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CHALLENGES IN SEAFLOOR CHARACTERISATION: FROM POINT TO MAP

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ABSTRACT
The field of seafloor mapping has now reached maturity, and the last decades have seen tremendous improvements in the accuracy and coverage of the acoustic instruments used in seafloor mapping. Modern sonars can detect objects on the seabed as small as a few centimetres and cover swath ranges as large as 60 km. Multibeam echosounders, sidescan sonars, interferometric and synthetic-aperture sonars, parametric arrays and many other acoustic instruments are increasingly used in synergy to map the seabed and its immediate sub-surface, for applications ranging from habitat mapping to buried waste identification. Technology-driven advances in computer processing have ensured large amounts of information can be collated, analysed, mosaicked and, to some degree, interpreted automatically. Yet, the transition from individual, "point" measurements of acoustic scattering to maps of seabed types and object properties is still fraught with problems and uncertainties. Drawing on typical applications from around the world, the challenges to true seafloor characterisation are presented along with recent advances in underwater acoustics theory and in seafloor imaging, and how these results can be presented to non-specialists in Geographic Information Systems and Decision-Support Systems.

ADVANCES IN SEAFLOOR MAPPING

Traditional Instruments
Single-beam, down-looking echosounders have long been the tool of choice for underwater habitat mapping, because they are simple to use and widespread on nearly all vessels. Echosounders are not always calibrated, but often give a very good estimate of the depth and type of seabed. The shape of the echo can be analysed quantitatively (e.g. [1,2]) to derive more information about the local habitat. Innovative techniques were also developed to extract additional details from the echoes of the secondary lobes (e.g. [3]). However, single-beam echosounders only provide information on the seabed immediately below the surveying vessel. The footprint on the seabed varies in size, depending on the water depth and the local slopes. Sub-surface penetration is often an issue in sedimentary areas, and so is overlying biota such as algae (e.g. [4]). Seafloor coverage is therefore variable and rather small.

Multibeam echosounders became widely accessible in the late 1980s and work on the same principles. Transmitting a large number of beams (up to 120 for some instruments), they cover a wide swath on the seabed (up to 20 times the water depth in some cases). These systems principally acquire bathymetry measurements for each beam, but, increasingly, backscatter strengths can also be derived from the individual measurements. Targets smaller than the footprint can now be resolved by some systems, using the "split aperture" method (picking of the zero-differential phase point). Multibeam echosounders have proved particularly attractive for the mapping of Exclusive Economic Zones. Because of the high standards of calibration usually attached to these systems (e.g. IHO-S44 for bathymetry), multibeam systems have proved particularly adapted to repeat surveys of near-shore areas. Processing is highly standardised, giving a good point of comparison between products from different systems. Knowledge of the local bathymetry, at each point where backscatter has been acquired, can be used to correct the imagery and represent it using the exact local incidence angles. Analysis of the imagery itself proves different from the sidescan sonar case, partly because the footprint on the seabed is generally much larger (100 m compared to a few metres), partly because of the difference in frequency and beam widths.

Sidescan sonars have been used since the 1960s [5,6] and show the highest degree of improvement, both in resolution and in overall image quality (Figure 1). Usually deep-towed, they survey swaths from a few tens of metres to 60 km or more. This coverage is attained by transmitting two beams (broad in the vertical plane and narrow in the horizontal plane), one on each side. The processing steps are less standardised, depending on the manufacturer, despite the consensus on the types of corrections desirable (e.g. [6]). Sidescan sonar imagery usually shows a “finer” resolution than multibeam imagery, as it is affected, in decreasing order of importance, by the local imaging angle, the surface and volume characteristics of the seabed. Sub-surface penetration from sidescan sonars is not always quantified, and usually only known from experience with distinct systems, often anecdotal.

