Curvelet Processing and Imaging: Adaptive Ground Roll Removal

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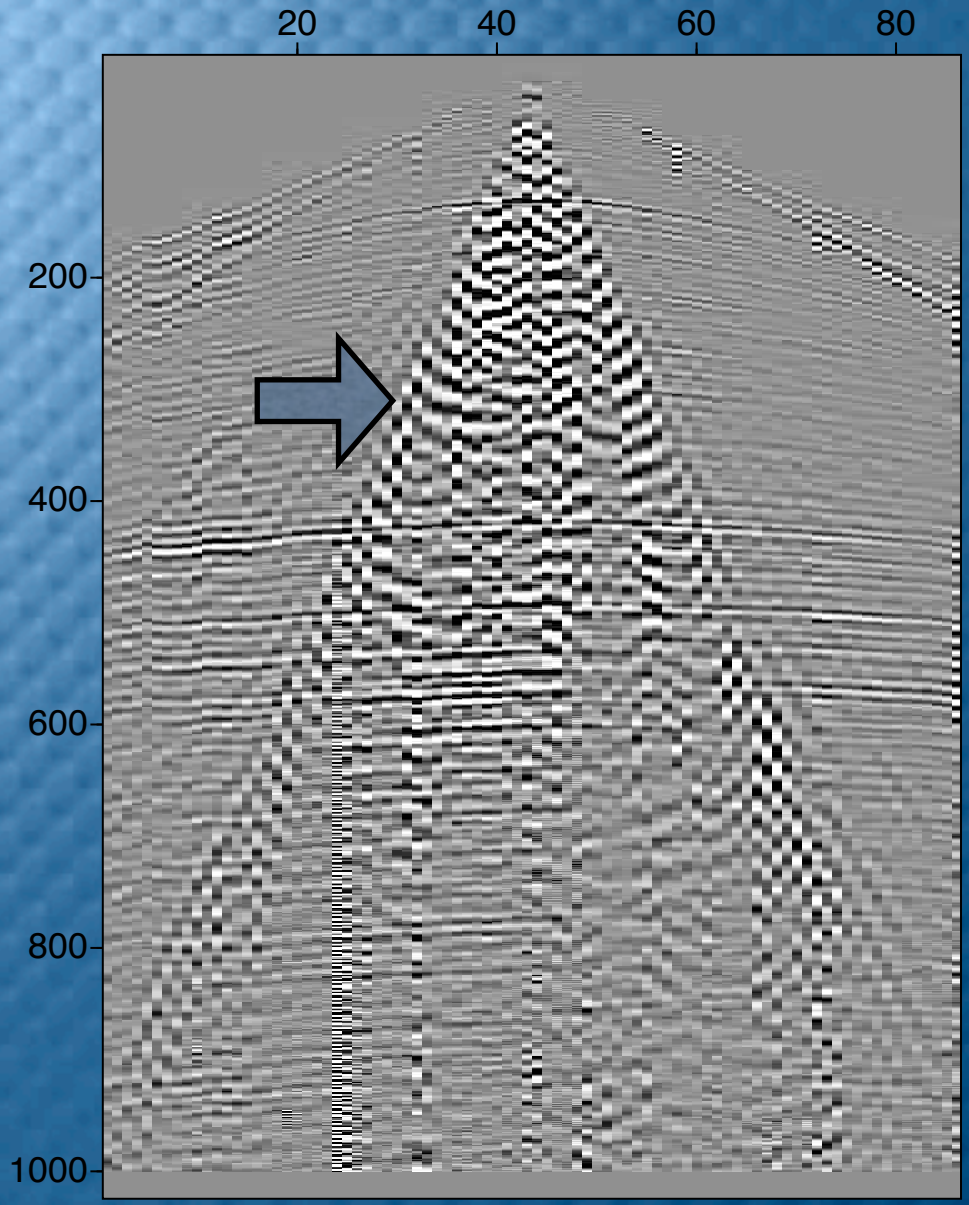
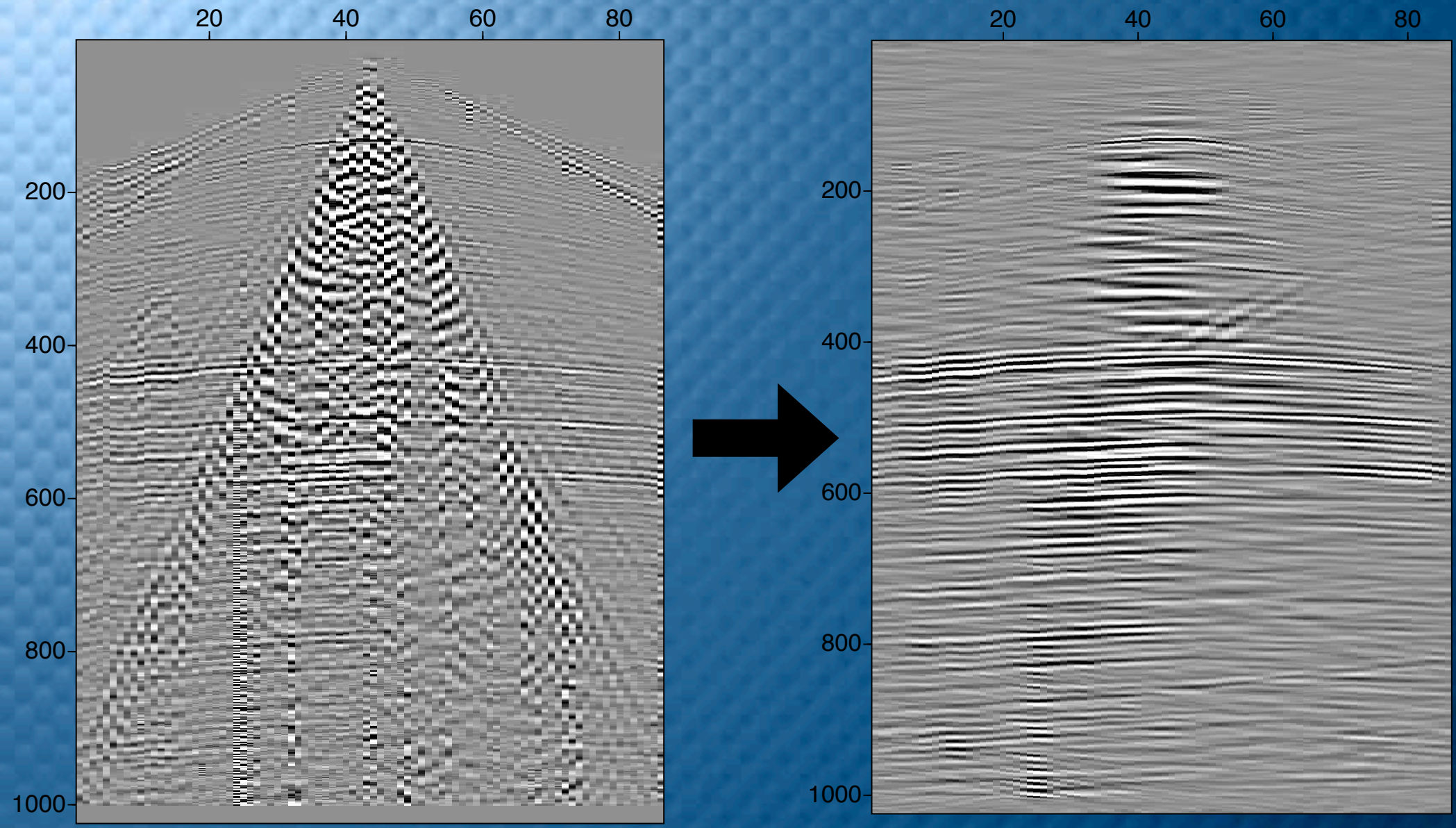
The Problem



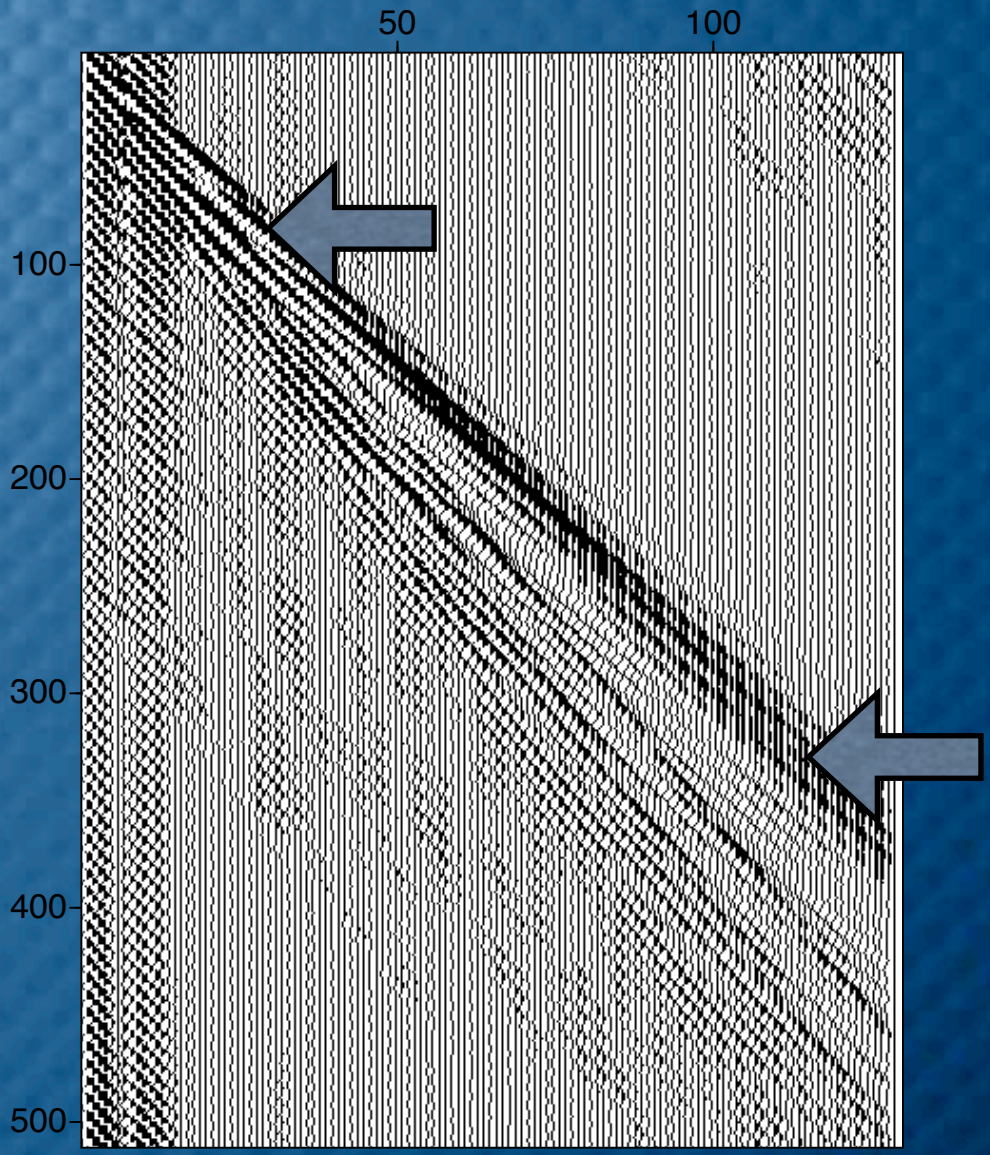
Oz25 Data Set from Yilmaz's Seismic Data Processing

What We Can Do



Ground Roll Properties

- Represented as a Rayleigh wave.
- Dispersive, Low Frequency
- Highly dependent on near surface properties
- Reduces SNR
- Generated in the frequency slope domain in the slant stack transform



(A.G. McMechan and M.J. Yeldin, Geophysics, 1981)

Two Problems to Solve

How Do We Identify What to Remove?

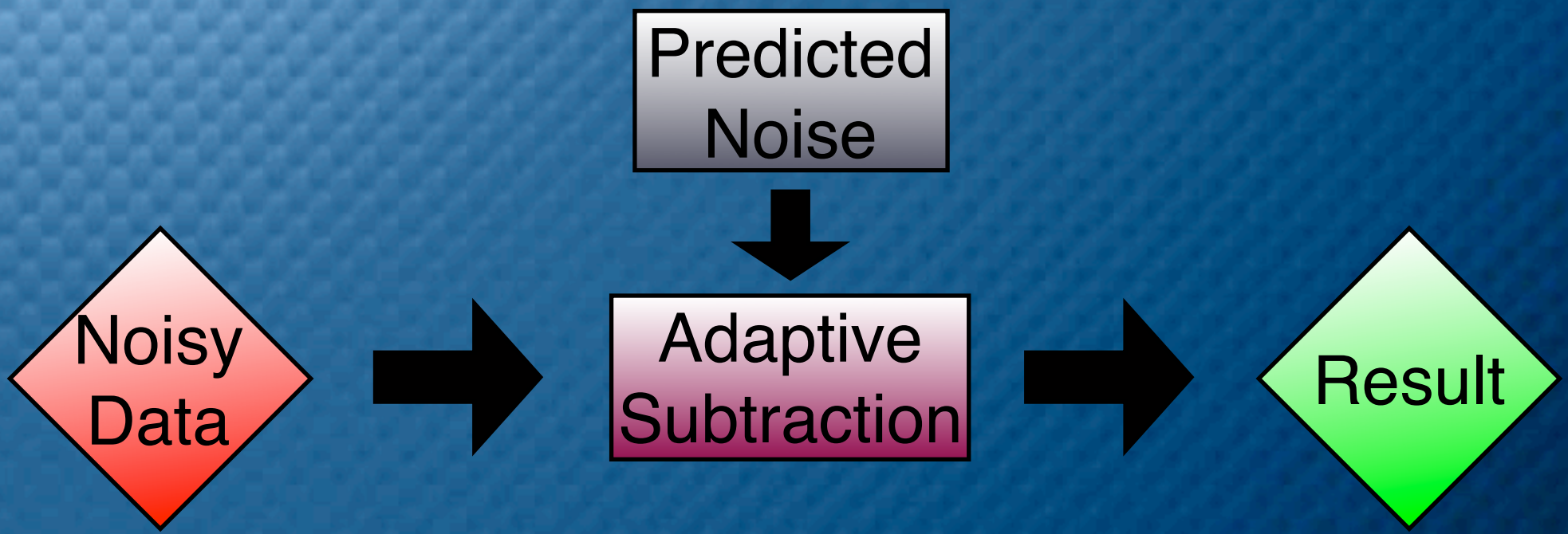
- Modeled Ground Roll
- Noise Prediction From Other Methods

How Do We Remove It?

