Mar Geophys Res (2007) 28:119–126
DOI 10.1007/s11001-007-9019-4

ORIGINAL RESEARCH PAPER

Remote estimation of surficial seafloor properties through the application Angular Range Analysis to multibeam sonar data

Luciano Fonseca · Larry Mayer

Received: 27 September 2005 / Accepted: 17 April 2007 / Published online: 19 June 2007

Abstract The variation of the backscatter strength with the angle of incidence is an intrinsic property of the seafloor, which can be used in methods for acoustic seafloor characterization. Although multibeam sonars acquire backscatter over a wide range of incidence angles, the angular information is normally neglected during standard backscatter processing and mosaicking. An approach called Angular Range Analysis has been developed to preserve the backscatter angular information, and use it for remote estimation of seafloor properties. Angular Range Analysis starts with the beam-by-beam time-series of acoustic backscatter provided by the multibeam sonar and then corrects the backscatter for seafloor slope, beam pattern, time varying and angle varying gains, and area of insonification. Subsequently a series of parameters are calculated from the stacking of consecutive time series over a spatial scale that approximates half of the swath width. Based on these calculated parameters and the inversion of an acoustic backscatter model, we estimate the acoustic impedance and the roughness of the insonified area on the seafloor. In the process of this inversion, the behavior of the model parameters is constrained by established inter-property relationships. The approach has been tested using a 300 kHz Simrad EM3000 multibeam sonar in Little Bay, NH. Impedance estimates are compared to *in situ* measurements of sound speed. The comparison shows a very good correlation, indicating the potential of this approach for robust seafloor characterization.

Keywords Angular Range Analysis · Acoustic backscatter · Multibeam sonar · Remote sensing · Model inversion

L. Fonseca (✉) · L. Mayer
Center for Coastal and Ocean Mapping,
University of New Hampshire, 24 Colovos Road,
Durham, NH 03824, USA
e-mail: luciano@ccom.unh.edu

L. Mayer
e-mail: larry.mayer@unh.edu

Introduction

The remote characterization of the seafloor by acoustic methods has important practical applications in a broad range of disciplines, including marine geologic, geotechnical, hydrographic, biological, fisheries and environmental research (Hughes-Clarke et al. 1996). Examples of seafloor acoustical and physical properties that we would hope to estimate remotely are the grain size, acoustic impedance (product of density and sound speed), acoustic attenuation and the roughness of the near-surface sediments. Unfortunately, these properties are not normally measured directly by remote sensing methods. Instead, we have to rely on measurements of other properties (e.g., depth, acoustic backscatter), and estimate the values of the desired seafloor properties by means of theoretical or empirical models. Multibeam sonars provide us with coincident measurements of depth and acoustic backscatter over a large swath of the seafloor and thus offer a promising tool for seafloor characterization.

The acoustic backscatter returned to a multibeam sonar is the result of a complex interaction of the acoustic wavefront with an often rough and inhomogeneous seafloor. The wavefront from a typical multibeam sonar system usually intersects the seafloor at an angle, and is subject to scattering, which redistributes the incident acoustic energy in multiple directions. The nature of the energy returned to the transducer (the observations) carries important information about the seafloor morphology and physical properties, providing valuable data to aid in the difficult task of seafloor characterization (de Moustier and Matsumoto 1993; Hughes-Clark et al. 1997). If we can establish a formal mathematical model that links the seafloor geoacoustic and physical properties to the observations, we can then attempt to invert the model and estimate the seafloor properties based on the remotely acquired acoustic backscatter. This paper describes an approach to analyze acoustic backscatter data that uses the angular dependence of the acoustic return in combination with an established seafloor interaction model and known physical property inter-relationships to predict seafloor properties.

Observations: acoustic backscatter and depth

The acquisition of reliable observations is the first requirement of any practical remote seafloor characterization method based on model inversion. Multibeam sonars have been developed to provide accurate bathymetric data with well established control and quality assurance procedures and carefully defined error models (Hare et al. 1995). These error models, however, have not yet been extended to include acoustic backscatter, where absorption of acoustic energy in the water column, seafloor slope and positioning of each acoustic beam on the seafloor, are among the factors that can affect the quantitative aspects of acoustic backscatter. So, in order to obtain an accurate measurement of acoustic backscatter, it is necessary to radiometrically correct the backscatter intensities registered by the sonar, and to geometrically correct and position each acoustic sample in a projected coordinate system (Fonseca and Calder 2005). The correction sequence starts with the original acquisition data, and requires that all modifications to the data be logged so that they can be considered for the radiometric corrections. Each raw backscatter sample must be corrected through the removal of time varying gains, transmit powers and receiver gains applied during acquisition, and then by the compensation for spherical spreading, attenuation in the water column and actual slope and area of insonification. Additionally, transmit and receive beam pattern corrections must be applied to all corrected samples.