All these instruments are generally used in combination. Multibeam echosounders give a general bathymetric map of the habitat. Shaded-relief topography shows seabed features in great detail, and backscatter imagery provides a “broad-brush” indication of the types of materials that constitute the seabed. This image is then “refined” with sidescan sonar imagery, which shows smaller features, generally at a higher frequency. Single-beam echosounder measurements, aligned along the track of the surveying vessel, provide point information about the immediate sub-surface (or, in some cases, the overlaying vegetation cover). These instruments are complementary: echo-sounder data can for example be used in the processing of the multibeam bathymetry, and multibeam bathymetry for sidescan sonar corrections. These maps present complex structures and processes (such as those visible in Figure 1), which need to be characterised with a high degree of accuracy.

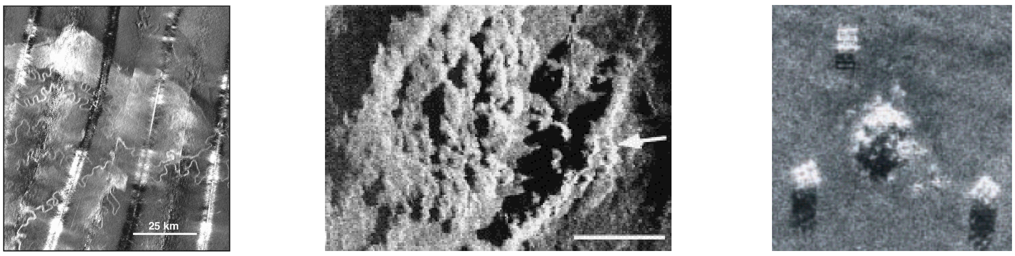


Figure 1.- Advances in seafloor mapping have in particular led to higher resolutions, increasing by an order of magnitude or more every decade. From left to right: GLORIA sidescan sonar imagery at 60-m resolution in the 1980s (courtesy NOCS-UK), TOBI sidescan sonar imagery at 6-m resolution in the 1990s [7] and SHADOWS SAS imagery at 15-cm resolution in 2006 [8].

Innovative Instruments

The instruments described above are now well accepted and have been the subject of many validation studies in different contexts (e.g. [9]). They have been improved throughout the years by better calibration, more thorough or complex processing (brought into reach by the immense advances in computer and storage technology), and increasing standardisation of the processing stages (e.g. [6]). Progress has been made through refinements such as signal generation and processing (e.g. Chirp-based profilers, [10]), non-linear interference (the base of parametric arrays) (e.g. [11]), interferometry (e.g. [12]) and synthetic-aperture (e.g. [8]). More agile architectures, such as autonomous platforms, have also contributed to these advancements (e.g. [13]).

More innovative approaches have used the increasing knowledge of physical scattering processes. Most of the acoustic scattering will be in the forward (specular) direction, and this intuitive view has been confirmed and refined by theoretical (e.g. [14]) and experimental studies (e.g. [15]). By transmitting from one platform and receiving on one (or several) physically-decoupled transducers, it is possible to “go where the information is” and optimise the collection of acoustic measurements (Figure 2, left). This is the principle of multistatic sonars (e.g. [16,17]). These instruments have now progressed to the stage where they can be used to confidently map specific sites or objects, e.g. buried waste ([18] and articles therein). Other approaches try to make the most of the acoustic information available, using background noise and/or opportunity sources such as passing planes or ships (e.g. [19,20]). These passive imaging systems can be used with a large amount of receivers and reconstruct the geoacoustic properties of the seabed and any neighbouring objects ("acoustic daylight imaging", e.g. [21]). They can also be used to correlate the acoustic field with other processes, such as animal behaviour (Figure 2, right) and local ocean processes. The main products of these innovative approaches are again maps of the acoustic field, which need to be interpreted.

