Applied Acoustics 70 (2009) 1298–1304

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Angular range analysis of acoustic themes from Stanton Banks Ireland: A link between visual interpretation and multibeam echosounder angular signatures

Luciano Fonseca [a,*], Craig Brown [b], Brian Calder [a], Larry Mayer [a], Yuri Rzhanov [a]

[a] *Center for Coastal and Ocean Mapping, University of New Hampshire, Durham, NH 03824, USA*
[b] *Centre for Coastal and Marine Research, School of Environmental Sciences, University of Ulster, Cromore Road, Coleraine Co. Londonderry BT52 1SA, UK*

ARTICLE INFO

Article history:
Available online 5 November 2008

Keywords:
Multibeam sonar
Backscatter
Benthic habitat
Seabed properties
Acoustic classification

ABSTRACT

Acoustic backscatter mosaics derived from multibeam and sidescan sonars are often used to estimate seafloor type and composition, which are important parameters in the description of benthic habitats. However, due to limitations of the mosaicking technique, backscatter mosaics are restricted in their capacity to unambiguously discriminate seafloor properties. A more adequate technique to characterize the seafloor is the analysis of backscatter angular response, since this response is an intrinsic property of the seafloor. Angular response analysis sometimes lacks spatial resolution, however, as this approach is limited to the swath width of the sonar. In this paper, we propose an approach to combine mosaicking and angular response analysis techniques in an attempt to take advantage of both the spatial resolution of the mosaic, and the angular resolution derived from the angular response analysis. The proposed method for analyzing the backscatter mosaic together with the backscatter angular response is applied to the acoustic backscatter acquired by a Simrad EM1002 multibeam sonar (95–98 kHz) on Stanton Banks, to the west of Scotland. First, a normalized acoustic backscatter mosaic is prepared for the survey area. Then, visual interpretation of the mosaic produces areas on the seafloor with similar textural patterns that we call acoustic themes. Finally, the average backscatter angular response of all the backscatter samples that fall within the same acoustic theme, regardless of the acquisition line they belong to, is compared to a formal mathematical model that links acoustic backscatter observations to seafloor properties. The inversion of the model is accomplished with a constrained iterative method known as angular range analysis (ARA), which produces estimates of the same acoustic impedance, roughness and the mean grain size of the insonified area of the seafloor. The results of the ARA inversion are compared to bottom photographs acquired in the area delimited by the acoustic theme, showing a very good correlation. The ability to discriminate benthic habitats may therefore be improved using this approach.

1. Introduction

The analysis of multibeam sonar data produces bathymetric models and acoustic backscatter mosaics, which can be used to derive estimates of the seafloor's spatial distribution of relief (and relief derivatives such as slope and rugosity), bottom type and composition. Traditionally, these estimates of seafloor properties have been used for geological mapping of the seafloor, and links between acoustic backscatter and surficial sediment characteristics are reported in the literature, e.g. [1]. Extending these primarily substrate-defining acoustic signatures to include the biology 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 [2–4]. It is important to note that this link is only valid to a certain extent, and this subject is still under discussion. Nevertheless, a number of seabed mapping surveys utilizing acoustic sonar techniques have used this concept to equate benthic habitat with seabed substrate type, in some cases with some success [5–9]. Although this simplified line of thought is intuitive (i.e. the habitat occupied by seabed organisms is the seafloor substrata), it should be recognized that substrate only becomes habitat when the intricacies of specified organisms are introduced. Therefore, a crucial step to adopting this approach is to establish the relationship between the seafloor acoustic properties and the surficial geological and biological characteristics of the seabed.

Backscatter information from multibeam sonar data offers a potential means to segment the seabed into acoustic facies – or more specifically acoustic themes (i.e. spatially defined regions with similar acoustic properties or features). Conventional, subjective, by-eye interpretation of sidescan sonar backscatter data has proven to be effective for delineation and mapping of seafloor habitats, particularly in regions where there are sharp demarcations

---

[*] Corresponding author. Tel.: +1 603 862 1862; fax: +1 603 862 0839.
E-mail address: luciano@ccom.unh.edu (L. Fonseca).

0003-682X/$ - see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.apacoust.2008.09.008

between neighbouring seabed types [5,6]. However, this approach is far less effective in areas where the level of seabed heterogeneity is high or where there is a gradual change in the seabed characteristics without clear demarcations in backscatter behavior [10,11]. This can lead to uncertainty or low confidence in the final habitat maps which are produced from such areas. A solution to this problem is to conduct objective automated classification of the acoustic data based on the backscatter signal. Although this can be difficult to achieve, it potentially offers a convenient method which may facilitate the delineation of benthic habitats. In this paper, we will concentrate our discussion on methods for mosaicking and for extracting seafloor type information from the backscatter measurements from a multibeam sonar data set.

There are two major obstacles in the preparation of backscatter mosaics. First, multibeam sonars do not normally record directly values of backscatter strength, but rather they collect data samples of relative magnitude that often do not come with any further documentation [12]. Second, even when it is possible to reduce the sonar observations to backscatter strength, we are still left with the task of removing the backscatter angular response, which represents the way that the backscatter strength changes with the angle of incidence. The removal of the backscatter angular response is an essential step in order to produce mosaics that show consistency across the swath (for a homogeneous seafloor), and not an angular variation. Removal of angular variation is not an easy task, as the angular response is an intrinsic characteristic of the seafloor. Therefore, we need to know something about the seafloor prior to assembling the backscatter mosaic. This presents a dilemma, as the primary idea behind assembling acoustic mosaics is to obtain some insight about the nature of the seafloor.

