preferred survey direction and only use cross-line imagery if no other data exists. This prioritization allows all data to be used but without user intervention of adding or subtracting input files.

In *SonarScope*, the idea is to define a spatial sampling consistent with the physical resolution of the measurement. Hence the inter-ping along-track spacing is proposed as a default value for the grid step. For mosaicking one survey line, each grid cell is populated by averaged samples from one same ping and Tx sector. In the case where several different pings insonify the same cell, only the data from the latest one is considered. When two mosaicked lines overlap, normally no blending between the two lines is allowed (but this can be overridden by experienced users). To delineate the frontier between the two adjacent survey lines, *SonarScope* applies by default an angle-based priority criteria: high-grazing angle data are preferred in order to define the selected active line. This is justified by the better resolution and signal/noise of inner beams. This approach makes it possible to apply AVG compensation operations at a post-mosaic stage. Moreover a near-nadir sector mask can be configured and applied during the mosaicking, to cope with specular effect; this is especially efficient for widely overlapping lines.

By default, *SwathEd* does not blend solutions for mosaicking: each cell value can be traced back to a single source line. The intersection between survey lines is the equidistant seam by default, however, this can be changed by a user-specified weighting scheme. There is no feathering between the lines and there is no attempt to balance the levels between the survey lines. There are additional user options to restrict look direction such that imagery can be mosaicked with a common look direction to achieve consistency in shadow directions, etc.; this is based on the heading at the time of the ping.

6.12 Image enhancements: de-speckling, feathering and other post-gridding corrections

This category of processing is to be applied on the mosaic as a raster image, and not on pre-mosaicking ungridded data.

6.12.1 *Software implementations*

No image enhancements are possible in *FMGT*.

MB Process does not include post-gridding options at the moment.

In *MB-System*, the subprogram *mbmosaic* generates GMT (Generic Mapping Tool) grids (CF compliant NetCDF). The GMT software includes a number of tools for filtering and processing grids.

In *PRISM*, a two standard deviation contrast stretch on the final imagery is usually used though a logarithmic stretch is also favored as the Gaussian distribution of backscatter imagery is often skewed to the lower values.
SonarScope provides a range of statistical filters, making it possible, for example, to clean out outliers using the data value histogram.

The only post-processing of imagery data available in *SwathEd* is block mean filtering.

6.13 Signal level / Mosaic units

After all the correction and normalization operations are complete and the backscatter data has been mosaicked (gridded) and possibly filtered, the resulting display is usually a grayscale image. The default solution could be considered to map all backscatter values (in dB) to a standard 8-bit grayscale (i.e. 0 to 255).

However, no standard exists for the mapping of backscatter values in the grid to color scale values in an image. Users are free to choose a black-to-white or white-to-black grayscale, or even another color scale. They may as well “crop” the data to a certain threshold depending on the standard deviation (*FMGT* has the automatic option to crop to 3σ) or subjectively chose values so as to maximize contrast over the range of measured values. Users are also free to apply the map color scale to backscatter either in dB or in linear units; actually the use of a logarithmic color scale is often preferred.

Frequently-observed inconsistencies in the backscatter mapping to grayscale values suggest that care must be taken to annotate backscatter maps with a grayscale indication. When two backscatter maps are to be compared, identical grayscale ranges should be chosen to facilitate a direct visual comparison.

6.14 Recommendations for backscatter processing

This chapter has illustrated that there may be more than one way to process backscatter data, and therefore, it is incumbent on processors to meticulously annotate their data products with metadata featuring both the data source and the subsequent processing. While it is unpractical to embed all of the metadata into legends and diagrams presented alongside the data product itself, it is recommended to make them available - for example as a special section in appendix to the data. The main purpose of such metadata would be to inform data users about how it was collected and processed so that it can be properly interpreted either on its own or in conjunction with other data sets.

To fully understand and make good use of the results, it is imperative that data processors have a full understanding of the algorithms employed in their processing, especially when using 3rd-party processing packages. To this end, developers of backscatter post-processing packages are encouraged to document fully (e.g. in the form of example calculations) the steps taken in backscatter processing operations. As a simple solution to allow the data user to interpret the backscatter data on his own, these metadata can take the form of a text log file mentioning the corrections implemented at each stage of the processing, as recapitulated in Table 6.1.

In order to facilitate the comparison between datasets, some form of standard coding of the various processing stages applied to the data may need to be eventually agreed upon. A suggested example of such an annotation coding will be proposed in Chapter 7.

Table 6-1 Example of metadata information for each of the processing steps applied.

Recapitulation of the processing steps applied to backscatter data

- Decoding of raw measurement units:
    - System used
    - Frequency
    - Data type / datagram version
- Gains:
    - Was the source level compensated for? Value?
    - Was the directivity compensated for? Values?
    - Were the built-in static and time-varying gains compensated for? Values?
- Medium and target losses:
    - What models of transmission losses were applied?
    - Absorption? Constant, depth-dependent, frequency dependent?
    - Model of insonified area correction.
- Geometrical corrections:
    - How were the XYZ positions of the samples calculated?
    - How were the incidence angles of the samples calculated?
- Angular dependence compensation:
    - What is the data subset (sliding window size) used to correct a sample?
    - What is the reference angle (if any? interval?)
    - Was the standard deviation corrected as well?
- Filtering and gridding:
    - Any pre-mosaic data filtering?
    - Cell resolution?
    - How were the values blended in a one cell?
    - What strategy for line overlap?
    - Any post-mosaic image enhancement correction?
- Final mosaic:
    - Projection?
    - Color scale? (minimum and maximum value, color scale used)

Beyond metadata, we recommend some good practices for generating mosaics from the combination of data from systems operating at different frequencies or data acquired at different times. Data processors should, in general, not combine data collected from systems operating at different frequencies into a single backscatter data product because the seafloor response can vary greatly with operating frequency. Combining data in this way would blur the seafloor response from individual system and decrease the meaning of the resulting data product. It is possible, however, to represent data collected at different frequencies in a single mosaic when the individual channels are represented separately in false color. Mapping acoustic response to the seafloor at a given frequency to a color band within the image retains the seafloor response. Data processors may combine data collected from different sonar systems that operate at the same frequency. Special care should be taken to ensure the systems provide commensurate results in identical conditions over the same area, i.e. the systems have been correctly calibrated.

Seafloor acoustic response in some areas may evolve with time due to changes in the dominant seafloor scatters. These changes can occur over a few days when due to large storms, to a few weeks after the imprint of a storm relaxes, to as long as a season when biological growth dominates the signal. The effect of these and other drivers is location and seafloor-type dependent. Therefore, care must be taken in combining measurements made over long time scales into a single data product. In this situation, processors are encouraged to carefully and clearly annotate in the final product when the source data was collected. Insetting maps with polygons similar to those used on nautical charts to indicate bathymetric source data may provide a convenient annotation method.

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CHAPTER 7 SYNTHESIS AND CONCLUSIONS ON BACKSCATTER MEASUREMENTS BY SEAFLOOR-MAPPING SONARS

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7.1 Report synopsis

The "Backscatter measurements by seafloor-mapping sonars: Guidelines and Recommendations" report is the fruit of 2 years of discussion from the members of the Backscatter Working Group (BSWG - http://geohab.org/bswg/). The document includes mainly one introductory chapter, five technical chapters (2 to 6), and the present synthesis.

Chapter 2 – **Background and Fundamentals** - (Weber and Lurton, 2015) is a thorough review of the physical phenomena involved in acoustic backscatter from the seafloor. The chapter provides a basement for both general understanding of the Backscatter Strength (BS), its measurement principles and its actual implementation and operation (in sonar systems). It can be also a starting point for the interpretation of the recorded data.

Chapter 3 - **Seafloor backscatter user needs and expectations** - (Lucieer et al., 2015) has synthetized today’s requirements of backscatter users (in the scientific community). The chapter benefited from a specifically designed user's survey run in August 2014 which provided good intelligence on the issues pertinent to seafloor backscatter and of relevance to users, manufacturer and scientists alike.

Chapter 4 - **Backscatter measurement by bathymetric echosounders** - (Brown et al., 2015) is a presentation of the fundamentals aspects of sonar engineering applied to seafloor backscatter measurement. The chapter details the various operations of sonar transmission and reception, the constraints met by current systems, and the solutions practically proposed by the various constructors. The discussion focuses on calibration operations, broken down along the various components of today’s current systems.

Chapter 5 - **Acquisition: best practice guide** - (Rice et al., 2015) is devoted to the operation aspects of seafloor reflectivity mapping. It deals with the preliminary requirements for the sonar system preparation, depending of the final purpose of the survey (calibration, settings…); and discusses the survey strategy for an optimized acquisition of the backscatter.

Chapter 6 – **Processing backscatter data: from datagrams to angular responses and mosaics** - (Schimel et al. 2015) focuses on the post-processing of reflectivity data. It addresses all the stages from data conversion to generation of final mosaic, and includes issues such as the successive transformations from the acoustical pressure of the incoming echo to the backscatter strength characteristic of the local seafloor. A detailed list of operations is provided according to the current sonar systems and the most used software suites available today.

The flow from chapter to chapter was intended to be logical and follow a natural progression for anyone seeking to undertake research, development or applied work utilizing backscatter imagery.

7.2 Recommendations

7.2.1 *Recommendations to operators*

This first set of recommendations is aimed at operators in the wide sense: engineers, hydrographers, fleet managers, and the like.

Akin to what is currently admitted and applied for hydrographic surveys implying bathymetry calibration, specific **calibration operations** of backscatter measurement should be made part of the routine of MBES operations. Consequently, operators should be trained for this specific purpose.

For a given sonar system, the reflectivity calibration operations should be conducted first and foremost by the constructor (see Chap. 4 and 5). This of course includes **factory hardware calibration**, but also and importantly, those required upon commissioning at-sea trials, which should involve the sonar's owners and operators, together with the constructor.

All along the sonar's life and according to the frequency of at-sea operations, operators should undertake **regular calibration operations** (see Chap. 5). The built-in checks should be run as often as possible, as these are normally not time-consuming and may be critical in revealing unwanted changes in the system's characteristics. Most importantly, operators should conduct regular and consistent overall calibrations over **reference natural seafloor areas**. We recommend that a small number of reference areas be identified to fulfill requirements such as general morphology, geological facies, and accessibility, and characterized in details during preliminary surveys, to check their planarity, homogeneity and stability. The initial survey(s) should be undertaken using a calibrated system and completed with ground-truthing operations. Furthermore, **cross-calibration**, with calibrated sonar as a check (such as a SBES calibrated in the fisheries way), should be done as often as possible and calibration time series should be built along the life cycle of the sonar system.

The **setting of MBES systems for the specific purpose of backscatter measurements** deserves to be better understood and applied by sonar operators (See Chap. 5). Today's training is obviously more orientated to hydrographic survey, and so are the tools, pre-settings and automated modes provided by manufacturers. In order to satisfactorily acquire backscatter data, operators should master the stakes of a correct setting of the signal amplitude dynamics (avoid both low SNR and saturation) and optimize their sonar's setting. Optimization should be facilitated by the development of new tools by constructors (see recommendation to constructors below). The acquisition configuration should be kept as stable as possible, trying to avoid the automated modes; instead, the goal is to define (ideally) only one optimized mode adapted to most of the cruise conditions, and minimizing any changes in source level, pulse duration, receiver gains and directivity patterns.

We recommend that operator's preference should be for **system configurations as simple as possible** (single Tx sector, CW rather than FM…). We are aware that this does not fit the current trend for sonar system technology, evolving toward more and more sophistication and automation. Indeed such an evolution toward an increasing complexity is certainly desirable for hydrography-orientated bathymetry operations, but the current experience shows that it is quite detrimental to backscatter survey quality. So a trade-off is to be found with bathymetry quality requirements – waiting for manufacturers either to define differentiated modes for bathymetry and reflectivity, or even, in the longer term, to design and build new systems mainly specialized in backscatter (see §6.1) complementing today's MBES which are above all bathymetric systems. For today's systems, it must be emphasized and well understood that the same settings may not be optimal for both bathymetry and reflectivity; hence for a given survey a trade-off must be agreed upon by end-users and operators.