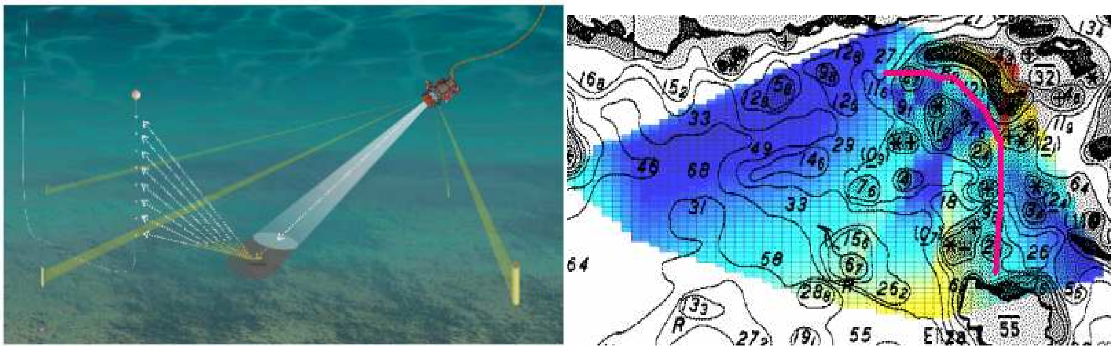


Figure 2.- Innovative instruments include bistatic sonars (left, from [18], as used in buried waste assessments) and passive imaging (right, from [20], correlating acoustic noise and whale feeding behaviour in British Columbia, Canada).

SEAFLOOR CHARACTERISATION

Interpretation, however, is often restricted to skilled specialists of different disciplines, and experience shows that an interpreter used to mid-ocean ridge volcanism will have problems adapting to mapping bioherms in a shallow-water habitat and *vice versa*. The huge amounts of data collected add to the complexity of the task: analyses of sonar mosaics can take days, especially if they are affected by artefacts, either left from the processing or from the acquisition itself (i.e. nadir tracks, ship noise, interference from other sounders). Human interpretation is difficult to standardise, and in certain conditions it can be error-prone. Computer-Assisted Classification (CAC) is therefore highly desirable. It is achieved in three stages: segmentation, classification and characterisation. Segmentation defines the partition of an image into several regions with distinct numerical characteristics, but with no interpretation. Classification goes one step further, and recognises these regions are also distinct physical entities, even if a physical feature can correspond to several partitions (e.g. "mud = partition 1 + partition 2") or a partition can correspond to several physical features (e.g. "corals and aggregated rubbles"). Characterisation is the next step, in which the regions are associated to definite characteristics: physical (e.g. particular density), chemical (e.g. oil slick or metal target), geological (e.g. turbidite) or biological (e.g. *Posidonia* clump). These three stages are often confused, for marketing reasons or because they have overlapping definitions in different disciplines.

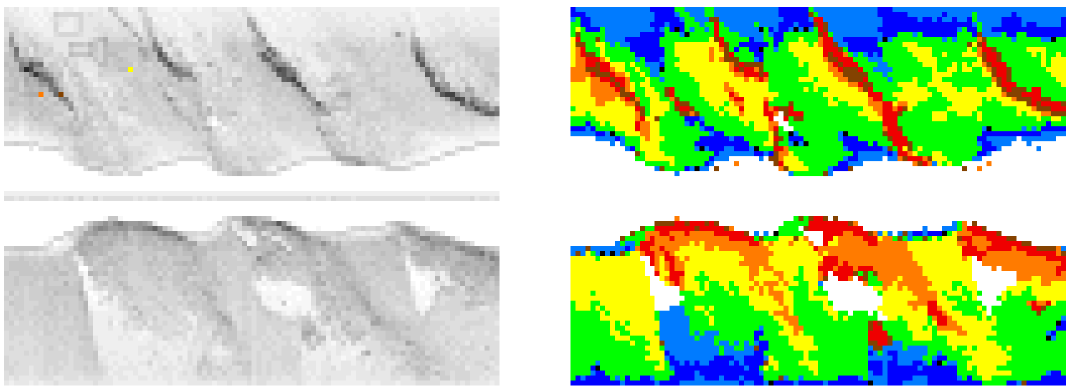


Figure 3.- Example of seafloor characterisation on a sidescan sonar record (courtesy GeoAcoustics Ltd.). Specialist software correctly identifies the different seabed types. But their exact characterisation requires a skilled interpreter or calibration with pre-existing data.