Surprisingly, the same angular response that creates a problem in the assembly of easily interpretable backscatter mosaics is a critical component of many approaches to remote seafloor characterization. Numerous studies have shown the potential of using the angular response of the seafloor for the remote estimation of seafloor properties [13–16]. Examples of important seafloor acoustical and physical properties that can be estimated based on angular response analyses are grain size, acoustic impedance, acoustic attenuation and the acoustic roughness of the near-surface sediments. As with the mosaicking problem, there are two major obstacles to the analysis of angular response. First is the requirement of having accurate measurements of backscatter strength. Second is the implicit assumption that the seafloor is uniform across the swath, which is often not the case.

2. Spatial resolution versus angular resolution

Given the importance of the angular response, it becomes obvious that any mosaicking procedure that requires the removal of angular response information to produce coherent mosaics (the general case) reduces our ability to derive quantitative seafloor characterization information. Thus mosaicking results in a loss in angular resolution, in that it is a many to one mapping. On the other hand, the analysis of angular responses preserves the full angular resolution of the sonar signal, and consequently our ability to characterize the seafloor. However, this analysis is limited to the swath width of the sonar, which reduces substantially the spatial resolution. So we can say that mosaics have high spatial resolution, but low angular resolution, while the angular response analysis has low spatial resolution but high angular resolution. These two methods appear to be complementary.

One possible approach to combining these two methods would be to take advantage of the high spatial resolution of the mosaic, and use image processing techniques, like texture analysis, to segment areas with similar backscatter signatures. With that, we could then calculate an average angular response for the segmented area, and this average angular response could then be used for seafloor characterization as well as the assembly of a more accurate mosaic. For this work, we will visually separate areas on the backscatter mosaic with similar texture and gray level around the sites where bottom photographs were acquired. The result of this interpretation will define areas on the seafloor with similar acoustic responses, which we call themes. Each acoustic theme will have a characteristic average backscatter angular response, which is the stack (average per angular bin) of all the acoustic backscatter samples that fall within the acoustic theme, regardless of the acquisition line they belong to. This average angular response will then be compared to a formal mathematical model that links acoustic backscatter observations to seafloor properties.

3. From raw data to backscatter strength

In order to test the approach described above, we used acoustic backscatter acquired by a Simrad EM1002 (95–98 kHz) multibeam sonar during normal survey operations conducted on the survey vessel Celtic Explorer around Stanton Banks, west of Scotland in the spring of 2005 [17]. The digital numbers registered in the Simrad EM1002 sonar record are not exactly final normalized values of backscatter strength, so it was necessary to radiometrically correct them, and to geometrically correct and position each acoustic sample in a projected coordinate system [12]. First, all the gains and time-varying gains applied during acquisition were removed from the original observations using information provided by the manufacturer. Then, the observations were corrected for the terms of the sonar equation, which are: transmission loss, the actual area of insonification projected on the bathymetric surface, source level, and transmit and receive beam patterns. Additionally the backscatter values were corrected for the seafloor bathymetric slope, which came from the multibeam bathymetry. The result of this processing was the corrected backscatter angular response for the survey area. The technique presented here can also be applied to sidescan sonar time series, by reducing the raw sidescan observations to estimates of backscatter strength. The confidence in the calculations is limited though, as the acquisition geometry is only partially controlled and the bathymetric surface is often unknown.

4. From angular responses to mosaics

The corrected backscatter angular response cannot be directly mosaicked since the resulting mosaic would not be uniform across the swath, i.e. it will show high values near nadir, and lower values at greater incident angles. As an exercise, such a mosaic was assembled and the results are shown in Fig. 1a. It is clear that the resulting artifacts make the interpretation of the mosaic extremely difficult. The standard technique used to avoid these artifacts is the Angle Varying Gain (AVG) correction; the difficulty is in choosing which AVG curve to use.

There are many standard methods used to calculate the AVG corrections necessary to normalize the backscatter strength across the swath (e.g. remove the backscatter angular response). The most common ones are the Lambertian corrections with two parameters [19], Chebyshev filters [20] and moving averages [18,21]. All of these methods are empirical and equally valid from the perspective of data analysis and digital image enhancement and therefore the choice is subjective; there is not a unique or optimal solution for the problem of AVG removal. The solution will always be a compromise between the uniformity across the swath and the existence of artifacts. Once we agree upon a method for removing the angular response, we still have to normalize the backscatter values across the swath. The most common solu-