In the case of multibeam sonar data where detailed bathymetry is known, the effective incident angle can be calculated from the scalar product of the beam vector (from the footprint on the seafloor to the transducer) and the normal to the bathymetric surface at the boresight of the footprint, which is the projection of the principal axis of the beam on the seafloor. As the backscatter strength is calculated per unit of area, the actual footprint area of the incident beam must be taken into account for proper radiometric reduction. The effective area of insonification is calculated based on the bathymetric surface, the transmit and receive beamwidths, the pulse length and range to the transducer.

The acoustic backscatter signal sampled at the transducer head is also subject to stochastic fluctuations that produce a speckle noise in the registered backscatter data. The removal of the speckle noise through stacking and through the use of a morphological median filter with a percentile threshold (Fonseca and Calder 2005) improves considerably the interpretability of the data, and this aids in the process of seafloor characterization. The result of the application of these processing steps is the best estimate for the actual backscatter strength returning from the seafloor. With accurate estimates of backscatter strength, the acoustic backscatter values from different acquisition lines can be reduced to a near-calibrated scale of scattering strength (Fig. 1). In the absence of an absolute calibration of the sonar, these estimated measurements are only relative values, but in certain conditions they can yield reliable near-absolute results.

High-frequency acoustic backscatter model

Once the above-described corrections have been applied to the observed backscatter, the next step toward the remote characterization of the seafloor is the definition of an acoustic backscatter model. This is an essential tool to link seafloor properties to angular signatures measured by multibeam sonars. Usually, high-frequency backscatter models consider two different processes: interface scattering and volume scattering (Ivakin 1998). The interface scattering occurs at the water-sediment interface where the

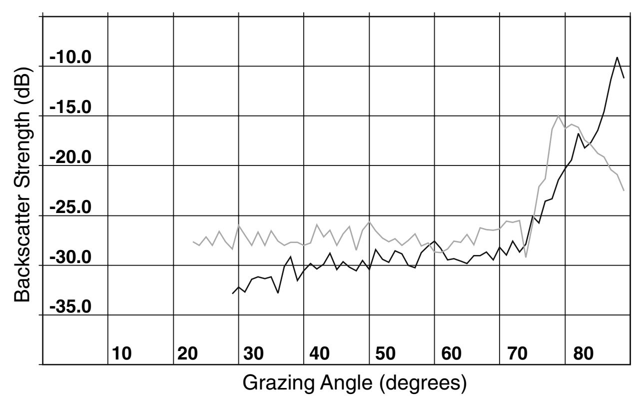

Fig. 1 Backscatter angular response of a small patch on the seafloor, acquired by a Simrad EM3000 multibeam sonar. The *gray line* shows the original observation and the *black solid line* the backscatter angular response after all the geometric and radiometric corrections were applied. Note that the seafloor had a considerable slope, so that the maximum backscatter in the original observation was not at nadir, but at a grazing angle of 80°. The geographical position of this seafloor patch is shown as a *small yellow box* at the *top* of Fig. 4a

seafloor acts as a reflector and scatterer of the incident acoustic energy. A portion of the incident acoustic energy will also be transmitted into the seafloor, although the amount of penetration into the seafloor will be reduced with increasing frequency and thus attenuation. This transmitted energy will be scattered by heterogeneities in the sediment structure, which are the source of the volume scatter (Novarini and Caruthers 1998). In this work we used the effective density fluid model derived from the Biot theory (Williams 2001), with some modifications for the calculation to the volume scattering contribution (Fonseca et al. 2002). The parameters used in this model are the sound speed ratio (ratio of sediment sound speed to water sound speed), the density ratio (ratio of sediment density to water density), the loss parameter (ratio of imaginary wave number to real wave number for the sediment), the porosity, the permeability, the tortuosity, the exponent of bottom relief spectrum, the strength of bottom relief spectrum, and a volume scattering parameter (Williams and Jackson 1998; Williams 2001; Fonseca et al. 2002).

