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Developments in the application of multibeam sonar backscatter for seafloor habitat mapping

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ABSTRACT

Human impacts on the seafloor environment have reached unprecedented levels. To facilitate ocean management and mitigate these impacts, there is a need to improve our understanding of seabed habitats. Recent developments in acoustic survey techniques, in particular multibeam echosounders (MBES), have revolutionised the way we are able to image, map and understand benthic ecosystems. Using MBES, it is now cost-effective to image large areas of the seafloor, and such surveys provide baseline data from which thematic maps of the seabed environment, including maps of benthic habitat, can be derived and interpreted in conjunction with in situ ground-truthing data. This paper provides an overview of recent developments in the application of MBES for seafloor habitat studies, with a focus on the use of backscatter data for surficial geology and habitat mapping. In March 2006, a MBES backscatter workshop brought together a number of international research teams/groups working on novel methods for interpretive/classification routines for segmentation of the backscatter into acoustic classes with the potential to facilitate the delineation of seabed geological and habitat characteristics. This paper introduces the common data set used as part of the workshop, sets out the research context in which the different studies were conducted, and outlines the main themes of the papers presented in Section 6.

1. Introduction

More than half of the world's population live within 100 km of the sea, with 13 out of the 15 largest cities in the world on or near the coast. Effects of denser population and accelerating climate change include the disappearance of ecosystems, coastal erosion, over-fishing, marine pollution and a higher vulnerability to marine disasters such as tsunamis. With this increasing human pressure on the world's oceans, it is now widely accepted that there is an urgent need for improved spatial management of marine systems (e.g. [1]). Many human impacts are associated with the seafloor environment, and to assist management decisions there is a requirement for accurate and comprehensive maps of seabed characteristics including bathymetry, surficial geology and benthic habitat. Aerial and satellite remote sensing techniques are now widely used to produce accurate and detailed wide area maps of terrestrial regions which have proved invaluable for the spatial management of terrestrial systems [2–4]. However, the application of these techniques in marine systems is restricted to shallow water depths due to the limited penetration of light through seawater (and back), leaving the vast majority of the seabed environments beyond the scope of these methods. It is only recently, through developments in acoustic survey technologies, that marine scientists have been able to match the quality of terrestrial mapping efforts in the marine realm (e.g. [5,6]). In particular, developments in multibeam echosounder (MBES) technology have provided a mapping tool which is beginning to supersede other types of conventional acoustic survey systems (e.g. single beam echosounders, sidescan sonar) for wide-scale offshore mapping [7]. Using MBES, it is now possible to produce accurate, aerial-like images of the seafloor, and a number of nations are now using MBES to systematically map their territorial waters (e.g. Irish National Seabed Survey). This trend is exacerbated by the need to map Exclusive Economic Zones and inventory their resources (e.g. [8]). With increasing anthropogenic pressures on the marine environment, it is likely that this systematic offshore mapping approach will become more widely adopted in order to provide marine-based maps for management applications [1,6].

2. Habitat mapping

The term habitat is commonly defined as a place where a micro-organism, plant or animal lives [9]. Habitats can be defined on the assumption that organisms distribute themselves along environmental gradients and that their clusters define distinct sets of environmental factors. We can map habitats as spatially definable

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areas where the physical, chemical and biological conditions are distinctly different from surrounding areas [10]. Habitat mapping is therefore defined as the physical, complete description of a particular environment, both in space (seabed but also water column and immediate sub-surface) and in time (e.g. through the tide cycles or the seasons). This is an ideal definition, as it does not account for physical and technical limitations. Water column measurements are often limited to localised CTD/SVP profiles, with acoustic systems either removing data from the water column or compressing it beyond usability to focus on the seabed data. Similarly, sub-surface properties are usually known through localised sampling or imaging, and their acoustic expression is subsumed within the overall seabed scattering. Recent progresses in underwater acoustics (e.g. [19,31,36]) mean these limitations could be overcome through hardware/software developments in the next years. In most if not all cases, habitat mapping is therefore still restricted to the seabed and features on the seabed. Similarly, the ideal definition of habitat mapping as encompassing variations in time is limited by the difficulty of measuring, let alone mapping, biological and physical changes over tidal, seasonal or longer time frames. In most cases, then, habitat mapping is, and should be interpreted as, a snapshot in time.

