The effect of incident angle on statistical variation of backscatter measured using a high-frequency multibeam sonar

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ABSTRACT

Multibeam systems are capable of recording acoustic backscatter signals received from a wide swath of the seafloor. Backscatter characteristics are well correlated with morphological and physical properties of the seabed. Thus, a multibeam sonar system is a potentially useful tool for seafloor characterisation work. As part of the Coastal Water Habitat Mapping project, a subproject of the CRC for Coastal Zone, Estuary and Waterway Management, multibeam data and ground-truthing video data have been collected from various sites around Australia, including Cockburn Sound in Western Australia. One of the aims of the project is to investigate the capability of multibeam systems to map seafloor habitats. Initial work has concentrated on the processing of the backscatter pulse form. However, for the backscatter to be a useful tool in tracking changes in seafloor habitats it needs to be invariant to system settings, oceanic conditions and beam geometry. Most of these parameters can be easily corrected for, except for angular dependence of backscatter. Variation in backscatter due to incident angle is commonly seen in swath sonar images, typically as higher intensities at nadir angles than for oblique incidence, which can be hard to compensate. Here a new angular dependence correction algorithm, developed by the CWHM project, is examined to see how effective it is at correcting for this phenomenon. The results have implications for the use of multibeam sonar in seabed classification, which are discussed.

INTRODUCTION

Multibeam sonar (MBS) systems are one of the most effective tools available to map the seafloor (Kenny et al. 2003). This is because MBS systems are capable of recording acoustic backscatter signals received from a wide swath of the seafloor. These signals are primarily used to derive high-resolution bathymetry, however, in recent years research has concentrated on utilising the backscatter signal to infer certain physical properties of the seafloor. Acoustic backscatter characteristics are well correlated with morphological and physical characteristics of the seabed. Thus, a multibeam sonar system is a potentially useful tool for seafloor characterisation work.

As part of the Coastal Water Habitat Mapping (CWHM) project, a subproject of the CRC for Coastal Zone, Estuary and Waterway Management, multibeam data and ground-truthing video data have been collected from various sites around Australia, including Cockburn Sound in Western Australia. One of the aims of the project is to investigate the capability of multibeam systems to map seafloor habitats in shallow coastal waters. Initial work has concentrated on the processing of the backscatter signal to derive parameters to be used for seafloor classification. Part of this work involves the adequate correction of the backscatter images to make them independent of incident angle to enable further analysis for seafloor characterisation work. In this paper, we consider the effects of incident angle on high frequency backscatter intensity and a new method of correction for those effects developed within the CWHM project.

Producing MBS backscatter images

At present, there are two main methods to log the backscatter signal in MBS systems: sidescan and snippets. Sidescan involves forming two wide-angle receive beams (port and starboard) that log a sidescan-like time series of intensities. Snippets are fragments of the individual ‘time series’ of intensities from each beam centred around the bottom pick. Although sidescan could potentially offer finer spatial resolution, snippets can be remapped on the seafloor with more precision, as they are co-located with the bathymetric samples. This means that seafloor images generated from snippets would allow a more accurate mapping of habitat boundaries and less uncertainty in monitoring studies, which are important issues in coastal management. Hence, the CWHM project has focused on utilising snippets for the production of backscatter images. The method adopted by the CWHM project is to estimate the surface backscatter coefficient (Medwin & Clay 1998) for each beam, using the average intensity (reduced to pulse width) within each snippet and is outlined by Gavrilov et al. (2005).

Correcting MBS backscatter data

The backscatter (snippet) signal received by MBS systems can be influenced by various parameters, which can be categorised into system settings (e.g. power, gain, pulse length, etc), acoustic propagation conditions (e.g. absorption and spreading loss), beam geometry (e.g. range, incident angle, foot print size, etc) and seafloor properties (seafloor roughness, acoustic properties). It is important that the received backscatter signal is fully corrected so that it is invariant to system settings, propagation conditions and beam geometry so that changes in the backscatter can be attributed to changes in the seafloor properties, and thus, be used to derive information about the substrate and geomorphology of the seabed.