While the acoustic backscatter is as a complex function of the acoustic and physical properties listed above, and possibly of others like the grain size distribution or even vertical gradients in density and sound speed (Pouliquen and Lyons 2002), the three main parameters that control the model are the acoustic impedance, the seafloor roughness, and the sediment volume heterogeneities (Fonseca et al. 2002). As a result, the backscatter strength measured by multibeam sonars is not only controlled by the acoustic impedance contrast between the water and the sediment, which is the key for the seafloor characterization, but also responds to the seafloor roughness and to sediment volume heterogeneities. The ambiguity between contributions of roughness, impedance and volume heterogeneities is the main difficulty in the direct determination of seafloor properties based on remotely acquired backscatter. The technique proposed here attempts to address this problem by separating the returned acoustic backscatter into components due to impedance contrast, roughness and volume scatter.

Angular Range Analysis

We call the approach we are taking Angular Range Analysis, as it divides and analyzes the returned acoustic backscatter into discrete angular regimes. The variation of backscatter strength as a function of the grazing angle, i.e., the angular response curve, represents, for a certain frequency, an inherent property of the seafloor (Jackson and Briggs 1992). Although the angular response curve or angular signature reveals subtle differences in the backscatter response from different seafloor materials, this information is normally lost during standard backscatter processing which typically applies an angle varying gain equalization function to the swath data in order to produce backscatter mosaics that show a consistent gray level for the same seafloor type regardless of the angle of insonification. The proposed Angular Range Analysis attempts to preserve this angular signature and uses the full backscatter time series during the analysis.

Angular Range Analysis is applied to a seafloor patch, which is 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 stacking of consecutive pings reduces the speckle noise common to any acoustic method, and is the swath-sonar equivalent of the seismic stacking. The stacking process limits the spatial resolution of the Angular Range Analysis but is essential to noise reduction in the acoustic backscatter. It is also important to note that the backscatter angular response of each ping must be corrected for radiometric and geometric distortions, as discussed above, before the stacking. A particularly critical step is the slope correction, through which all the soundings will be migrated to their true angular position (Fig. 1).

Aspects of the Angular Range Analysis are analogous to the amplitude versus offset (AVO) analysis, which is normally applied to multichannel seismic reflection data. AVO analysis has been used successfully in the oil industry for the exploration and characterization of subsurface reservoirs, and is based on the fundamental observation that seismic amplitudes vary with the offset between the seismic source and detector (which translates to different angles between the sources and the detectors), and that this variation is due to different acoustic properties in the subsurface reflectors (Castagna and Backus 1993). In an analogous way, multibeam sonars acquire acoustic backscatter over a wide range of incidence angles, and the variation of the backscatter with the angle of incidence is an intrinsic property of the seafloor. With appropriate alterations, some ideas from the multichannel seismic reflection AVO analysis can be applied to the backscatter angular response acquired by multibeam sonars.

Another idea borrowed from the seismic AVO-analysis is the partial stacking technique, which is a simple and practical way of preserving some angular information from the original observations. The partial stacking technique separates the backscatter angular response in angular ranges, that is the near, the far and the outer ranges. Thus, the near soundings, i.e., the soundings with grazing angles closer to the nadir, will be processed separately from the far soundings, i.e., the soundings with shallow grazing angles. Another technique used to preserve part of the angular signature is to compute the slope and the intercept of the angular response curve (Fig. 2). The slope is strongly influenced by the seafloor roughness, while the intercept is strongly influenced by the impedance, although the actual relationship is complex and is described by a mathematical model for the acoustic backscatter (Jackson and Ivakin 1998).

ARA-parameters

The slopes and intercepts extracted from the angular ranges of the angular response curve (Fig. 2) are treated as feature vectors, which in this manuscript are called ARA-parameters. The near range includes grazing angles from 90° to 65°, the far range from 65° to 35°, and the outer range from 35° to 5°. The limit between the far and outer ranges is chosen so as to identify the critical angle, beyond which penetration of the acoustic field into the seafloor will be insignificant and volume scatter should be very small. The limit between the near and the far range is chosen to be next to a changeover angle, beyond which the scattering is better explained by perturbation theory, which assumes that the seafloor roughness will yield only small phase differences to the incident acoustic field (Ishimaru 1978). In the near range, four ARA-parameters are extracted from the seafloor patch: the near-mean backscatter, the near-slope, the near-intercept and the near-angle, which is the average grazing angle for all the sounding stacked in this range (Fig. 2). The near-intercept is calculated at 80° in order to avoid the nadir instability, which is very common in sonars. In the far range, the ARA-parameters far-mean, far-angle, far-slope and the far-intercept at 50° are calculated. In the outer range, only the ARA-parameter outer-mean is calculated and used for the analysis, as it has a correlation to the critical angle of reflection defined by the sound speed ratio between the water and the sediment.