In the terrestrial realm, habitat is often defined and structured by the dominant vegetation types or by human structures, which provide the physical setting and 3-dimensional structure of the habitat for associated fauna [11–13]. Optical terrestrial remote sensing methods are often able to distinguish and delineate vegetation type, and thus habitat, on the basis of spectral signatures combined with other associated remotely sensed measures (e.g. elevation, slope, etc.) [3]. In contrast, marine benthic habitats tend to be structured by their two- or three-dimensional geomorphological characteristics coupled with overlying hydrographic parameters [13], which makes them much more challenging to map. Indeed, these regions cover by far the majority of the seafloor environment. The exception are biogenic structures (e.g. coral reefs, sponge reefs, mussel beds) or shallow water habitats which are dominated by vegetation (e.g. kelp forests, seagrass beds), which have been mapped with a great deal of success using acoustic remote sensing methods (e.g. [14–18]),

The vast majority of the ocean floor, therefore, is structured and defined primarily by geomorphological characteristics. For many years, acoustic backscatter images (from sidescan sonar and more recently MBES) have been used to map these features (e.g. [19,20]) and strong links between acoustic backscatter and surficial sediment characteristics are reported in the literature (e.g. [21,22]). In these regions, the extension of the use of backscatter delineation to include the biology, and thus identify and map the habitat of the seafloor, is a logical progression since many studies detailing organism-substrate interactions, at least to some degree, report a link between benthic community structure and substrate type [23–25]. Many habitat mapping studies have applied this concept to equate benthic habitat with seabed substrate type, in some cases with some success [26–29]. However, our ability to delineate regions based on backscatter characteristics is often limited by the quality of the acoustic data, and this has been particularly apparent for MBES data sets.

3. Developments in MBES backscatter processing

Early MBES systems were extensions of single beam echosounders and both hardware and processing software have greatly evolved in the last 30 years (e.g. [7,30,31]). These instruments transmit several beams (up to more than 200 for some instruments), covering a wide swath on each side of the ship's track (up to 20 times the water depth in some cases). Their high-resolution bathymetry is generally calibrated to very high standards. With similar resolution, and exact co-registration, measurements of the variations in strength of the return signal give indications of seabed types and their geoacoustic properties (such as grain size, sound speed, density, porosity, roughness and volume parameters). MBES backscatter imagery is roughly similar to sidescan sonar backscatter imagery, which has been widely used for geological studies of the seabed over many years [19]. However, the backscatter imagery from a MBES was, until recently, far less satisfactory than the imagery from an equivalent sidescan system. This was mainly due to the lower along-track resolution of MBES systems (1–3°) compared to sidescan systems (less than 1°), and the optimal range of incidence angles for backscatter measurement achieved by a towed sidescan sonar system (which have lower grazing angles) compared to a hull-mounted MBES (e.g. [31,32]).

Recent on-going developments in data collection and processing of multibeam backscatter, combined with the availability of co-registered bathymetry, have drastically improved the quality of the imagery, giving as much or more information than is available with sidescan sonar alone [32,33]. Marine scientists are now turning to MBES in preference to sidescan sonar to produce high-resolution offshore seabed maps due to the benefit of collecting both bathymetric and backscatter data simultaneously [1,34,35]. MBES backscatter measurements can now be routinely recorded as (e.g. [36]): complete backscatter waveforms from each beam ("snapshots"), sidescan-like time series of amplitudes derived from snapshots by combining the backscatter signals from all beams ("pseudo-sidescan"), fragments of the full backscatter envelope around the bottom return signal from each beam ("snippets") and maximum amplitudes from each snippet (i.e. one value per beam). The amount and diversity of data available creates the need for appropriate MBES backscatter classification techniques and several approaches have been published over the last 15 years or so (cf. reviews in [36,37]). They can be divided into two rough groups: geoacoustic approaches, using additional information (e.g. from ground measurements) and feature-based approaches, using image analyses as with other types of sonar images (e.g. sidescan).