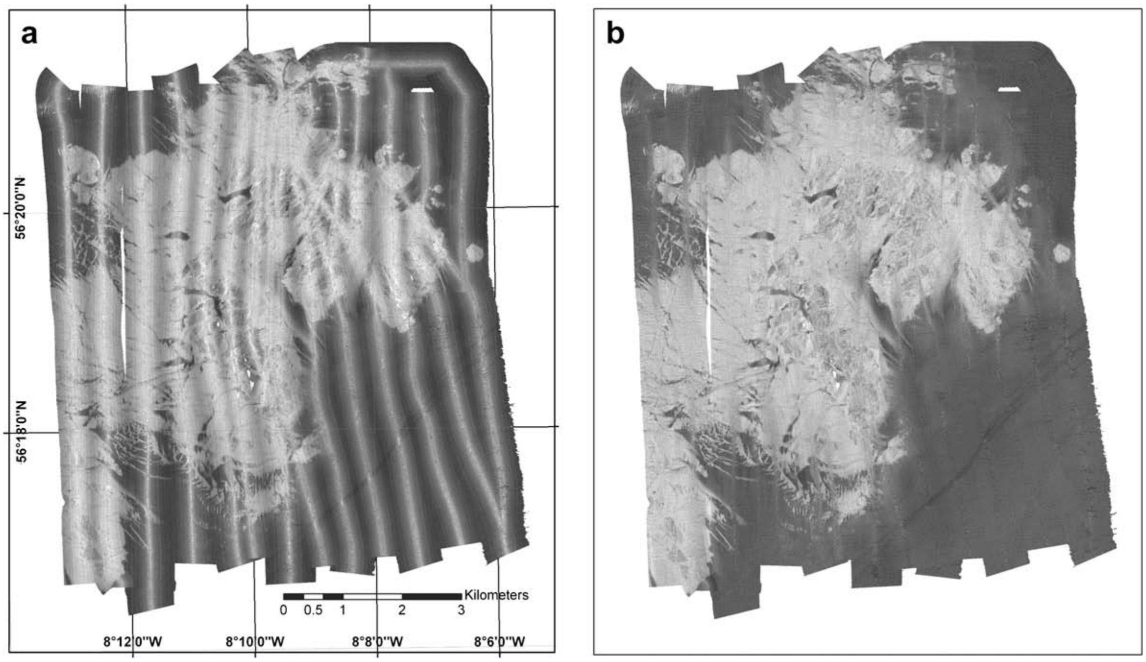


Fig. 1. (a) Acoustic backscatter mosaic of the surveyed area assembled with no AVG correction. The data were acquired with a Simrad 1002 (95 kHz) on Stanton Banks, Ireland. (b) Final acoustic backscatter mosaic (0.5 m resolution) with AVG correction and feathering between adjacent lines.

tion is to normalize the backscatter at 45°, but some approaches use the backscatter value at 10° as the normalization level. These approaches are equally valid, although they generate different looking mosaics; reinforcing the argument that the mosaic alone is a weak representation of the seafloor acoustic response. For the final corrected mosaic shown in Fig. 1b, the normalization was done to the average backscatter value calculated between grazing angles from 20° to 60°. Another source of artifacts in mosaics is the mosaicking technique, i.e. the way the overlap area between adjacent acquisition lines is shown in the final mosaic. In Fig. 1b we use a feathering technique suggested by Rzhanov et al. [22].

The choice of a suitable AVG correction method, of a normalization angle and of mosaicking technique are thus subjective, so that the mosaic is not a unique representation of the distribution of backscatter strength in the area. As a result, areas with different angular response, i.e. different sediment types, can be mapped to the same pixel value in a backscatter image mosaic (Figs. 2 and 4a, Area A). Furthermore, areas with similar sediment texture can be mapped to different pixel values in the backscatter mosaic (Figs. 2 and 4b, Area B). Consequently, the visual or pixel-value based analyses of mosaics may not be the most appropriate method for seafloor characterization. Instead, the inherent angular response should be preserved and used for this purpose.

5. Angular range analysis (ARA)

The variation of the backscatter strength with the angle of incidence is an intrinsic property of the seafloor, which can be used in more robust methods for acoustic seafloor characterization. Although multibeam sonars acquire backscatter over a wide range of incidence angles, the angular information is lost during standard backscatter processing and mosaicking. In this work we will use an approach called angular range analysis, which attempts to preserve the backscatter angular information, and use it for remote estimation of seafloor properties [16]. For that, a series of parameters are

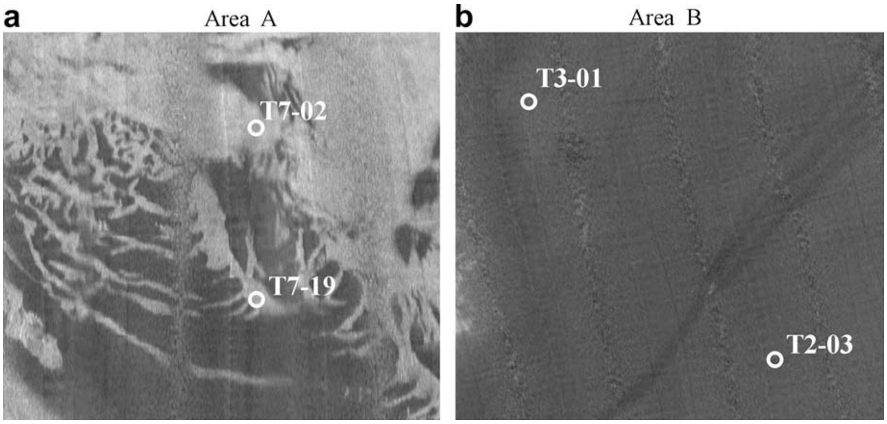


Fig. 2. (a) The areas covered by the bottom photographs T7-02 and T7-19 show different sediment textures (Fig. 7, acoustic themes I and III), but were mapped to the same value in the backscatter mosaic (−12.9 dB and −13.4 dB, respectively). (b) The areas covered by the bottom photographs T2-03 and T3-01 show similar sediment textures (Fig. 5, patches I and II), but were mapped to different values in the backscatter mosaic (−28.4 dB and −25.9 dB, respectively).

calculated from the stacking of consecutive time series over a spatial scale that approximates half of the swath width.