One important ARA-parameter used to characterize the backscatter angular response is the orthogonal-distance. According to the backscatter model, this parameter is correlated to volume heterogeneities, more specifically the amount of free fluid, normally gas, in the sediment structure (Fonseca et al. 2004). The orthogonal-distance is extracted from an intercept-slope graph, where all the coordinate pairs (total-intercept, total-slope) of the survey are plotted in a Cartesian plane (Fig. 3). The total-slope and the total-intercept for each seafloor patch are defined as the slope and the intercept of the line connecting the two points: (near-angle, near-mean) and (far-angle, far-mean). The background trend line for the survey is defined as the linear regression of all coordinate pairs (total-intercept, total-slope), excluding the patches with very high inverted acoustic impedance. The orthogonal-distance ARA-parameter is defined as the geometric orthogonal-distance of each coordinate pair to the background trend line (Fig. 3).

Model inversion

The direct inversion of acoustic backscatter for key physical properties is an ill-posed problem, in the sense that a solution may not be unique or may not even exit. In order overcome this limitation, we applied a constrained iterative inversion of the model, imposing constraints based on well established inter-relations for sediment physical properties

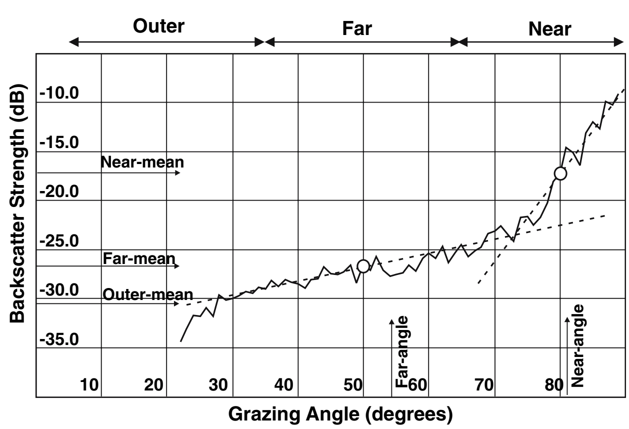

Fig. 2 Stacked backscatter angular response measured by a Simrad EM3000 multibeam sonar, with some ARA-parameters. Note the limits for the near, far and outer ranges. The *dashed line* at the near range defines the near-slope and the near intercept (*white circle*). Similarly, the *dashed line* at the 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

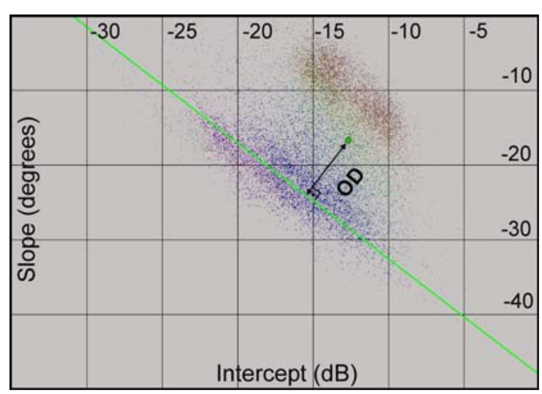

Fig. 3 Intercept–slope graph with background trend line (green line). Each analyzed seafloor patch contributes one point to this graph. The points are color-coded with the acoustic impedance obtained from the final model inversion shown in Fig. 4b. Note that the patches with similar impedance follow a trend in the intercept–slope plane. The ARA-parameter orthogonal-distance (OD) of one particular seafloor patch is shown in the graph, and the geographical position of this patch is shown as a *small red box* at the *center* of Fig. 4a

(Hamilton 1974), and building parametric equations with the angular range parameters (ARA-parameters) extracted from the backscatter angular response curve. It is important to stress the distinction between the model parameters and the ARA-parameters. The model parameters are the parameters necessary to calculate the forward acoustic backscatter model (Williams 2001), while the ARA-parameters are the feature vectors extracted from the ranges of backscatter angular response. The inversion of the acoustic backscatter model is regularized by the adjustment of the ARA-parameters and not by the adjustment of the model parameters. For that, the same ARA-parameters calculated for the measured backscatter angular response of the survey patch (patch-ARA-parameters) are also calculated for a modeled backscatter angular response (model-ARA-parameters).