Geoacoustic approaches aim at matching individual backscattered waveforms to shapes expected from specific types of terrain (due to the sediment grain size, porosity, density, etc.). Validated for single beam echosounders (SBES) (e.g. [38–40]), these approaches have been extended to MBES data (e.g. [41]), sometimes incorporating other parameters as well, like the 132 features currently calculated by the commercial software QTC (e.g. [42,43]). More mathematically involved approaches have tried matching groups of returns to statistical distributions typical of distinct terrains (e.g. [44,45]).

Rather than looking at the full waveforms of individual returns, feature-based approaches try to find specific features at the local or regional level. Analyses of the bathymetry alone have included matching to specific templates (e.g. [46]), spectral analyses (e.g. [47]) and fractal analyses (e.g. [48]). They can be adapted to MBES backscatter measurements. Hughes-Clarke et al. [49] combine for example the angular response of backscatter with information from the local bathymetry. Mitchell and Hughes-Clarke [46] use a similar technique, adding measurements of topographic curvature to improve the precision. The angular variations of MBES backscatter have been used with models of amplitude-offset changes on series of stacked pings (e.g. [50–52]), or empirically (e.g. [53]). Other approaches used include Markov random fields (e.g. [54]), textures [55,56] and combination of several approaches (e.g. [43]).

The vitality of research into MBES backscatter classification techniques is evident from these few references, representative of a much wider set of publications (e.g. [57] and references there-

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in). Their applications have covered all depths, from abyssal plains to mid-ocean ridges and coastal waters. But their relevance to seafloor habitat mapping is not always immediate, and the comparison of their relative merits and/or their complementarities still needed to be done, preferably with a common data set.

4. MBES backscatter classification workshop: 30–31 March 2006

As part of the European Union Interreg funded MESH project (Mapping European Seabed Habitats: www.searchmesh.net [58]), a 2-day technical workshop was held at the University of Ulster, Northern Ireland, to bring together international research groups involved in the development of procedures and techniques for processing and interpreting MBES backscatter data.

Much of the research in this field is focusing on data cleaning techniques, image enhancement, and automated classification procedures for objective identification and mapping of acoustic facies (as visible in the previous section's review). The application of the findings from this research is highly relevant for benthic habitat studies on the continental shelf. Improved MBES backscatter imagery and automated acoustic classification procedures will directly benefit benthic habitat studies and have the potential to greatly improve our understanding of benthic ecosystems.

The workshop encouraged invited research teams to bring along examples of their own approaches/techniques for open discussion. The main objectives were to critically evaluate techniques and approaches for processing and interpreting MBES backscatter data in order to improve our understanding, identify future areas of research and provide recommendations of how MBES backscatter data is used for mapping seabed habitats. Workshop sessions covered topics on data processing, data quality assessment, backscatter classification, automated routines and habitat assessment.