When backscatter mapping is the priority, the planning and design should be adapted specifically. The survey strategy will be similar to a topography survey, drawing a network of parallel tracks with a few cross-lines (see Chap. 5). The difference will be rather in the usable angle sector, and hence in the line spacing. The intermediate angle range has to be favored, avoiding both the extreme ends of swaths (with poorer SNR and degraded bathymetry accuracy and resolution) and the specular central part of the swath (especially at low frequencies). This latter point is of special importance: a homogeneous quality of backscatter measurement over a given area can be obtained only if the specular sector is replaced by oblique-angle insonification from another line; unfortunately this implies to run extra lines, at the expense of a loss in coverage efficiency. Ideally, the complete area should be covered only with beam angles between 20° and 60°. Moreover, if possible, some angular redundancy should be obtained in the area coverage – i.e. it is interesting that each point is insonified according to several different angles of incidence.

In case of multiple surveys on one same target area (e.g., for monitoring purposes) the highest similarity is to be imposed on the survey conditions; this includes heading directions, survey line patterns, and sonar settings. Every effort must be made to decrease the sensor-caused artificial variations between the successive surveys.

7.2.2 Recommendations to users

Acquisition & processing

Together with the operators, users of backscatter data must be aware that the acquisition of a good-quality data raises a number of specific constraints, generally more drastic than what is commonly admitted for bathymetry: it should be emphasized that ensuring good-quality bathymetry is a necessary but not sufficient condition for reliable backscatter mapping!

A number of compromises have to be made. As explained above, some ship time must be devoted to the system calibration. This may be limited to a short survey over a reference area, and is not very different from the requirements of a bathymetry calibration sequence – ideally it could even be done to conduct both calibrations over common reference areas (see Chap. 5). The coverage strategy of the surveyed area is normally more demanding than for just bathymetry, since the best quality data comes mainly from the intermediate oblique angle sector. This imposes that the survey line spacing is tight enough; even possibly the specular sector should be completely avoided. Needless to say, this should decrease the coverage efficiency and lead to increase the survey duration – and cost. The weather-dependent degradation of survey conditions must be taken seriously, since its impact on the backscatter data may become significant before becoming noticeable in the bathymetry quality.

The post-processing operations regarding data compensation are very important steps, which require time and effort from experienced operators (See Chap. 6). Despite all the efforts made today by software developers, the number and complexity of these operations remains high. Similarly to bathymetry, it is suggested to use one of the software suites available today and to have the operators trained to it, rather than trying to develop home-made tools. It is also recommended that the same sonar and software configurations are used along the years, minimizing the installation of new intermediate releases; this is especially important for teams concerned with long-term monitoring of the seafloor characteristics: ensuring a data comparability and consistence across a major change of sonar system or software is an issue of first importance. The BSWG is of course conscious that this recommendation does not serve the immediate commercial interest of HW and SW constructors; although the industry could possibly find its interest in proposing more simple, robust, and stable systems, prone to reach a wider public of customers.

Modeling & interpretation

Regarding seafloor **backscatter modeling**, the tools available today make it possible to explain and describe the various phenomena involved in the backscattering process and to predict the order of magnitude of the phenomena involved in idealized configurations (see Chap. 2). However, too much of the modeling effort has concentrated for years on the theoretical study of canonical problems, with insufficient regard to the practical interest of the resulting products. A recommendation for the future is to favor the modeling of real-world seafloor configurations; if this proves to be unpractical or unrealistic, an alternative way to go is to develop the building and populating of data libraries including backscatter measurement results (parametered in angle and frequency, and documented by ground-truthing observations), and made widely accessible.

The dedicated operations of **backscatter data interpretation** have been little addressed by the BSWG (see Chap. 3) – although a number of fundamental and useful elements for addressing them are given along the document. As a corollary to the above discussion about modeling, it should be well understood that no model exists today able to give, from an inversion process of backscatter measured as a function of angle and possibly frequency, a set of geological or biological parameters accurate enough to satisfy the expectations of geoscientists or biologists at a level comparable to the one they can reach by direct observation and sampling. So our recommendation is rather to complete backscatter measurements by ground-truthing as often as possible, and to build data libraries connecting the acoustical data and the in-situ observation and sampling operations.

Causes of uncertainty in sonar seafloor-mapping are many; the backscatter physical phenomena are very complex; and the modeling is designed for idealized canonical configurations. Hence it is of prime importance for backscatter users, whatever their field of application, to stay aware of the sonar backscatter data limitations and uncertainties, and not to over-interpret them.

7.2.3 Recommendation to constructors

Before addressing possible future new sonar instruments dedicated to backscatter measurements (see §7.3), a number of recommendations can be expressed regarding the improvement of functionalities of current systems.

These recommendations to sonar constructors can be summarized under two categories:

- Design and implement dedicated backscatter calibration and measurement tools;
- Reduce the hardware-driven uncertainties in backscatter measurements

The report has clearly and emphatically shown the importance of backscatter calibration (Chap. 4 and 5). While the final responsibility for a proper calibration is on the operators, the constructors can certainly improve a lot the current situation of existing systems and of their future evolutions.

Factory calibration of individual systems is supposed to be a standard procedure in the sonar industry today. However, not all manufacturers do provide details of the associated procedures and their results. It is desirable that calibration procedures are applied at several steps in the manufacturing process: transducers and electronic modules should be qualified in factory, as individual elements (in frequency response, angular directivity, linearity with level…) and the results be recorded and made available to the customer. The overall response of the instrument should also be checked in factory conditions, when this is practically feasible (for instance, very-high frequency systems in test tank, over a reference target). Finally some sort of final calibration should be conducted once the sonar system has been installed onboard, as a part of the sea-acceptance test operations: presumably survey of reference areas should be the best practical solution.

A general effort of information toward customers is to be made by the constructors. For one given model of sonar, detailed information should be given about the nominal characteristics (averaged, while realistic) of the system implied in the backscatter measurement, since this knowledge is paramount all along the acquisition and processing stages (See Chap. 3 to 6). This generic information should be completed by the system's individual data: the qualification measurement results should be systematically provided to customers. Moreover documentation about system calibration operations should be incorporated inside the User's Guide and Operator's Manual, regarding the checking of individual modules as well at the overall calibration of the system.

While the above recommendations do not require material modifications of existing systems, a second category of recommendations concerns new functionalities to be implemented on existing systems without modifying their general structure.

The self-calibration of individual modular elements of a sonar system (transducers, power amplification, receiver input and filters) should be operated using a number of built-in functionalities. A number of them already exist: automated impedance measurements of transducers in Kongsberg MBES, transfer function checking using a calibrated voltage in Reson Seabat… It is left to the constructors to imagine the best solutions, the purpose being to provide the sonar operator with some simple functionalities, easy to run and reliable, and giving in a few minutes a complete check-up of the sonar chain in terms of backscatter measurement. The results of these operations should be accounted for in the settings of the sonar, so that the system can be "self-calibrated" as well as possible.

When an overall calibration is possible (e.g. over a well-known reference area, or by cross-comparison with another calibrated system), one should be able to input the calibration results inside the system, so that the real-time results of the survey come from a calibrated sensor.

Most seafloor-mapping sonars today propose automated "modes" aimed at optimizing the system setting according to the local conditions, and to facilitate the tasks of surveyors. These adaptive modes are primarily designed for bathymetry applications. This makes perfect sense in a historical perspective; however with today's evolution of the users' expectations, different new settings could be proposed. Indeed **specific modes aimed at backscatter** should be imagined: minimizing the number of sectors and frequencies, favoring a smooth angular response and longer pulse durations, avoiding FM pulses… For today's systems based on a modular architecture of all-digital signal processing, such new functionalities should not cause too dramatic changes in the current models.

Various issues are still pending, e.g.: which control can be applied by users to be sure that all the processing operations are correctly compensated for inside the system; which parts or functions of a given system are the most prone to induce changes in the recorded levels, and which ones are definitely stable; and up to which point the external calibration procedures are able to compensate for variations of the system response.

Developers of processing software may be in a closer relationship to users than the hardware constructors, and better aware of users' expectations. Hence a feedback from the SW companies toward sonar constructors should help to improve the data processing applied inside the sonar systems. It is our feeling that all the communities would benefit from a two-way exchange between hardware and software constructors.

Table 7-1 Summary of the main recommendations to operators, users and constructors.

Recommendations	Operators	Users	Constructors
Specific training on backscatter theory and data acquisition	✓	✓	✓
Factory calibration of MBES			✓
On commissioning calibration	✓		✓
Built-in check	✓	✓	
Field calibration over test area – including ground truthing	✓	✓	
Keep acquisition configuration stable	✓		
Keep simple system configuration	✓	✓	
Prioritize survey design for BS acquisition	✓	✓	
Acquire good concomitant bathymetry	✓	✓	
Use available software suites	✓	✓	
Develop a data library of BS		✓	
Develop modeling		✓	
Keep limitation and uncertainties in mind	✓	✓	✓
Design and implement dedicated backscatter calibration and measurement tools			✓
Reduce the hardware-driven uncertainties in backscatter measurements			✓
Develop user manual			✓
Provide system characteristic			✓

7.3 *Future perspective*

This document and the work of the BSWG have brought to light a number of issues pertinent to the seafloor backscatter reflectivity at large. Those issues are essentially two-fold:

1. Issues related to **data acquisition and processing**, thus associated with development of hardware, improvement of software and post-processing procedures and methodologies. These issues are complex, intrinsically linked with the theory of marine acoustics, electronics and environmental sciences.
2. Issues associated with **the meaning and the use of the information** generated by backscatter-related surveys and studies. With that comes a need to better inform what is done with the data and to push for the holy-grail of backscatter research, which arguably would be the automated quantification of the physical backscatterers in the water column and on the seafloor, in a way linkable to the observables expected by the various user's communities.

There is indeed a plethora of suggestions that can be made as to how these two overarching issues should be addressed, but attempting to make an exhaustive list is deemed to failure. Nevertheless, and building on the experience of the BSWG, we provide below some ideas that may provide a means to initiate such a list.

7.3.1 Issues related to data acquisition and processing

Indeed, further **dedicated studies on backscatter** theory and measurement will and should continue, and would undoubtedly require a mix of modeling and ground-truthing. Of note in the previous chapters (especially Chap.2 and 6) were the issues of footprint modeling, the geometrical description of the insonification, and the impact of the water column absorption upon the recorded levels. While the issue of absorption by the ideal seawater has already generated an abundant literature of its own, much remains to be done regarding the accidental causes of absorption (mainly air bubbles caused by weather conditions and/or platform hydrodynamics).

Arguably, one of the most often raised issues in this volume has been the need for calibration. Whilst the reader is encouraged to go back to the relevant chapters (Chap. 4 and 5) to devise an appropriate strategy on calibration, there is most likely a need to improve the formal definition of calibration procedures under their various forms, with emphasis on cross-calibration methods, and definition and use of reference areas fulfilling appropriate criteria.

Could these requirements lead – on a longer term - toward the **development of new sonar systems** specialized in seafloor backscatter measurement? We emphasized in various places of this report that optimization of MBES may be different for bathymetry and for reflectivity measurement purposes. So it is legitimate to wonder if MBES could be set differently according to their current application, and even if the design of specialized sonars for seafloor reflectivity could make sense.

In the first place, future MBES designed for BS should be structured more simply. The multiplication of Tx sectors with individual directivity patterns and pulse frequencies proves to be counterproductive (backscatter-wise) because of the inherently resulting increase of complexity which is never perfectly compensated for in post-processing. Also the system settings should be kept as stable as possible along a survey, which is in conflict with the use of automated modes making possible short-term variations of the sonar settings.

Specific BS functionalities could be proposed, based on a bathymetry-orientated structure (see §7.2.3). More radically, it could be envisioned to follow what is done in space-borne radar, and design specific sonar systems aimed at reflectivity, sacrificing the resolution for an averaged and reliable measure of backscatter. Some drastic structure simplifications (a single Tx sector, with simplified directivity patterns and signal design) could be compensated by innovative functionalities, such as multiple distant frequencies operated simultaneously, or swaths steerable at several azimuth angles. These various functionalities exist in satellite-borne scatterometers, e.g. for applications to the wind direction measured from the sea-surface backscatter.