The inversion of the model is done iteratively by adjusting the near-slope, the near-intercept, the far-intercept, the far-slope, and the orthogonal-distance from the model to the observations, with the model parameters constrained by equations published by Hamilton (1974). These equations are based on thousands of direct measurements made in the laboratory, and are summarized as a series of regression equations relating grain size to porosity, density and attenuation, and also sound speed in the sediment to density and porosity. The regression equations and the measurements themselves give reasonable upper and lower bounds for a given property when only one of the measured properties is known. By using these results, the constrained iterative inversion does not allow the model parameters to assume all possible values, but rather constrains them within the range of minimum and maximum values given by the regression equations and the empirical database.

For the inversion, an initial set of model parameters is chosen based on the ARA-parameters of the seafloor patch being analyzed or based on a previous model inversion from an adjacent patch. First, the roughness parameters of the model are adjusted iteratively until the near-slope of the modeled angular response equals the near-slope of the measured backscatter patch. Then the sound speed ratio and the density ratio parameters of the model are adjusted iteratively until the near-intercept of the modeled angular response equals the near-intercept of the patch. We note that the model parameters are constrained, so that a change in the sound speed ratio can yield to changes in density ratio, loss parameters etc., if the upper or lower bounds defined by the Hamilton's equations are reached. The far-intercept of the model is adjusted to the far-intercept of the patch by changing the volume parameter, the sound speed ratio and the density ratio. The maximum volume parameter allowed is proportional to the orthogonal-distance ARA-parameter for the seafloor patch. The far-slope and the outer-mean are adjusted by changing the sound speed, while maintaining the same impedance-ratio. Once the inversion process adjusts the model-ARA-parameters to the patch-ARA-parameters, the process is repeated iteratively until the distance between these two feature vectors is minimized. Thus, the criteria for convergence are based on the fit of the patch-ARA-parameters to the model-ARA-parameters. As a result, the inversion can yield to an imperfect curve fitting between the model and the measured angular response, but on the other hand, converges to a more robust and feasible estimate of the model parameters.

Once the constrained iterative inversion converges to a set of model-ARA-parameters, it is assumed that the model is a good representation of the seafloor patch, such that the model parameters, which include the sound speed ratio, the density ratio, and roughness parameters (Williams 2001) can be used to describe the insonified area. In this fashion, based on the calculated ARA-parameters and the constrained iterative inversion of the acoustic backscatter model, it is possible to estimate the acoustic impedance, the seafloor roughness and volume backscatter of the insonified area on the seafloor.

Example from Little Bay, New Hampshire

Angular Range Analysis was applied to an acoustic remote sensing dataset acquired in the summer of 2003 in Little Bay, NH. The data were collected with a Simrad EM3000 multibeam sonar, which is a shallow water system operating at 300 kHz, forming 127 beams over an angular sector of 130°. The survey mapped water depths from 6 to 24 m, with bottom sediments ranging from gravel to clay. The analysis started with the backscatter time series stored in raw Simrad datagrams, which were then corrected for radiometric and geometric distortions as described earlier. Radiometric corrections included the removal of the time varying and angle varying gains applied during acquisition, calculation of the true grazing angle with respect to a bathymetric model, correction for the area of insonification and for received and transmitted beam patterns. Additionally, it was necessary to remove the Lambertian correction and the near nadir time varying gain compression that are applied by the manufacturer to the backscatter time series during acquisition (Hammerstad et al. 1991). The radiometrically and geometrically corrected backscatter was then compared to the mathematical model.

Based on the calculated ARA-parameters and the constrained iterative inversion of the acoustic backscatter model we estimated the acoustic impedance and the roughness of the insonified area on the seafloor (Fig. 4). In Little Bay, the estimated impedance was compared to *in situ* measurements of sound speed. These measurements were conducted in October 2003 and April 2004 (Kraft et al. 2004) using the *In situ* Sound Speed and Attenuation Probe, which inserts two orthogonal matched pairs of transducer probes operating