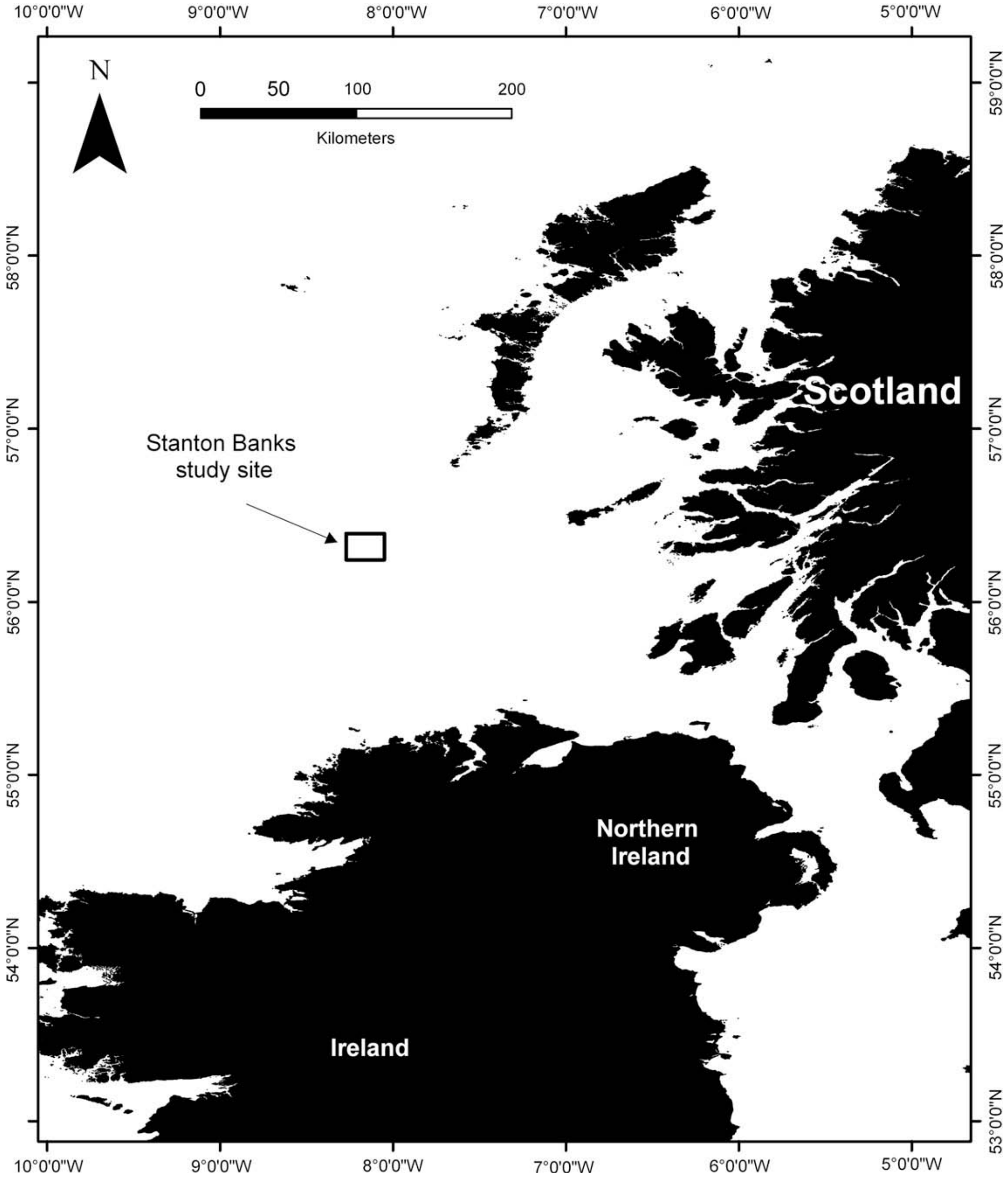

Fig. 1. Location of the study site: Stanton Banks, approximately 120 km north of Ireland, and 120 km west of mainland Scotland.

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Issues relating to accuracy, predictive capability and system limitations were also discussed in order to identify priority areas for further research.

Specifically the aims of the workshop were:

- To assess the utility of MBES data, in particular the use of backscatter data, for the production of seabed habitat maps.
- To review and discuss different approaches for improving MBES backscatter imagery.
- To discuss different automated backscatter classification techniques/ approaches for mapping benthic habitats.
- To identify knowledge gaps and future research areas.
- To report on the significance of the findings for the management and monitoring of marine benthic habitats.