7.3.2 Issues associated with information sharing

The use of, and uptake of backscatter-related products in applied research or engineering sector still remains extremely limited today. The possibility to acquire BS concomitantly to bathymetry data during MBES operation is usually known by operators but rarely by managers and planners, let alone the benefits that such data could provide to any marine business. One of the reasons for undertaking this work was in part to **promote the use of backscatter** by improving the knowledge of the methods and tools related to backscatter data, and providing information on the potential benefits that backscatter-focused research could provide to environmental, exploration, engineering and hydrographic work.

The constitution of the BSWG provides one relative measure of the community's interest on Backscatter (Figure 7-1). Clearly, the dominant sector with an interest in this topic comes from the public sector, with 66% of the members of the BSWG coming from Government organizations and universities. The industry sector here being only represented by software developers and system manufacturers (11% each), and survey companies representing only 11%. Likewise the dominance of the US on the subject is conspicuous (Figure 7-1).

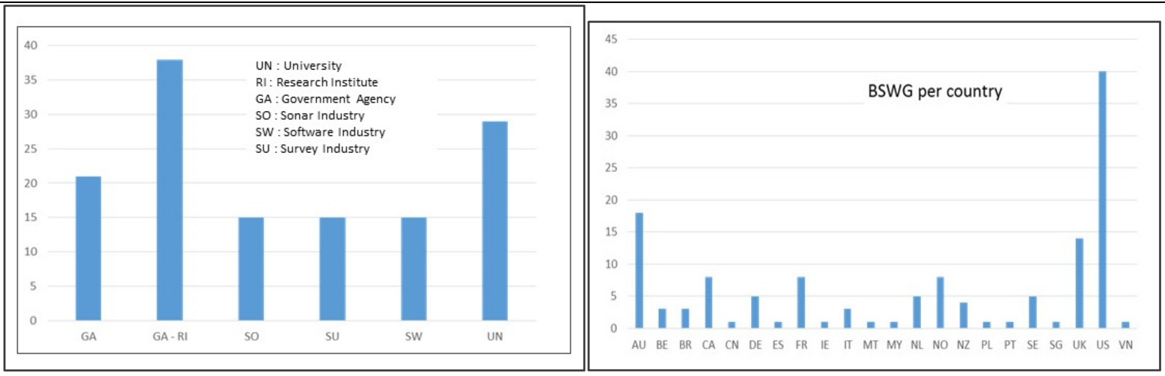

Figure 7-1 The BSWG per sector (left) and by country (right).

We can see four ways of publicizing the use of backscatter imagery in the community, besides encouraging fundamental and applied research projects either on the backscatter data itself or on the derivative it provides.

First, there is a need for **increasing the exchange of data** resulting from well-controlled acquisition experiments, thus fulfilling the requirements proposed in this document, including the need to develop proper ground-truthing protocols.

Second, the development of **a nomenclature of processing levels of backscatter**, as suggested in Chapter 6.14, may provide a means to better compare final processed products from various origins. The processing and post-processing of backscatter data is complex, and it can potentially impact strongly on the final data product, so that knowledge of the processing sequence is critical for the interpreters for them to make valid and meaningful decision. A normalized metadata format featuring the processed levels of backscatter, and designed to accompany the data at all level of the acquisition-processing-modeling sequence, would need to be formally defined and validated by a larger group of people than the authors of the documents. The involvement of the entire BSWG (133 people presently) could potentially result in a positive and acceptable outcome. A suggestion for such a nomenclature is proposed in Table 7-2.

Third, the idea of **a reference data library** was raised in Chapter 3. Such a library - or atlas - widely accessible and conveniently updatable would include a series of typical or unique acoustic facies, with a limited amount of comment. Similar libraries exist for e.g., seismic reflection profiles. Their aim is to facilitate interpretation of imagery mosaics. This initiative has recently been developed via the GeoHab community through an art-like atlas of reflectivity images. The Visual Soundings initiative has a vision for an art book of acoustic seabed imagery (See http://visualsoundings.blogspot.co.nz/). This work in progress could be used as a starting point. This is no mean feat, as the atlas should be encompassing, robustly validated, edited and published, probably online. Arguably, such an atlas should make use of the previous recommendation, i.e. include some metadata on history of acquisition/processing.

Fourth is the need for **standardization of operations**. The purpose is to homogenize as far as possible a number of operations, making it possible to compare directly data from various systems, and to ensure compatibility between the results obtained by different processing software suites.

Table 7-2 Suggestion of a nomenclature of processing levels applied to backscatter data.

I. Data Acquisition	**A**	Raw or TVG applied	A0	Echo level, raw – no TVG (Time Varying Gain)
			A1	Target Strength, manufacturer's TVG applied for TL
			A2	BS, manufacturer's TVG applied for TL and FE
			A3	Customized RVG applied for TL and FE / Other
			A4	Modeled TL and coefficient parameters.
			A5	Other
	B	Array directivity compensation	B0	No directivity compensation
			B1	Compensation from a directivity pattern model (manufacturer's)
			B2	Equalization from a statistical average modulation (user's)
			B3	Customized model for directivity pattern (fitted to statistics)
			B4	Other
	C	Seafloor Angular compensation	C0	No BSAD compensation
			C1	BSAD Compensation from theoretical model (Lambert's…)
			C2	Compensation from model with adaptive parameters (e.g. KM's specular)
			C3	Customized BSAD (model fitted to statistics)
			C4	Other
	D	Level of reference	D0	No level reference considered
			D1	Level reference from the manufacturer (nominal value)
			D2	Relative reference level from calibration operation
			D3	Absolute reference Level from calibration operation
			D4	Other
	E	Seafloor Incident angle	E0	Flat seafloor, no refraction by SVP
			E1	Flat seafloor, SVP refraction
			E2	Local across-track slope (derived from one ping), no SVP refraction
			E3	Local across-track slope (derived from one ping), SVP refraction
			E4	Local slope (from bathymetry, incl. along-track slope), no SVP refraction
			E5	Local slope (from bathymetry, incl. along-track slope), SVP refraction
			E6	Other
	F	Resolution in time (or range)	F0	Fundamental raw signal resolution (at basic sampling frequency)
			F1	Undersampled time signal
			F2	Filtered time signal
			F3	Customized resolution (range dependent…)
			F4	Other
II. Map Generation	**G**	Geo-referencing	G0	No geo-reference
			G1	Geographic reference (lat, long)
			G2	Projected reference (Mercator, UTM …)
			G3	Other
	H	Mosaicking	H0	Order (1st, last, top, bottom,…)
			H1	Quality (angle, no specular, etc…)
			H2	Statistical (average, median, …)
			H3	Other
	I	Interpolation	I0	No interpolation
			I1	Over NaN only
			I2	Averaging/smoothing
			I3	Other
	J	Representation	J0	Grey level 0-255
			J1	RGB
			J2	CMYK
			J3	dB value
			J4	Other
	H	Reference angle	H0	No reference angle
			H1	Vertical incidence
			H2	Fix angle at 45 degrees
			H3	Other

7.4 General conclusion

Finally the BSWG was able to complete his task just in time; the self-imposed two-year duration of the project (from GeoHab-2013 to GeoHab-2015) was respected. This duration was not an easy choice: the project had to be long enough for addressing such complex topics at a level of details making the result useful, requesting a significant workload from a chairing group and a team of contributors who were all part-time volunteers, while avoiding their saturation.

The collaborative contribution from the six chapter coordinators (senior author of their chapter), thirteen co-authors, along with two editors and one sub-editor, all with various professional backgrounds and specialties, hopefully provide some guarantee of quality and objectivity to the document, which was also reviewed in part or in full by some of the industrials who contributed to the project. This thorough process, however, still needs a return from the whole BSWG. Hence we encourage feedbacks and comments to be sent to us. This may at a later stage warrant a second edition, although this is yet to be discussed and agreed upon.

Although the goal of having a final report completed and distributed by May 2015 has indeed been reached, the BSWG project should presumably not stop at this stage.

Obviously it is desirable that updates are provided to the current document; an obvious reason for this is the constant evolution of the technical characteristics of the sonar systems and the processing software suites. It is hence useful to mandate a specific team in charge of this task – i.e. releasing new issues of this document on typically a yearly basis.

Moreover, the perimeter of the investigations by the BSWG has been limited to the seafloor echoes processing, following the sonar data flow downstream from signal transmission to extraction of a referenced backscattering strength. This self-limitation may be felt as frustrating by a number of the report’s readers. Hence two major possible extensions of the present project have already been identified:

- The **final stages of the data post-processing**: segmentation of the reflectivity maps into homogeneous acoustical facies, extraction of relevant descriptors, classification of the responses along seafloor archetypes, extraction of objective characteristics… Note that the BSWG has already browsed many of the issues underlying these final operations.
- The use of seafloor-mapping sonar **data from the water column**. This has not been undertaken yet for several reasons, mainly (1) the very rapid evolution of the users’ needs and interest for this field of application, and the corresponding offer by constructors, resulting in a situation certainly not stabilized today and hardly prone to a state-of-the-art operation; (2) the existence of a similar ICES project conducted in the field of fisheries sonar, and (3) the will of deliberately restricting the BSWG tasks to a practically manageable perimeter

Most importantly, in any case, the success of this document will only be judged by the uptake of the recommendations by all (stakeholders, manufacturers, software developers, and end-users, including scientists) and a resulting improvement of the protocols, methodologies and overall consistency in the use of the backscatter. This will take time, but will most definitely require the members of the BSWG first and foremost to endorse the recommendation and implement them. Since this is through the GeoHab annual meetings that we have been able to gather the BSWG and the small group of highly motivated and skilled people who actually wrote the document, it is most logically through GeoHab that the document should be distributed and advertised first.

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APPENDIX 1 - ACRONYMS

Acronym	Full Spelling
ADC	Analog to Digital Converter
AGC	Automatic Gain Control
ARA	Angular Range Analysis
AVG	Angle Varying Gain
BS	Backscatter Strength
BSAD	Backscatter Angular Dependence
BSWG	Backscatter Working Group
CCOM	Center for Coastal & Ocean Mapping
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Conductivity, Temperature, Depth profile
CYMK	Cyan Yellow Magenta Key (black)
CW	Continuous Wave signal
DR or D_R	Receiver directivity pattern
DT or D_T	Transmitter Directivity Pattern
DTM	Digital Terrain Model
EL	Echo Level
FE	Footprint Extent
FFT	Fast Fourier Transform
FM	Frequency Modulated signal
GR	Receiver Gain
GLCM	Gray-Level co-occurrence matrices
HF	High Frequency
HV	High Voltage (driving a Tx transducer)
IL	Intensity Level
KM	Kongsberg Maritime
LF	Low Frequency
MBES	Multibeam Echosounder
MTL	Medium and Target Level
NIWA	National Institute of Water and Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
PDBS	Phase Difference Bathymetry Sonar
PDF	Probability Density Function

Acronym	Full Spelling
PMBS	Phase Measuring Bathymetry Systems
RDF	Raw Data Files
RGB	Red Green Blue
RL	Received Level
ROI	Region of Interest
RX or Rx	Receiving transducer or array
RxBP	Receive Beam Pattern
SBES	Single Beam EchoSounder
SAR	Synthetic Aperture Radar
SH	Receiver sensitivity
SIS	Kongsberg Maritime Seafloor Information System
SL	Source Level
SNR	Signal to Noise Ratio
SPL	Sound Pressure Level
SSP	Sound Speed Profile
SSS	Side Scan Sonar
SVP	Sound Velocity Profile
TL	Transmission Loss
TRU	Transmission/Reception Unit
TS	Target Strength
TVG	Time Varying Gain
TX or Tx	Transmitting transducer or array
TxBP	Transmit Beam Pattern
UNH	University of New Hampshire
UTM	Universal Transverse Mercator coordinate system
WCD	Water Column Data
TxBP	Transmit Beam Pattern

APPENDIX 2 – GLOSSARY

Term	Definition
*.all (a.k.a. 'dot all')	Raw data files generated by Kongsberg systems
Absorption (Absorption loss)	Refers to the wave energy lost as it is absorbed and dissipated by seawater through pure water viscosity or chemical reactions. The absorption coefficient mainly depends on frequency, temperature, salinity and hydrostatic pressure (e.g. Francois-Garrison model), its effect can be increased by the presence of suspended matter (gas bubbles, mineral particles, plankton...). Often the most limiting factor in acoustic propagation, limiting reachable range at high frequencies.
Absorption Profile	Dependence of the absorption coefficient with depth. Normally obtained from the salinity and temperature measured (or estimated) as a function of depth and computed for a given frequency.
Acoustic Facies	The spatial organisation of seafloor patches with common acoustic responses and the measurable characteristics of this response. Most often simply represented by the post-processed backscatter data.
Active sonar	An acoustical transmission-reception system dedicated to the detection and measurements of echoes of signals transmitted for this purpose and returned from targets.
Amplitude Shading	see Array Shading
Angle Varying Gain (AVG)	Amplitude correction device, whose purpose is to equalize the physical processes depending on incidence angle.
Angular Curve(s)	see Backscatter Angular Dependence
Angular Range Analysis (ARA)	An analysis of the backscatter level variation versus angle, where several regimes are defined and described by a limited number of parameters usable as descriptors for classification and characterization.
Array Shading	A fundamental array processing method, in which the individual sensors are weighted (decreasing to the array's ends) to minimize the unwanted contributions from sidelobes
Automatic Gain Control (AGC)	AGC is the commonest scaling type used in digital data processing. At every instant, an average amplitude is computed within a window of fixed length, for comparison to a reference level in order to adjust the gain applied for the current sample.
Averaging	Averaging (taking the mean of a series of numerical values of a same quantity) is the simplest and the most widely used method in signal processing. Its main purpose is to decrease the level of random fluctuations present in a measurement result; it is an obvious way to improve the Signal to Noise Ratio.