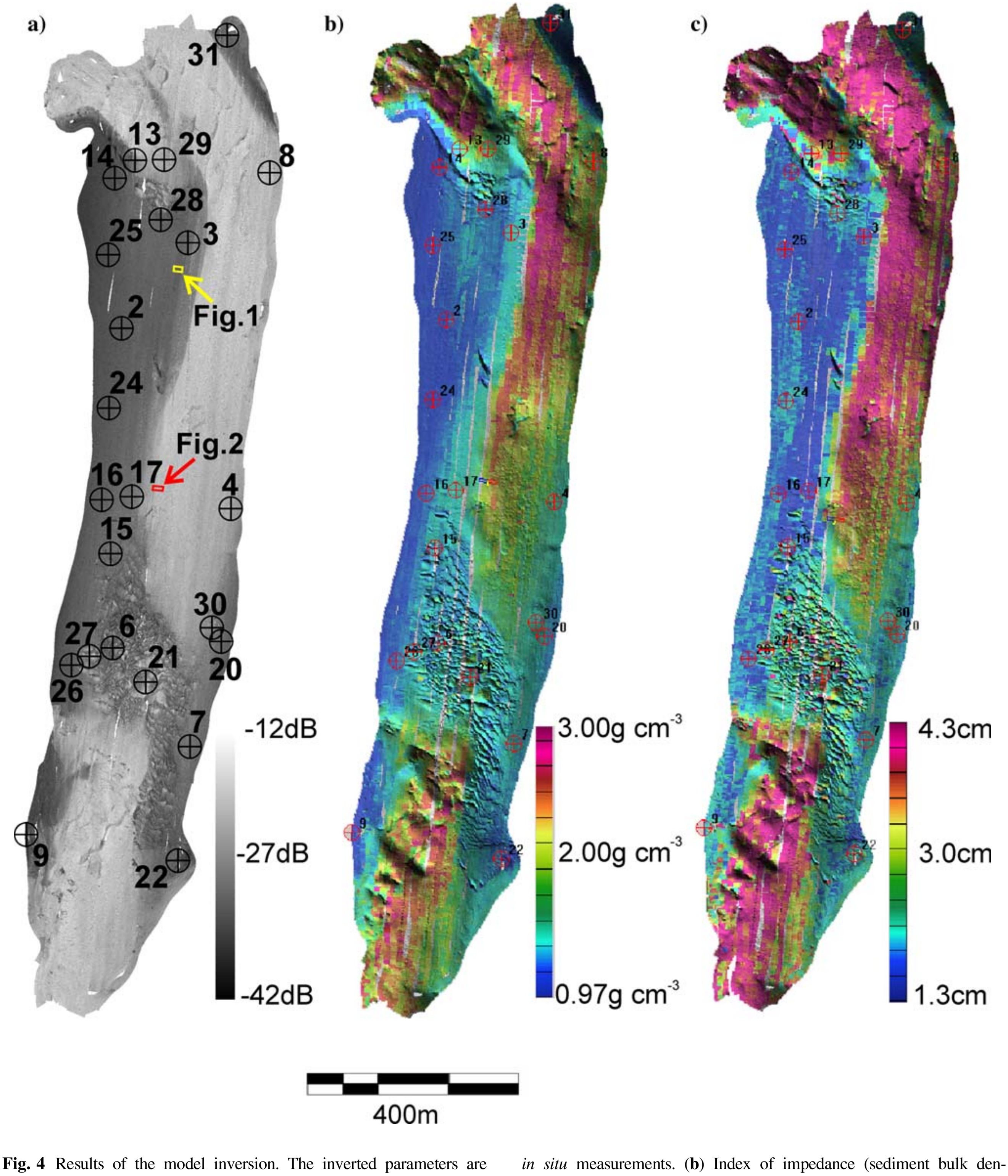

Fig. 4 Results of the model inversion. The inverted parameters are represented by a color scheme draped over the sun-illuminated bathymetry. (**a**) Acoustic backscatter mosaic with low backscatter in *black* and high backscatter in *white*. The circles show the location of the *in situ* measurements. (**b**) Index of impedance (sediment bulk density × sound speed ratio), draped over sun-illuminated bathymetry, color coded with low index in *blue* and high index in *red*. (**c**) Roughness, rms height in cm, color coded and draped over sun-illuminated bathymetry

at frequencies of 40 and 65 kHz into the seafloor (Mayer et al. 2002). The comparison between *in situ* and remotely estimated measurements showed a very good correlation (R^2 = 0.88; Fig. 5). We also compared the same *in situ* measurements of sound speed with the average corrected backscatter extracted from the mosaic shown in Fig. 4a. The