Both system settings and acoustic propagation conditions are easily corrected for, however, artefacts in backscatter images due to beam geometry are less easy to remove. In particular, the angular dependence of backscatter strength can be persistent in backscatter images, characterised by stronger return at vertical incident angles, known as 'nadir striping' (Parnum, Siwabessy & Gavrilov 2004). Attempts made at correcting through theoretical models, which are usually based on Lambertian law, seem to be inadequate especially for the modern high frequency multibeam systems currently used for shallow water work (Parnum, Siwabessy & Gavrilov 2004). Furthermore, there are no universal models for angular backscatter correction suitable for every seabed type. The authors' experience has found that it is best to use an empirical approach, by removing the spatially averaged angular response derived for a set of pings from the backscatter data. This approach has been implemented by the CWHM project and is detailed in Gavrilov et al. (2005).

While the production of backscatter images should aim to compensate fully for beam geometry, the angular dependence information should not be discarded or lost as it is a fundamental characteristic of backscatter from rough surfaces that can be exploited for seafloor classification (Hellequin, Boucher & Lurton 2003; Hughes Clarke 1994; Parnum, Siwabessy & Gavrilov 2004). The method adopted by the CWHM project not only corrects for beam geometry, but also retains the angular dependence information to be used for seafloor characterisation.

Seafloor characterisation using MBS Backscatter

In shallow water surveys, very high frequency MBS systems are generally used as they offer much better spatial resolution. For example, the Reson 8125 (which is used in the CWHM project) operates at 455 kHz and can measure bathymetry with a resolution of a few centimetres. However, at such a high frequency the scale of seafloor roughness appears much larger than the wavelength of sonar signals, which in the case of the Reson 8125 is about 3 mm. Therefore, the relative phase of signals that are reflected from elementary scatterers on the seabed surface and contribute to the backscatter signals, will have a random distribution. Thus, statistical characteristics and distribution of backscatter can be used for backscatter characterization rather than individual backscatter samples (Hughes Clarke 2004).

This random variance in high frequency swath sonar backscatter data has lead to various approaches to seafloor characterisation using statistical measures of data distribution, *e.g.* measures of image texture, such as Grey Level Co-occurrence Matrices (GLCMs) (Huvenne, Blondel & Henriet 2002) and Probability Density Functions (PDFs) (Hellequin, Boucher & Lurton 2003). However, many of these methods rely on the MBS backscatter distribution being independent of beam geometry. Therefore, before work on seafloor classification can occur it is important to analyse primary parameters derived to determine the influence of beam geometry; in particular, artefacts in the data resulting from angular dependence of backscatter. This paper will examine the effects of incident angle on MBS backscatter data and its correction using the empirical correction (discussed above) over a homogeneous area of seabed.

METHODS

Study areas

The results presented were obtained from MBS data collected within a 50 x 150m area in the Cockburn Sound in Western Australia, and hereafter known as Site 1. Site 1 is 8±1m deep, and video data has shown the seabed type to be coarse, uncohesive, flat sand.

Table 1. RESON SeaBat 8125 Sonar Specifications.

Operating Frequency	455 kHz
Swath Coverage	120º (3.5 X Water Depth)
Beam Width, Along Track	1.0º
Beam Width, Across Track	0.5º (at Nadir)
Number of Horizontal Beams	240
Range Resolution	1.0 cm
Maximum Ping (update) rate	40 pings s^{-1}

Data collection

MBS bathymetric and backscatter (snippet) data were collected at Site 1 on 13 July 2004 using a Reson SeaBat 8125. Specifications of the SeaBat 8125 sonar system are given in Table 1, and the settings selected for Site 1 are given in Table 2. At Site 1 four transect lines (A)-(D) were repeated as closely as possible with the same orientation and vessel speed (7 knots).

Table 2. RESON SeaBat 8125 settings used for survey of Site 1 in Cockburn Sound.