As described in Fonseca and Mayer [16], for the angular range analysis, several parameters are extracted from seafloor patches, which are defined as the stack of a number of consecutive sonar pings (normally between 20 and 30), chosen to approximate the dimension of the swath width in the along-track direction. Each stacked angular response defines two distinct seafloor patches, one for the port side and another for the starboard side. The stacked angular responses are then divided in angular ranges: the near range includes incident angles from 0° to 25°, the far range from 25° to 55°, and the outer range from 55° to 85° (Fig. 3). In the near range, four parameters are extracted from the seafloor patch: the near-mean backscatter, the near-slope, the near-intercept (at 10°) and the near-angle, which is the average grazing angle for all the sounding stacked in this range. In the far range, the parameters far-mean, far-angle, far-slope and the far-intercept at 40° are calculated, and in the outer range, only the outer-mean is extracted. The last parameter is the orthogonal distance, which is extracted from an intercept-slope graph [16]. The average angular response is then compared to a formal mathematical model that links acoustic backscatter observations to seafloor properties [23]. In the process of this inversion, the behavior of the model parameters is constrained by established inter-property relationships [24,25]. The inversion of the model produces estimates of the acoustic impedance, roughness and consequently the mean grain size of the insonified area of the seafloor. Applying this inversion procedure to all the patches in the Stanton Banks survey area, we obtain a map of the distribution of index of impedance (the product of sediment bulk density and sound velocity ratio) shown in Fig. 4a.

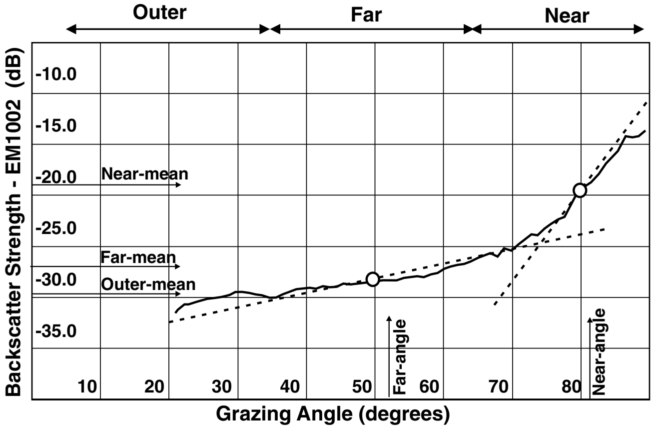


Fig. 3. Stacked backscatter angular response with some ARA parameters. Note the limits for the near, far and outer ranges. The dashed line at the near range defines the near-slope and the near intercept (white circle). Similarly, the dashed line at the far range defines the far-slope and the white circle 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.

6. Comparison with bottom photographs

The survey to collect bottom photographs was conducted on June 2006 aboard the RV Corystes, using a Simrad Osprey color video camera mounted on a metal drop frame [17]. The vessel was allowed to drift at each ground-truthing station to capture digital images of the seabed onto DVD for further analysis. Vessel position was logged using DGPS during each deployment. The camera frame was also equipped with a Photosea 1000 A 35 mm camera and a Photosea 1500S strobe. Photographs were randomly taken throughout each of the video tows and were time, date and position stamped from a ship-board GPS.

The bottom photographs used for the analysis are approximately 1 m^2 in dimension, and are not exactly co-registered with the backscatter mosaic. Even though a USBL system was used to obtain the position of the camera frame on the seafloor relative to the vessel position, there was still an uncertainty of around +/−10 m (due to a technical problem with the USBL system). How-