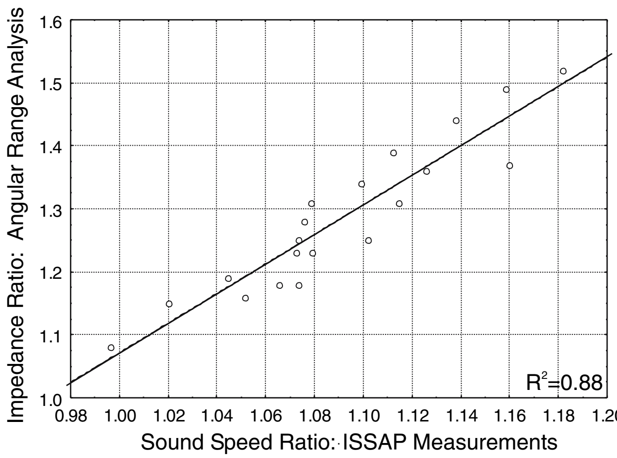

Fig. 5 Remotely estimated acoustic impedance versus *in situ* measurements of sound speed. The location of the *in situ* measurements are shown in Fig. 4a. Note the very good linear correlations (R^2 = 0.88)

average backscatter is calculated in a bin of 10 m × 10 m around the location of the *in situ* measurement. The results are shown in Fig. 6. Note that the correlation between the *in situ* sound speed measurement and the average backscatter (R^2 = 0.73) is lower than the correlation shown in Fig. 5. This is expected, as the backscatter is controlled not just by the impedance contrast, but also by the seafloor roughness and the volume contribution. In this sense, the Angular Range Analysis separated the contributions from the impedance contrast and roughness from the angular response, resulting in the improved correlation shown in Fig. 5.

Robust estimates for acoustic impedance are the key for remote acoustic seafloor characterization methods, as the acoustic impedance can be used directly to predict the sediment mean grain size and porosity, among other physical properties (Richardson and Briggs 2004; Hamilton 1974). These predictions can be done based on simple linear and quadratic regressions, which show a good correlation between the desired seafloor property and the index of impedance (sediment bulk density × sound velocity ratio). These published regressions can then be applied directly to the values derived from the Angular Range Analysis, showed in Fig. 4b. Additionally the seafloor roughness estimates as shown in Fig. 4c, expressed in terms of rms heights, are important parameters in the description of seafloor habitats, and consequently helpful in remote habitat characterization (Cutter Jr et al. 2003; Yoklavich et al. 1998).

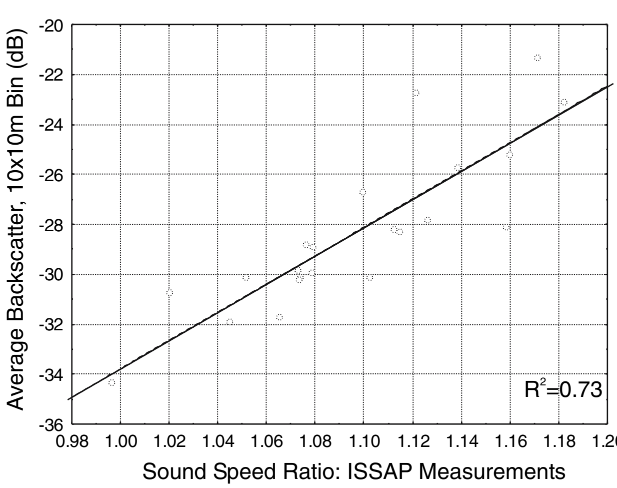

Fig. 6 Average backscatter versus *in situ* measurements of sound speed. The location of the *in situ* measurements are shown in Fig. 4a. The average backscatter is calculated in a bin of 10 m × 10 m around the location of the *in situ* measurement. Note the lower linear correlations (R^2 = 0.73), when compared to Fig. 5

Conclusions

The Angular Range Analysis of multibeam sonar data is a promising technique for acoustic seafloor characterization. This technique was successfully applied to the Simrad EM3000 multibeam sonar data from Little Bay. The remotely estimated impedance was compared to *in situ* measurements of sound speed, indicating a strong correlation between these two acoustic parameters. Additional field work is required to include a larger sample of sediment types. The key to the success of this approach is the collection of radiometrically calibrated and geometrically corrected acoustic backscatter data in conjunction with a well-defined model for the interaction of sound with the seafloor. As our understanding of the interaction of sound with the seafloor improves, the proposed technique, which is in principle independent of the underlying model, can easily incorporate new modeling approaches.

Acknowledgement This research was supported by the Office of Naval Research under the GEOCLUTTER program.