- Incorporate Prior Predictions
- Use Adaptive Subtraction

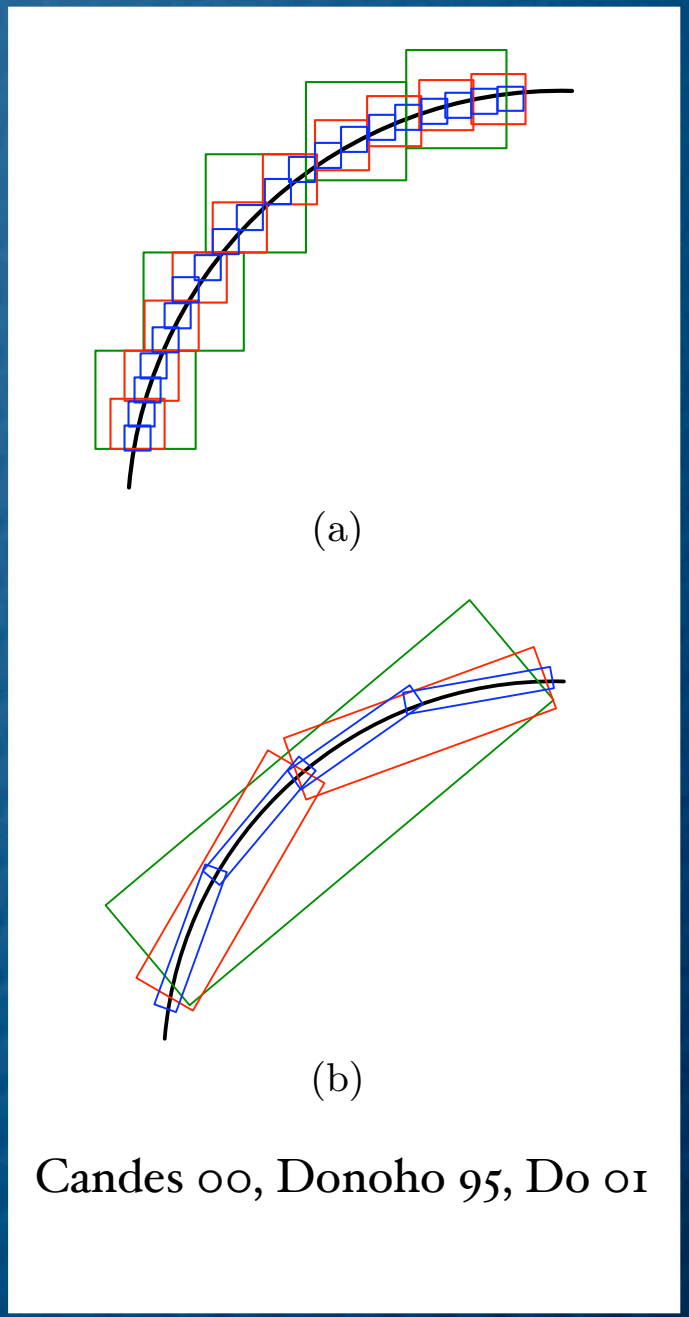
Our Use Of Hyperbolic Radon Filtering

- Identifies hyperbolic reflectors from the signal
- May produce artifacts with conventional subtraction
- We can use the predicted noise with adaptive subtraction

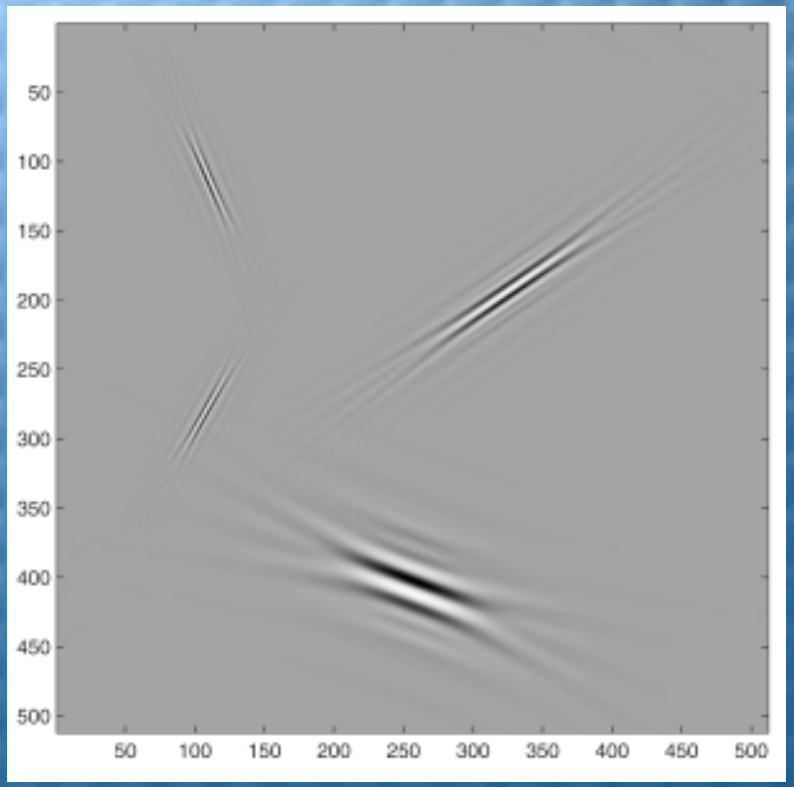


Wavelets and Curvelets

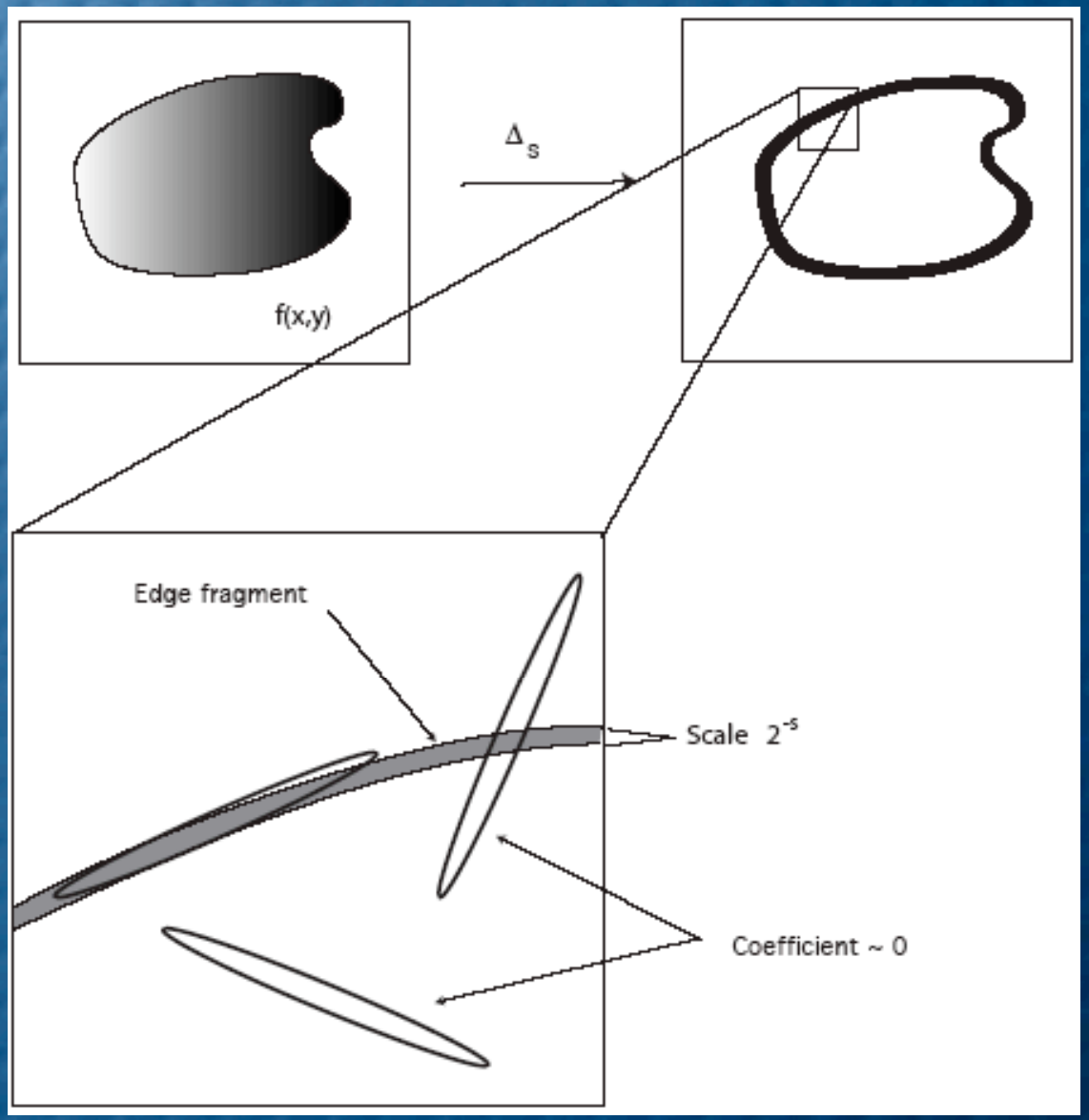
- Wavelets:
  - Represent time and frequency
  - Multi-Scale
- Curvelets:
  - Local in position and angle
  - Strongly anisotropic at fine scales (parabolic scaling principle: length² ~ width)



Curvelets

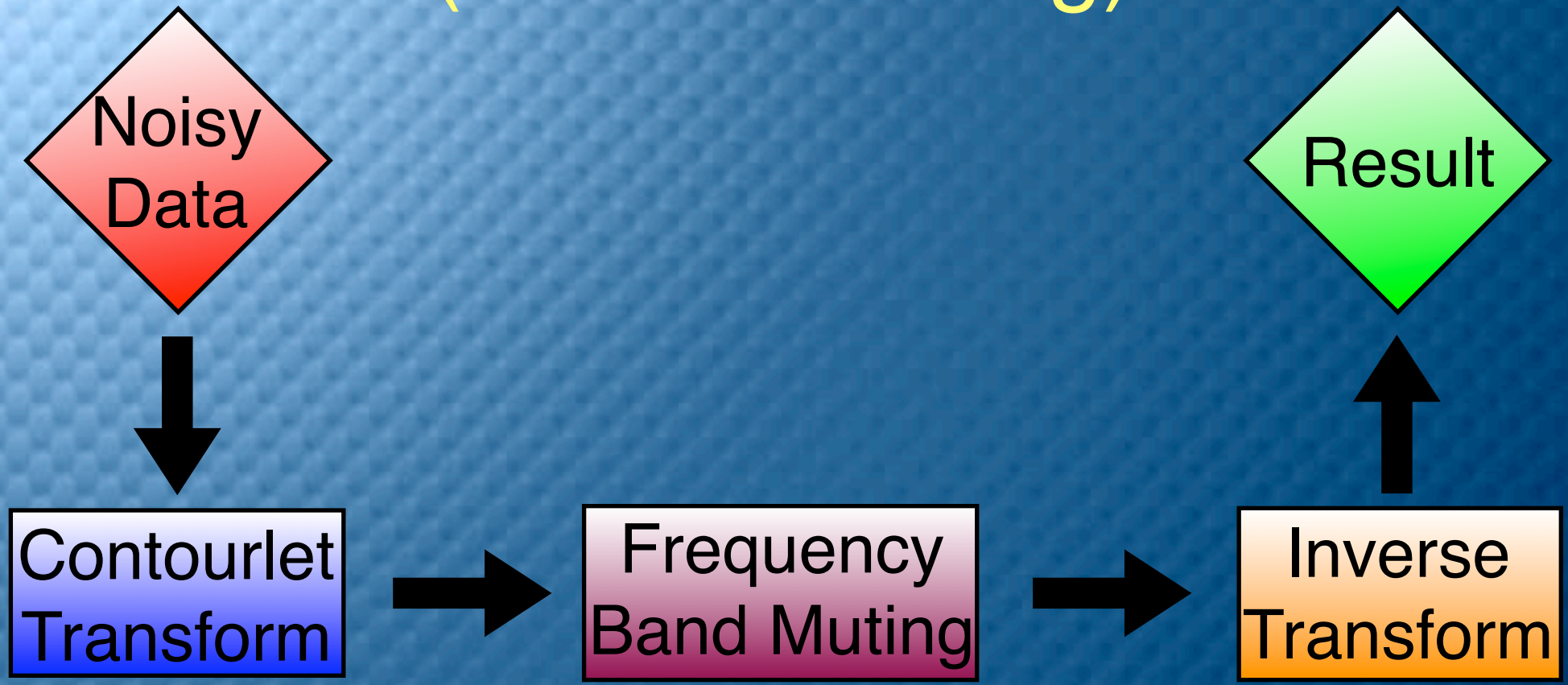


Candes 02, Do 02



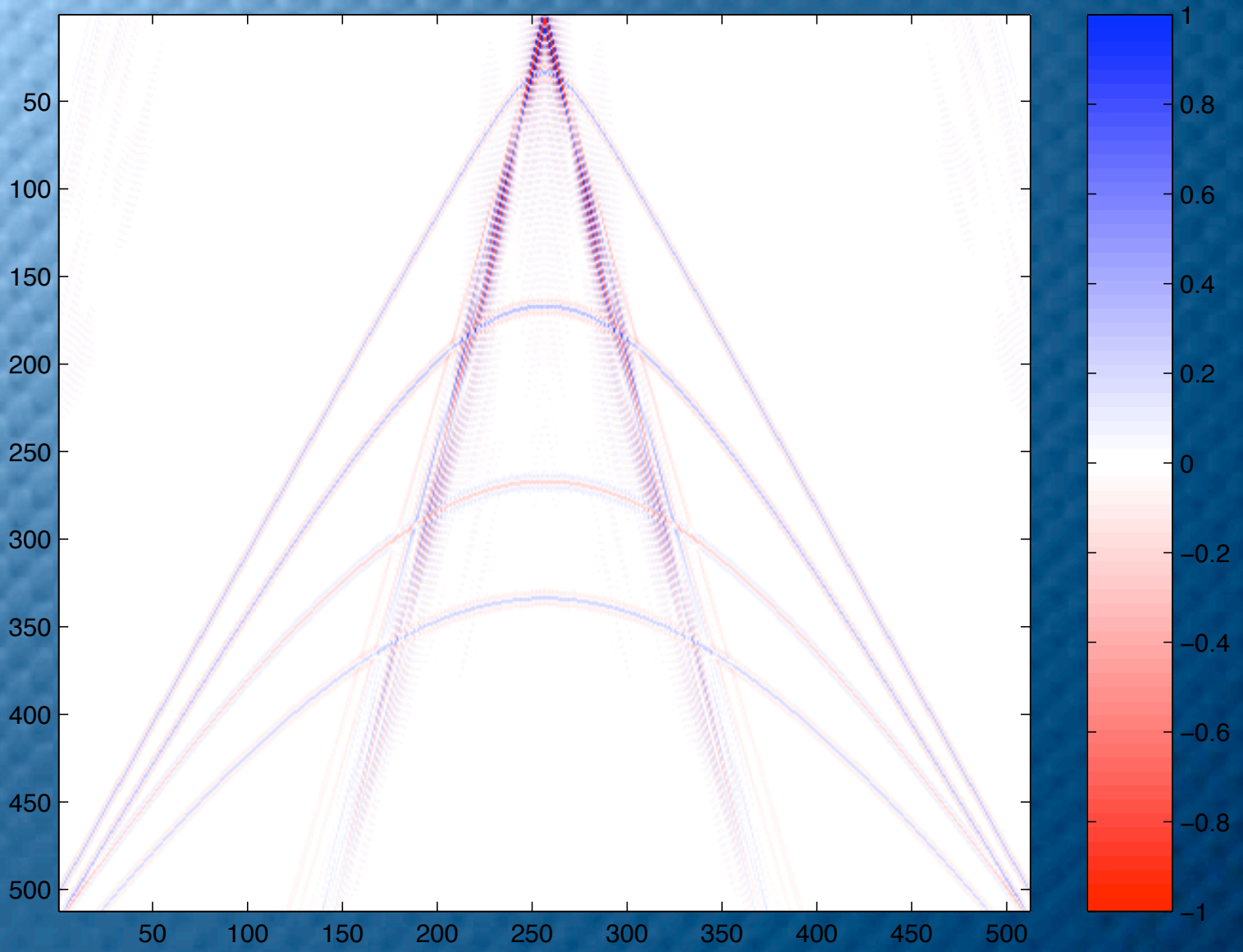
Candes 02, Do 02

Contourlet Band Muting (Linear Filtering)