Ping rate	16 pings s^{-1}
Transmit power	208 dB re 1 μPa
Pulse length	72 μs
Receiver gain	4 dB
Gain mode	Time Varying Gain (TVG)
Auto gain	off

Data processing

Snippets of the first 500 pings were processed using the method outlined by Gavrilov *et al.* (2005), which can be broken down into three main steps:

1. Estimate of surface scattering coefficient

Estimates of the surface backscatter coefficient (Medwin & Clay 1998) were calculated from the snippet data and corrected for spreading loss, absorption loss and footprint size.

2. Correcting for angular dependence

To correct for angular dependence of backscatter an empirical method was used, which calculates the average angular response for backscatter intensity level within a spatial window (here 100 pings) that slides along the swath line with a 50 per cent overlap. The average angular dependence was subtracted from the backscatter intensity level within each section of the swath line that spans the central half of the averaging window. Then the absolute level of backscatter was reconstructed by adding the average level measured within the interval of 30±2 degrees.

3. Gridding

A median technique was used to grid the data, which calculates the median within equal spaced cells. Using this method data were gridded to 0.1m, 0.25m, 0.5m and 1m cell sizes.

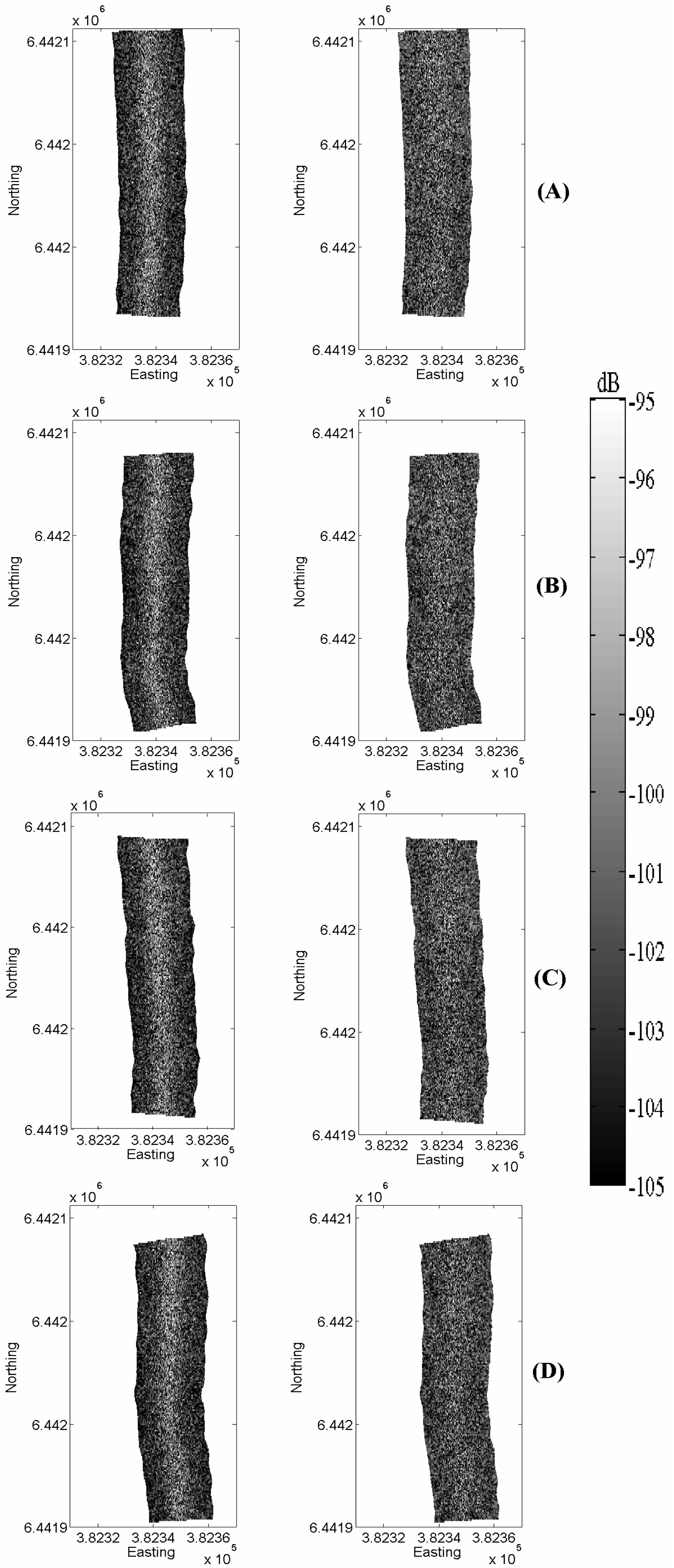

Figure 1. Ungridded backscatter images before (left column) and after (right column) corrected for angular dependence of transect lines (A)-(D).

RESULTS

1. Backscatter data over a homogeneous area of flat sand – before corrected for angular dependence

Backscatter strength images of the seafloor before and after correction for angular dependence of four separate transects (A) – (D) over Site 1 located in the Cockburn Sound, Western Australia are shown in Figure 1 (left column). Before correction, images show the characteristic higher values in the centre of the track, so-called 'nadir striping'. This geometric artefact is not only undesirable, but hinders further image processing techniques, such as texture analysis, which is useful for seafloor characterisation work.