5. Common data set

As part of the workshop, a common data set was made available to all workshop participants. It was collected as part of the MESH project over Stanton Banks, a site in the north-east Atlantic approximately 120 km north of Ireland and 120 km west of mainland Scotland, in water depths ranging from 60 to 190 m (Figs. 1 and 2). The survey site covered 7.5 km x 9 km, and was surveyed in November 2005 by the Irish Marine Institute, using a Kongsberg-Simrad EM1002S operating at 95 kHz, hull-mounted on R/V *Celtic Explorer*. Angular coverage was set at 130°, providing acceptable data density and quality. Primary positional data was acquired using the Fugro-Starfix High-Precision GPS system, providing ±0.2-m positional accuracy. Secondary positional data was acquired with the Kongsberg-Simrad Seapath (KSS) 200, also providing real-time heading, attitude, position and velocity by integrating the signal characteristics of the inertial measurement unit and the GPS. An AML Smart Sensor sound velocity profiler (SVP) directly fed the EM1002, whilst the self-contained Moving Vessel Profiler (MVP) 200 was used as required to measure CTD/SVP profiles. Bathymetric data quality was monitored online and corrective actions (i.e. additional SVPs and MVPs) taken in the case of data quality deterioration. Regular checks of processed lines were performed to test for mismatches between lines, due to differences in sound velocity or other sources of error. As sound velocity is a critical factor, a SVP graph was monitored regularly on the online EM1002 station to analyse changes in sound velocity.

MBES (bathymetry and backscatter) data were processed using CARIS/Hydrographic Information Processing System (HIPS) and CARIS/Sonar Image Processing Software (SIPS) v5.3 SP1 from Caris Ltd. Individual survey lines were tidally corrected using predicted tides from *Polpred* (Proudman Oceanographic Institute, Continental shelf Model CS3-30HC), calibrated by data from an Aanderaa WLR-7 self-recording tide gauge. Depth data were subsequently reduced to the Lowest Astronomical Tide based on Malin Head datum.

Data were made available to workshop participants as uncleaned measurements (*raw.all* formats) and as GeoTIFF files, along with all necessary ancillary information. Bathymetric and backscatter mosaics of the survey site are shown in Fig. 2. The MBES measurements were supplemented with ground-truthing data in the form of 90 seabed photographs, taken in June 2006 by *R/V Corystes* during a later cruise. The vessel was allowed to drift at

