PSAdaptive Eigenstructure Classification and Stochastic Decorrelation Filters for Coherent Interference Suppression in the Acoustic Zoom Method*

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Abstract

The Acoustic Zoom® (AZ) Method is an unconventional oil and gas exploration technology for 3D/4D seismic imaging that offers unique resolution and direct focusing of non-specular backscatter energy returns in land and marine environments. The receiver array has sixteen spokes (eight lines through a hub) at ~22.5° increments. This array was deployed to intersect GGS's Wrangler 3D survey in Wilson County, Texas, over the prolific Eagle Ford, Austin Chalk, and Buda (limestone) formations. The AZ purpose-designed array, covering 12.5 km^2, encompassing over 4,000 receivers and with recorded frequencies up to 170 Hz, acquired over two terabytes of data. Five vibroseis locations were established in a cross configuration at a quarter of wavelength separation. At each of the five vibroseis locations, 512 sweeps were generated and vertically stacked for 2,560 sweeps. By design, AZ accentuates the rich content of non-specular backscatter energy by directly probing underlying geophysical properties of the earth where conventional migration accentuates specular reflections from ambiguous impedance changes in the subsurface. The totality of energy backscattered in the direction and range of a corresponding beam forms each AZ image. AZ adds value to existing 3D surveys by reconstructing complementary components of recorded energy that 3D seismic rejects as incoherent noise. Imaging of non-specular returns requires significant attenuation of coherent background interference (e.g. ground roll, specular reverberation) achieved by combining the narrow beam-width of the receiver array with adaptive classification and filtering of specular energy using Singular Value Decomposition, Stochastic Spectral Decorrelation, and advanced Eigen-structure methods. This approach replaces conventional filters that could introduce artifacts greater than the non-specular signals being sought.

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Objectives

The Acoustic Zoom (AZ) seismic beamforming method is an unconventional oil and gas exploration technology. AZ adds value to existing 3D surveys by reconstructing complementary non-specular components of the recorded energy that 3D seismic processing rejects as incoherent noise. Imaging of non-specular returns requires significant attenuation of coherent background interference (e.g. ground roll, specular reverberation) achieved by combining the narrow beamwidth of the receiver array with adaptive classification and filtering of specular and non-specular energy using singular value decomposition (SVD), a proprietary stochastic spectral decorrelation (SSD) algorithm, and advanced eigen-structure methods. The resulting algorithm is analogous to the Hough transform (in image processing) extended to patterns for geophysical reflections and diffractions. This approach replaces conventional filters that could introduce artifacts greater than the non-specular signals being sought.

Introduction

The AZ method adapts all eigenstructure-based classification and filtering algorithms to each individual image point, thereby casting the imaging problem into a non-convolutional form. Adaptive processing allows the AZ method to include more realistic models of propagating wavefields, including frequency attenuation of the source wavelet, for example. Conventional seismic processing casts the imaging problem into convolutional form to allow efficient processing using Fourier transforms. In the hierarchy of beamforming methods that includes delay-sum (Bartlett beamformer), delay-filter-sum (Capon, Frost beamformers), and adaptive delay-filter-sum, the present method is adaptive delay-classify-filter-sum.

Eigen-structure Classification and Beamforming

Non-specular signals are separated from specular interference using eigen-structure methods. The decomposition of the AZ method is exact and invertible. A trace gather is flattened according to a specified travel-time equation (Figure 1). The decomposition of the gathered data u is performed using a projection functional P that performs the following operation:

$$\overline{u} = \overline{u}_{\parallel} + \overline{u}_{\perp} = P\{\overline{u}\} + (\overline{u} - P\{\overline{u}\}) \tag{1}$$

where $\overline{u}_{\parallel} = P\{\overline{u}\}$, $\overline{u}_{\perp} = \overline{u} - P\{\overline{u}\}$ and $\overline{u} = R\{u\}$ where R is the operation that transforms the original dataset into a flattened dataset. The defining property of the projection functional is the requirement that

$$P^2 = P\{P\{\dots\}\} = P\{\dots\} = P. \tag{2}$$

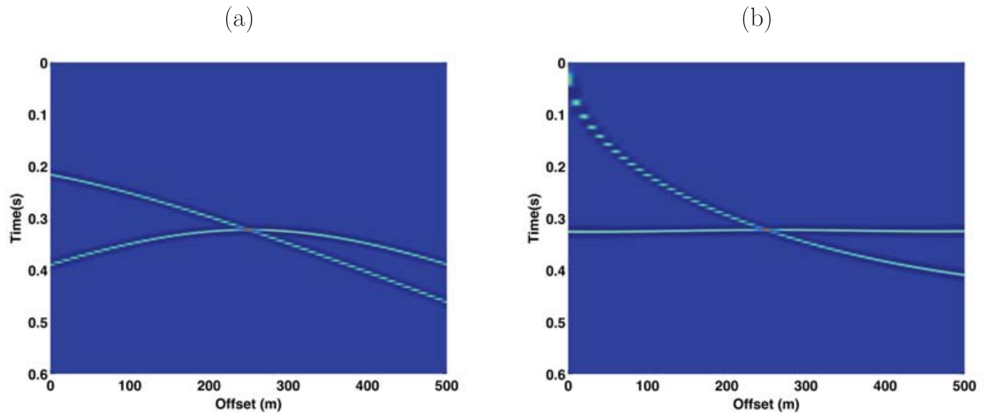

(a) (b)