The different distributions of backscatter values across the swath is more evident in histograms of the backscatter coefficient of the four transect lines (for selected beams) at vertical, moderate and far oblique angles, shown in Figure 2. At vertical incident angles (beams 121-126) for all transects the range of backscatter coefficient values is larger and its distribution is much flatter compared with far-oblique angles, which has a much more Rayleigh-like distribution. The difference seen here is due to physically different regimes of scattering within different angular domains (Jackson et al., 1986). At near-nadir angles, specular backscattering dominates the contribution of acoustic energy backscattered from the small-scale roughness of the seafloor surface and from volume inhomogeneities in the sediment. Since the horizontal scale of spatial change in the local slope can be larger than the beam footprint, backscatter samples of the seafloor by different pings may be statistically dependent, and therefore the distribution of backscatter energy may be different from the Rayleigh law. Moreover, a large difference between the specular and off-specular backscatter results in large dispersion of backscatter energy measured at near-nadir angles, which gives the wide-ranged histogram seen in Figure 2. At far-oblique angles of incidence, the contribution of specular scattering is negligible, if the large-scale slope of the surface roughness is not very high. In this regime, backscattering from the small-scale roughness of the seafloor surface and volume backscattering from the sediment contribute most to the backscatter energy. Both small-scale roughness and volume backscatterers are generally smaller than the beam footprint and the total backscatter energy is a combination of statistically independent contributions from elementary scatterers, which makes the backscatter distribution to tend to the Rayleigh-like one. The transition between these two domains is seen at the moderate angles. However, it is important to note, that while the distribution varies considerably across the swath, the backscatter distribution between transects is very consistent.

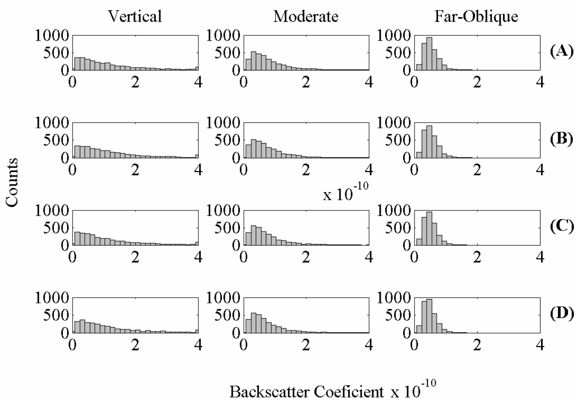

Figure 2. Histograms of backscatter coefficient not corrected for angular dependence at vertical (beams 121-126), moderate (beams 180-185) and far-oblique (beams 230-235) incident angles for transect lines (A)-(D).