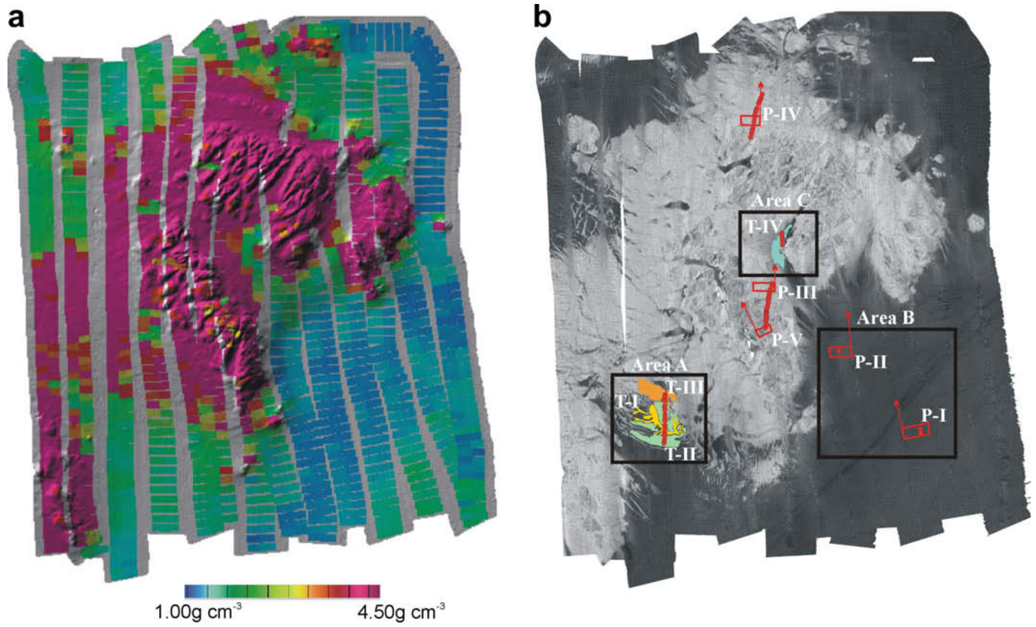


Fig. 4. (a) Map of the distribution of index of impedance for the survey area, obtained by calculating the ARA inversion for each seafloor patch. Note the lower resolution of the map (150 m), when compared to the mosaic resolution (0.5 m). (b) Location map showing the sites were bottom photographs were acquired (red circles) and the seafloor patches that were compared to the photographs (red boxes). The arrows show the navigation direction. The colored polygons show the four acoustic themes that were separated by visual interpretation in Areas A and C.

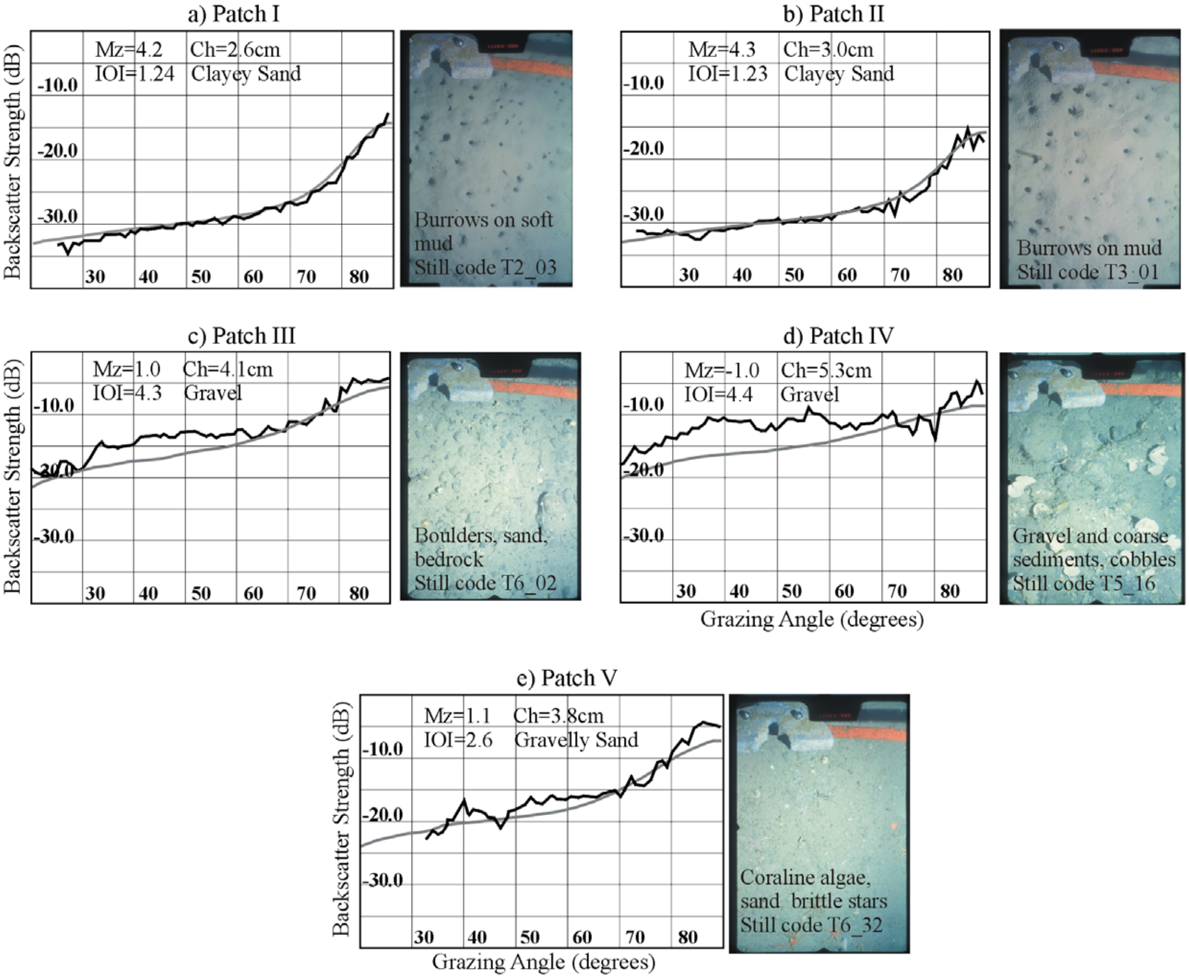


Fig. 5. Comparison between the result of the model inversion and bottom photographs. The solid back lines show the measured angular response inside the patch. The gray lines show the result of the model inversion. Mz is the mean grain size, Ch is a measurement of acoustic roughness (rms height difference for points separated by 1 m [26]), IOI is the index of impedance. The name of the sediment is given based on the mean grain size. The description of the photograph was done during the acquisition survey.

ever, most of the ground stations fall within relatively homogeneous acoustic areas and the degree of positional accuracy is sufficient for the purpose of ground-truthing the acoustic classification.