Figure 1: Synthetic shot-gather before (a) and after (b) move-out correction shows a hypothetical reflection and diffraction having different travel time profiles (move-outs).

A time window (Figure 2) of a flattened gather of data is defined as

$$A = A(\tau_i) = \begin{bmatrix} \overline{u}(x_r, x_s, \tau_{(i-\Delta)}) \\ \vdots \\ \overline{u}(x_r, x_s, \tau_{(i)}) \\ \vdots \\ \overline{u}(x_r, x_s, \tau_{(i+\Delta)}) \end{bmatrix} \tag{3}$$

where the bar over u denotes a flattening operation, and the time window spans times from $\tau_{(i-\Delta)}, \dots, \tau_{(i)}, \dots \tau_{(i+\Delta)}$ where the width of the time window is $2\Delta + 1$. The analyzing wavelet image $W = \vec{w} \otimes \vec{g}$ is the outer product of a source wavelet $\vec{w}$ and a true amplitude radiation pattern $\vec{g}$ (Figure 2b), normalized so that $W^T W = 1$.

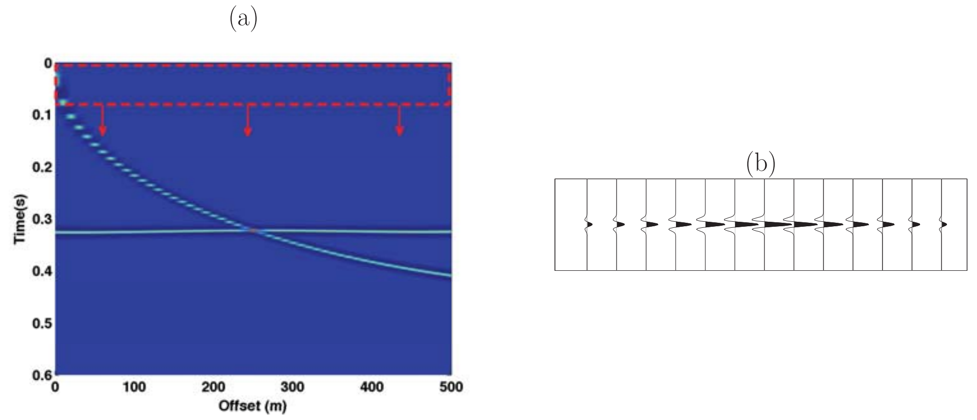

(a) (b)

Figure 2: (a)Eigen-structure classification is applied to a sliding time window of a flattened data gather using an analyzing wavelet image corresponding to the signal being sought. (b) The analyzing wavelet image combines a source wavelet with a true amplitude radiation pattern adapted to each image point.

Each window of data is exactly decomposed as a sum of eigen-images Q_m using SVD. The data window is projected onto the analyzing wavelet template by

$$A_{\parallel} = \sum_{m=1}^{M} |\sigma_m \mathrm{trace}(W^T Q_m)| Q_m \tag{4}$$

The spatial vector component of $A_{\parallel}$ corresponding to the central τ_i value of the flattened time window is written into the corresponding gather of processed data. The residual vector of data may be similarly saved for further processing. The analysis window is then advanced by one unit of time and processing proceeds until the entire data gather is analyzed.

The AZ method described here can incorporate repeated application of forward and inverse flattening and projection transforms, consecutively isolating sources of interference prior to a final isolation of the signal in a flattened gather of data. In practice, the improvement is marginal over the direct approach presented here. More refined approaches are also possible.