2. Backscatter data over a homogeneous area of flat sand – after corrected for angular dependence

After corrected for angular dependence, backscatter strength images of transects (A) – (D) (Figure 1, right column) have a more uniform appearance across the swath compared with before correction (left column). In particular, there is a notable reduction in higher values in the centre of the track. This is supported by the track-average backscatter strength values at different angles of incidence measured across the swath for transects (A)-(D) before and after angular correction, shown in Figure 3. Before correcting for angular dependence, the mean backscatter strength at vertical incidence (Beam 120) is about 3 dB higher than that at far-oblique angles (Beams 1 & 240). Whereas, after the angular dependence correction is applied the mean backscatter strength is uniform across the swath. Figure 4 also highlights the previously mentioned consistency between transects, here shown by the mean backscatter strength, which for all corrected transects is -102 dB, which also happens to be the median for all corrected data.

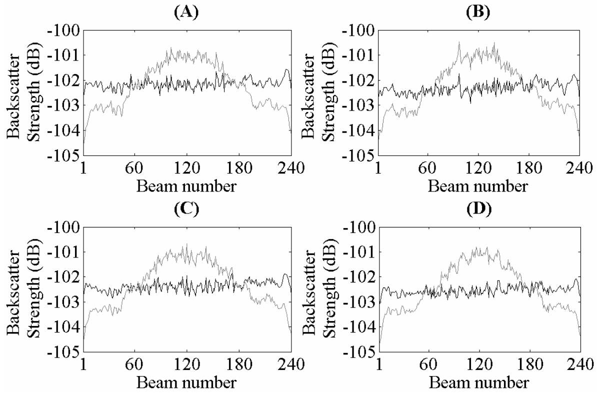

Figure 3. Mean backscatter strength across the swath for transect lines (A)-(D) with (black) and without (grey) correction for angular dependence.

While the images corrected for the angular dependence look visually better, the distributions of backscatter values across the swath, shown in Figure 4, has not significantly changed. Although the distribution at vertical incidence is less flat (with a more rapid exponential decay) and the mode at far-oblique angles is slightly less prominent than before correction, the distributions are very similar. There is still a significant difference in the distribution of backscatter from different angular domains. However, this is perhaps to be expected as the correction applied effects only first order statistics, such as the mean, but does not change the overall distribution of data or higher statistical moments. This is an important issue, particularly if statistical analysis of the backscatter distribution is to be utilised in seafloor classification. Specifically, differences in image texture or PDFs could be attributed to artefacts due to angular dependence of backscatter, not changes in seafloor habitat. However, to implement such analysis data usually requires gridding, which should have an averaging effect on the data. The extent to which this removes this angular artefact is examined below.

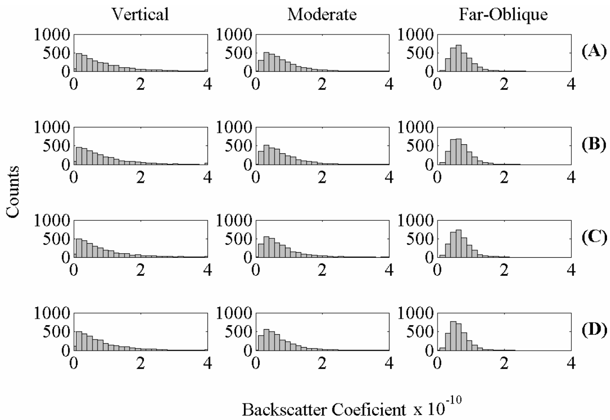

Figure 4. Histograms of backscatter coefficient corrected for angular dependence at vertical (beams 121-126), moderate (beams 180-185) and far-oblique (beams 230-235) incident angles for transect lines (A)-(D).

3. Backscatter data over a homogeneous of flat sand – with correction for angular dependence and gridded

Backscatter images of transect (A) corrected for angular dependence and gridded to 0.1-m, 0.25-m, 0.5-m and 1-m cell size are shown in Figure 5. The effect of smoothing by gridding is evident, for instance, the spatial variability of backscatter strength values in a 0.25-m grid is notably higher than in 1-m grid, which is to be expected.