The comparison between the bottom photographs and the results of the angular range analysis is shown in Fig. 5. In the mosaic shown in Fig. 4b, the area enclosed by Patch II (P-II) had a higher backscatter than the area enclosed by Patch I (P-I). The bottom photographs show very similar sediments, and the ARA inversion converges to the same sediment (clayey sand). However, the ARA inversion confers to Patch II a higher acoustic roughness (3 cm) than to Patch I (2.6 cm). This difference in acoustic roughness may be a result of a higher degree of bioturbation in the area inside Patch II. The photographs obtained from Patches III (P-III) and IV (P-IV) show a rocky seafloor with gravel, bedrock and some sand. The ARA inversion converges to gravel, which is the upper limit for the gain size analysis. Nevertheless, Patch IV show a higher acoustic roughness (5.3 cm) than Patch III (4.1 cm), which agrees with the visual inspection of the photographs. The ARA inversion of Patch V converges to gravelly sand, and the bottom photograph shows coarse sand sediment with pebbles.

7. Acoustic theme analysis

The major limitation of this map shown in Fig. 4a is the low spatial resolution of the seafloor patches, which can be an issue in areas of high spatial variability. For instance, Fig. 6 (also shown in Fig. 4, Area A) shows an area where the angular response is not uniform across the swath, as it encompasses the complex boundary between two different seafloor types. The angular response of this area is clearly the combination of the angular response of the surrounding areas, and the ARA inversion shown in Fig. 4a is not able to discriminate the different facies inside the seafloor patch.

The simplest way to overcome this limitation in resolution is to use the high spatial resolution of the mosaic to define areas on the seafloor with similar angular responses – the acoustic themes – and calculate one average angular response per acoustic theme, rather than across the sonar swath. Thus the angular response would not be limited to the swath width of one acquisition line, but would rather relate to all beams from all acquisition lines that intersect a certain acoustic theme on the seafloor. The ARA inversion technique can be applied to this average angular response of the acoustic theme. Figs. 4 and 6b show four acoustic themes that were separated on the backscatter mosaic, and the results of the inversion are shown in Fig. 7. The ARA inversion for acoustic themes II, I and III, shows a gradation: muddy sand, medium sand and gravelly coarse sand, which is in accordance with the bottom photographs and with the visual interpretation of the photographs that was done during acquisition. Acoustic theme IV, which is shown in Fig. 4b, could not be described by a single patch, so the

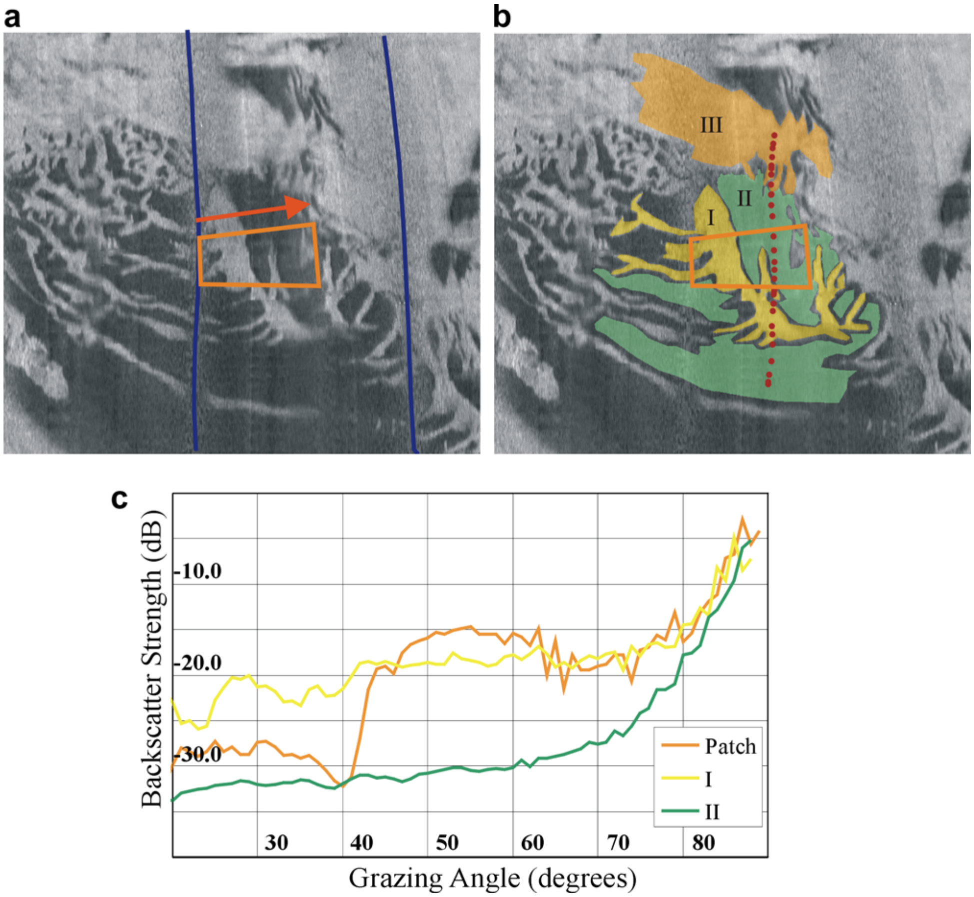
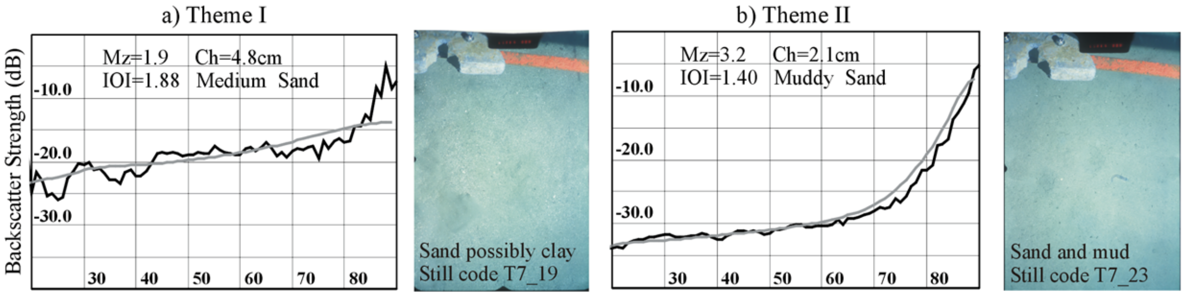


