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Seafloor Characterization Through the Application of AVO Analysis to Multibeam Sonar Data

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SEAFLOOR CHARACTERIZATION THROUGH THE APPLICATION OF AVO ANALYSIS TO MULTIBEAM SONAR DATA

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In the seismic reflection method, it is well known that seismic amplitude varies with the offset between the seismic source and detector and that this variation is a key to the direct determination of lithology and pore fluid content of subsurface strata. Based on this fundamental property, amplitude-versus-offset (AVO) analysis has been used successfully in the oil industry for the exploration and characterization of subsurface reservoirs. 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. Building on this analogy, we have adapted an AVO-like approach for the analysis of acoustic backscatter from multibeam sonar data. The 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 (i.e. true incidence angle), time varying and angle varying gains, and area of insonification. Once the geometric and radiometric corrections are made, a series of "AVO attributes" (e.g. near, far, slope, gradient, fluid factor, product, etc.) are calculated from the stacking of consecutive time series over a spatial scale that approximates half of the swath width (both along track and across track).

Based on these calculated AVO attributes and the inversion of a modified Williams, K. L. (2001) acoustic backscatter model, we estimate the acoustic impedance, the roughness, and consequently the grain size of the insonified area on the seafloor. The inversion process is facilitated through the use of a simple, interactive graphical interface. In the process of this inversion, the relative 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, N.H., an area that we can easily access for ground-truth studies. AVO-derived impedance estimates are compared to in situ measurements of sound speed and AVO-derived grain-size estimates are compared to the direct measurement of grain size on grab samples. Both show a very good correlation indicating the potential of this approach for robust seafloor characterization.

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Seafloor Characterization

Remote seafloor characterization by means of acoustic methods has practical applications in a broad range of disciplines, not only in traditional marine geological, geotechnical and hydrographic research but also in biological, environmental and fisheries studies (Hughes-Clarke et al., 1996). Examples of important seafloor acoustical and physical properties to be estimated are the gain size, the acoustic impedance (density x sound speed), acoustic attenuation and the roughness of the near-surface sediments. Unfortunately, these properties are not normally measured directly by remote sensing methods. We have to rely on the indirect measurements (the observations), and estimate the values of the seafloor properties (the observables), by means of a theoretical or empirical models.

The remote indirect observations of interest are the acoustic backscatter signals acquired by multibeam and sidescan sonars. These observations carry important information about the seafloor morphology and physical properties, providing valuable data to aid the difficult task of seafloor characterization. Once we establish a formal mathematical model that links the observables to the observations, we can attempt to invert the model and estimate the seafloor properties based on the remotely acquired acoustic backscatter.

Observations: Acoustic Backscatter

The acquisition of more reliable observations is the first requirement of any practical remote seafloor characterization method based on model inversion. Since the primary observation of an acoustic remote sensing method is the acoustic backscatter, it is necessary to radiometrically correct the backscatter intensities registered by these sonars, and to geometrically correct and position each acoustic sample in a projected coordinate system (Fonseca and Calder 2005). The processing sequence starts with the original acquisition data, so that all the logged parameters will be considered for the radiometric corrections. Each raw backscatter sample is corrected by removing the variable acquisition gains, power levels and pulse widths, according to the manufacture's specifications. Additionally, a residual beam pattern correction is removed on a ping by ping basis.

If the detailed bathymetry is known, the effective incident angle is calculated from the scalar product of the beam vector (form the transducer to the footprint) and the normal to the bathymetric surface at the boresight of the footprint. As the backscatter strength is calculated per unit of area and per unit of solid angle, the actual footprint area of the incident beam should 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 subject to stochastic fluctuations that produce a speckle noise in the registered backscatter data. The removal of the speckle noise improves considerably the interpretability of the data, and this aids in the process of seafloor characterization (Fonseca, 1996). The final result of this processing is the best estimate for the actual backscatter cross-section returning from the seafloor, so that the acoustic backscatter values from different acquisition lines are reduced to a near-calibrated scale of scattering strength, and can be directly compared to a mathematical model.