The extent to which the gridding process has removed differences in backscatter distribution due to angular effects can be seen by tracking the standard deviation (a second moment) of backscatter strength across the swath, shown in Figure 6. There is no significant difference in the standard deviation of backscatter strength for non-gridded data with and without angular dependence correction for all transects. Both show a higher standard deviation at vertical incidence (Beam 120) than that at oblique angles, which tails off either side of the centre. Although data gridded at the smallest cell size (0.1m) for all transects has a lower standard deviation of backscatter strength than ungridded data, it still exhibits across the swath differences, suggesting that this data set still contains angular artefacts. However, as the cell size increases the standard deviation of backscatter strength across the swath not only decreases, but also becomes more uniform. For the data gridded at 0.5m and 1m there shows no sign of correlation between the standard deviation and incident angle.

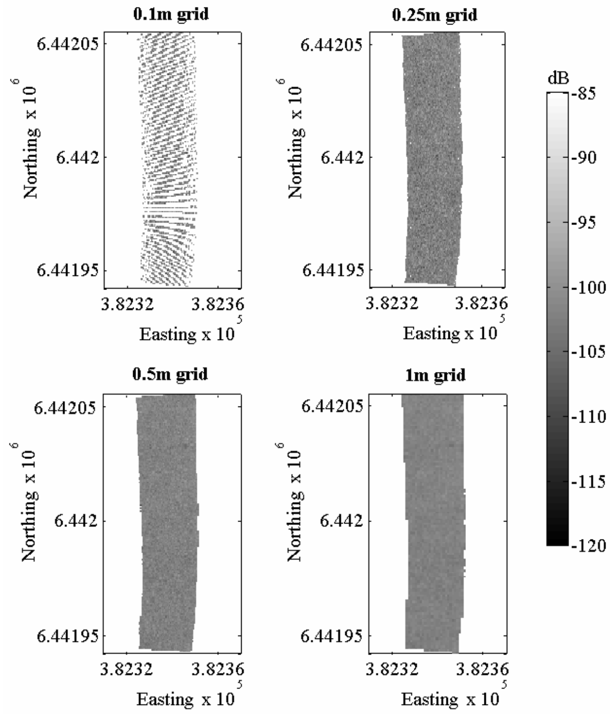

Figure 5. Backscatter images of transect (A) corrected for angular dependence and gridded to 0.1m, 0.25m, 0.5m and 1m cell sizes.

While gridding suppresses the effect of angular dependence, it also smooths the data, which could mean losing information about the seafloor properties. This effect is demonstrated in Figure 7, which gives the normalised histograms of data from Figure 5 (i.e. Transect (A) gridded to 0.1m, 0.25m, 0.5m and 1m) along with the ungridded backscatter strength of transect (A) with and without angular dependence correction applied. The difference in distributions between ungridded data is a slight shift (0.3 dB difference between median values), for reasons given previously. As cell size increases, not surprisingly, the range of values decreases. Again the mean and median remain reasonably uniform, but PDFs and higher order statistics,