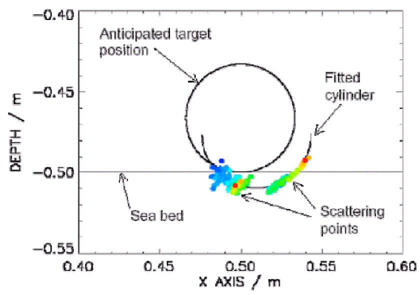
Image-based characterisation

Many techniques exist to characterise the seabed from its acoustic maps. They have been reviewed in [22] and only a few will be presented here, due to lack of space. QTC-View is a famous commercial system [23]. This system uses a large number ($\geq$ 166) of statistical descriptors at the echo level and at the image level, reduced to 3 descriptors by Principal-Component Analysis. These descriptors are enough to classify different types of seafloor, although the exact physical meaning of each descriptor is not available. System calibration needs to be performed before each survey, by collecting a few hundred echoes at sites representative of the region to be surveyed (as indicated by seabed sampling). New seabed classes can also be recognised during post-processing. TexAn [24] is a different system, working on the textural information available in the image. They are quantified with a stochastic method based on Grey-Level Co-occurrence Matrices, from which two parameters (named entropy and homogeneity) are derived. These statistical descriptors can be directly related to physical/acoustic processes. Entropy measures the lack of spatial organisation in the local texture, and is related to the roughness. Homogeneity is directly proportional to the amount of local similarities and has been modified to describe local textural organisation. This technique requires prior experience in a similar context or input from an interpreter to extend the classification into a full characterisation but can detect details invisible to the human eye, however experienced. Multibeam-based techniques need to be different from sidescan sonar ones, because of the distinct acoustic processes and processing schemes. Textural analyses, for example, do not seem to work very well, and conventional image processing schemes are hampered by the high speckle. Markov Random Fields have met with some success in multibeam imagery, associated to optimisation algorithms such as simulated annealing. Combining the angular backscatter response with local bathymetry is another approach of interest (e.g. [25]), showing good classification accuracies even at high surveying speeds (up to 16 knots). Other techniques, based on neural networks and Artificial Intelligence, have also been used, but only in selected applications and with limited results. These different approaches and software have been validated in many applications (particularly QTC-View and TexAn), and they provide accurate maps of specific characters of the seabed, user-defined or selected automatically on the basis of statistical criteria. But even when accurately recognising seabed regions or objects based on their acoustic characteristics, they usually cannot provide accurate characterisation and unambiguously identify a particular region as “coarse sand with long-wavelength ripples” or “hollow metallic target”. Apart from obvious cases or simplified analyses (e.g. outcrop on smooth sediments), the exact interpretation of each classified region still requires the need of a skilled interpreter. The thresholds for classification will also depend on the software, or on the application, some of them favouring the detection of even very small classes, on the basis that they might be significant (e.g. mine in cluttered background), whereas some will favour merging regions to provide maps more similar to what a detailed visual interpretation would yield. Could more local analyses of the acoustic scattering help to achieve full and systematic characterisation?

