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The use of multibeam backscatter angular response for marine sediment characterisation by comparison with shallow electromagnetic conductivity

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ABSTRACT

In this empirically-driven research, multibeam backscatter angular response analysis is presented, together with shallow electromagnetic data and groundtruthing, to examine its suitability as a proxy for sediment characterisation. Backscatter angular curves extracted from Kongsberg EM1002 sonar (95–98 kHz), acquired in the Malin Basin to the northwest of Ireland, have been selected as a case study. Standard angular backscatter features and newly derived curvature features are examined and cross compared. Exhaustive statistical analysis has been performed on the data to elucidate the complex relationship between multibeam backscatter and sediment properties. Subtle subsurface sediment property gradients across the basin identified by the conductivity system are also captured by the newly derived backscatter features. The results reveal that Near-range backscatter is better suited for subsurface sediment characterisation in soft, fine-grained sediments than far-range. Furthermore, the analysis has constrained the optimum interval for such characterisation to in-between 4° and 16° for the parameters of this study. A number of shape features (slope, first derivative, second derivative and Fourier-smoothed least-squares-fitted curvature) have been examined, and their suitability discussed, in terms of sediment characterisation and, in particular, as potential proxies for delineating the boundary between sand- or silt-dominated sediment facies. Nonetheless, curvature features are found to be independent from average angular backscatter response, but outperform both first and second derivatives when correlating with conductivity in the central part of this case-study with fine-grained homogeneous sediments.

1. Introduction

Multibeam echosounders (MBES) have become the most widely used technique for seabed mapping worldwide, with the result that large volumes of MBES data are now held in databases and widely used in a variety of marine disciplines. Exploitation of the relationship between acoustic backscatter (BS) and sediment characteristics in particular, has applications in many marine-related fields including marine benthic mapping [6,33], geotechnical studies [36] and marine spatial planning (e.g. [35]. Despite substantial theoretical and empirical research over the last decades (e.g. [29,38]; reviews by [1,2] the fundamental relationship between acoustic BS and sediment properties remains insufficiently constrained [1,13,26] and there is a particular lack of empirical studies examining the relationship.

The main parameters controlling high-frequency MBES BS response can be subdivided into interface (seafloor) processes, primarily acoustic impedance and seafloor roughness, and volume (subsurface) processes, primarily heterogeneity. Variations in the relative contribution of surface and subsurface controls with angle of incidence are, theoretically, intrinsic properties of the seafloor [28,15].

Seabed sediment characterisation using MBES BS has been performed, for the most part, using angle-compensated BS strength and image-based techniques (e.g. [13,19,37]). Although robust, this methodology is associated with an inherent loss of information during the angle normalisation process and, because normalisation

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is usually to a large angle of incidence, the data produced are, from a theoretical perspective, more suitable for analyses focusing on the sediment surface rather than the subsurface.

The potential of non-normalised, angular response curves for seabed discrimination was first explored over two decades ago by de Moustier and Matsumoto [9], Hughes Clarke [28] and Hughes Clarke et al. [29]. This developed into Angular Range Analysis (ARA) after Fonseca and Mayer [14] which uses a formal mathematical model to link BS angular observations to sediment properties. More recently, angular BS has been used for predictive seabed mapping by Hamilton and Parnum [24] and Huang et al. [26]. Typically, angular BS analysis subdivides the BS returns into discrete sectors based on grazing angle: Near-, Far- and Outer-ranges (NR, FR, OR) from steepest to shallowest grazing angles respectively. The limit between NR and FR is determined by the changeover angle (~25°). The limit between the FR and OR is based on the critical angle (in general between 55° and 75°) beyond which the acoustic signal is mostly reflected at the seafloor interface. It is worth noting that the Fonseca et al. [15] study in angular BS analysis in the Stanton Bank used the same platform and MBES system as this study.

Recently, it has been reported that statistical parameters extracted from the angular response curves can be utilised to describe important BS features while being insensitive to minor systematic variations and bias [14,29,28]. In particular, both the mean and slope are found to provide useful information for predictive seabed mapping [26,27]. Consideration of geometrical properties using other features, such as curvature, could provide further insights into the sediment properties.