Backscatter	Generation of a non-coherent echo of the acoustic wave in the same direction as the angle of incidence, used in general to mean back to the sonar transducer. This phenomenon, caused by a rough target is different from coherent reflection (prevalent on a smooth surface).
Backscatter Angular Dependence	The variation of Backscatter Strength according to angle. Its typical shape is a maximum value around normal incidence (specular peak); a quasi-constant value at intermediate oblique angles; and a faster decrease at grazing angles. This angular dependence is considered as a robust classifying feature.
Backscatter Strength	The quantity expressing the capability of a unit surface (or volume) element (1m² or $1m^3$) of an extended target (seafloor, water column) to backscatter sound waves. It is defined as the intensity ratio between the incident wave (plane) and the backscattered wave (spherical) considered at unit distance (1 m) from the target. Combined with the local footprint, the Backscatter Strength provides the Target Strength.
Bathy Intensity	(R2Sonic Systems) A single-value of backscatter intensity per beam. Currently representing the average signal level over the beam footprint.
Beam Intensity	(Kongsberg Systems) Backscatter data produced by Kongsberg systems; represents the average signal level over a given beam's footprint.
Beam Magnitude	(Reson systems) Backscatter data produced by Reson systems in datagrams 7006 and 7027; the 32-bit float value is the magnitude of the beam time series at the sample closest to the bottom detection location.
Beam Pattern	see Directivity Function
Beam Time Series	see Snippets
Beamforming	Formation of a transmitting or receiving beam of an acoustic signal by phase (or time) shifting the signal from a series of transmitters or receivers; beamforming allows listening or transmitting preferentially along one direction, or a set of directions, without physically tilting the array; this is the fundamental working principle of multibeam echosounders.
Beamwidth / Beam aperture	The beamwidth, or beam aperture, is the measure of the angle covered by a directivity lobe, normally considered at a -3 dB fall-off from its maximal value. The effective beamwidth is the aperture of an ideal beam constant level inside the main lobe, zero outside) integrating the same power amount as the actual directivity pattern.
Bottom Detection	Signal processing operation by which the physical seafloor is detected from the echo received inside a beam.
Bragg Wavenumber	The wavenumber corresponding to in-phase scattered contributions generated by a grating with spacing 'd' at incidence angle Θ. The Bragg wavenumber $k=2p/\lambda$ is defined by $2.d.\sin\Theta = n.\lambda$.

BSCorr File	(Kongsberg systems) Dedicated files including the parameters of a model describing the directivity patterns of the Tx sectors; these data are used to compensate for the data recorded and equalize the resulting BS measurement. Adjustment of these parameters is a delicate matter, normally conducted at commissioning during Sea Acceptance Tests.
Calibration	The process by which an instrument is checked and adjusted by comparison with a standard, so that it is deemed as performing satisfactorily and is capable of collecting data within some reasonable expectations (usually in terms of measurement accuracy, according to user needs and/or to meet agreed upon specifications), in a repeatable fashion, and coherently with some verifiable reference. Calibration is termed as "absolute" when it is performed relatively to an objective reference; and "relative" when it is not and makes possible only comparative measurements.
CalTone	(Reson systems) A built-in test consisting of the transmission of a known voltage through the Rx channels, in order to estimate the individual responses of the electronics stages.
Classification	The process where segments are grouped into homogeneous subsets of objects. There are two overarching types of classification: unsupervised and supervised. Unsupervised (or objective) classification is where the elements of a map are assembled then assigned a meaningful class. The classes are unknown but differentiated by the algorithm. The process is repeatable and independent of user selection. Supervised (subjective) classification is when the classes are known or defined prior to segmentation. The classification algorithm is trained on a ground-truthed subset where the classes are set *a priori* by the user. Supervised classifications are highly dependent on the training dataset (size, representativeness, and information content) defining the existing classes. Classification usually follows segmentation.
Confusion surface / volume	The elementary surface (or volume) intercepted by a sonar at a given instant, practically limited by the directivity pattern and the signal duration. All the point targets located inside the confusion surface/volume contribute together to the echo, and cannot be differentiated.
Continuous Wave (CW)	The simplest and most common type of sonar signal used in echosounders: a sine wave at a nominal carrier frequency, gated by a duration T (defining its range resolution and frequency bandwidth).
Critical angle/angle of intromission	At the interface between two media characterized by different sound speed values c_1 and c_2, the wave propagation is modified according to Snell's law. If $c_2>c_1$, the transmission inside the second medium is possible only for incident angles smaller than a limit defined as the critical angle, and given by $\arcsin(c_1/c_2)$: at more grazing angles, a total reflection of the wave occurs, the reflection coefficient goes to unity. Conversely, if $c_2<c_1$, at a given angle the reflection coefficient may tend to zero - all the wave energy passes into the second medium; this configuration is only met for very soft seafloors.

Datagram	A self-contained, independent entity of data carrying information from the source to the destination computer. MBES datagrams include measured bathymetry and backscatter, time, vessel attitude, position, etc.
Depression angle / Elevation angle	Angle (of a sound ray path, in the sonar context) measured respectively below (depression) and above (elevation) the horizontal.
Directivity Function	The angular pattern describing the spatial spreading of the acoustical intensity radiated by a sound source, or received by a hydrophone. Expressed in dB as 10log of the intensity normalized by its maximum value (most often along the axis of the main lobe).
Directivity Pattern	see Directivity Function
Discrete Target (*also* Point Target)	A target with dimensions small enough for being insonified at once inside the sonar resolution cell (delimited by the beamwidth and/or the pulse duration). Most often, small fishes or gas bubbles can be considered as point targets.
Divergence	When it propagates inside an unlimited medium, the field radiated by a sound source spreads on a wider and wider surface; in case of a "point" source with homogeneous radiation, this surface is a sphere. This spreading is the geometrical divergence phenomenon, causing a decrease of the local sound intensity with range: the transmitted power being spread over an increasing surface, its intensity (the local flux of power) diminishes accordingly. In a perfect homogeneous medium, the local intensity decreases as the inverse range squared - hence the famous "20logR" transmission loss.
Dolph-Chebychev window	A very popular law for array shading, fixing the level of all sidelobes at a given level and minimizing the width of the main lobe.
Dynamic focusing	Compensation of the incoming wave sphericity, by delaying the individual sensors accordingly. In reception, the focusing point can be changed dynamically according to the range to the target (proportional to time).
Dynamic Range	The ratio (in dB) of the largest to the smallest intensity of sound that can be reliably transmitted or reproduced by a particular system.
Echo Level (*EL*)	The intensity level of the acoustic wave backscattered and received by the sonar system; equal to the source level (*SL*) minus 2x the transmission loss (*TL*) plus the target strength (*TS*).
Evanescent Wave	Wave with an amplitude decaying exponentially.
Extended Target - Extended surface/volume target	Targets geometrically delimited by the sonar characteristics (beam width, signal duration) rather than by their own dimensions. The seabed is an example of an extended surface target. A plankton layer or a large fish school are extended volume targets.

Far-field (of tranducer/projector)	For a given array or transducer, the regime in which all the points of the array contribute with a negligible phase difference, maximizing the resulting level.
Footprint Extent	see Spatial Resolution or Confusion Surface/Volume
Footprint time series	see Snippets
Frequency Modulation (FM)	An active sonar signal, based on a sine wave whose frequency varies (often linearly) with time, possibly over a long duration. A FM signal (or "chirp") is not used directly in reception, it has to be first shortened through the operation of "pulse compression".
Gray Level Co-occurrence Matrices (GLCM)	A statistical method of examining texture that considers the spatial relationship of pixels, also known as the gray-level spatial dependence matrix. The GLCM functions characterize the texture of an image by calculating how often pairs of pixel with specific values and in a specified spatial relationship occur in an image, creating a GLCM, and then extracting statistical measures from this matrix.
Grazing angle	The angle of the sound ray path with the seafloor, defined by a locally tangent plane. For a ray parallel to a flat seafloor, grazing angle is 0°; orthogonal to the seafloor, grazing angle is 90°.
Ground-truthing	A model validation process done through using physical, biological samples to attach a degree of confidence to the end product. This generally requires physical sampling (sediment cores or grabs) or camera / video techniques. Sediment grains size and density, as well as seafloor roughness often require separate analysis prior to ground-truthing.
Habitat	The combination of environmental and biological conditions that promote occupancy by a given group of seabed species.
Habitat mapping	A process that aims to represent different types of habitat geographically, by delineating them spatially in distinct combinations of physical, chemical and biological conditions.
Hydrophone	An underwater electro-acoustical transducer used in reception, possibly over a wide frequency bandwidth. It is characterized by its sensitivity (in dB re 1 V / 1 µPa), its directivity and its frequency response. The equivalent in the air is the microphone.
Impedance / Acoustic impedance	The acoustical quantity relating the sound pressure with the vibration of molecules of a particular acoustic medium at a given frequency. Computed as the product of the medium density and sound velocity. The impedance contrast is the ratio between acoustical impedances of two propagation media; it is a good indicator of the reflection coefficient at normal incidence.
Incident angle/Incidence angle	The angle of the sound ray path with the perpendicular to the target interface at the impact point. For a flat horizontal seafloor, it is the angle with the vertical; horizontal incidence is 90° and vertical incidence (i.e. nadir) is 0°.

Incident signal	The signal at its arrival onto the target or at the sonar's receiving array.
Interface backscatter / Surface backscatter	The component of seafloor backscatter generated by the boundary between the water and the underlying seafloor. It depends on both the interface roughness and the impedance contrast.
Interface roughness	The degree of small relief corrugating the seafloor interface. For sonar backscatter, the relevant roughness is at the scale of the acoustical wavelength.
Intromission angle	See Critical angle
Lambert law	Classical law in optics, describing the angle-dependence of the light scattered intensity as proportional to the squared cosine of the incident angle.
Level Calibration / Calibrated data	The measurement of a target strength (or backscatter strength) implies to have available the physical values of the incident and the backscattered signals. Hence calibration operations are needed in order to retrieve the exact levels of the signal level transmitted by the sonar and the sensitivity at reception. Calibrated backscatter data account for these preliminary operations.
Lommel-Seeliger law	Classical law in optics, describing the angle-dependence of the light scattered intensity as proportional to the cosine of the incident angle.
Long-pulse Regime	Regime of target insonification in which the signal is long enough for covering the complete beam footprint area.
Mammal Protection Mode	(Kongsberg systems) An option provided by some echosounders in which the system starts with a low SL (nominal level minus 10 or 20 dB) and increases gradually over a given time span (“Soft Startup”).
Mills Cross	An array structure designed to obtain narrow beams in both along- and across-ship directions. The Rx and Tx arrays are long and narrow, and disposed orthogonally each other. This principle is very generally used in low-frequency MBES.
Multibeam Echosounder or Multibeam Sonar	Multibeam echosounders form a high number of narrow beams at controled angles, enabling them to measure simultaneously multiple sounding points along one (or more) wide sector across-ship. They are also able of recording backscatter intensity inside the formed beams. This duality makes them today the favorite sonar tool for seafloor mapping.
Near-field (of transducer)	For a given array or transducer, the regime in which the array points contribute with significant phase differences, creating an interference-like fluctuating field close to the transducer.
NetCDF	NetCDF (Network Common Data Form) is a set of software libraries and self-describing, machine-independent data formats that support the creation, access, and sharing of array-oriented scientific data [from Wikipedia].