Point-based characterisation

Local scattering has been the object of many studies, at first for echosounder measurements. Although the scattering patch can be large enough to encompass different types of seabed, and tempered by parameters such as the depth or directivity pattern, it is possible to compare the echo to a database of theoretical and actual shapes (e.g. [1]). Because of hardware constraints and processing time, this is usually limited to a fixed number of seabeds (7 in this case), of direct use to the intended community (e.g. fisheries). Refinements have used fractal analyses and neural networks (e.g. [2]). The Roxann system was developed in the late 1980s and uses two values derived by integrating the tail of the first echo and the full second echo. The former, E1, is associated to seabed roughness and the latter, E2 corresponds to its “hardness”. Two-dimensional displays of E1 vs. E2 are used to characterise different types of seabed. The original signal is irreversibly affected by the processing, and Roxann requires calibration each time it is installed on a new system/platform. Nonetheless, it is widespread and has been used in many areas. Similar techniques have been used on multibeam waveforms, compared with databases or analysed in multivariate space (e.g. [26]). Some of these techniques provide relatively accurate characterisations of the seabed, although it is based on ad hoc evidence, corresponds to relatively large scattering areas and is sometimes proved inaccurate by seabed sampling.

Some of the innovative techniques presented earlier offer the potential for more detailed measurements. For example, multistatic sonars have been shown to detect even small targets and differences within (e.g. [15,27,28]). As Figure 4 (left) shows, the individual scatterers making up objects and/or the seabed can be identified. For each, the scattering strength will be associated to a single configuration geometry (incidence angle, scattering angle, bistatic angle). These can then be used in the plethora of scattering models that aim at explaining the acoustic response from sediments (e.g. [29,30,31,32]) or targets [33,34,35]. Figure 4 (right) shows however that distinct physical characteristics could yield the same acoustic response, adding ambiguity to the characterisation if only one geometry is used. These acoustic models, however complex and thorough, are however based on approximations to intricate mathematical descriptions of scattering, and fine-tuned to simple cases (e.g. silt or sand, unmixed, or metal cylinders, but with no dents). A high amount of work has gone into these models in the last decades, but their application to real-world problems is often limited by the much lower amount of experimental validation available. This can be contrasted with the situation for electromagnetic scattering in the microwave region, where a high amount of theoretical work has gone in pair with a high amount of experimental validation (arguably much more easily attainable). The end-users of planetary radar imaging can now be provided with equations and tables, directly associating one measurement (frequency, geometry, scattering strength) to one type of terrain or target, unambiguously defined. This is not the case (yet?) for acoustic measurements.



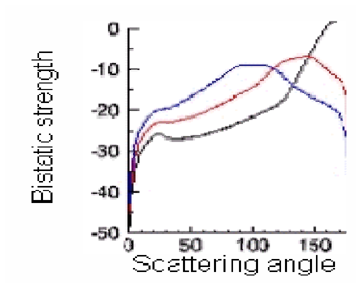


Figure 4.- Left: reconstruction of a target imaged by a multistatic sonar (Blondel et al., 2006). The exact geometry of acquisition is known for each individual scatterer, and acoustic simulations could explain the range of physical characteristics yielding this scattering. Right: example from the “Jackson” model of bistatic sediment scattering(APL-UW, 1994), for different roughness values. Note how some curves overlap, meaning that an individual measurement could be characterised in a non-unique way.

CONCLUSIONS

This article aimed at showing the important advances that have been made over the last decades, both in terms of instruments for mapping the seabed and in terms of characterisation tools. Existing instruments have become much more accurate and powerful, whilst new instruments such as multistatic sonars are fast becoming tools of choice for more local surveys. For each type of instrument, there exists at least one technique of classification and/or characterisation. However, except in highly controlled situations and homogeneous terrains, the results of characterisation can be very ambivalent or undecisive. This is particularly noticeable in certain types of applications, like shipwreck mapping. The interpreter looking at the seabed away from the wreck will be able to use traditional characterisation tools. Closer to the wreck, the seabed risks being littered with cargo and debris, and characterisation will often be limited to recognising different types of objects likely to not be part of the seabed, but will not find what they are (fishing net? metal grid? ballast? unrelated lobster pot or outcrop?). The challenge of providing accurate and general characterisation tools, across all types of seabed mapping, has not been won yet. The example of radar imaging shows it can be addressed by closely integrating the mapping tools, the scattering models and the experimental validation in a wide variety of contexts.

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