High-Frequency Acoustic Backscatter Model

The next step towards the remote seafloor characterization 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 cross-section models consider two different processes: interface scattering and volume scattering (Ivakin, 1998). The interface scattering occurs at the water-sediment interface, where the seafloor acts as a reflector and scatterer of the incident acoustic energy. A portion of the incident acoustic energy will be transmitted into the seafloor. 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 acoustic backscatter is normally modeled as a complex function of many sediment acoustic and physical properties, but the three main parameters that control the model are the acoustic impedance, the seafloor roughness, and the sediment volume heterogeneities. 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 the sediment volume heterogeneities. This ambiguity between roughness, impedance and volume heterogeneities is the main difficulty in the direct determination of seafloor properties based on remotely acquired backscatter. The AVO analysis will address this problem by separating the portions of the acoustic backscatter due to impedance contrast, roughness and volume scatter.

AVO Analysis – Model Inversion

In our attempts to invert the backscatter model, it became clear that its direct inversion was an ill-posed problem. In order overcome this limitations, we applied a constrained iterative inversion of the model, imposing constraints based on Hamilton relations for sediment physical properties (Hamilton, 1974), and building parametric equations with the AVO (amplitude-versus-offset) parameters calculated from the backscatter angular response.

AVO analysis is normally applied to multichannel seismic reflection data and has been used successfully in the oil industry for the exploration and characterization of subsurface reservoirs. AVO analysis is based on the fundamental property that the seismic amplitude varies with the offset between the seismic source and detector, which translates to different angles on incidence, and that this variation is due to different acoustic properties in the subsurface reflectors (Castagna 1993). Multibeam sonars acquire acoustic backscatter over 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, a similar approach to seismic AVO analysis can be applied to the acoustic backscatter.

The variation of backscatter strength as a function of the grazing angle represents, for a certain frequency, an inherent property of the seafloor (Jackson and Briggs, 1992). Although this angular variation or angular signature reveals subtle differences in the backscatter response of different materials on the seafloor, this information is normally lost during a normal backscatter processing, after an angle varying gain equalization function is applied to the swath data in order to produce a backscatter mosaic. The AVO Analysis tries to rescue this angular signature, by preserving the full backscatter time series during the analysis.

A simple and practical way of preserving some angular information from multibeam data is the use of the partial stacking technique similar to the one used in seismic processing. For that, the near soundings, i.e. the soundings with grazing angle closer to the nadir, will be processed separately from the far sounding, i.e., the sounding 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. The slope has a good correlation with the seafloor roughness, while the intercept has a good correlation with the impedance, although the actual relationship is complex and is described by the mathematical model for the acoustic backscatter.

The AVO Analysis is applied to a seafloor patch, which is defined as the stack of a certain number of consecutive sonar pings, normally between 20 and 30. Each stacked angular response defines two distinct seafloor patches, one for the port side and another 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. After the stacking, the corrected backscatter angular response is divided to thee intervals: near, far and outer ranges.

The near range includes grazing angles from 90° to 65°, the far range form 65° to 35°, and the outer range 35° to 5°. In the near range, the mean backscatter, the slope, and the 80° intercept of the stacked backscatter are calculated and stored as AVO attributes (Figure 1). The near-intercept is calculated at 80° in order to avoid the nadir instability, very common in swath sonars. In the far range, the attributes of mean backscatter, slope and the intercept at 55° are calculated. In the outer range, only the mean backscatter is stored as an attribute, as it has a correlation to the critical angle of reflection defined by the sound-speed ration between the water and the sediment. One important AVO parameter used to characterize the backscatter angular response is the Fluid-Factor. According to the backscatter model, this attribute responds to volume heterogeneities, more specifically the amount of free fluid, normally gas, in the sediment structure (Fonseca et al 2005).

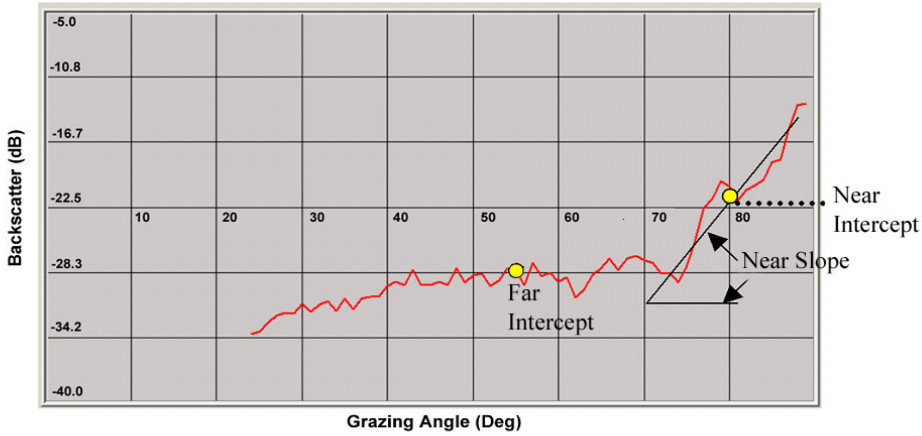


Figure 1 – Stacked backscatter angular response measured by a simrad EM3000 multibeam sonar, with some AVO parameters.