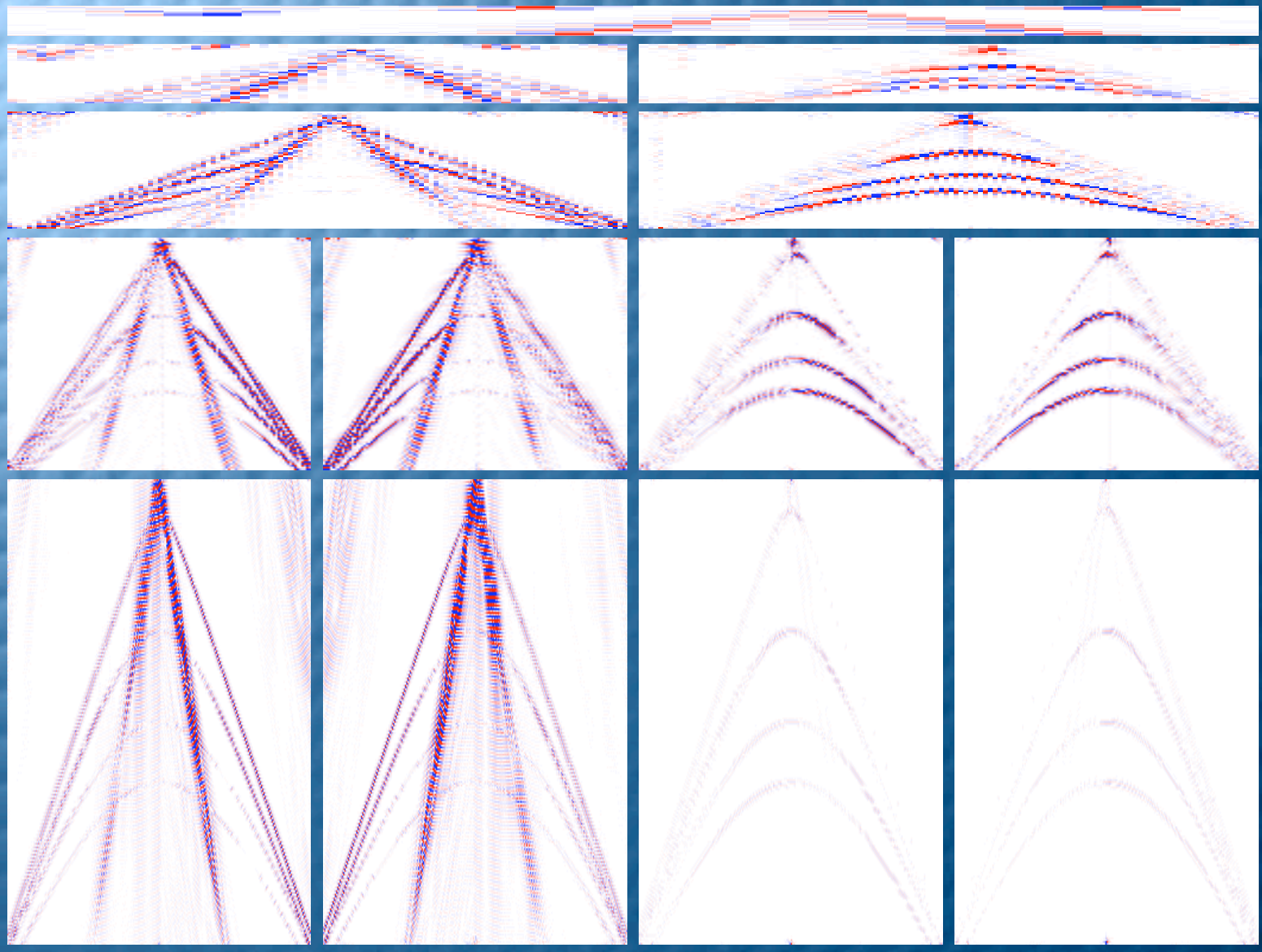
- Global & linear
- Similar to F-K Filtering

Contourlet Band Filtering
Synthetic Example



Steep Parabolic Curves and Dispersive Ground Roll

Contourlet Coefficient Sectors

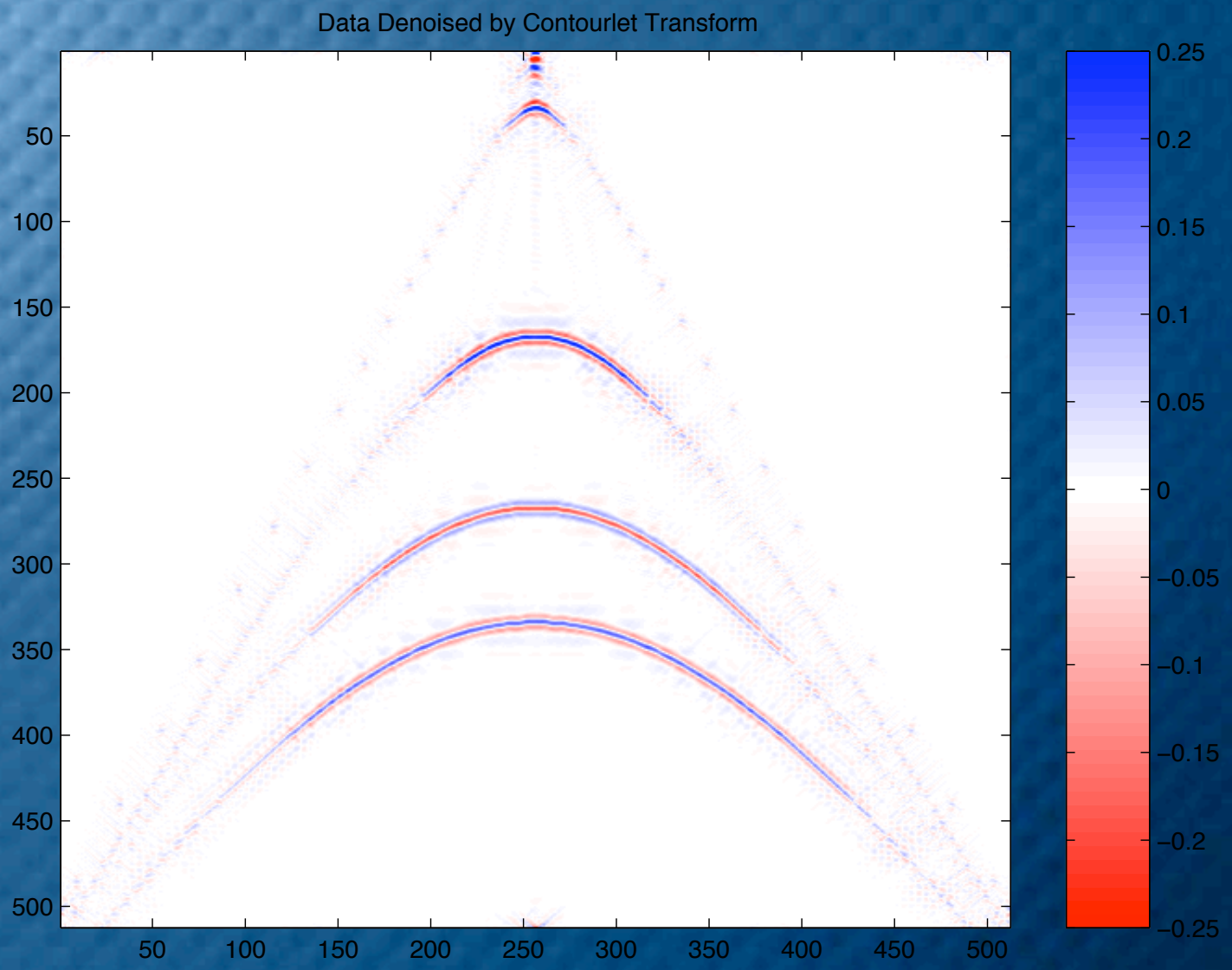


Each band represents a group of coefficients that represents and individual part of the signal

Reconstructed Contourlet Denoised Signal

Problems:

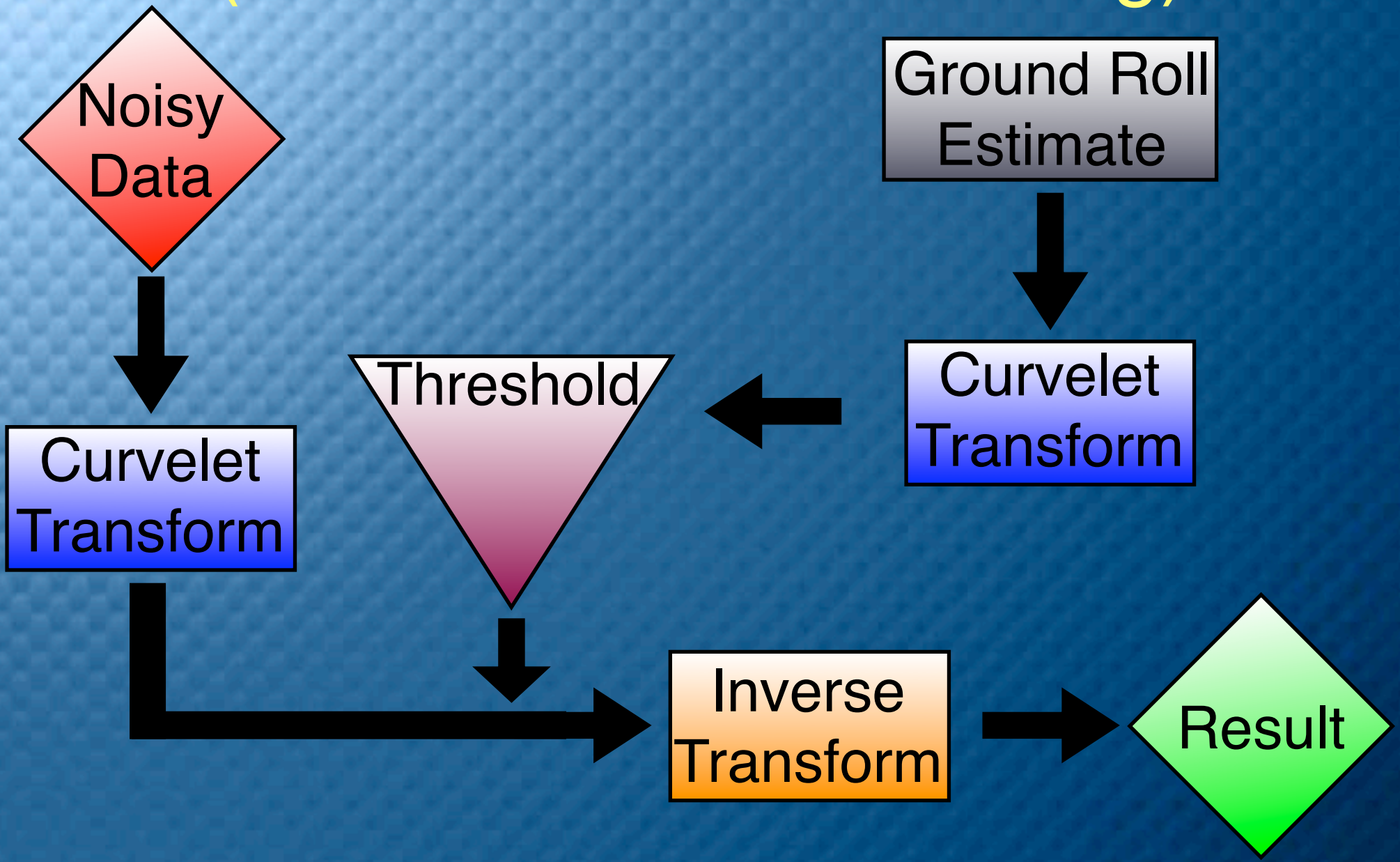
- Steep events removed
- Artifact located at apex



Curvelet Adaptive Subtraction

- Smart
  - Local in Position and Dip
  - Allows Incorporation of Prior Predictions
- Flexible
- Relatively Phase Insensitive

Curvelet Adaptive Subtraction (Non-Linear Thresholding)



Curvelet Adaptive Subtraction

$$\overbrace{\mathbf{d}}^{\text{noisy data}} = \underbrace{\mathbf{m}}_{\text{noise-free}} + \overbrace{\mathbf{n}}^{\text{pred. noise}}$$

$$\hat{\mathbf{m}} \; : \; \min_{\mathbf{m}} \frac{1}{2} \| \mathbf{C}_n^{-1/2} \left(\mathbf{d} - \mathbf{m} \right) \|_2^2$$

$$\hat{\tilde{\mathbf{m}}} \; : \; \min_{\tilde{\mathbf{m}}} \frac{1}{2} \| \mathbf{\Gamma}^{-1} \left(\tilde{\mathbf{d}} - \tilde{\mathbf{m}} \right) \|_2^2 + \lambda^2 \| \tilde{\mathbf{m}} \|_p$$

$\mathbf{C}_n =$ Covariance $\quad \mathbf{\Gamma}^2 =$ Diagonal of the Covariance