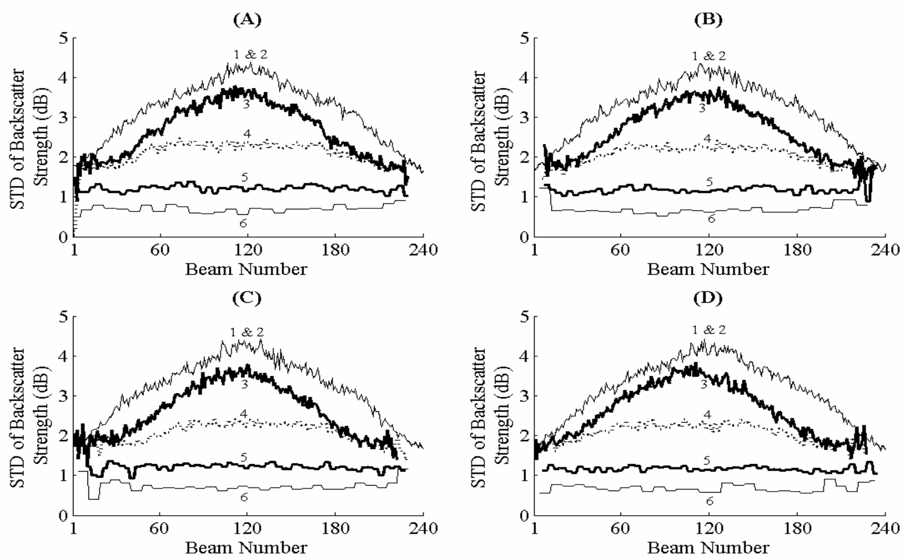

Figure 6. Standard deviation of backscatter strength across the swath for transect lines (A)-(D) not gridded (1) with and (2) without correction for angular dependence, and for corrected data gridded to (3) 0.1m, (4) 0.25, (5) 0.5m and (6) 1m cell sizes.

which are potentially more useful in seafloor classification work, will change. Thus, there is a trade-off when gridding data, the cell size needs to be big enough to remove beam geometry artefacts, but not so big that useful information is lost.

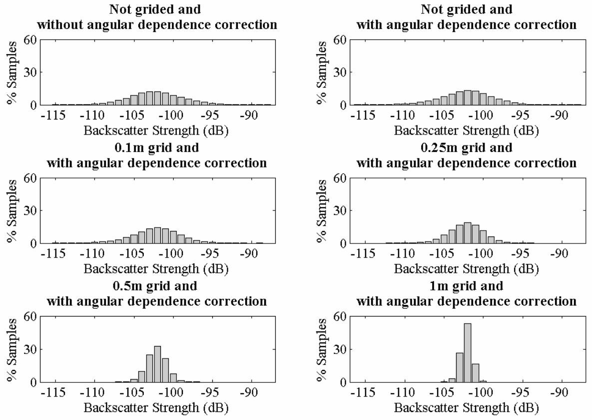

Figure 7. Histograms of backscatter strength for transect (A). Top row: ungridded data both with and without correction for angular dependence. Bottom two rows data corrected for angular dependence, and gridded to 0.1m, 0.25m, 0.5m and 1m cell sizes.

The optimal gridding size and the possible use of interpolation techniques are beyond the scope of this paper and require further work. Nevertheless, for the current data set 0.5m seems an appropriate cell size to grid the data. However, this is specific to this data set, the optimal grid size will change with various factors, including water depth, seabed type and multibeam system used to collect the data. For instance, in deeper water the footprint size will be larger (as well as the number of samples in the snippet signal), and thus, this could potentially reduce the effect of incident angle on the backscatter distribution, but the density of data will be coarser; so that will have to be taken into consideration in deciding what cell size to grid data. Also, for this work the Reson 8125 was used to collect the data, and this unit uses a flat receive array, which means the across-track beam width increases with increasing incident angle. Whereas, systems using a circular receive array, e.g. the Reson Seabat 8101, which has a uniform across-track beam width, will possibly reduce the effect of incident angle on backscatter distribution. So, these factors need closer examination.

CONCLUSIONS

Multibeam systems are a useful tool in seabed mapping, providing high-resolution backscatter data across a wide swath of the seafloor. The backscatter distribution data remained consistent between transects over the same area of homogeneous seafloor. However, along track banding caused by angular dependence needs to be corrected to allow characterisation techniques, such as texture mapping, to be successful. A new empirical angular correction algorithm has been demonstrated, which provides visually equalised images. Nevertheless, even after this correction has been applied the distribution of backscatter variation is still very different across the swath. To help solve this problem data can be gridded, which has an averaging effect, and at large enough cell sizes reduces the influence of incident angle on backscatter distribution. However, the process of smoothing can also remove valuable information about the properties of the seafloor. Thus, there is an optimal cell size, one that is large enough to remove angular artefacts, but still retains useful information about the seafloor. Further work is needed in examining the effect of different depth, seabed types and multibeam systems on angular variation in backscatter distribution.

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