The Fluid-Factor is part of a series of parameters that can be extracted from a slope-intercept graph. For that, equations 1 and 2 are used to calculate the total gradient and the total intercept for each survey patch, and all the pairs (slope, intercept) of the survey are plotted in the Cartesian plane (Figure 2). Then, the background trend line for the survey is defined as the linear regression of all coordinate pairs (gradient, intercept) in the gradient-intercept plane (Equation 3). Finally, the fluid factor attribute (Equation 4) is calculated as the orthogonal distance of each coordinate pair to the background trend (Equation 4). The final parameter extracted from the plane is the product, defined as the multiplication of the gradient by the intercept.

Based on the calculated AVO attributes 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.

$$B = \frac{Far - Near}{\sin^2(\theta_{far}) - \sin^2(\theta_{near})}$$ Equation 1

$$A = \frac{Far + Near}{2} - B\left(\frac{\sin^2(\theta_{far}) + \sin^2(\theta_{near})}{2}\right)$$ Equation 2

$$Background\ Trend = g * A + d$$ Equation 3

$$Fluid\ \ Factor = \frac{-gA + B - d}{\sqrt{g^2 + 1}}$$ Equation 4

Where,

A: Total gradient of the angular response;

B: Total intercept of the angular response;

Near: Average backscatter in the near range;

Far: Average backscatter in the far range;

g: Slope of the background trend line (see Figure 2);

d: Intercept of the background trend line (see Figure 2);

θ_{far}:Average incident angle of the sounding in the far range;

θ_{near}: Average incident angle of the sounding in the near range;

Example from Little Bay, NH

AVO analysis was applied to an acoustic remote sensing dataset acquired in the summer of 2003 in Little Bay, NH (Figure 3). The equipment used was a Simrad EM3000 multibeam sonar, which is a shallow water system operating at 300kHz, forming 127 beams in an angular sector of 130 degrees. The survey mapped water depths from 6 to 24m, with bottom sediments ranging from gravel to clay. The analysis started with the backscatter time series stored in raw Simrad datagrams, which was then corrected for radiometric and geometric distortions. 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, and correction for footprint size. Additionally, it was necessary to remove the lambertian correction and the near nadir time-varying-gain compression that were applied to the backscatter time series during acquisition. The radiometrically and geometrically corrected backscatter was then compared to the predictions of the mathematical model.

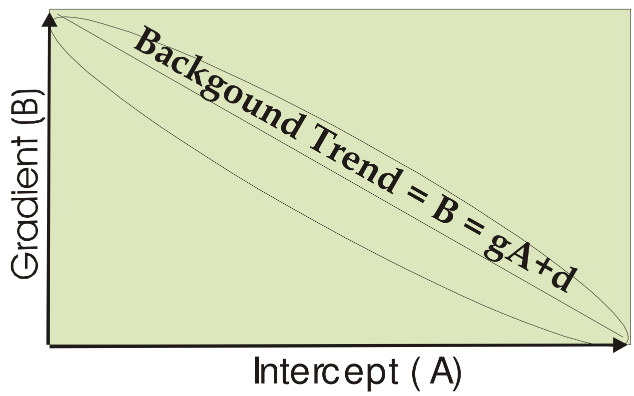


Figure 2 – Gradient-Intercept graph with background trend line.