Curvelet Adaptive Subtraction

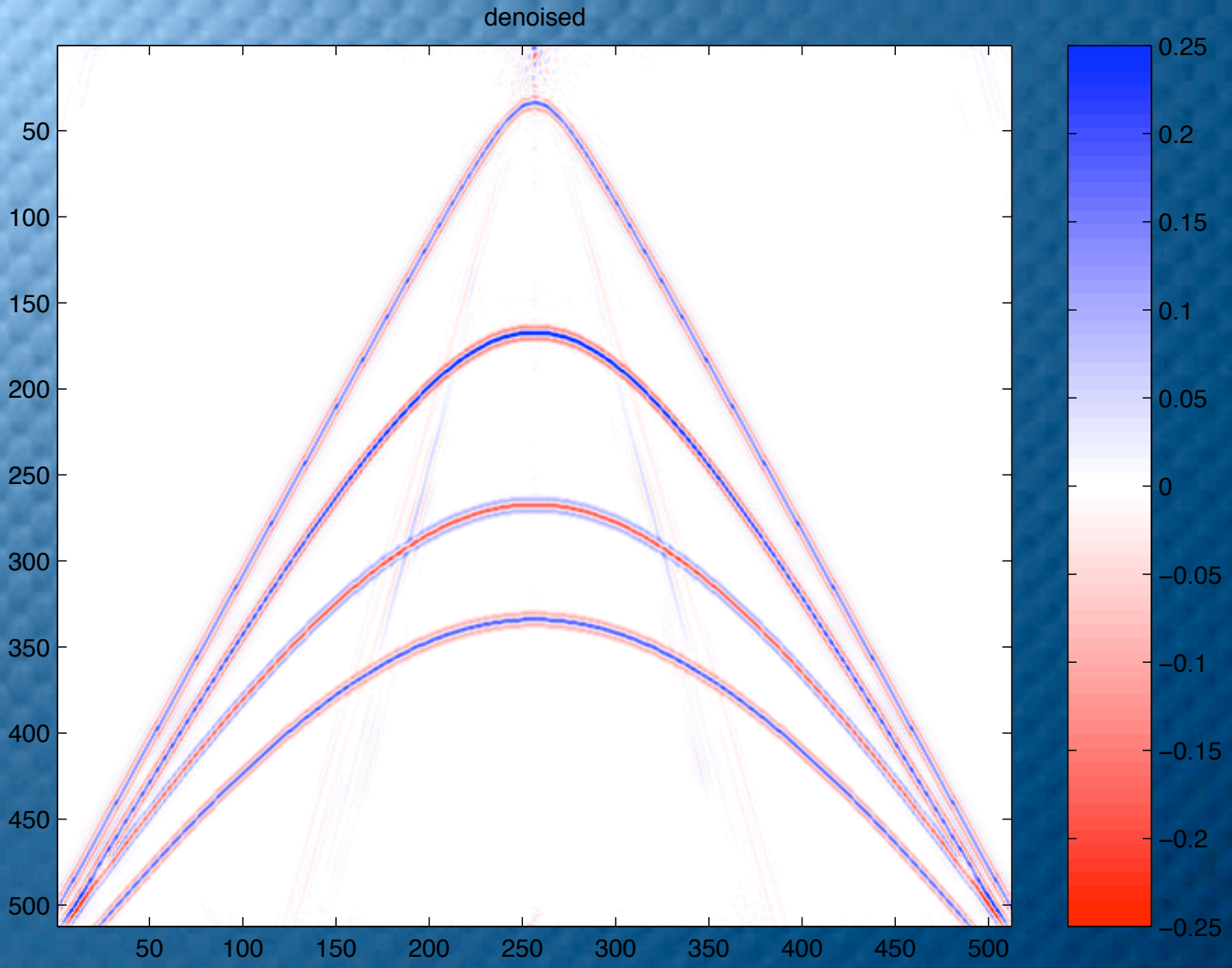
$$\mathbf{\Gamma} = |\mathbf{B}\mathbf{n}_p|$$

$$\hat{\mathbf{m}} = \mathbf{B}^T \mathbf{\Theta}_{\lambda\Gamma} \left(\mathbf{B}\mathbf{d} \right)$$

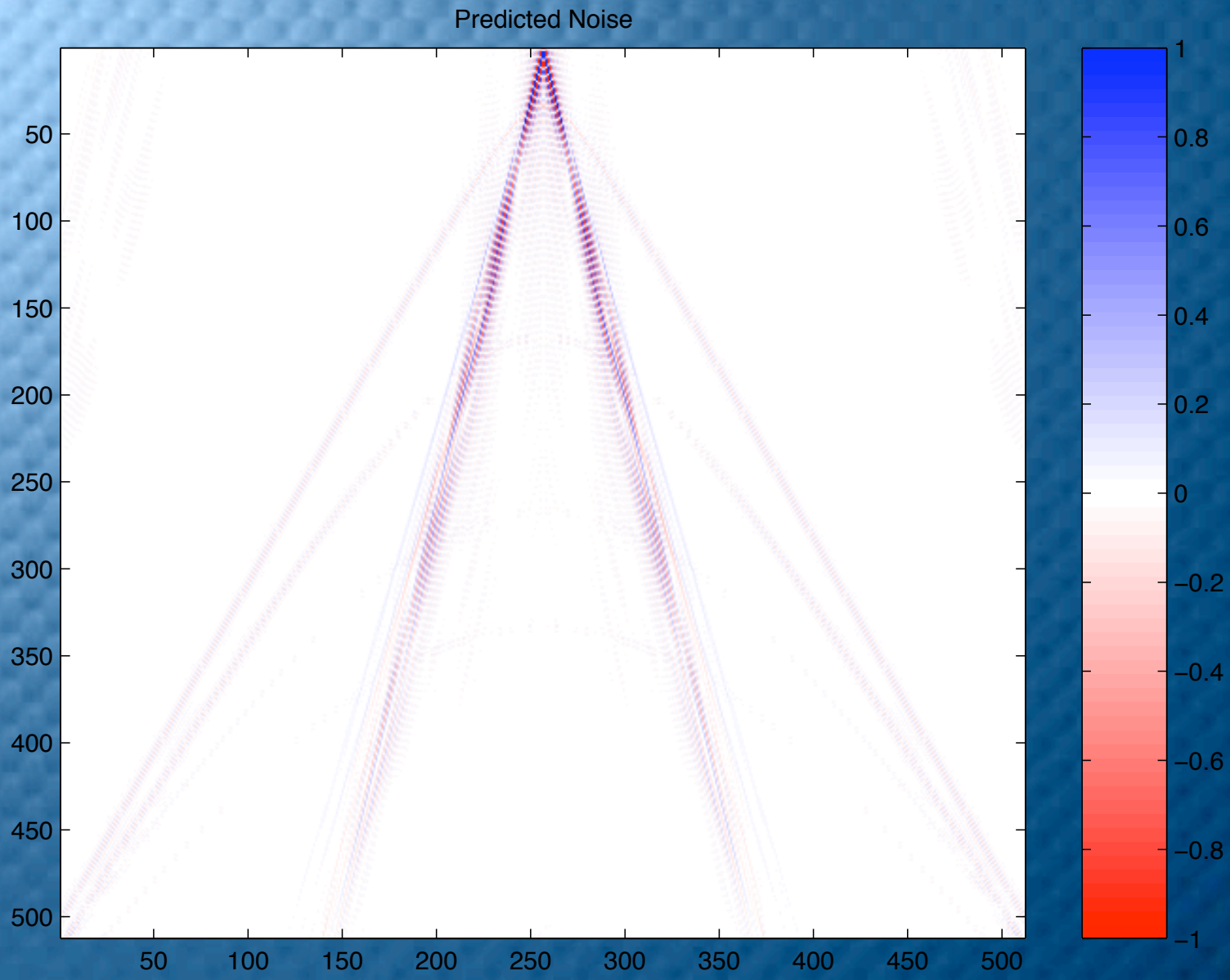
$\mathbf{\Theta}_{\lambda\Gamma} =$ Hard or Soft Threshold

$\lambda =$ Control Parameter

Curvelet Adaptive Subtraction Synthetic Example

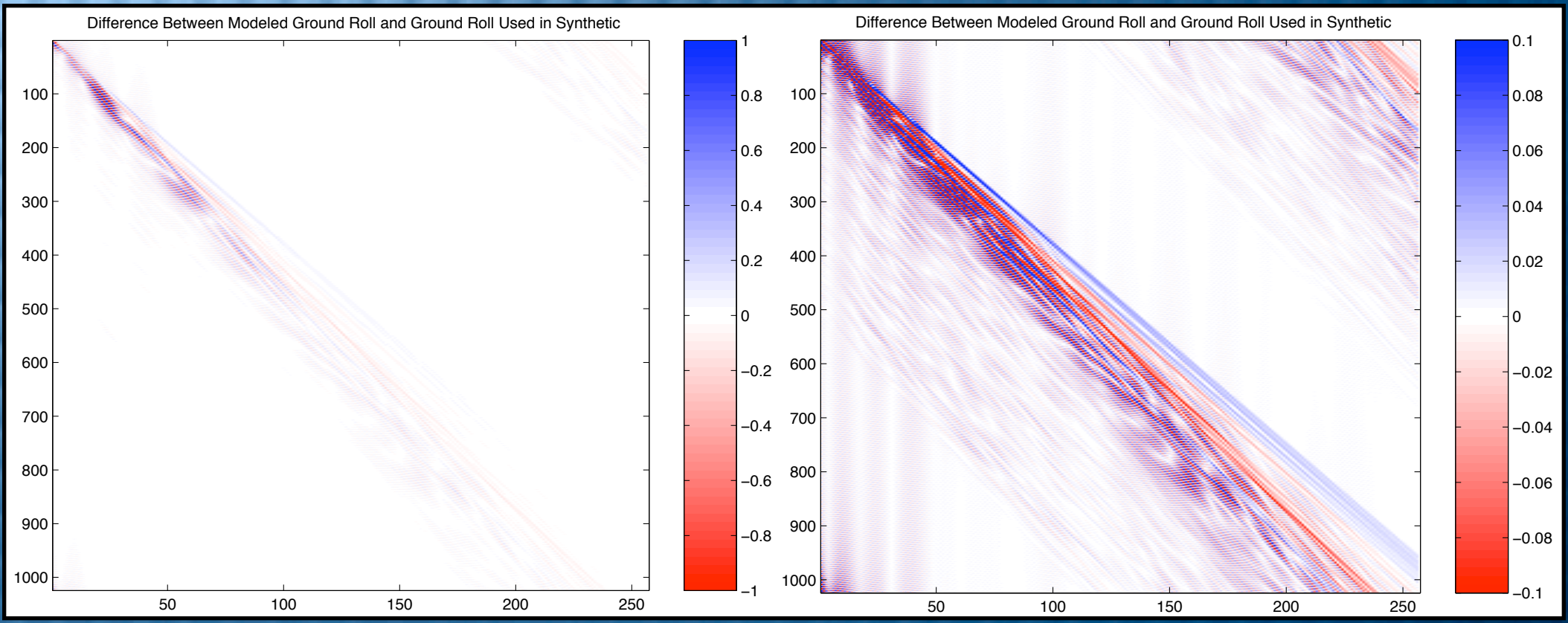


Predicted Noise



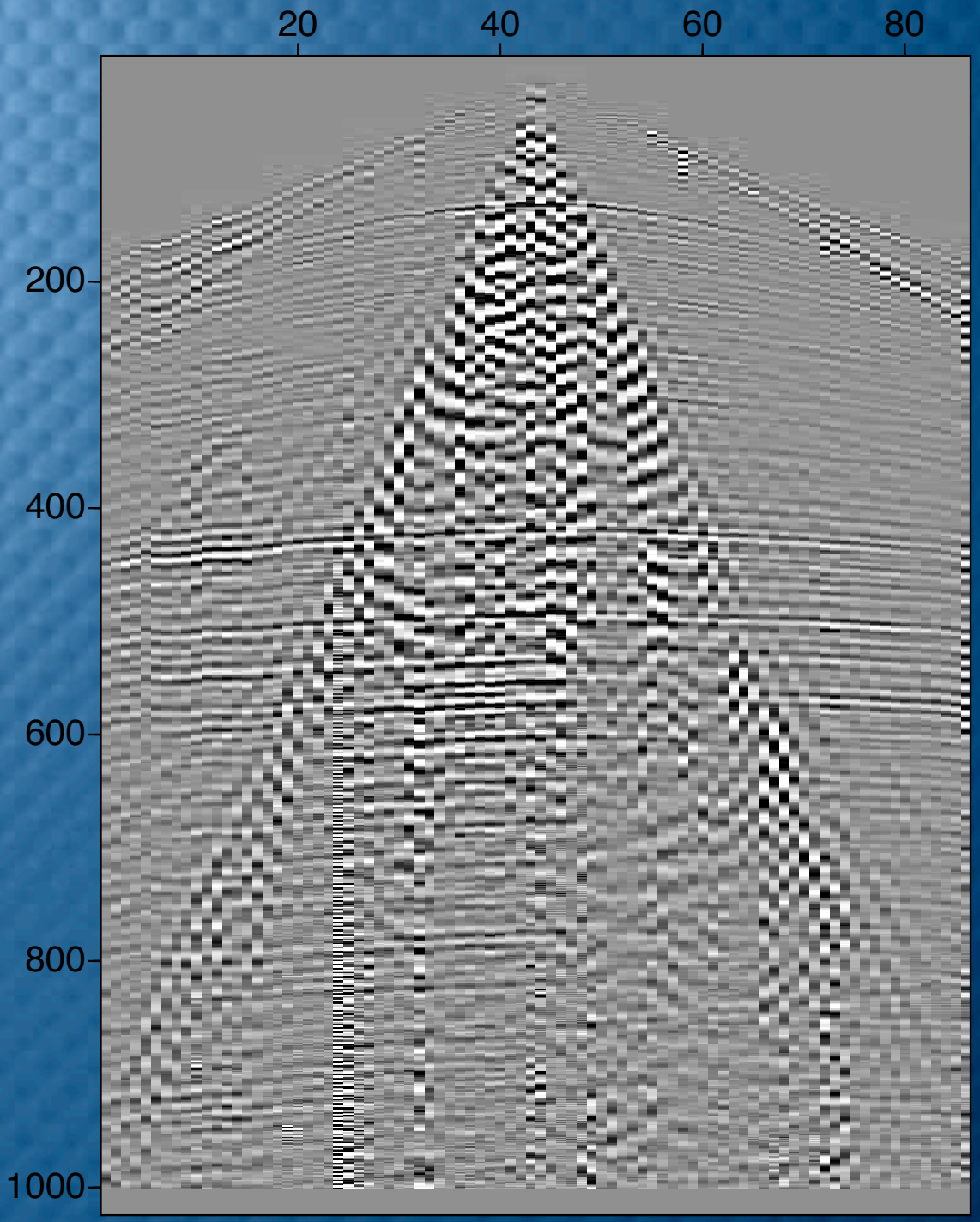
Ground Roll Difference:

Shown is the difference between the estimated ground roll and the actual ground roll



Difference is on the order of the ground roll

Curvelet Adaptive Subtraction: Real Data Example



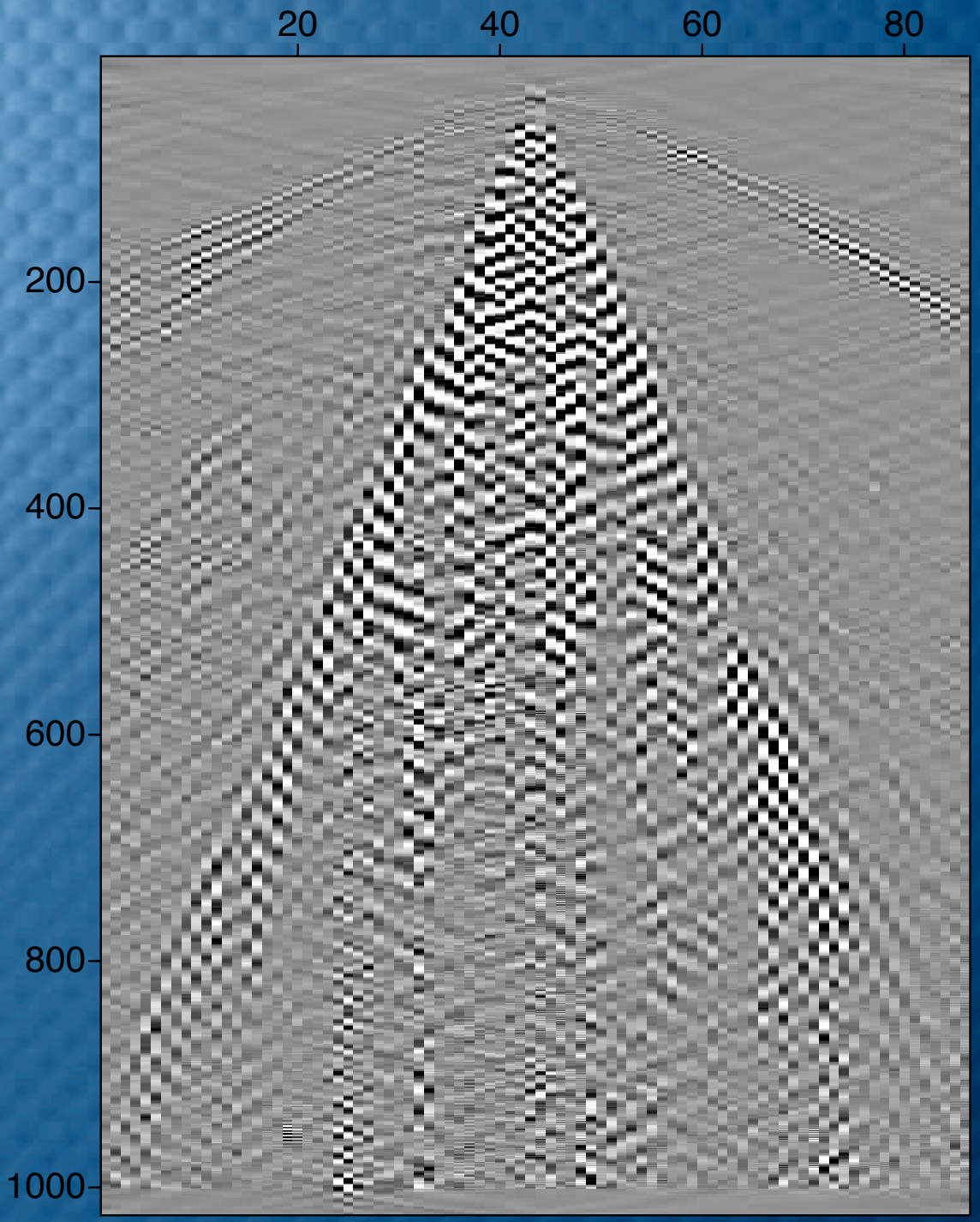
Oz25 Signal With Ground Roll

Radon Predicted Noise:

Two Choices:

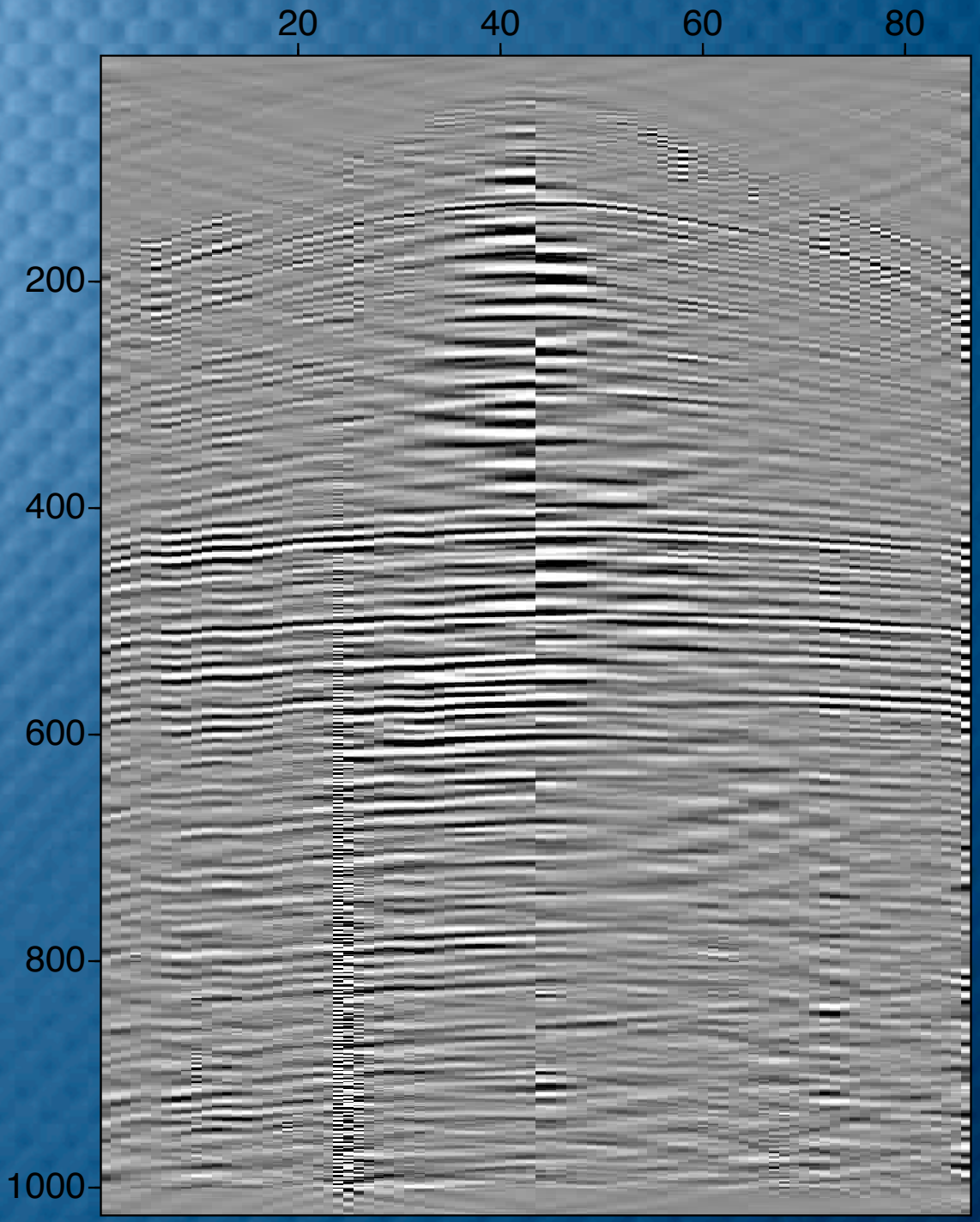
1. Subtract predicted noise from data

2. Use predicted noise to define threshold for curvelet adaptive subtraction



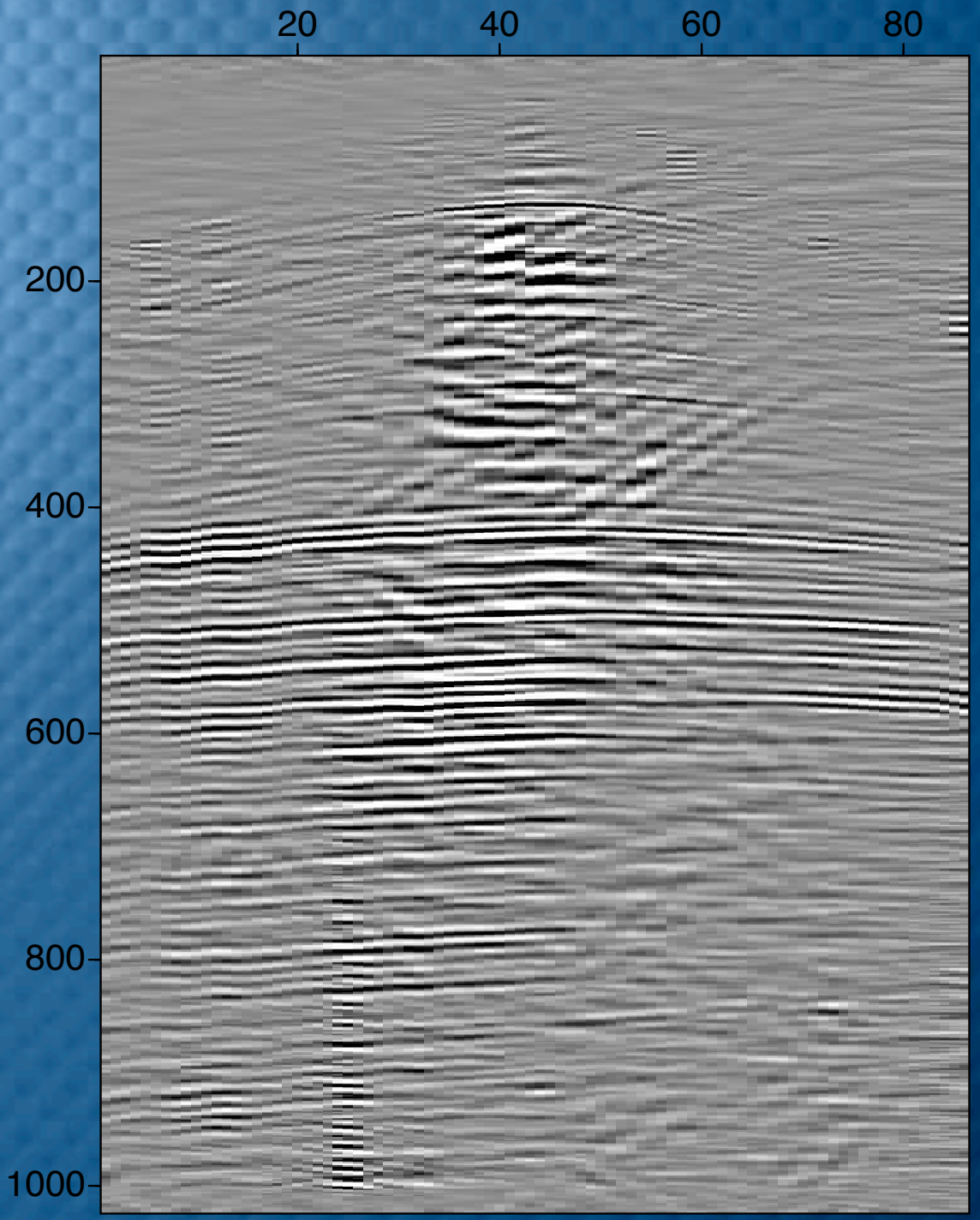
Low Quality Radon Denoised Data

Subtraction of the Radon predicted noise from the data



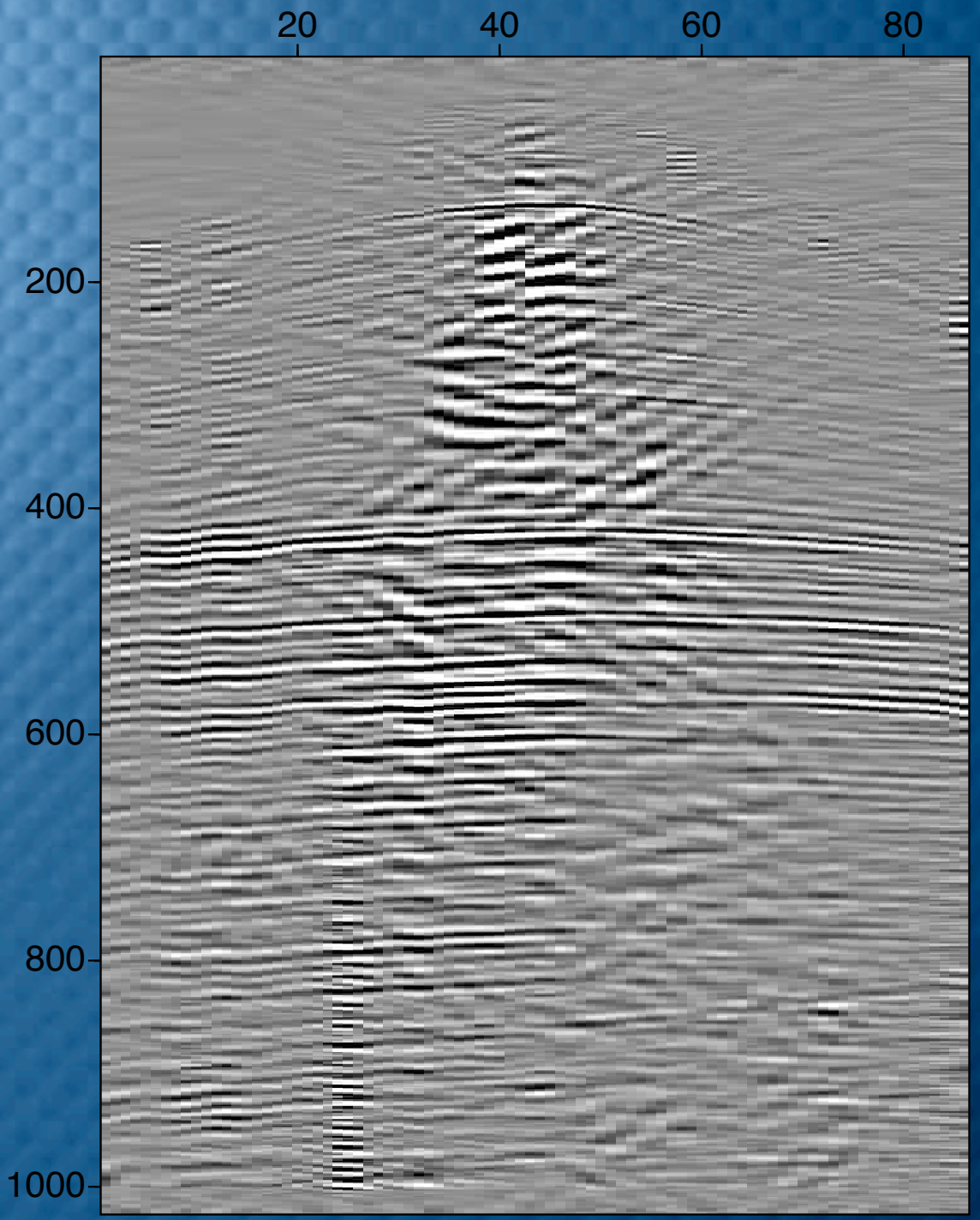
Curvelet Denoised Data From Soft Non-Linear Threshold