Fig. 6. (a) Detail of the backscatter mosaic showing one seafloor patch, depicted as the orange box, and the navigation track in blue. The orange arrow shows the look direction of the sonar in the patch. (b) The seafloor patch crosses two distinct acoustic themes, (I) and (II). The red dots are the locations where bottom photographs were acquired. (c) Average angular responses of the acoustic themes and the patch. The angular response of the patch, the orange curve, appears to be the combination of the curves I and II.



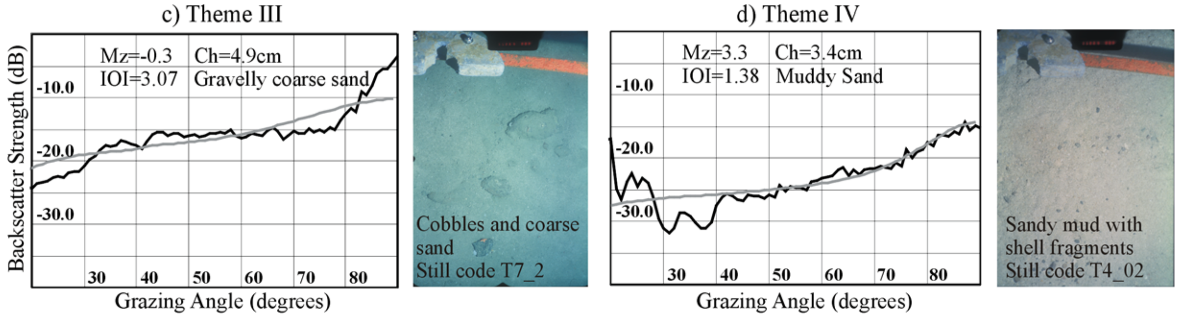


Fig. 7. Comparison between bottom photographs and the result of the model inversion for acoustic themes. The solid back lines show the measured angular response inside the patch. The gray lines show the result of the model inversion. Mz is the mean grain size in φ units, Ch is a measurement of acoustic roughness, IOI is the index of impedance. The name of the sediment is based on the mean grain size. The photograph was described during the acquisition survey.

acoustic theme analysis converged to muddy sand, which matches the visual interpretation of the photographs.

8. Conclusions

The angular range analysis estimates calculated for seafloor patches in the Stanton Banks survey area showed a very good correlation with coincident bottom photographs. However, the low spatial resolution of the seafloor patches, which is limited to the swath width, was an issue in areas of high spatial variability. In those areas, we use the high spatial resolution of the mosaic to visually define areas on the seafloor with similar angular responses – the acoustic themes – and calculate one average angular response per acoustic theme, rather than across the sonar swath. The angular range analysis applied to the average angular response of acoustic themes also showed a very good correlation with the bottom photographs. In this sense, this approach improved the spatial resolution of the angular response analysis, by using the high spatial resolution of the mosaic. Future work will include using methods for automatically segmenting the image simultaneously in both the textural space and in the angular response space. This approach offers potential for the remote discrimination and delineation of benthic habitats, combining automated image segmentation with informed and targeted ground-truthing.

Acknowledgements

The authors would like to thank the crew and scientific personnel of the RV Corystes and Celtic Explorer, for data collection. Data was collected as part of the Interreg IIIB Mapping European Seabed Habitats (MESH) project. The backscatter workshop was supported by the MESH project and Invest Northern Ireland Higher Education Innovation Funds. This research was supported by the Office of Naval Research under the Grant No. N00014-07-1-0666, and by the National Oceanic and Atmospheric Administration under the award number NA0NOS4001153.