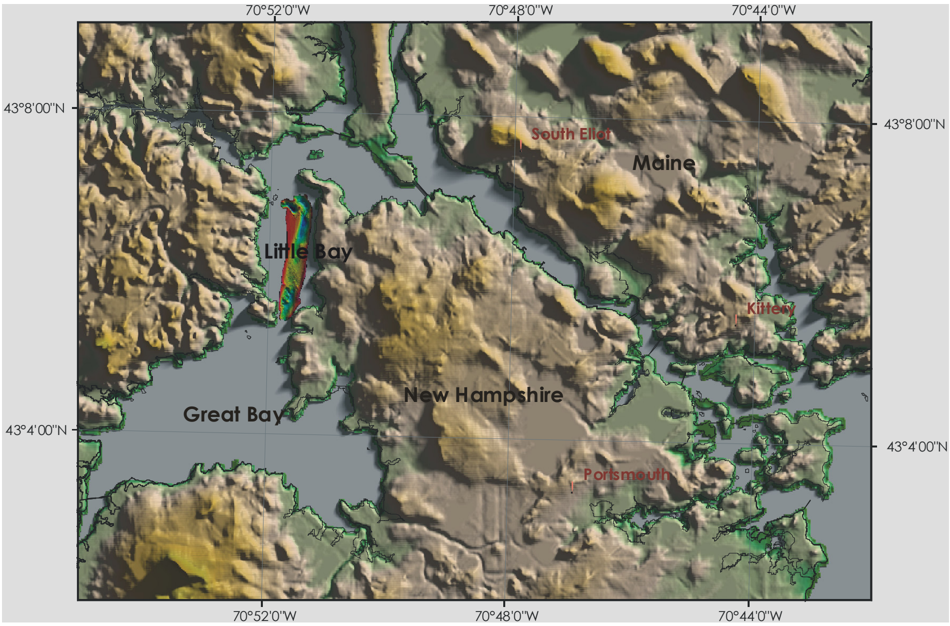
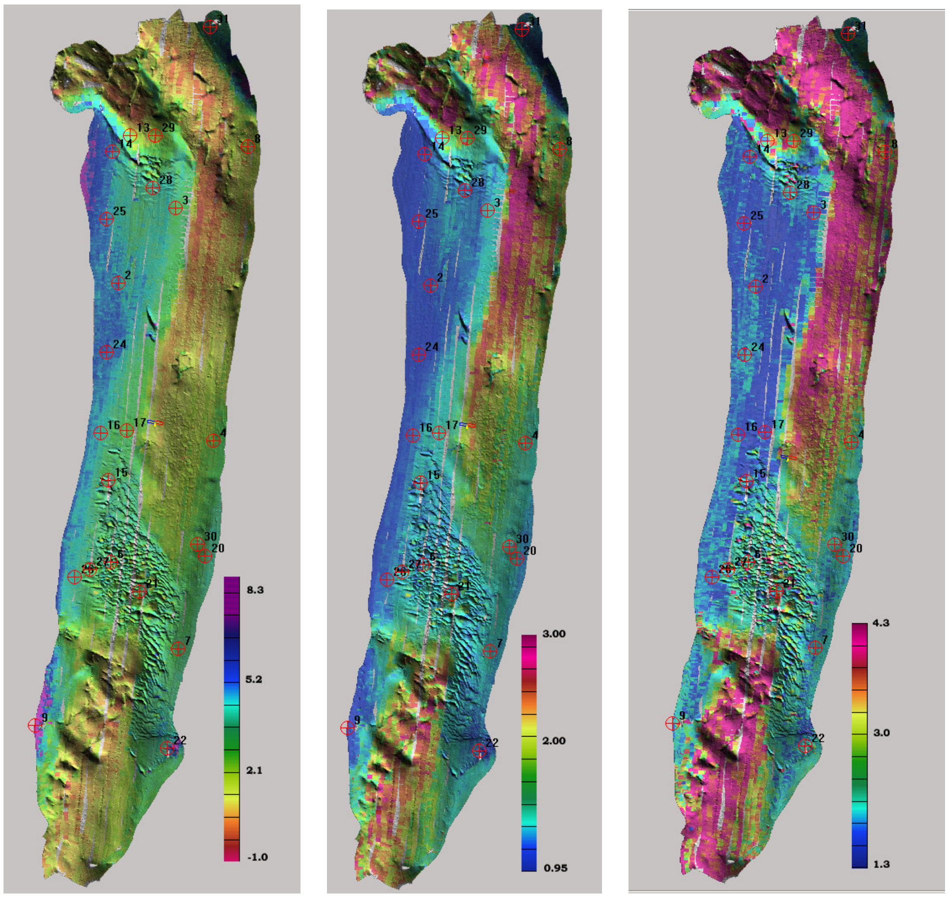


Figure 3 – Location map – Little Bay, NH.