- Increased Smoothing
- Some removal of top reflectors and right side of mid reflectors

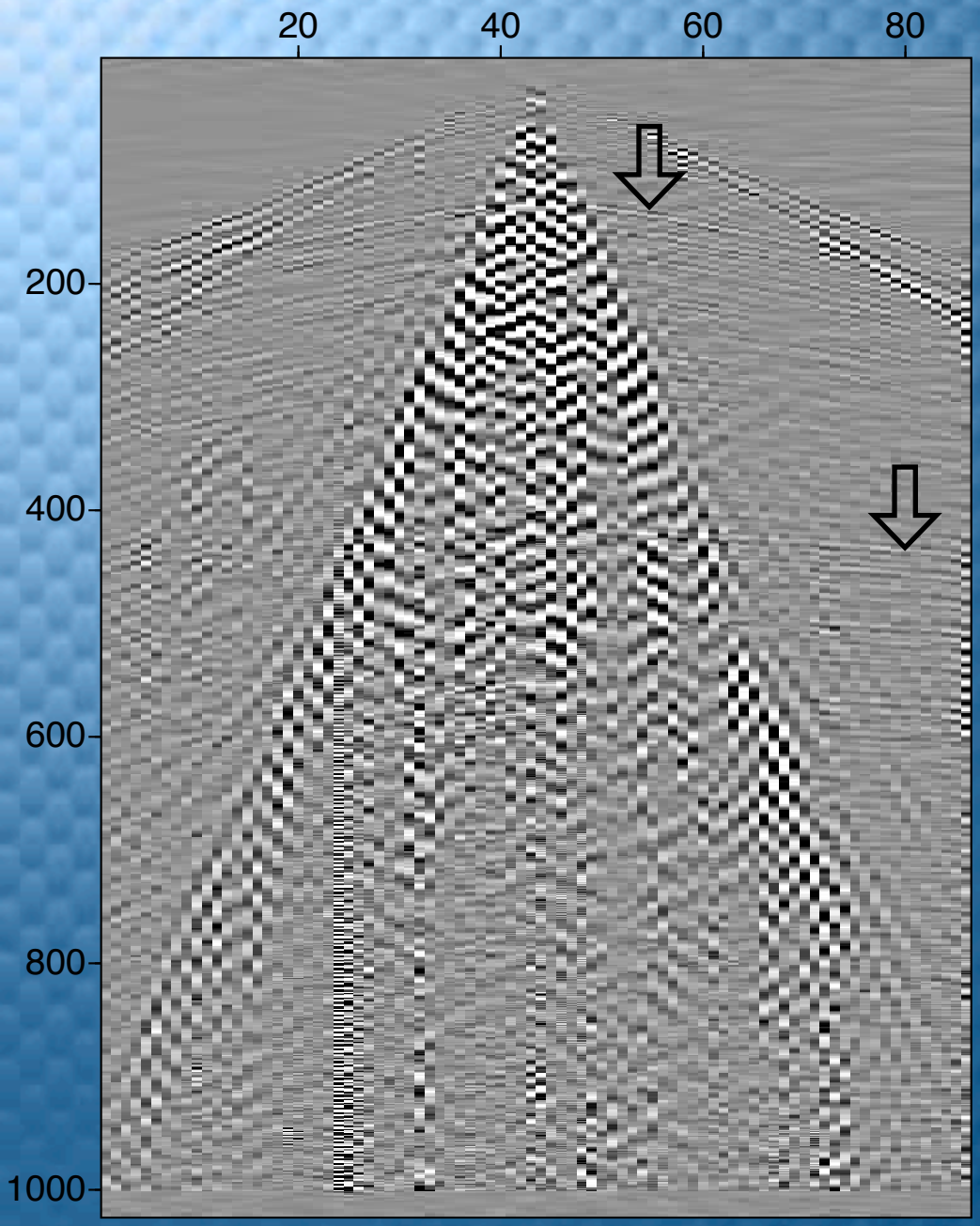


Curvelet Denoised Data From Hard Non-Linear Threshold

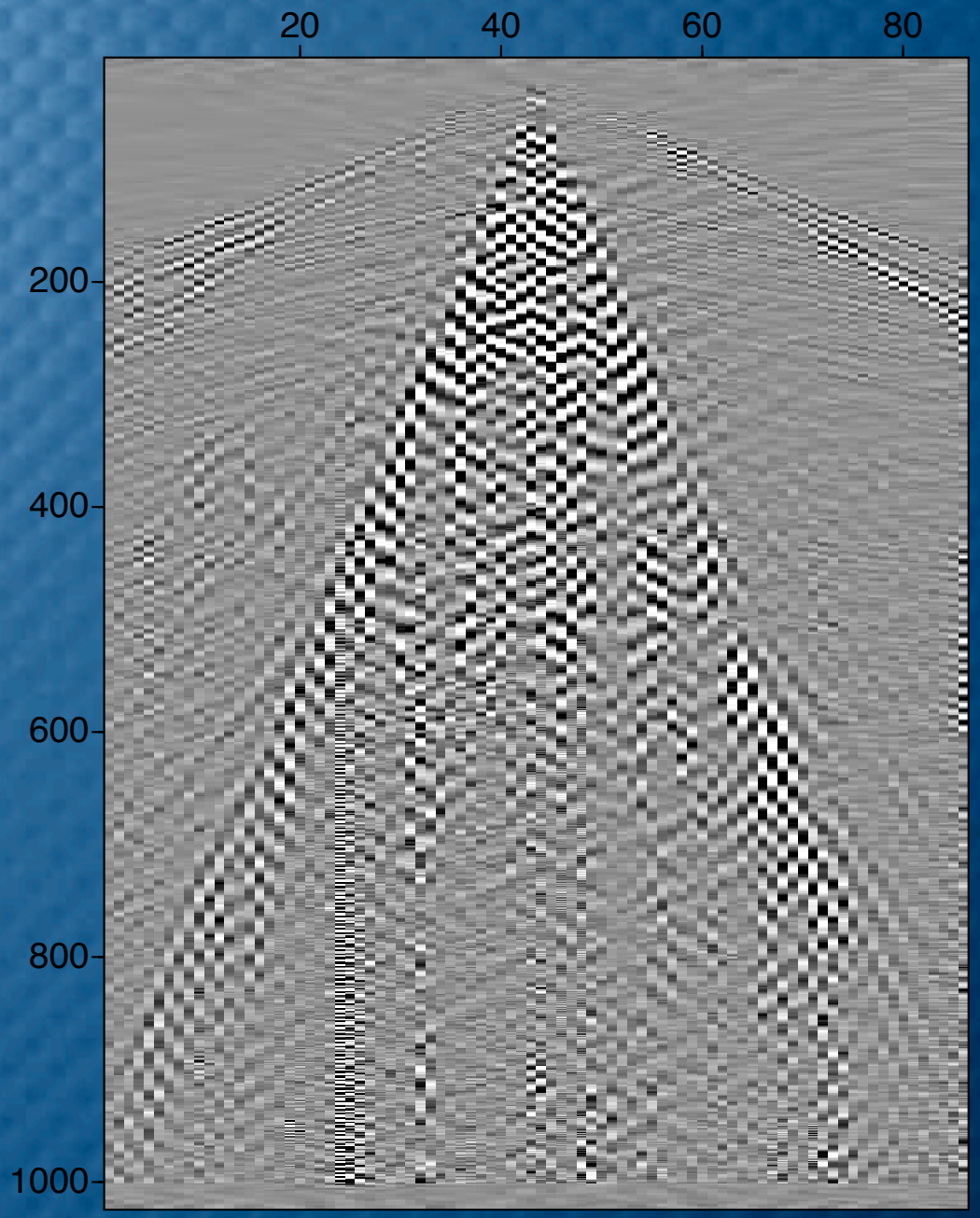
- Better reflector preservation
- Less smoothing



Curvelet Predicted Noise



Soft Thresholding



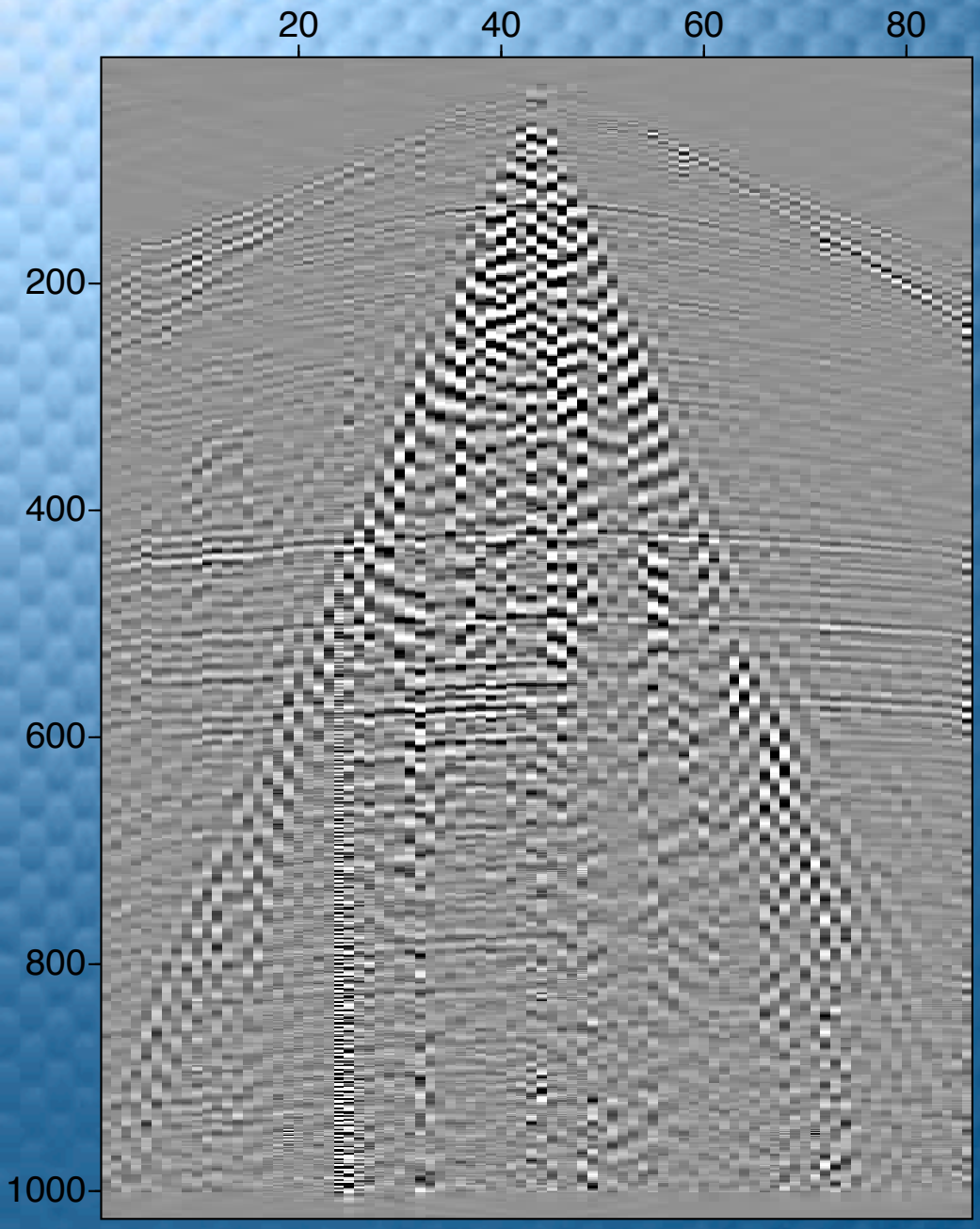
Hard Thresholding

Phase Preservation

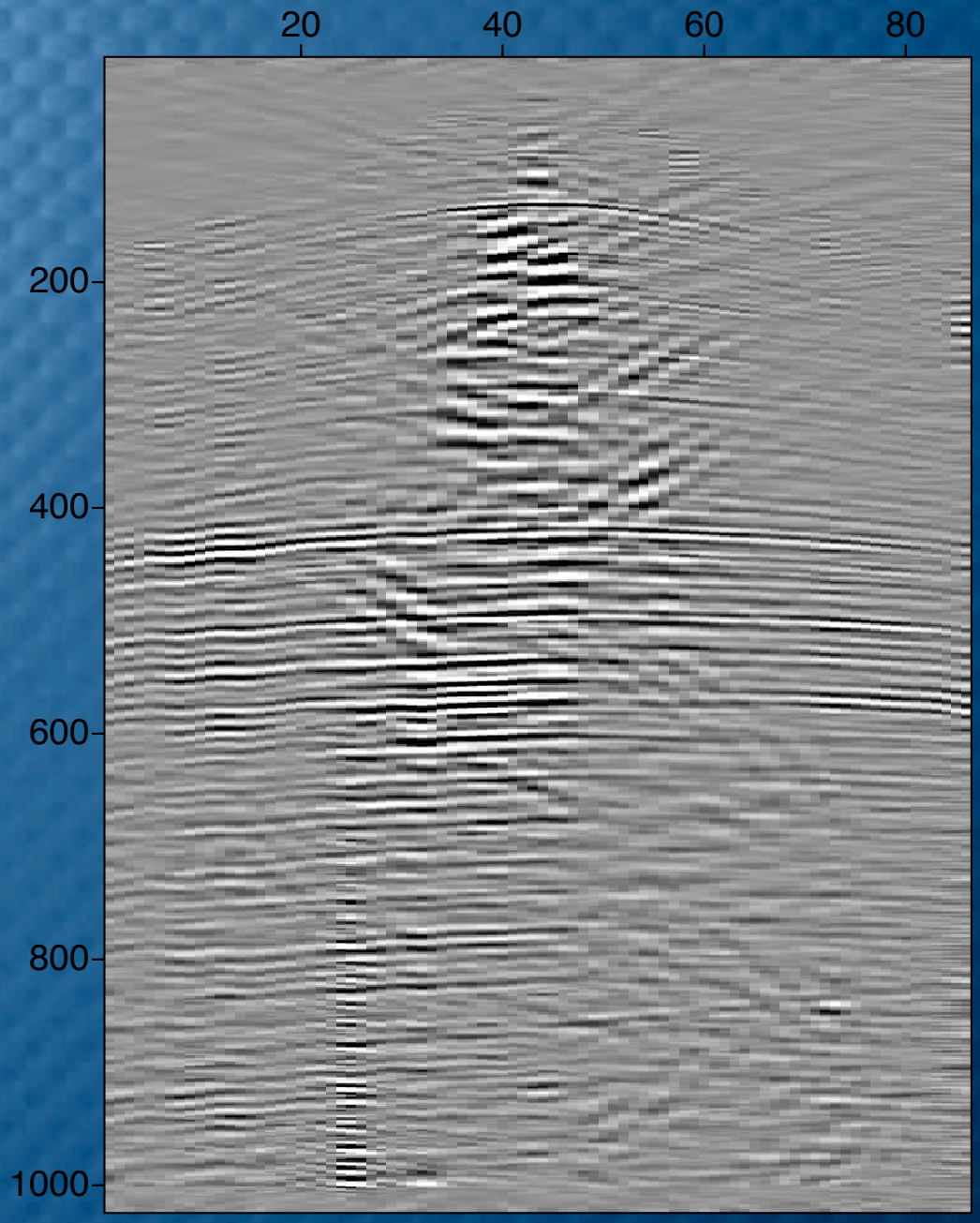
Give the predicted ground roll a 90 degrees phase shift. What would happen?