Noise floor	The measure of the signal created from the sum of all the noise sources and unwanted signals within a measurement system.
Noise Level	The acoustic pressure level measured at the receiver in the absence of the expected echo. In seafloor-mapping sonars, the causes of this noise floor are multiple: sonar electronic self noise, ship-induced acoustical, hydrodynamic and electrical self-noise, environmental noise (sea-surface, biological...). The noise level is usually given as a power spectral density, i.e. the power present in bandwidths of 1 Hz. It may be also expressed as its value integrated inside the receiver's bandwidth; it is then directly comparable to the echo level.
Nyquist frequency	½ of the sampling rate of a discrete signal processing system. This frequency gives the theoretical limit of the signal bandwidth that can be digitized without a loss of content.
Oblique range / slant range	In this context: the range computed geometrically from the sonar acoustical center to the target.
Per-beam intensity	(Reson systems) Format of backscatter data produced by older Reson systems.
Ping	An elementary transmission of a signal by an active sonar, normally happening at regularly spaced instants (ping cycle).
Probability Density Function	Captures the likelihood of finding the seafloor some distance away from the mean. It is usually modeled as a bell-shaped law, with its maximum at the average interface altitude.
Processing Dynamics	see Dynamic Range
Projector	A sonar transducer used in transmission, usually specialized in a narrow band of frequencies. It is characterized by its sensitivity (in dB re 1 µPa @1 m / 1 µPa), its directivity and its frequency response. The equivalent in the air is the loudspeaker.
Propagation Loss (*also* Transmission Loss)	Loss of intensity as acoustic waves propagate due to geometric spreading and absorption; the key parameter for acoustic systems as it constrains the amplitude of the signal received directly dependant on the signal-to-noise ratio.
Pulse length / Effective pulse length	The duration of the transmitted signal envelope. The definition is straightforward for a boxcar-shaped envelope. For a smoothed envelope, the effective duration is the duration of the ideal boxcar envelope with the same maximum amplitude and containing the same amount of energy.
r2s (dot r2s or *.r2s)	Raw data files produced by R2Sonic systems containing backscatter data.
Rayleigh law	A probability density function expressing the resulting amplitude distribution for a superposition of CW signals with comparable amplitudes and random phases. Very widely used in first approximation for the random signals in sonar and radar such as backscatter.

Rayleigh parameter	A parameter describing the degree of effective roughness of a surface for a given frequency; based upon the ratio of the relief elevation to the signal wavelength.
RDF	(GeoAcoustics systems) File extension of native GeoSwath Raw Data Files (".rdf").
Received Level	see Echo Level (in this context of active sonar)
Reception Sensitivity	The coefficient quantifying the level correspondence between the received acoustical signal and the electrical signal available for processing. It includes both the transducer sensitivity (transforming an acoustical pressure into an electrical output) and various operations on the electrical signal (impedance adaptation, pre-amplification, filtering).
Reflection	The process by which the incident path of a sound wave is diverted symmetrically to its direction of incidence by a plane interface. This physical phenomenon is rarely observable with multibeam echosounders, excepted at normal incidence on the seafloor. See Specular.
Refraction	The change of propagation direction of a wave (light, sound,…) due to a variation of speed in the propagation medium, and described by Snell's law. This effect is very significant in underwater acoustic propagation at near-horizontal directions, and has to be compensated e.g. for accurate bathymetry measurements.
Resolution Cell	See Confusion Volume
Reverberation	The "tail" of scattered signals following a transient signal transmitted in a complex medium. This phenomenon is very well-known in air acoustics, and the "reverberation decay time" is a primary criterion in building acoustics. In underwater acoustics the term is either used under this meaning; or, less properly, as an equivalent to backscattering.
Roughness Spatial Spectrum or Roughness Spectrum	The power associated with the various components of the spatial spectrum constituting the observed relief.
Saturation / Clipping	When the level of an electrical signal exceeds the physical limits (dynamic range) of the circuit, it is distorted by the clipping of the amplitude peaks. The information about the actual signal level is lost, the signal shape is modified and higher-order harmonic components appear in the spectrum. This phenomenon is usually detrimental. In sonar receivers, it is combatted either by adapting the signal level to the available dynamics (see Time Varying Gain) or by increasing the dynamic range of the receiver.
Scatterometer	A satellite-borne radar, structurally similar to a sidescan sonar, designed to measure calibrated backscatter for the Earth (or the sea) surface with a low resolution.

Seabed image	Generally, the representation of the seabed reflectivity be it a simple piling-up of time echoes (sidescan sonar image) or a georeferenced map of backscatter. "Seabed image" is also the traditional term for Snippets in Kongsberg MBES.
Sector Tracking	(Kongsberg systems) A real-time functionality equalizing the received level between sectors.
Segmentation or Data Segmentation	The process by which a dataset is partitioned in clusters or regions of contiguous pixels or individual grid cells, similar with respect to a range of selected parameters. A segmented image typically includes a large number of segments, with each segment representing a mixture of the parameters used. Segmentation can be pixel based, where each pixel is compared with adjacent ones, or object-based, where the shape of the segment is used for classification.
Short-pulse Regime	Regime of target insonification in which the signal is not long enough for covering the complete beam footprint area; the active target is the delimited by the signal length projection.
Sidelobes	The part of the directivity function outside the main lobe. The level of these unwanted contributions should be as low as possible.
Sidescan	(Reson systems) Backscatter data generated in datagram 7007; port and starboard variable bit depth magnitude time series. Each sample value is the maximum magnitude across all beams on one side after across-beam low pass filtering. In older systems, used an unsigned 16-bit integer for storage with values being proportional to linear pressure.
Sidescan Sonar	Sonar system towed at a low altitude above the seafloor and recording “acoustic images” of the interface details at shallow grazing angles.
Sidescan sonar image	The backscatter echo recorded by a sidescan sonar, as two series (port and starboard) of echoes vs time, displayed jointly, ping after ping, in order to build a plane representation of the seabed reflectivity in its very details. In its basic form, it is neither a topographic map (it cannot measure the relief) nor an objective measurement of backscatter (it is usually not calibrated in intensity, and cannot process the geometrical dependence). However sidescan sonar images are very useful data for a number of underwater activities, thanks to their high resolution and photo-like pictural quality.
Signal to Noise Ratio	The power ratio of a received signal to the background noise. It is one of the key descriptors of the quality of a sonar signal: the higher it is, the better is the measurement accuracy, whatever the targeted quantity (time, angle, or echo intensity).
Single Beam Echosounder	Sonar system measuring one sounding point vertically under a ship or an underwater vehicle
Snell's law	Defines the change of incident angle of a wave at the interface between two media with different velocity - valid for for light, radar, sound… The ratio of the incident angle cosine to the velocity is constant.

Snippets	(Reson & R2Sonic systems) Fragments of the full backscatter envelope around the bottom return signal from each beam. Term is used to describe a type of backscatter data generated by R2Sonic and older Reson systems, and referring to a time-series of data samples per beam.
Sound pressure & intensity	The acoustical pressure is the local variation of pressure caused by a sound wave. It is the physically observable acoustical quantity, measured as a variation around the constant hydrostatic pressure, and expressed in dB re 1 µPa. The acoustical intensity is the power flux associated with the sound wave, and hence combines the local pressure and the motion of the fluid particles; it is expressed in dB re 1 W/m².
Sound pressure level (SPL)	The level of acoustical pressure (in RMS value) observed at a point, expressed in dB re 1 µPa.
Source Level (SL)	The sound pressure level radiated at reference range (1 meter) from the source acoustical center, in the angular direction where the transmitted intensity is maximum. Expressed in dB re 1 µPa @ 1m.
Spatial Resolution	The spatial extent of the investigated medium as delimited by the sonar. For the seafloor, it is a section of the interface, delimited by the beam directivity pattern and possibly by the signal extent. The spatial resolution also defines the capability to separate two close scatterers.
Specular	The signal generated by the reflected energy to the sonar, as opposed to the backscattered energy. In an echosounding configuration, the specular only occurs perpendicular to the seafloor, i.e. vertically beneath the vessel (the nadir) for a horizontal seafloor.
Spherical Divergence/Spherical Spreading	The 1/R range dependency; expresses in first approximation the pressure decrease away from the source.
Swath Bathymetry Systems	Echosounders primarily designed for measuring sounding points at oblique angles over a wide stripe of seafloor. These are in majority multibeam echosounders; however a number of Phase Measuring Bathymetry Systems (PMBS), based on a similar design, belong to this category.
Target	A generic term for any object prone to generate an echo backward to an active sonar. In sonar operations, this term is rather reserved to the expected echoes: for a seafloor-mapping sonar, the seafloor is the target - while fishes or bubbles are usually not (excepted when they are!).
Target Strength (*TS*)	The ratio (expressed in dB re 1m²) between the intensity sent by the target back toward the transmitter and the incident intensity. The relative energy sent back by the target toward the sonar; it depends on the physical nature of the target, its external (and possibly internal) structure, and the characteristics of the incident signal (angle and frequency).
Temperature Profile	A depth-temperature profile used for correcting the raw data - through the sound speed profile for bathymetry or the absorption profile for backscatter.