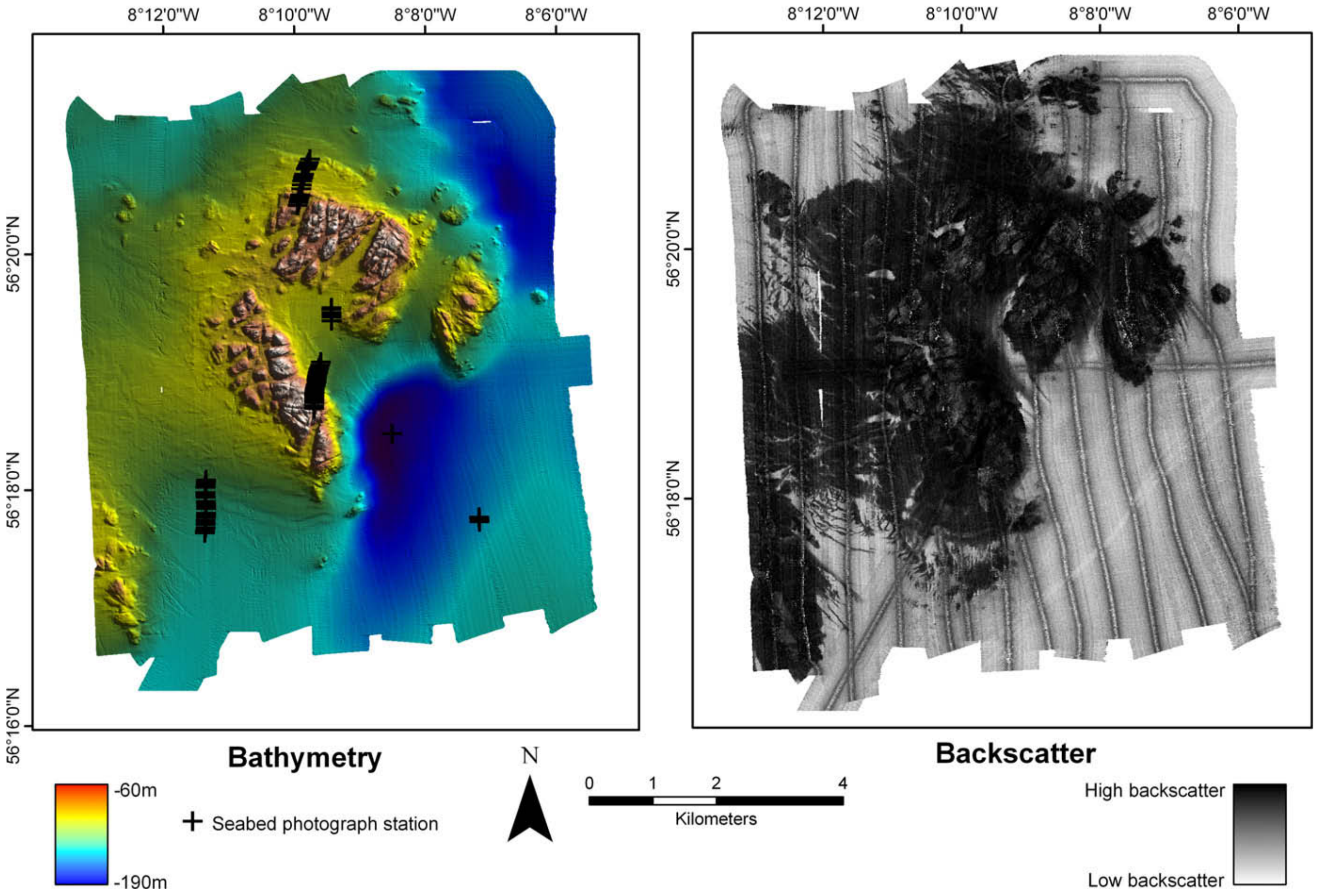

Fig. 2. Survey site at Stanton Banks: Left – MBES bathymetric data and photographic ground-truthing stations; Right – MBES backscatter mosaic.

each ground-truthing station to capture digital images of the seabed from a Simrad Osprey colour video camera mounted on a metal drop frame. The video system provided live images top-side and photographic stills images were collected at random intervals along the tow using a Photosea 1000A 35 mm (w/v) camera and a Photosea 1500S strobe. Vessel position was logged using differential GPS (DGPS) during each deployment and the tows were time-, data- and GPS-stamped. Positional data associated with each seabed photograph, along with a preliminary description of the dominant substrate type and any conspicuous fauna visible in each of the images, was made available in the form of a spread sheet as part of the common data set. Positions of the seabed photographs are shown in Fig. 2.

6. Special issue

The papers which follow in this special issue of *Applied Acoustics* describe a range of MBES backscatter classification techniques which have been applied to the common data set described above, and to a number of other data sets. The principles of backscatter interpretation for both MBES and sidescan sonar systems are described by Le Bas and Huvenne [32], and this paper provides an overview of current data acquisition and processing methods which are of importance for interpretation and automated classification of backscatter in the context of habitat mapping. The following papers present different approaches to the problem of classification. Ping-to-ping variability of MBES backscatter is analysed by Simons and Snellen [59]. They use a Bayesian approach, estimating both the number of seafloor types present in the survey area and the corresponding probability density functions of backscatter as a function of imaging angle. Working at the image level, Marsh and Brown [60] harness the potential of Artificial Neural Networks to classify backscatter and bathymetry together. A more local approach is taken by Preston [43], who combines empirical compensation of the surveying process with a large number of measures, the most significant of which are clustered using simulated annealing and a Bayesian metric. Techniques developed for sidescan sonar imagery are applied to multibeam backscatter imagery by Blondel and Gómez Sichi [56], who investigate variations in local acoustic textures (directly related to physical characteristics of the seabed), clustered using K-Means and an Euclidean metric. Finally, Fonseca et al. [52] combine mosaicking and angular response analyses in a constrained iterative inversion method. By investigating the same dataset, coming from different perspectives but striving toward and attaining similar results, these papers are complementing each other by showing the richness of different approaches.

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