- Direct subtraction will no longer be useful as the result will only amplify the differences.
- Curvelet adaptive subtraction works without a problem.

Phase Shifted Model Results

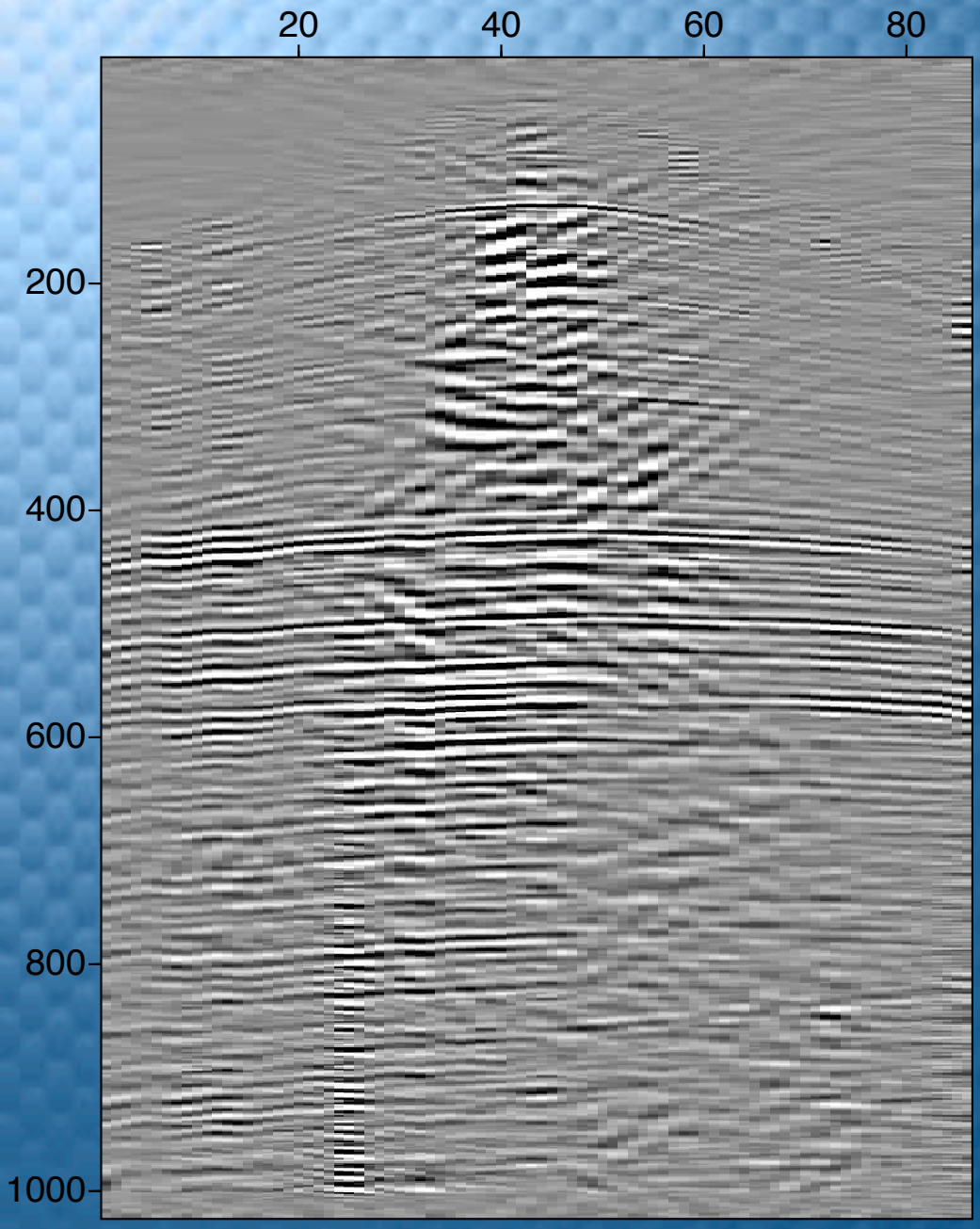


Subtraction

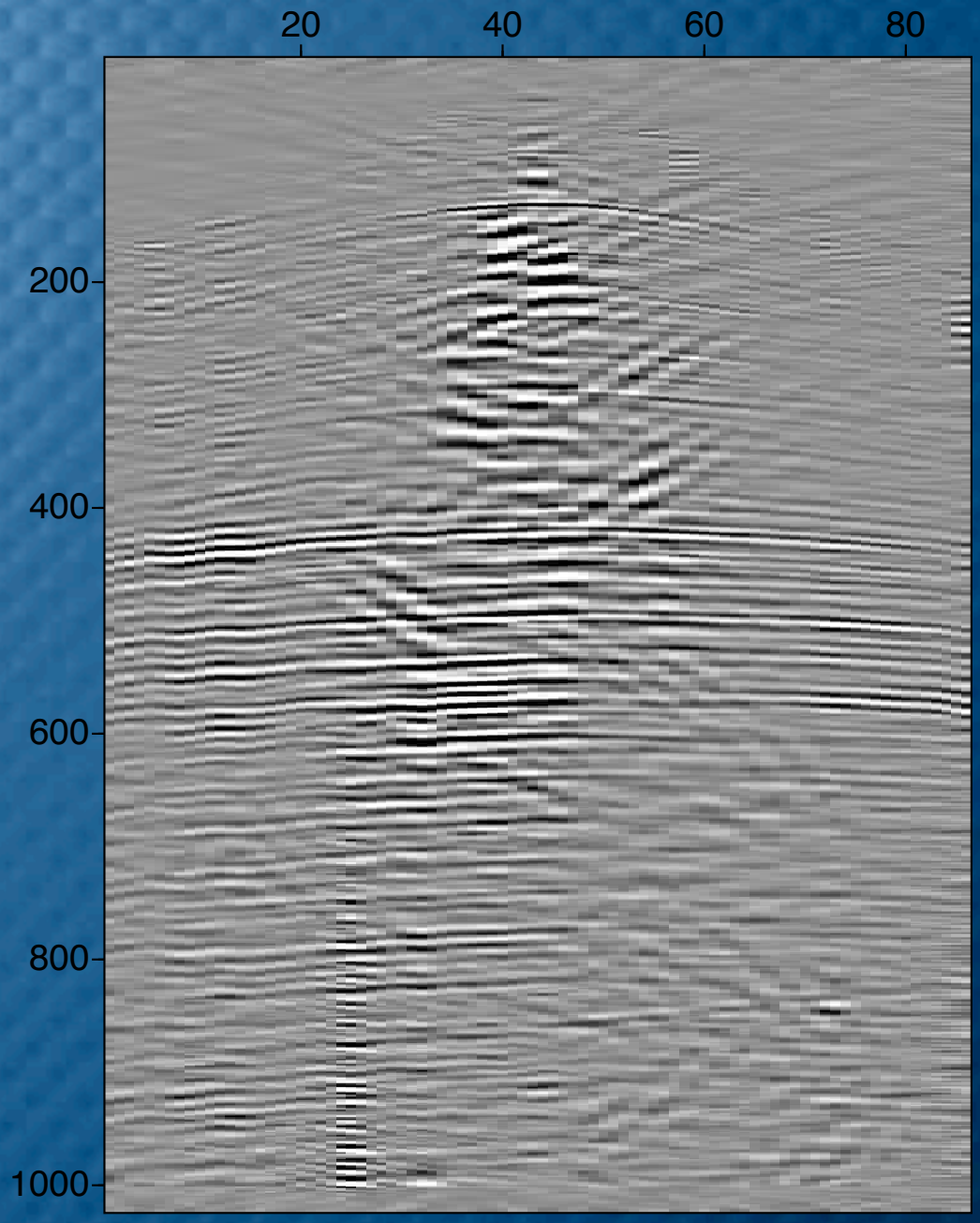


Curvelet Adaptive Subtraction

Phase Shifted Model Results

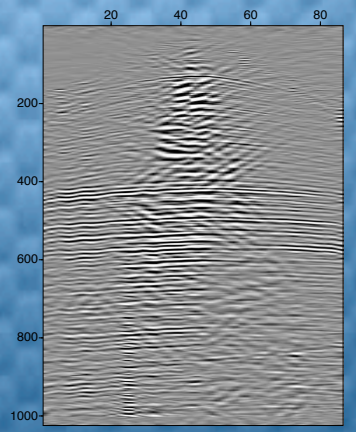


Results Without Phase Shift