A series of AVO attributes (near, far, slopes, gradients, fluid factor and product) were calculated from the stacking of 30 consecutive time series. The same AVO parameters calculated for the measured backscatter angular response were also calculated for a series of modeled backscatter angular response. The inversion of the model was done iteratively by adjusting the near-range slope, the near-range intercept, the far-range intercept, the far-range slope and the fluid-factor, with the model parameters constrained by Hamilton equations. The inversion is regularized by the adjustment of the AVO parameters and not by the adjustment of the model parameter, which showed to be a more robust approach. Based on the calculated AVO attributes and the constrained iterative inversion of the acoustic backscatter model we estimated the acoustic impedance, the roughness, and consequently the grain size of the insonified area on the seafloor (Figure 4).



a) b) c)

Figure 4 – Results of the model inversion and location of in-situ measurements. The inverted parameters are represented by a color scheme draped over the sun-illuminated bathymetry. a) Sediment grain size (ϕ); b) Impedance ratio; c) Roughness in cm.

In Little Bay, the estimated impedance and grain-size were compared to in-situ measurements of sound-speed taken from the R/V Gulf Challenger and to the direct analysis of grain size in grab samples. In October 2003 and April 2004, measurements of in-situ sound speed were completed in Little Bay, with two orthogonal matched pairs of transducer probes operating at frequencies of 40 and 65 kHz. (Kraft et al, 2004). In October 2003, sediment sampling with a Van grab sampler was also conducted from the R/V Coastal Surveyor. The comparison between in-situ and remotely estimated measurements showed a very good correlation, and the results are plotted in Figure 5.

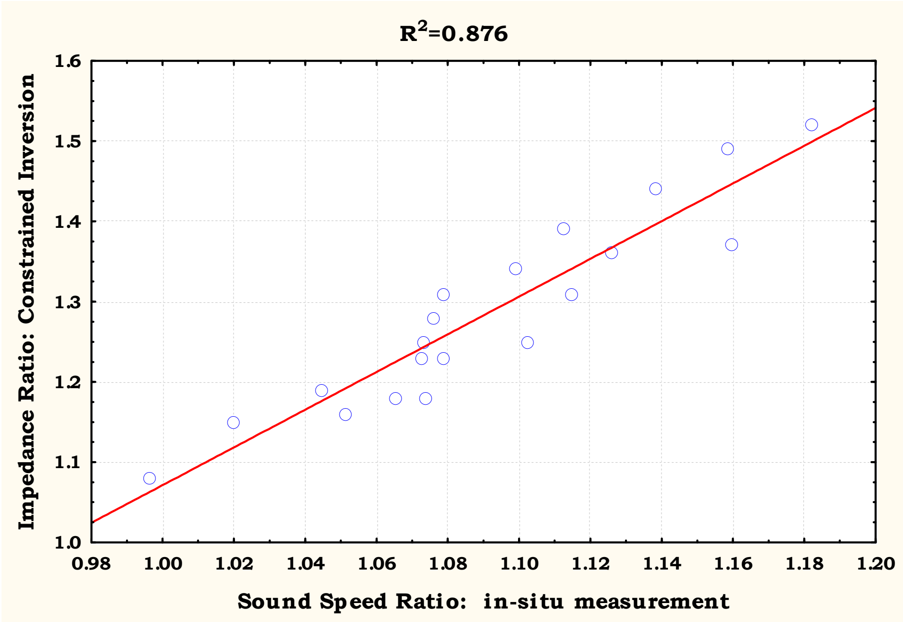


Figure 5 – Remotely estimated acoustic impedance versus in-situ measurements of sound speed. Note the very good linear correlations (R^2=0.876).

Conclusions

AVO analysis of Multibeam data is a promising technique for remote acoustic seafloor characterization. This technique was successfully applied to the Simrad EM3000 multibeam sonar data from Little Bay, where the remotely estimated impedance was compared to the in-situ measurements of sound speed, indicating a strong correlation between these two acoustic parameters. More accurate results will be possible with better observations, specifically radiometrically calibrated and geometrically corrected acoustic backscatter. Additionally, the definition of more precise acoustic backscatter models is essential for understanding the acoustic signature of seafloor sediments.

Acknowledgments

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