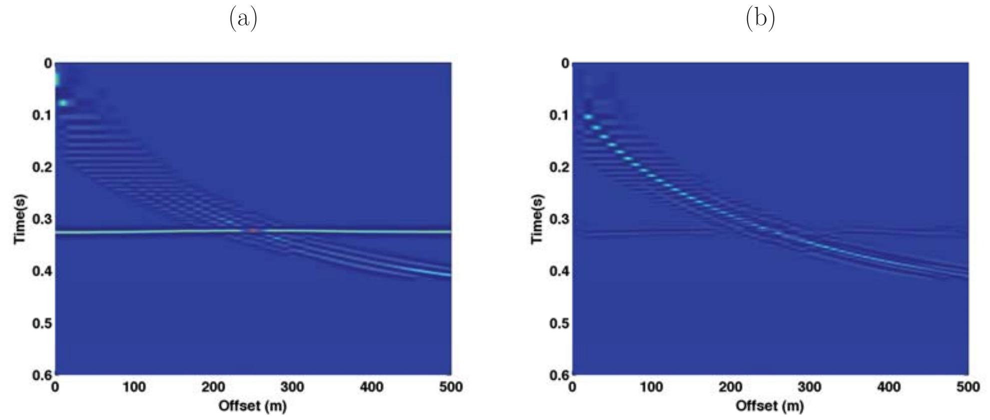
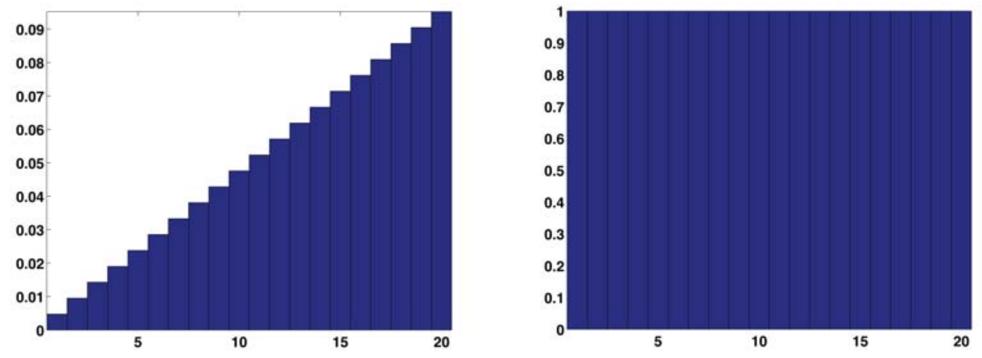

(a) (b)

Figure 3: The original gather of data is exactly decomposed into (a) signal and (b) residual (typically interference).

Stochastic Spectral Decorrelation Filter

The projection algorithm outputs a dataset that can undergo additional filtering during final beamforming and imaging. The objective is to define a set of weights that shapes the response of all source-receiver-image point combinations that have the same travel-times (i.e. same phase) and to whiten the frequency spectrum so that all phases are uniformly distributed. If all the in-phase amplitudes of reverberation are the same and their phases are uniformly distributed, then the contributions due to reverberation will stack out and approximately sum to zero (or preferentially suppressed). The stochastic spectral decorrelation (SSD) algorithm aims to whiten both the frequency and wave number distributions of the trace data over the array prior to beamforming. Unlike conventional Wiener filter algorithms used to determine the optimal filters, the SSD algorithm is deterministic and scalable to arrays of arbitrary size and geometry. Although the SSD filter is not optimal in the Wiener filter sense given its simple assumptions and the randomness of the reverberating wave-field, its robust and efficient performance allows the SSD filter to be adapted to each image point.

(a) Unnormalized Array Response (b) Whitened Array Response



(c) Non-Uniform Unknown Phase (d) Whitened Known Amplitudes and Phases

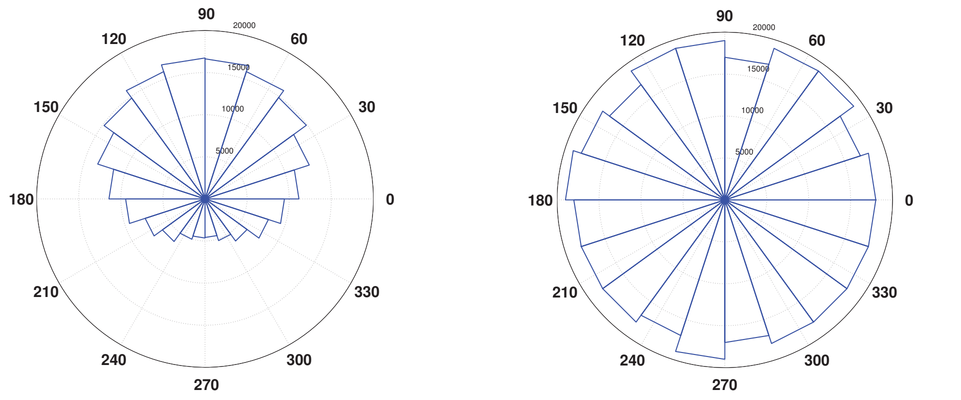


Figure 4: When the spatial and temporal frequencies of the reverberant wavefield are "whitened", these wavefields "stacked out" when the final beam forming image is calculated.