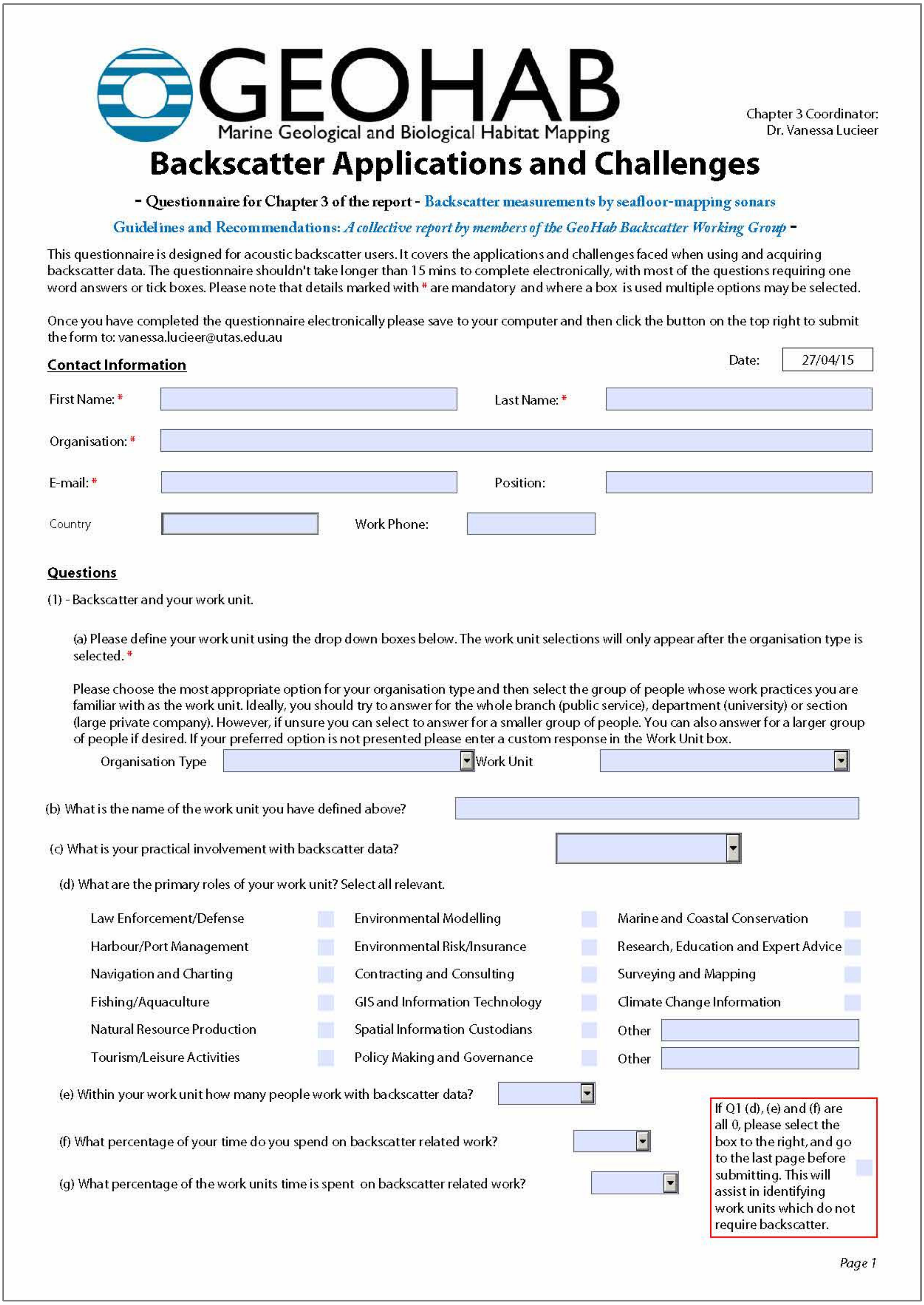
Time Varying Gain (*TVG*)	A correction applied to the received echo level to compensate for loss imposed by the distance between the target and the sonar system using the law expected for propagation loss, transposed into the time domain.
Transducer	An electro-acoustical system transforming an electrical current into an acoustic pressure (at transmission) or conversely an incident acoustic pressure into an electrical signal (at reception).
Transmission angle	The angle from the vertical of the sound wave as it is emitted from the transmitting array.
Transmission Loss (TL)	Loss of intensity, as acoustic waves propagate, due to geometric spreading and absorption; a key parameter for acoustic systems as it constrains the amplitude of the signal received directly dependant on the signal-to-noise ratio.
Transmit power	see Source Level
TruePix	(R2Sonic Systems) Backscatter data produced by R2Sonic systems. A sidescan-like single time-series of triplets (intensity, range, angle) for port and starboard sides. Sample ranges are regularly spaced. Intensity is taken from snippets data, taking the brightest return for the given sample range.
Tukey tapering	A windowing function, shaped as a cosine.
Volume backscatter	The component of seafloor backscatter generated by the inner structure of the seafloor, from various causes: heterogeneous granulometry, sediment layering, inclusion of shells, stones, gas bubbles, animals… It is specially significant in very soft sediments.
wcd (aka dot wcd or *.wcd)	(Kongsberg systems) Raw data files generated for storing water column data.
Windowing Function	See Array shading

APPENDIX 3 - COMMON SYMBOLS

Denotation	Full Term	Unit
A	Insonified surface	m^2
α	Exponential decrement / water absorption	Neper/m
a	In-water absorption, in dB per length unit	dB/m or dB/km
B	Insonified volume	m^3
b	Exponential decrement / absorption in the sediment	Neper/m
β	Absorption in the sediment in dB per wavelength	dB/λ
BS	Backscatter Strength	dB
c	Sound speed	m/s
D	Water depth	m
EL	Echo Level	dB re 1 µPa
f	[Sonar] Frequency	Hz or kHz
G	Gain	dB
H	Directivity pattern (in pressure), normalized	
h	Standard deviation of interface relief elevation	m
I	Acoustic Intensity	W/m^2
I_b	Intensity of backscattered wave	W/m^2
I_i	Intensity of incident wave	W/m^2
IL	Acoustical intensity level in dB	dB re 1 W/m^2
k	Acoustic wave number	m^{-1}
K	Interface roughness spectrum spatial wavenumber	m^{-1}
λ	Acoustical wavelength	m
Λ	Interface roughness spectrum spatial wavelength	m
L	Array Length	m
p	Acoustical pressure	Pa or µPa
P	Acoustical power	W
PG	Processing Gain	dB
θ	Incidence angle (ref.vertical axis)	deg or rad
R	Oblique range	m
ρ	Density	kg.m^3
RL	Received level	dB re 1 µPa
S	Power spectrum of the interface relief	
σ	Cross section	m^2
Σ	An arbitrary surface	m^2
S_b	Bottom backscattering strength	dB
SL	Source Level	dB re 1 µPa @1 m
SPL	Sound Pressure Level	dB re 1 µPa
S_V	Volume scattering strength	dB re 1 m^{-1}

s_v	Volume cross-section	m^{-1}
t	Time	s [second]
τ	Pulse duration	s
T	Time delay along signal propagation	s
TL	Transmission Loss	dB
TS	Target Strength	dB re 1 m^2
V	Reflection coefficient in pressure	Dimensionless
Z	Acoustical impedance	Rayleigh
ω	Angular frequency	
ϕ	Along-track incident angle	deg or rad
$\prod$	Total radiated acoustic power	W
ξ	Relief elevation related to the average interface plane	m
δ^2	variance of the distribution of facet slopes comprising the seafloor	

APPENDIX 4 – USERS' QUESTIONNAIRE



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Marine Geological and Biological Habitat Mapping

Chapter 3 Coordinator:
Dr. Vanessa Lucieer

Backscatter Applications and Challenges

- Questionnaire for Chapter 3 of the report - Backscatter measurements by seafloor-mapping sonars
Guidelines and Recommendations: *A collective report by members of the GeoHab Backscatter Working Group* -

This questionnaire is designed for acoustic backscatter users. It covers the applications and challenges faced when using and acquiring backscatter data. The questionnaire shouldn't take longer than 15 mins to complete electronically, with most of the questions requiring one word answers or tick boxes. Please note that details marked with * are mandatory and where a box is used multiple options may be selected.

Once you have completed the questionnaire electronically please save to your computer and then click the button on the top right to submit the form to: vanessa.lucieer@utas.edu.au

Date: 27/04/15

Contact Information

First Name: *
Last Name: *
Organisation: *
E-mail: *
Position:
Country
Work Phone:

Questions

(1) - Backscatter and your work unit.

(a) Please define your work unit using the drop down boxes below. The work unit selections will only appear after the organisation type is selected. *

Please choose the most appropriate option for your organisation type and then select the group of people whose work practices you are familiar with as the work unit. Ideally, you should try to answer for the whole branch (public service), department (university) or section (large private company). However, if unsure you can select to answer for a smaller group of people. You can also answer for a larger group of people if desired. If your preferred option is not presented please enter a custom response in the Work Unit box.

Organisation Type
Work Unit

(b) What is the name of the work unit you have defined above?

(c) What is your practical involvement with backscatter data?

(d) What are the primary roles of your work unit? Select all relevant.

- Law Enforcement/Defense ☐
- Harbour/Port Management ☐
- Navigation and Charting ☐
- Fishing/Aquaculture ☐
- Natural Resource Production ☐
- Tourism/Leisure Activities ☐
- Environmental Modelling ☐
- Environmental Risk/Insurance ☐
- Contracting and Consulting ☐
- GIS and Information Technology ☐
- Spatial Information Custodians ☐
- Policy Making and Governance ☐
- Marine and Coastal Conservation ☐
- Research, Education and Expert Advice ☐
- Surveying and Mapping ☐
- Climate Change Information ☐
- Other
- Other

(e) Within your work unit how many people work with backscatter data?

(f) What percentage of your time do you spend on backscatter related work?

(g) What percentage of the work units time is spent on backscatter related work?

If Q1 (d), (e) and (f) are all 0, please select the box to the right, and go to the last page before submitting. This will assist in identifying work units which do not require backscatter. ☐

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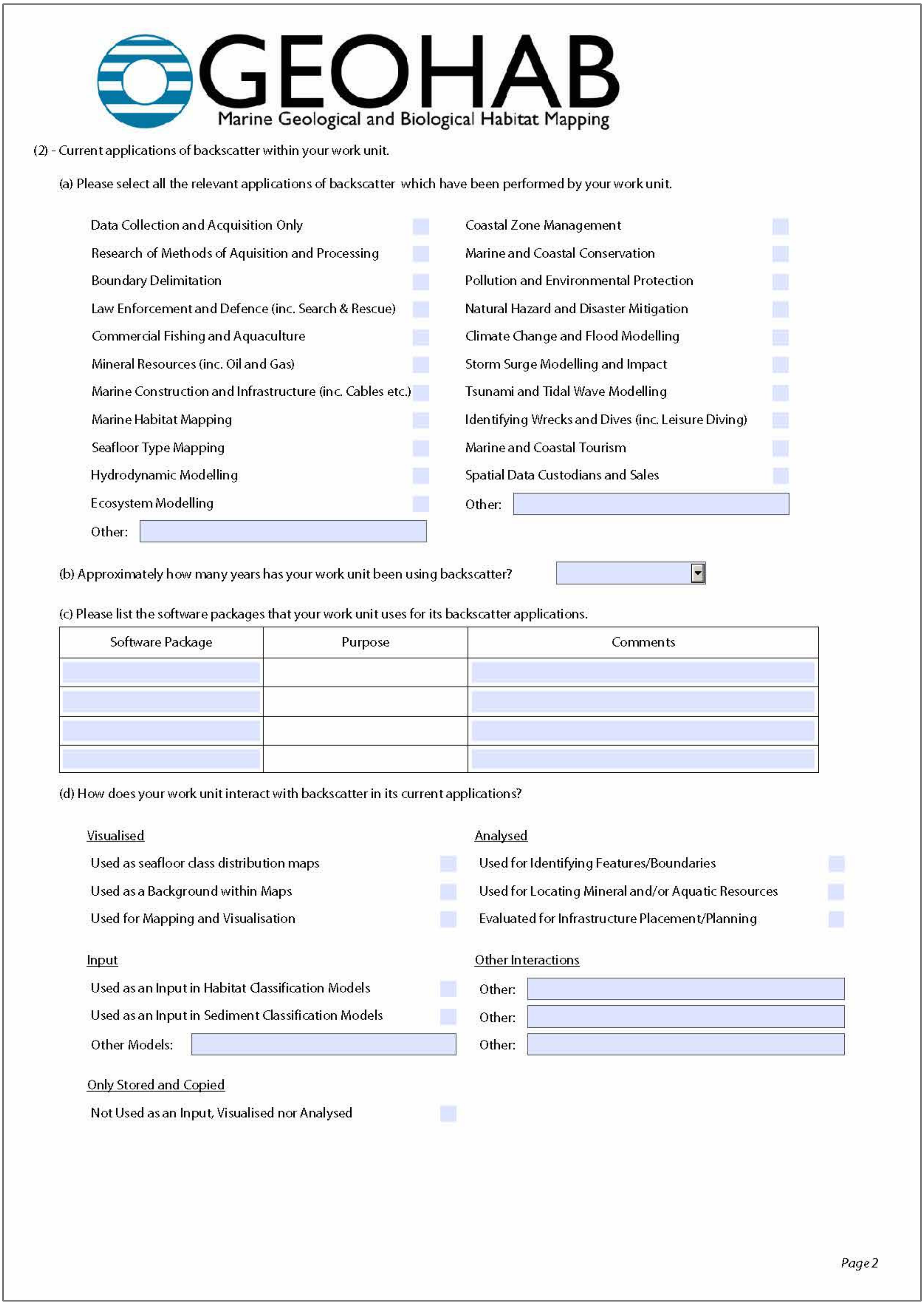

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(2) - Current applications of backscatter within your work unit.

(a) Please select all the relevant applications of backscatter which have been performed by your work unit.