References

Castagna JP, Backus MM (eds) (1993) Offset-dependent reflectivity–theory and practice of AVO analysis. Society of Exploration Geophysicists, Tulsa

Cutter RG Jr, Rzhanov Y, Mayer LA (2003) Automated segmentation of seafloor bathymetry from multibeam echosounder data using local Fourier histogram texture features. J Exp Mar Biol Ecol 285/286:355–370

de Moustier C, Matsumoto H (1993) Seafloor acoustic remote sensing with multibeam echo-sounders and bathymetric sidescan sonar systems. Mar Geophys Res 15:27–42

Fonseca L, Calder B (2005) Geocoder: an efficient backscatter map constructor. Proceedings of the U.S. Hydrographic Conference 2005, San Diego

Fonseca L, Mayer L, Orange D, Driscoll N (2002) The high-frequency backscattering angular response of gassy sediments: model/data comparison from the Eel River margin, California. J Acoust Soc Am 111(6):2621–2631

Fonseca L, Mayer L, Kraft B, Richter B, Brandsdottir B (2004) AVO analysis of multibeam backscatter, an example from Little bay,

NH and Skjalfandi bay, Iceland. Proceedings of AGU fall meeting 2004, San Francisco
Hamilton E (1974) Prediction of deep-sea sediment properties: state-of-the-art. In: Inderbitzen AL (ed) Deep-sea sediments, physical and mechanical properties, Plenum Press, New York, pp 1–43
Hammerstad E, Pohner F, Parthoit F, Bennet J (1991) Field testing of a new deep water multibeam echo sounder. Proc IEEE Oceans 2:743–749
Hare R, Godin A, Mayer L (1995) Accuracy estimation of Canadian swath (multibeam) and sweep (multi-transducer) sounding systems. Canadian Hydrographic Service and University of New Brunswick Publication, Fredericton
Hughes-Clark J, Mayer L, Wells D (1996) Shallow-water imaging multibeam sonars: a new tool for investigating seafloor processes in the coastal zone and on the continental shelf. Mar Geophys Res 18:607–629
Hughes-Clarke J, Danforth BW, Valentine P (1997) Areal seabed classification using backscatter angular response at 95kHz. In: Pace NG, Pouliquen E, Bergen O, Lyons AP (eds) SACLANTCEN conference proceeding CP-45, Lerici, pp 243–250
Ishimaru A (1978) Wave propagation and scattering in random media. Multiple scattering, turbulence, rough surfaces and remote sensing, vol 2. Academic, San Diego
Ivakin AN (1998) A unified approach to volume and roughness scattering. J Acoust Soc Am 103(2):827–837
Jackson DR, Briggs KB (1992) High-frequency bottom backscattering: roughness versus sediment volume scattering. J Acoust Soc Am 92(2):962–977
Jackson DR, Ivakin AN (1998) Scattering from elastic sea beads: first-order theory. J Acoust Soc Am 103(1):336–345
Kraft BJ, Fonseca L, Mayer L, McGillicuddy G, Ressler J, Henderson J, Simpkin PG (2004) *In situ* measurement of sediment acoustic properties and relationship to multibeam backscatter. J Acoust Soc Am 115 (5):2401
Mayer L, Kraft B, Simpkin P, Jabs E, Lynskey E (2002) *In situ* determination of the variability of seafloor acoustic properties: an example from the ONR GEOCLUTTER area. In: Pace N, Jensen F (eds) Impact of littoral environmental variability on acoustic prediction and sonar performance. Kluwer Academic, Dordrecht, pp 115–122
Novarini JC, Caruthers JW (1998) A simplified approach to backscattering from a rough seafloor with sediment inhomogeneities. J Oceanic Eng 23(3):157–166
Pouliquen E, Lyons AP (2002) Backscattering from bioturbated sediments at very high frequency. IEEE J Oceanic Eng 27(3):388–402
Richardson MD, Briggs KB (2004) Empirical predictions of seafloor properties based on remotely measured sediment impedance. In: Porter MB, Siderius M (eds) High frequency Ocean acoustic conference, AIP press, Melville, pp 12–21
Williams KL (2001) An effective density fluid model for acoustic propagation in sediments derived from Biot theory. J Acoust Soc Am 110(5):2276–2281
Williams KL, Jackson DR (1998) Bistatic bottom scattering: model, experiments, and model/data comparison. J Acoust Soc Am 103(1):169–181
Yoklavich MM, Greene HG, Cailliet GM, Sullivan DE, Lea RN, Love MS (1998) Habitat associations of deep-water rockfishes in the submarine canyon: and example of a natural refuge. Fish Bull 98:625–641