Conclusion

The AZ method provides a systematic method by which an arbitrary radiation pattern may be embodied as an analyzing image template. The method projects the observed data image onto this component image template to determine the agreement between the observed data and the component data model. This projection operation is dependent on defining a scalar product (or projection) operator for images. Prior to beamforming, the flattened gather of data is first exactly classified as either consistent with the template for the signal or not consistent with the same template. The output is a measure that is proportional to the agreement between the data image and the template image. This is analagous to the output of the Hough transform (in image processing) extended to patterns for geophysical reflections and diffractions. Image templates can be developed to image particular geophysical properties of commercial value.

References

Guigné, J.Y., Stacey, A.J., Clements, C., Azad, S., Pant, A., Gogacz, A., Hunt, W., and Pace, N.G., Acoustic Zoom High-Resolution Seismic Beamforming For Imaging Specular and Non-Specular Energy of Deep Oil and Gas Bearing Geological Formations, submitted to Journal of Natural Gas Science & Engineering, July 2014.

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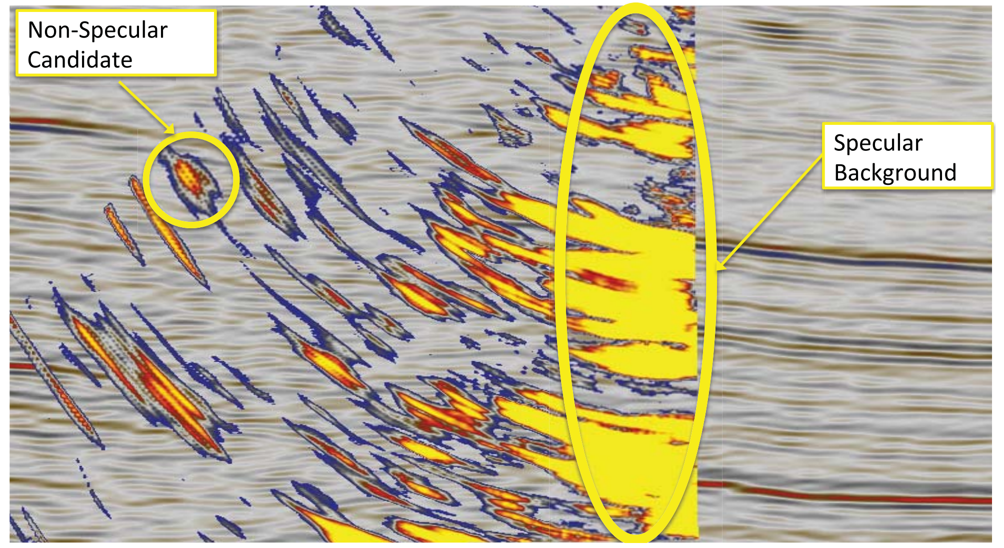
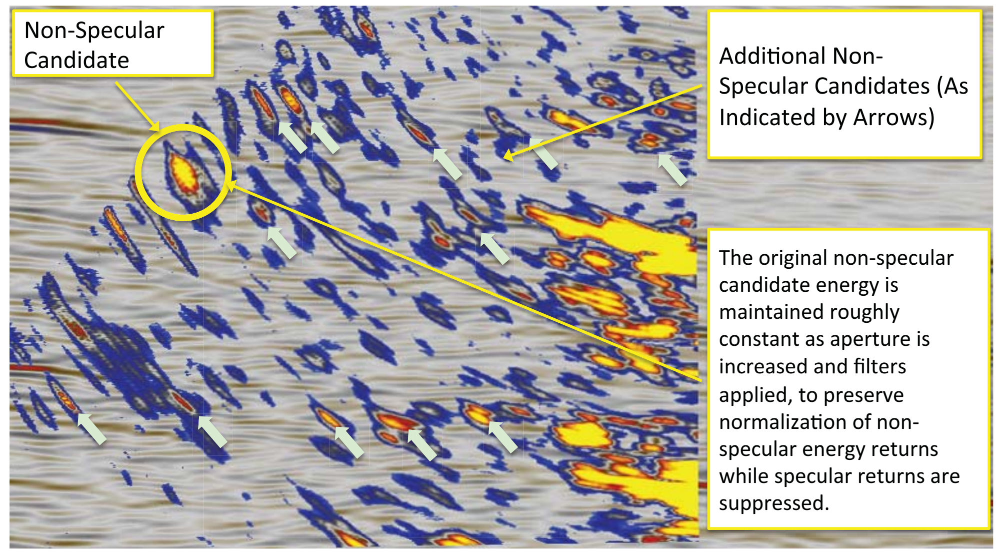


Figure 5: A subset of the full array is used to identify potential non-specular candidates while rejecting sources of specular returns.


Non-Specular Candidate

Additional Non-Specular Candidates (As Indicated by Arrows)

The original non-specular candidate energy is maintained roughly constant as aperture is increased and filters applied, to preserve normalization of non-specular energy returns while specular returns are suppressed.

Figure 6: Large aperture imaging enhances non-specular signals and suppresses reverberant background.