Data Collection and Acquisition Only ☐
Research of Methods of Aquisition and Processing ☐
Boundary Delimitation ☐
Law Enforcement and Defence (inc. Search & Rescue) ☐
Commercial Fishing and Aquaculture ☐
Mineral Resources (inc. Oil and Gas) ☐
Marine Construction and Infrastructure (inc. Cables etc.) ☐
Marine Habitat Mapping ☐
Seafloor Type Mapping ☐
Hydrodynamic Modelling ☐
Ecosystem Modelling ☐
Other: ______

Coastal Zone Management ☐
Marine and Coastal Conservation ☐
Pollution and Environmental Protection ☐
Natural Hazard and Disaster Mitigation ☐
Climate Change and Flood Modelling ☐
Storm Surge Modelling and Impact ☐
Tsunami and Tidal Wave Modelling ☐
Identifying Wrecks and Dives (inc. Leisure Diving) ☐
Marine and Coastal Tourism ☐
Spatial Data Custodians and Sales ☐
Other: ______

(b) Approximately how many years has your work unit been using backscatter? ______ ▾

(c) Please list the software packages that your work unit uses for its backscatter applications.

Software Package	Purpose	Comments

(d) How does your work unit interact with backscatter in its current applications?

Visualised
Used as seafloor class distribution maps ☐
Used as a Background within Maps ☐
Used for Mapping and Visualisation ☐

Analysed
Used for Identifying Features/Boundaries ☐
Used for Locating Mineral and/or Aquatic Resources ☐
Evaluated for Infrastructure Placement/Planning ☐

Input
Used as an Input in Habitat Classification Models ☐
Used as an Input in Sediment Classification Models ☐
Other Models: ______

Other Interactions
Other: ______
Other: ______
Other: ______

Only Stored and Copied
Not Used as an Input, Visualised nor Analysed ☐

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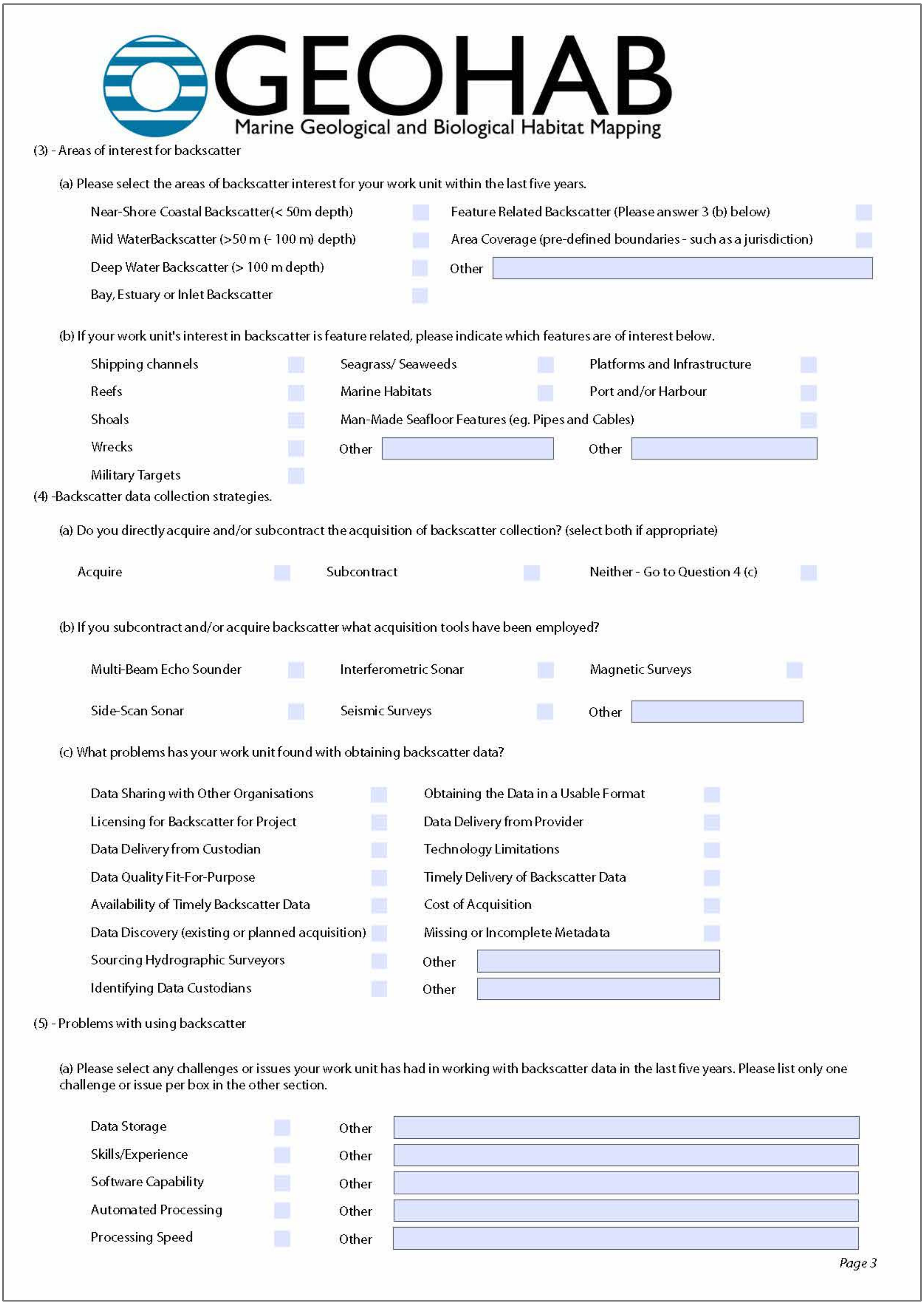

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(3) - Areas of interest for backscatter

(a) Please select the areas of backscatter interest for your work unit within the last five years.

- Near-Shore Coastal Backscatter(< 50m depth) ☐
- Mid WaterBackscatter (>50 m (- 100 m) depth) ☐
- Deep Water Backscatter (> 100 m depth) ☐
- Bay, Estuary or Inlet Backscatter ☐
- Feature Related Backscatter (Please answer 3 (b) below) ☐
- Area Coverage (pre-defined boundaries - such as a jurisdiction) ☐
- Other

(b) If your work unit's interest in backscatter is feature related, please indicate which features are of interest below.

- Shipping channels ☐
- Reefs ☐
- Shoals ☐
- Wrecks ☐
- Military Targets ☐
- Seagrass/ Seaweeds ☐
- Marine Habitats ☐
- Man-Made Seafloor Features (eg. Pipes and Cables) ☐
- Other
- Platforms and Infrastructure ☐
- Port and/or Harbour ☐
- Other

(4) -Backscatter data collection strategies.

(a) Do you directly acquire and/or subcontract the acquisition of backscatter collection? (select both if appropriate)

- Acquire ☐
- Subcontract ☐
- Neither - Go to Question 4 (c) ☐

(b) If you subcontract and/or acquire backscatter what acquisition tools have been employed?

- Multi-Beam Echo Sounder ☐
- Side-Scan Sonar ☐
- Interferometric Sonar ☐
- Seismic Surveys ☐
- Magnetic Surveys ☐
- Other

(c) What problems has your work unit found with obtaining backscatter data?

- Data Sharing with Other Organisations ☐
- Licensing for Backscatter for Project ☐
- Data Delivery from Custodian ☐
- Data Quality Fit-For-Purpose ☐
- Availability of Timely Backscatter Data ☐
- Data Discovery (existing or planned acquisition) ☐
- Sourcing Hydrographic Surveyors ☐
- Identifying Data Custodians ☐
- Obtaining the Data in a Usable Format ☐
- Data Delivery from Provider ☐
- Technology Limitations ☐
- Timely Delivery of Backscatter Data ☐
- Cost of Acquisition ☐
- Missing or Incomplete Metadata ☐
- Other
- Other

(5) - Problems with using backscatter

(a) Please select any challenges or issues your work unit has had in working with backscatter data in the last five years. Please list only one challenge or issue per box in the other section.

- Data Storage ☐
- Skills/Experience ☐
- Software Capability ☐
- Automated Processing ☐
- Processing Speed ☐
- Other
- Other
- Other
- Other
- Other

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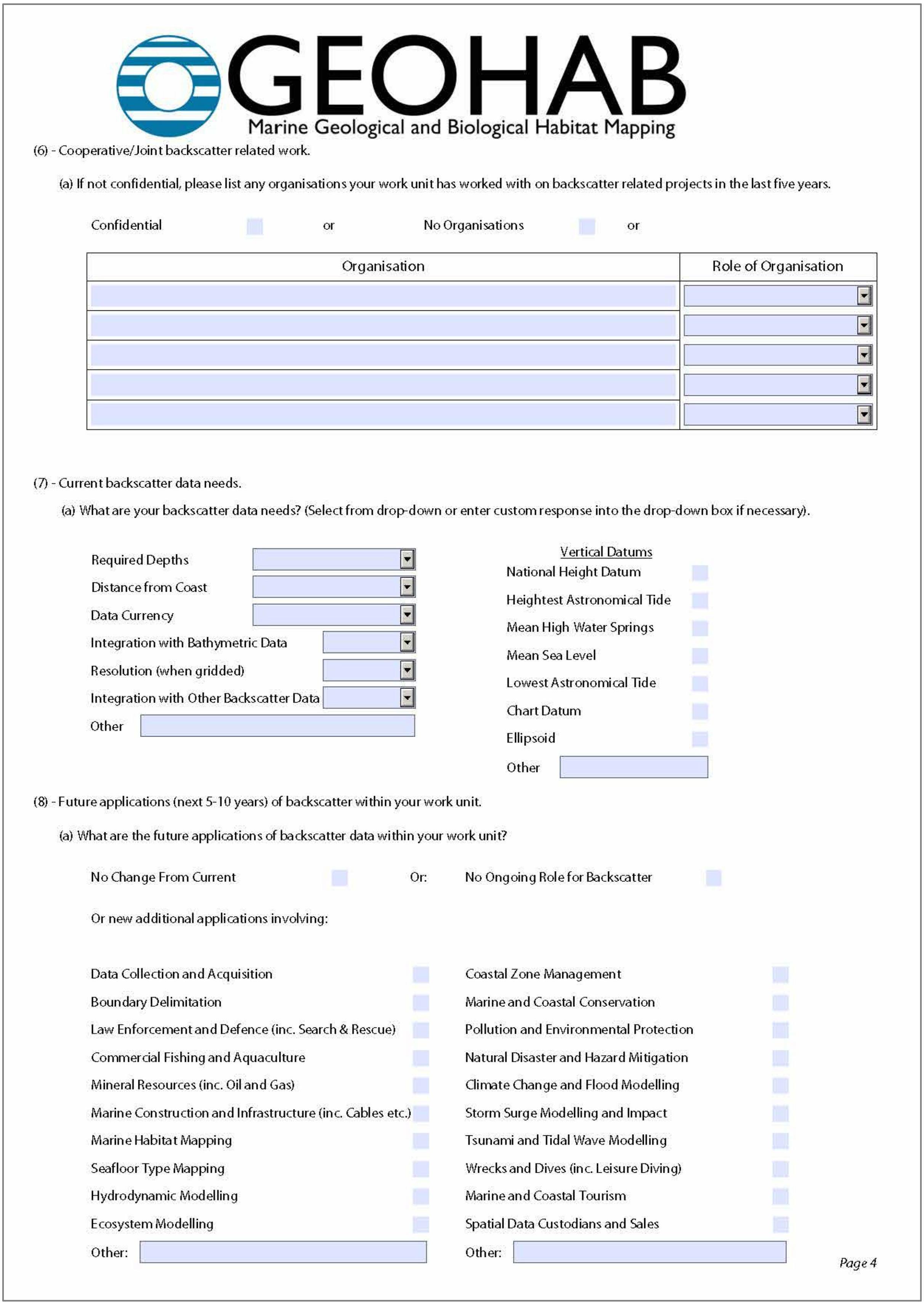

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(6) - Cooperative/Joint backscatter related work.

(a) If not confidential, please list any organisations your work unit has worked with on backscatter related projects in the last five years.

Confidential ☐ or No Organisations ☐ or

Organisation	Role of Organisation

(7) - Current backscatter data needs.

(a) What are your backscatter data needs? (Select from drop-down or enter custom response into the drop-down box if necessary).

Required Depths

Distance from Coast

Data Currency

Integration with Bathymetric Data

Resolution (when gridded)

Integration with Other Backscatter Data

Other

Vertical Datums

National Height Datum ☐

Heightest Astronomical Tide ☐

Mean High Water Springs ☐

Mean Sea Level ☐

Lowest Astronomical Tide ☐

Chart Datum ☐

Ellipsoid ☐

Other

(8) - Future applications (next 5-10 years) of backscatter within your work unit.