In addition, over the last decade a number of studies have, with some success, used angle-normalised MBES BS data as a direct proxy for specific seabed sediment properties [18,19] most commonly sediment grain size (e.g. [8]). However, the grain size parameters explored are only a subset of the indices available for describing seabed sediments and sub-surface properties in particular, for example porosity or compaction, are conspicuously understudied. Electric conductivity measurements from marine electromagnetic surveys, as used in this study, offer an exceptional opportunity to address this lack as they provide information on subsurface properties over a continuous area and can, therefore, be directly compared with the subsurface signal captured by MBES BS data. The ability of conductivity to accurately capture bulk sediment properties has been well established in the literature [12] and Baasch et al. [4] report using electric conductivity and magnetic susceptibility from marine electromagnetic profiling data to identify and map sediment facies on a clastic shelf system. Furthermore, in homogenous, soft, fine-grained sediments conductivity can be confidently converted into apparent porosity using well established empirical models [3,31]. The unique geophysical dataset presented here, therefore, offers an unprecedented opportunity to compare bulk sediment properties, in terms of conductivity, with the MBES BS angular response.

This paper examines the relationship between MBES angular BS observations and shallow conductivity measurements in order to explore the relationship between seabed sediments and the different angular BS domains. In this way a new, robust BS feature suitable for characterisation of unconsolidated near-seabed sediments is proposed. Sub bottom data and shallow sediment cores have been used to aid in this process.

2. Data acquisition and processing

2.1. Case study: Malin Basin

The study area is located in the Western and Central part of the Malin Basin, on the Irish continental shelf, approximately 70 km offshore of northwest Ireland (Fig. 1). Water depth ranges from 140 to 180 m. The Malin shelf, in general, has complex geomorphology with unconsolidated glaciomarine sediments [11]. However, the Western part of the study area is characterised by soft, homogenous, fine-grained sediment and a smooth and flat seafloor. In the central Malin Basin, sediments are also fine-grained and homogenous but here they are punctuated by over 220 gas pockmarks formed in clusters around the main structural lineaments [16,34,39]. This part of the Malin Basin has previously been characterised in terms of electromagnetic (EM) data [16].

2.2. Multibeam backscatter data

Multibeam data for this study was acquired in 2003 as part of the Irish National Seabed Survey [10], using a Kongsberg EM1002 MBES operating at 95–98 kHz. The sonar, which comprises 111 beams, was used in equiangular mode with a regular angular coverage of 126°, pulse length of 700 μs and wavelength of 16 mm. Beam width is 2 × 2° with a typical footprint on the seafloor from 5 to 10 m^2. The uncalibrated, source amplitude BS was used to produce area-normalised BS strength. The conversion procedure, as is usual, was carried out by the system-specific acquisition software, together with the MBES hardware. Both the acquisition software and transducer hardware applied a series of corrections for source-level and receiver sensitivity, attenuation, spherical spreading in the water column and grazing angle effects as detailed by the manufacturer [25]. Of the many lines collected in the 2003 survey, line 182 was selected for this study as it is almost coincidental with the track of the electro-magnetic survey (no more than 50–150 m apart; see Fig. 1).

2.3. Electromagnetic data

The towed-electromagnetic (EM) system used in this study comprises three main components, the deck electronics, a transmitter, and the receiver string. The seafloor components of the system (transmitter and receivers) form a ~40 m-long array, which was towed in contact with the seafloor at speeds of 1–2 knots.

The EM transmitter, a horizontal magnetic dipole, generated harmonic magnetic fields over a range of frequencies (~200 Hz to 200 kHz), and the three receivers, tuned to measure these magnetic fields, were towed at fixed distances behind (4 m, 12.6 m and 40 m). At a given frequency, the strength of magnetic fields decays away from the transmitter as a function of the conductivity of the seafloor (i.e. according to the skin depth), decaying more rapidly in more conductive media. The sensitivity of the magnetic dipole–dipole system, along with the physics of the propagation of the fields through the seafloor are presented in Cheesman [7]. Further details of the system are given in Evans [12].

The conductivity measured is a function of the lithological character of the sediment to a depth of approximately half that of the distance at which the receiver is towed. Using EM data from the 12.6 m receiver only (EM13), the conductivity used in this study is therefore a function of the properties of approximately the first few metres of sediment while the MBES BS profiles are a function of the properties of the sediments shallower than 1 m depth [16].

2.4. Sediment characterisation

Sub-bottom profile data were acquired using a heave-corrected SES Probe 5000 3.5 kHz transceiver in conjunction with a hull-mounted 4 × 4 transducer array. Acquisition post-processing was carried out using CODA seismic software. An average estimated acoustic velocity of 1650 ms^{-1} was used to calculate the thickness of the shallow sedimentary units. Spatial resolution was circa 1 m