References

[1] Collier JS, Brown CJ. Correlation of sidescan backscatter with grain size distribution of surficial seabed sediments. Mar Geol 2005;214:431–49.
[2] Gray JS. Animal-sediment relationships. Oceanogr Mar Biol Ann Rev 1974;12:223–61.
[3] Rhoads DC. Organism–sediment relations on the muddy seafloor. Oceanogr Mar Biol Ann Rev 1974;12:263–300.
[4] Snelgrove PVR, Butman CA. Animal–sediment relationships revisited: cause versus effects. Oceanogr Mar Biol Ann Rev 1994;32:111–77.
[5] Brown CJ, Cooper KM, Meadows WJ, Limpenny DS, Rees HL. Small-scale mapping of seabed assemblages in the Eastern English Channel using sidescan sonar and remote sampling techniques. Estuar Coast Shelf Sci 2002;54:263–78.
[6] Brown CJ, Hewer A, Meadows WJ, Limpenny DS, Cooper KM, Rees HL. Mapping seabed biotopes at Hastings Shingle Bank, Eastern English Channel. Part 1. Assessment using sidescan sonar. J Mar Biol Assoc UK 2004;84:481–8.
[7] Cochrane GR, Lafferty KD. Use of acoustic classification of sidescan sonar data for mapping benthic habitat in the Northern Channel Islands, California. Cont Shelf Res 2002;22:683–90.
[8] Kostylev VE, Todd BJ, Fader GBJ, Courtney RC, Cameron GDM, Pickrill RA. Benthic habitat mapping on the Scotian shelf based on multibeam bathymetry, surficial geology and sea floor photographs. Mar Ecol Prog Ser 2001;219:121–37.
[9] Martinez JV. Analysis of multibeam sonar data for the characterization of seafloor habitats. Master thesis. University of New Brunswick, Canada; 2000. p. 153.
[10] Brown CJ, Hewer AJ, Limpenny DS, Cooper KM, Rees HL, Meadows WJ. Mapping seabed biotopes using sidescan sonar in regions of heterogeneous substrata: case study east of the Isle of Wight, English Channel. Underwater Technol 2004;26:27–36.
[11] Brown CJ, Collier JS. Mapping benthic habitat in regions of gradational substrata: an automated approach utilising geophysical, geological, and biological relationships. Estuar Coast Shelf Sci 2008;78:203–14.
[12] Fonseca L, Calder B. Clustering acoustic backscatter in the angular response space. In: Proceedings of the US hydrographic conference. Norfolk, VA; 2007.
[13] de Moustier C, Matsumoto H. Seafloor acoustic remote sensing with multibeam echo-sounders and bathymetric sidescan sonar systems. Mar Geophys Res 1993;15:27–42.
[14] Hughes-Clarke J, Danforth BW, Valentine P. Areal seabed classification using backscatter angular response at 95 kHz. In: Pace NG, Pouliquen E, Bergen O, Lyons AP, editors. In: SACLANTCEN conference proceeding CP-45. Lerici; 1997. p. 243–50.
[15] Pouliquen E, Lyons AP. Backscattering from bioturbated sediments at very high-frequency. IEEE J Oceanic Eng 2002;27(3):388–402.
[16] Fonseca L, Mayer L. Remote estimation of surficial seafloor properties through the application angular range analysis to multibeam sonar data. Mar Geophys Res 2007;28(2):119–26.
[17] Brown CJ. Developments in the application of multibeam sonar backscatter data for seafloor habitat mapping. Appl Acoust 2009;70(10):1242–7.
[18] Fonseca L, Calder B. Geocoder: an efficient backscatter map constructor. In: Proceedings of the US hydrographic. San Diego, CA; 2005.
[19] Hammerstad E, Pohner F, Parthoit F, Bennet J. Field testing of a new deep water multibeam echo sounder. Proc IEEE Oceans 1991;2:743–9.
[20] Cervenka P, de Moustier C. Sidescan sonar image processing techniques. IEEE J Oceanic Eng 1993;18(2):108–22.
[21] Chavez Jr PS. Processing techniques for digital sonar images from GLORIA. Photogramm Eng Rem Sens 1986;52(8):1133–45.
[22] Rzhanov Y, Linnett L, Forbes R. Underwater video mosaicing for seabed mapping. In: Proceedings of the IEEE conference on image processing, vol. 1; 2000. p. 224–7.
[23] Williams KL. An effective density fluid model for acoustic propagation in sediments derived from Biot theory. J Acoust Soc America 2001;110(5):2276–81.
[24] Hamilton E. Prediction of deep-sea sediment properties: state-of-the-art. In: Inderbitzen AL, editor. Deep-sea sediments physical and mechanical properties. New York: Plenum Press; 1974. p. 1–43.
[25] Richardson MD, Briggs KB. Empirical predictions of seafloor properties based on remotely measured sediment impedance. In: Porter MB, Siderius M, editors. High-frequency ocean acoustic conference. Melville: AIP Press; 2004. p. 12–21.
[26] Jackson DR, Winebrenner DP, Ishmaru A. Application of the composite roughness model to high-frequency bottom backscattering. J Acoust Soc America 1986;79(5):1410–22.