(a) What are the future applications of backscatter data within your work unit?

No Change From Current ☐ Or: No Ongoing Role for Backscatter ☐

Or new additional applications involving:

Data Collection and Acquisition ☐

Boundary Delimitation ☐

Law Enforcement and Defence (inc. Search & Rescue) ☐

Commercial Fishing and Aquaculture ☐

Mineral Resources (inc. Oil and Gas) ☐

Marine Construction and Infrastructure (inc. Cables etc.) ☐

Marine Habitat Mapping ☐

Seafloor Type Mapping ☐

Hydrodynamic Modelling ☐

Ecosystem Modelling ☐

Other:

Coastal Zone Management ☐

Marine and Coastal Conservation ☐

Pollution and Environmental Protection ☐

Natural Disaster and Hazard Mitigation ☐

Climate Change and Flood Modelling ☐

Storm Surge Modelling and Impact ☐

Tsunami and Tidal Wave Modelling ☐

Wrecks and Dives (inc. Leisure Diving) ☐

Marine and Coastal Tourism ☐

Spatial Data Custodians and Sales ☐

Other:

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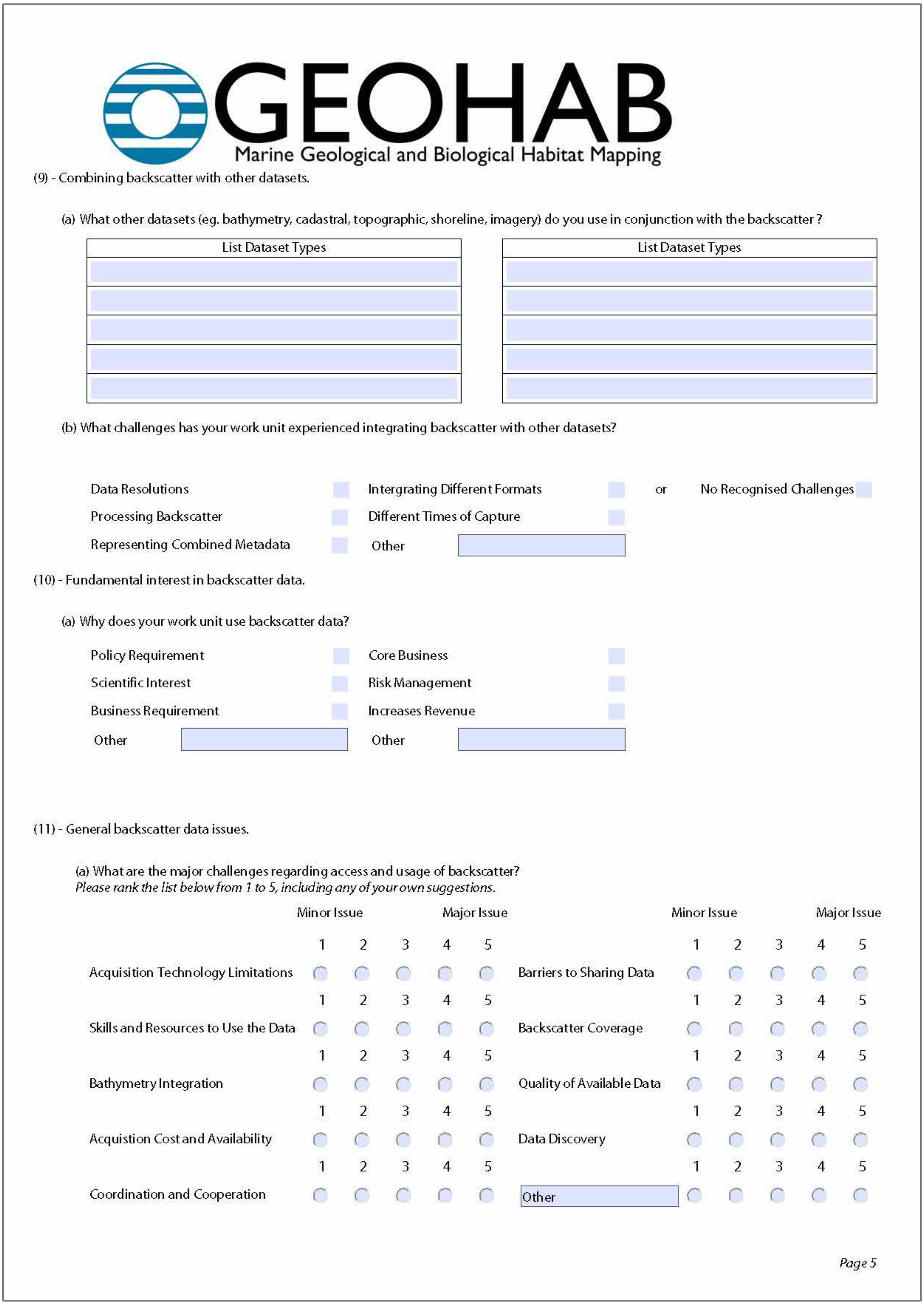

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(9) - Combining backscatter with other datasets.

(a) What other datasets (eg. bathymetry, cadastral, topographic, shoreline, imagery) do you use in conjunction with the backscatter ?

List Dataset Types	List Dataset Types

(b) What challenges has your work unit experienced integrating backscatter with other datasets?

Data Resolutions ☐ Intergrating Different Formats ☐ or No Recognised Challenges ☐
Processing Backscatter ☐ Different Times of Capture ☐
Representing Combined Metadata ☐ Other

(10) - Fundamental interest in backscatter data.

(a) Why does your work unit use backscatter data?

Policy Requirement ☐ Core Business ☐
Scientific Interest ☐ Risk Management ☐
Business Requirement ☐ Increases Revenue ☐
Other Other

(11) - General backscatter data issues.

(a) What are the major challenges regarding access and usage of backscatter?
Please rank the list below from 1 to 5, including any of your own suggestions.

	Minor Issue				Major Issue		Minor Issue				Major Issue
	1	2	3	4	5		1	2	3	4	5
Acquisition Technology Limitations	○	○	○	○	○	Barriers to Sharing Data	○	○	○	○	○
	1	2	3	4	5		1	2	3	4	5
Skills and Resources to Use the Data	○	○	○	○	○	Backscatter Coverage	○	○	○	○	○
	1	2	3	4	5		1	2	3	4	5
Bathymetry Integration	○	○	○	○	○	Quality of Available Data	○	○	○	○	○
	1	2	3	4	5		1	2	3	4	5
Acquistion Cost and Availability	○	○	○	○	○	Data Discovery	○	○	○	○	○
	1	2	3	4	5		1	2	3	4	5
Coordination and Cooperation	○	○	○	○	○	Other	○	○	○	○	○

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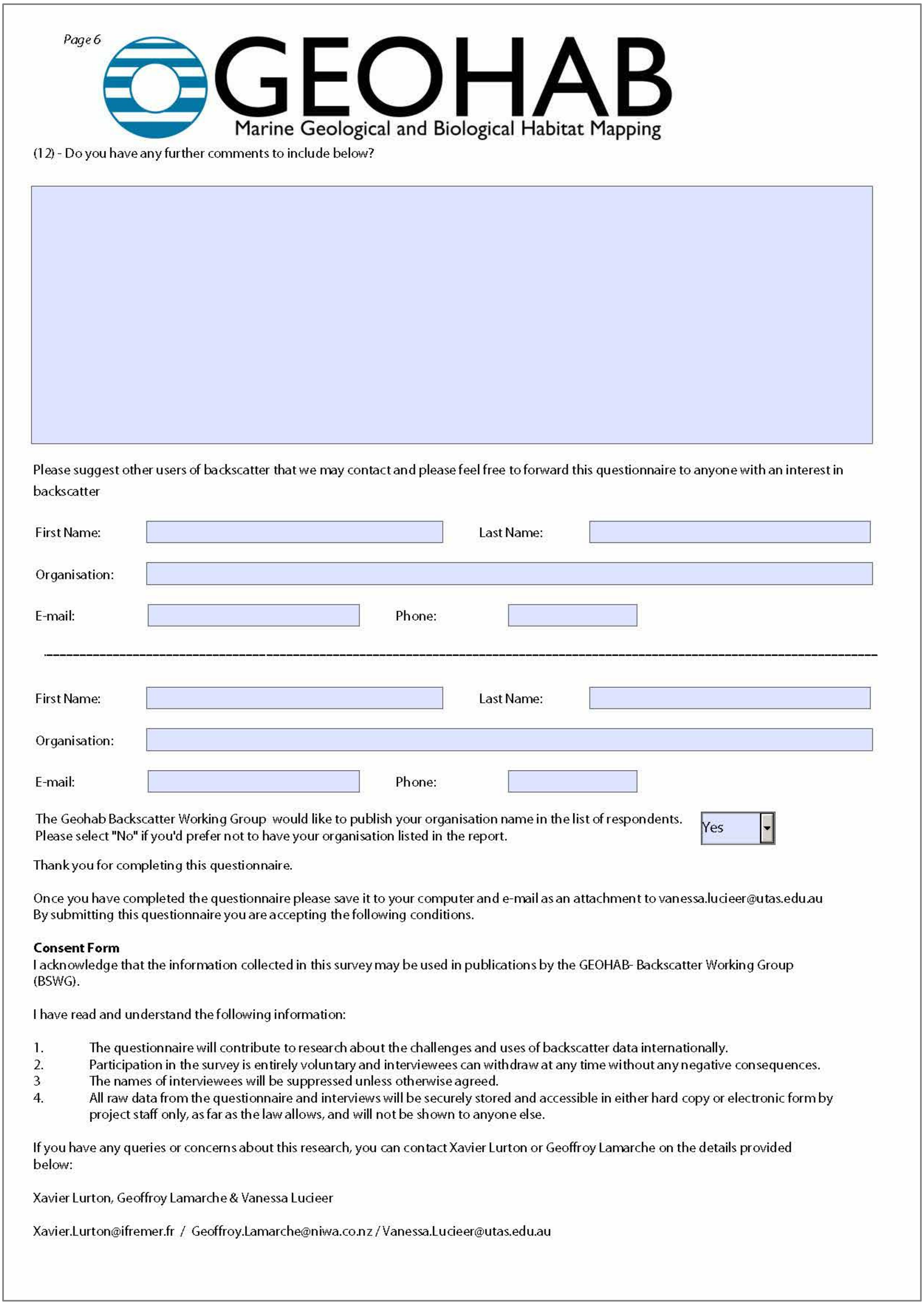

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(12) - Do you have any further comments to include below?

Please suggest other users of backscatter that we may contact and please feel free to forward this questionnaire to anyone with an interest in backscatter

First Name: Last Name:

Organisation:

E-mail: Phone:

First Name: Last Name:

Organisation:

E-mail: Phone:

The Geohab Backscatter Working Group would like to publish your organisation name in the list of respondents.
Please select "No" if you'd prefer not to have your organisation listed in the report. Yes ▾

Thank you for completing this questionnaire.

Once you have completed the questionnaire please save it to your computer and e-mail as an attachment to vanessa.lucieer@utas.edu.au
By submitting this questionnaire you are accepting the following conditions.

Consent Form
I acknowledge that the information collected in this survey may be used in publications by the GEOHAB- Backscatter Working Group (BSWG).

I have read and understand the following information:

1. The questionnaire will contribute to research about the challenges and uses of backscatter data internationally.
2. Participation in the survey is entirely voluntary and interviewees can withdraw at any time without any negative consequences.
3 The names of interviewees will be suppressed unless otherwise agreed.
4. All raw data from the questionnaire and interviews will be securely stored and accessible in either hard copy or electronic form by project staff only, as far as the law allows, and will not be shown to anyone else.

If you have any queries or concerns about this research, you can contact Xavier Lurton or Geoffroy Lamarche on the details provided below:

Xavier Lurton, Geoffroy Lamarche & Vanessa Lucieer

Xavier.Lurton@ifremer.fr / Geoffroy.Lamarche@niwa.co.nz / Vanessa.Lucieer@utas.edu.au

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Taihoro Nukurangi

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