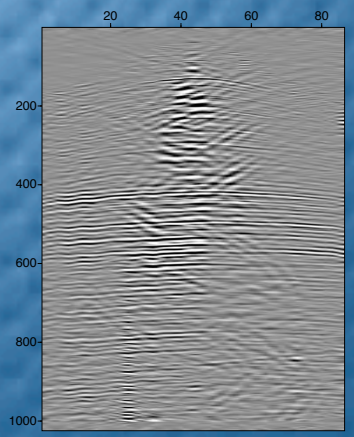


Results With Phase Shift

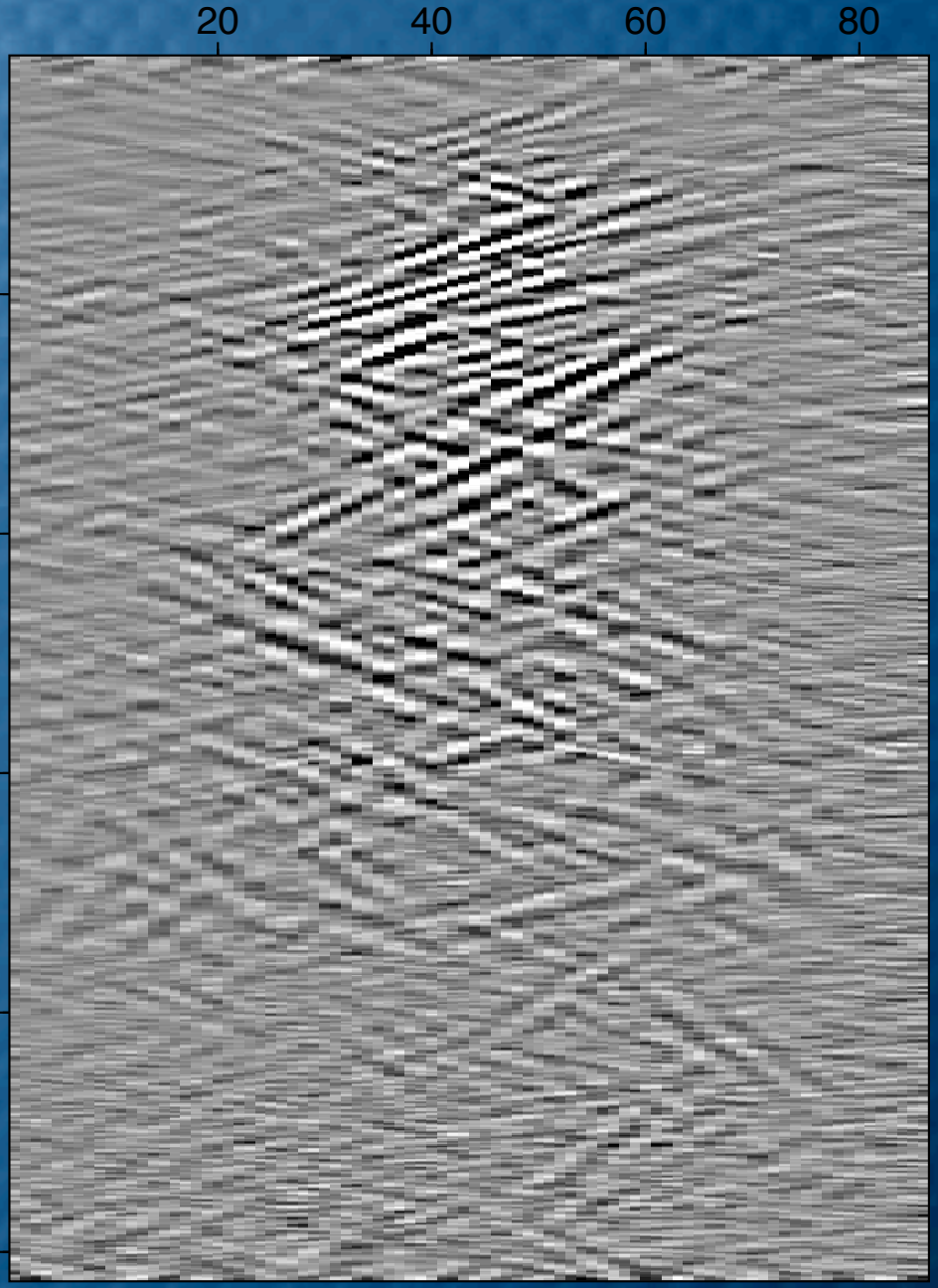
The Difference



Results Without Phase Shift

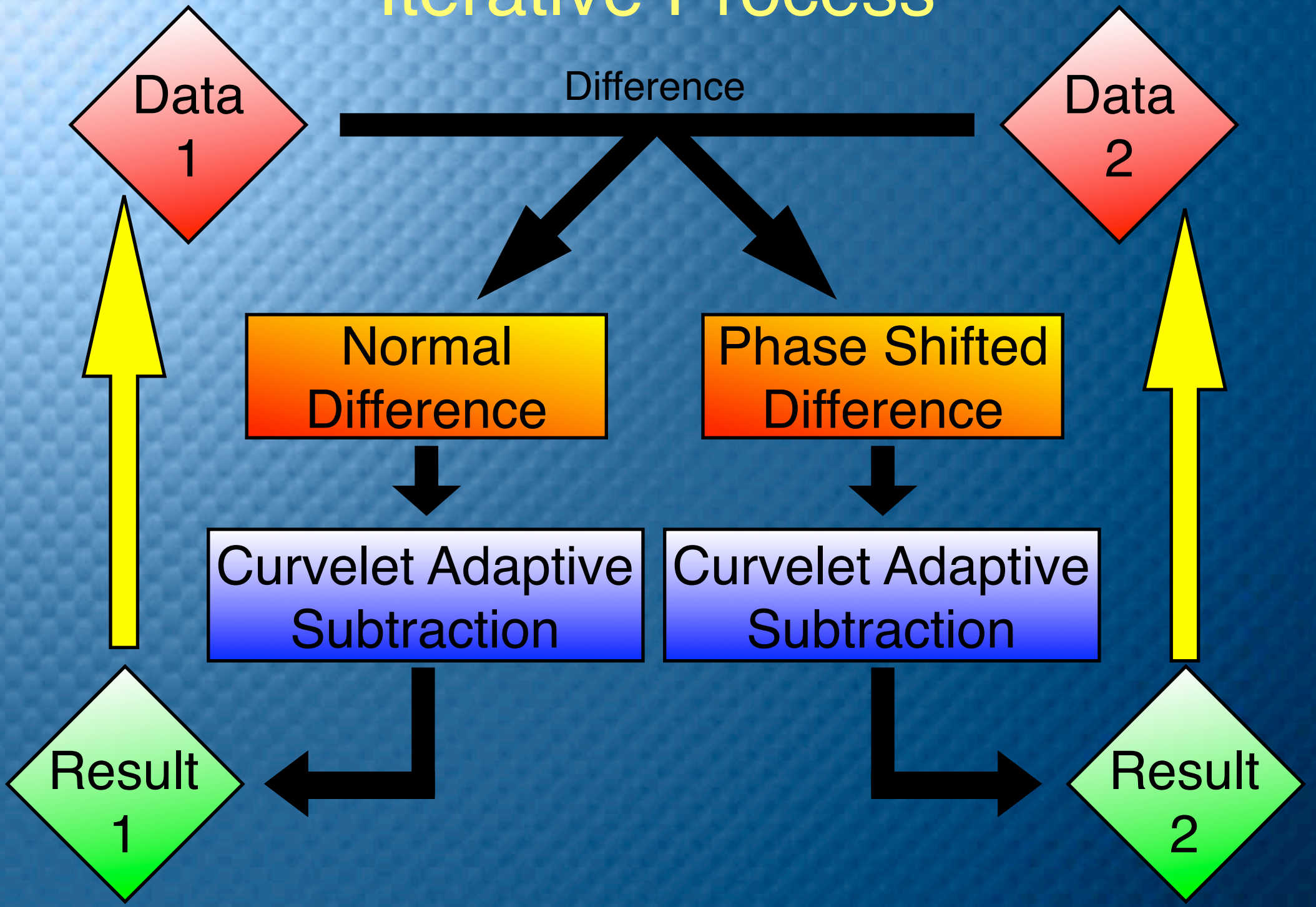


Results With Phase Shift

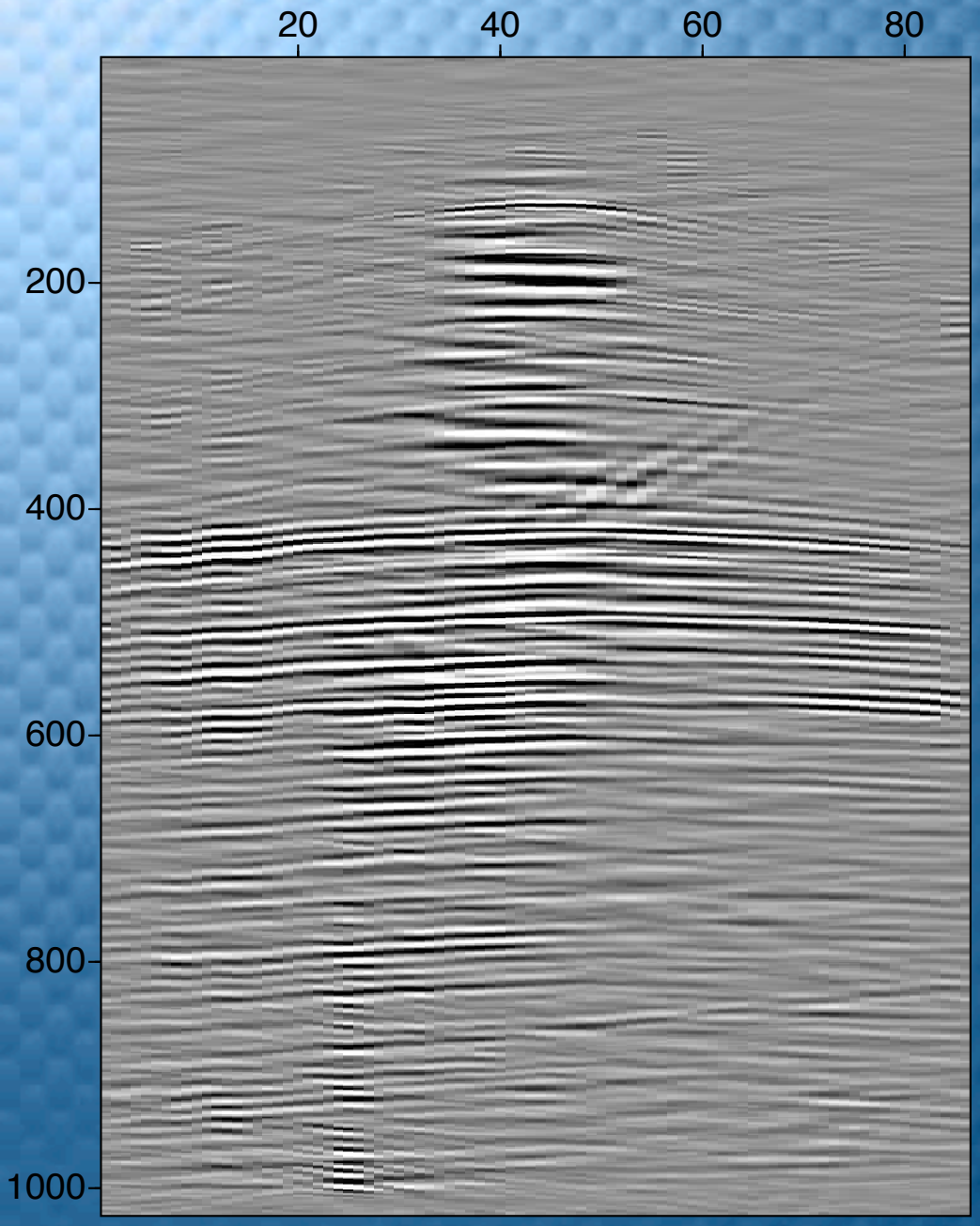


Difference

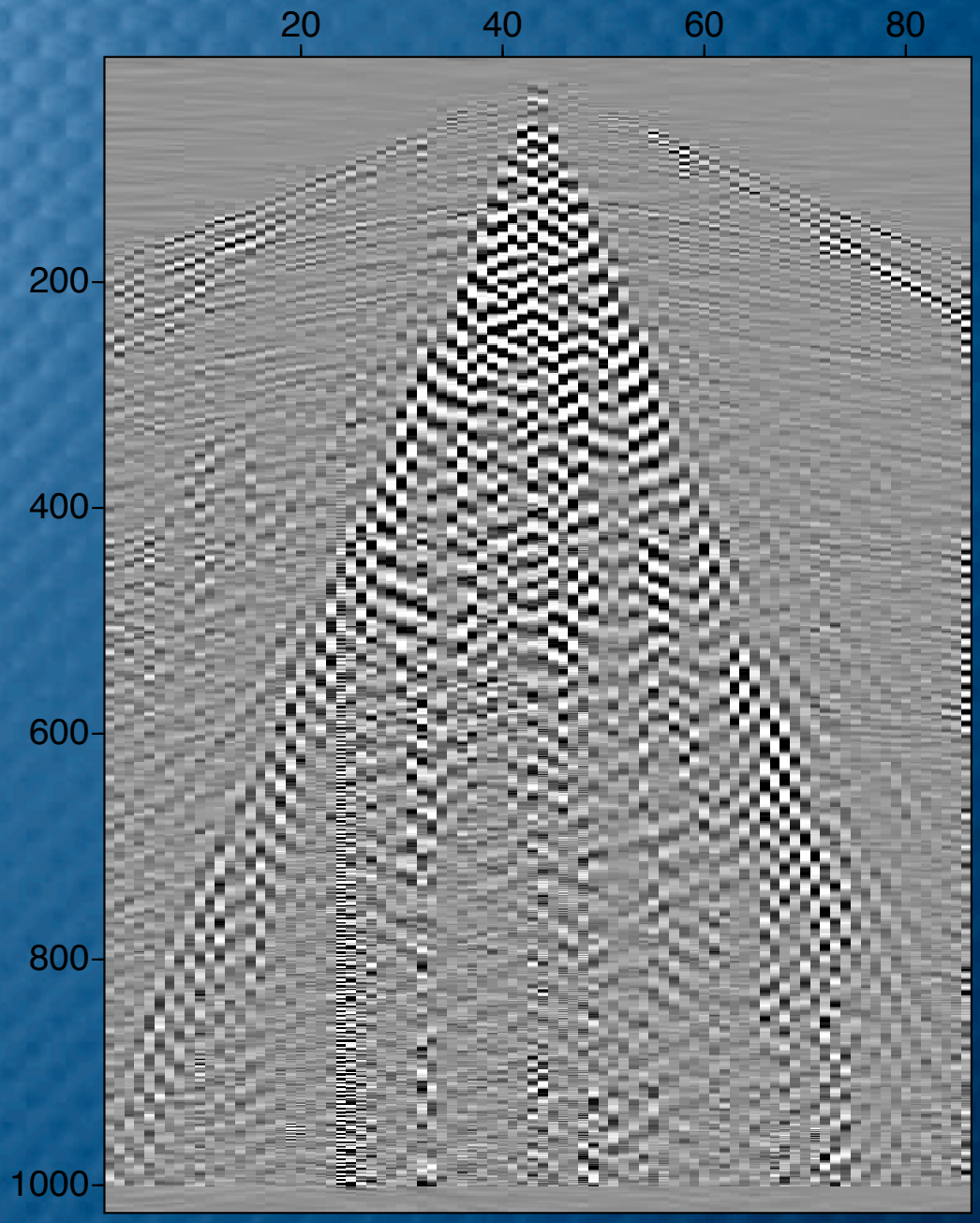
Iterative Process



Iterative Result

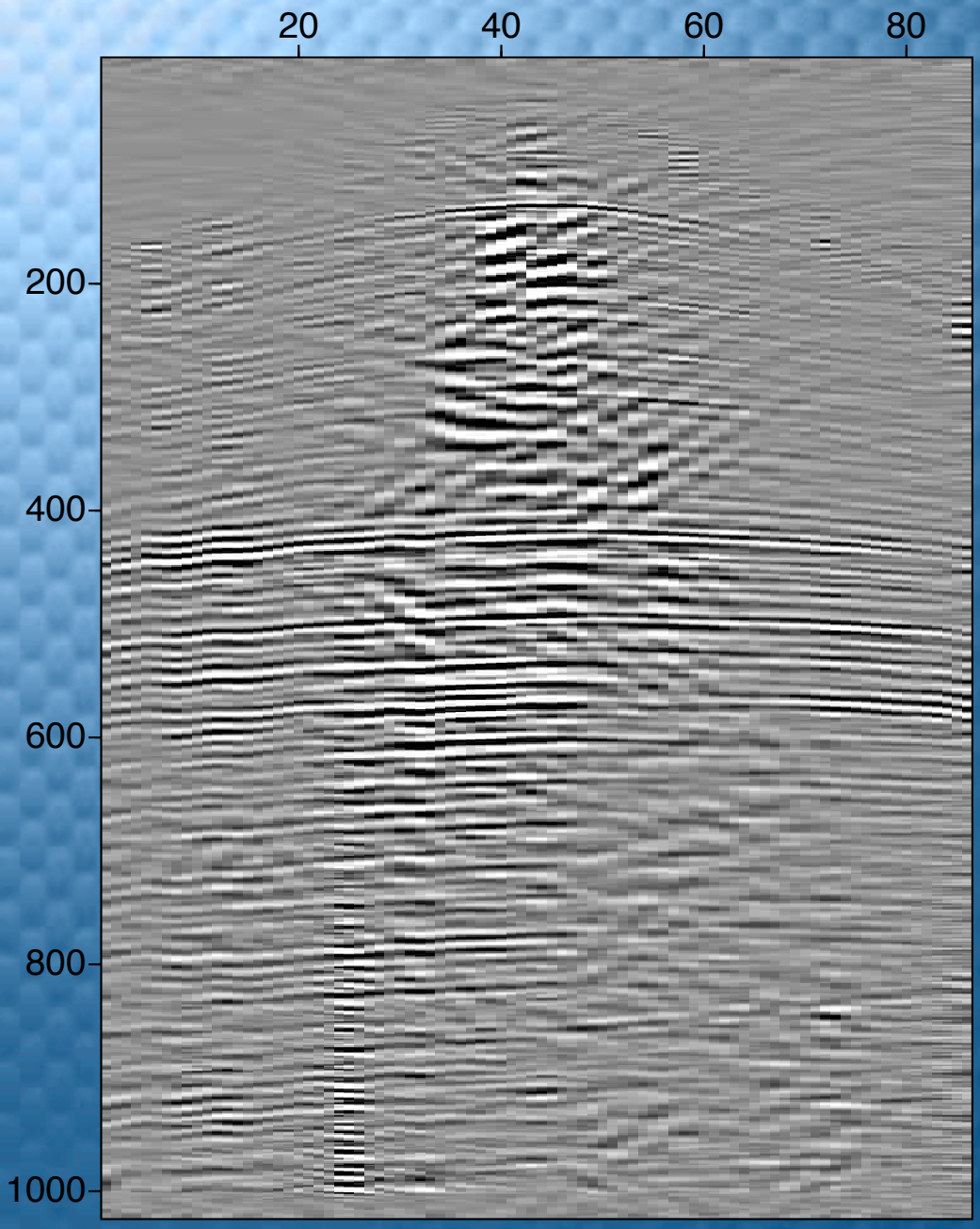


Result After 3 Iterations

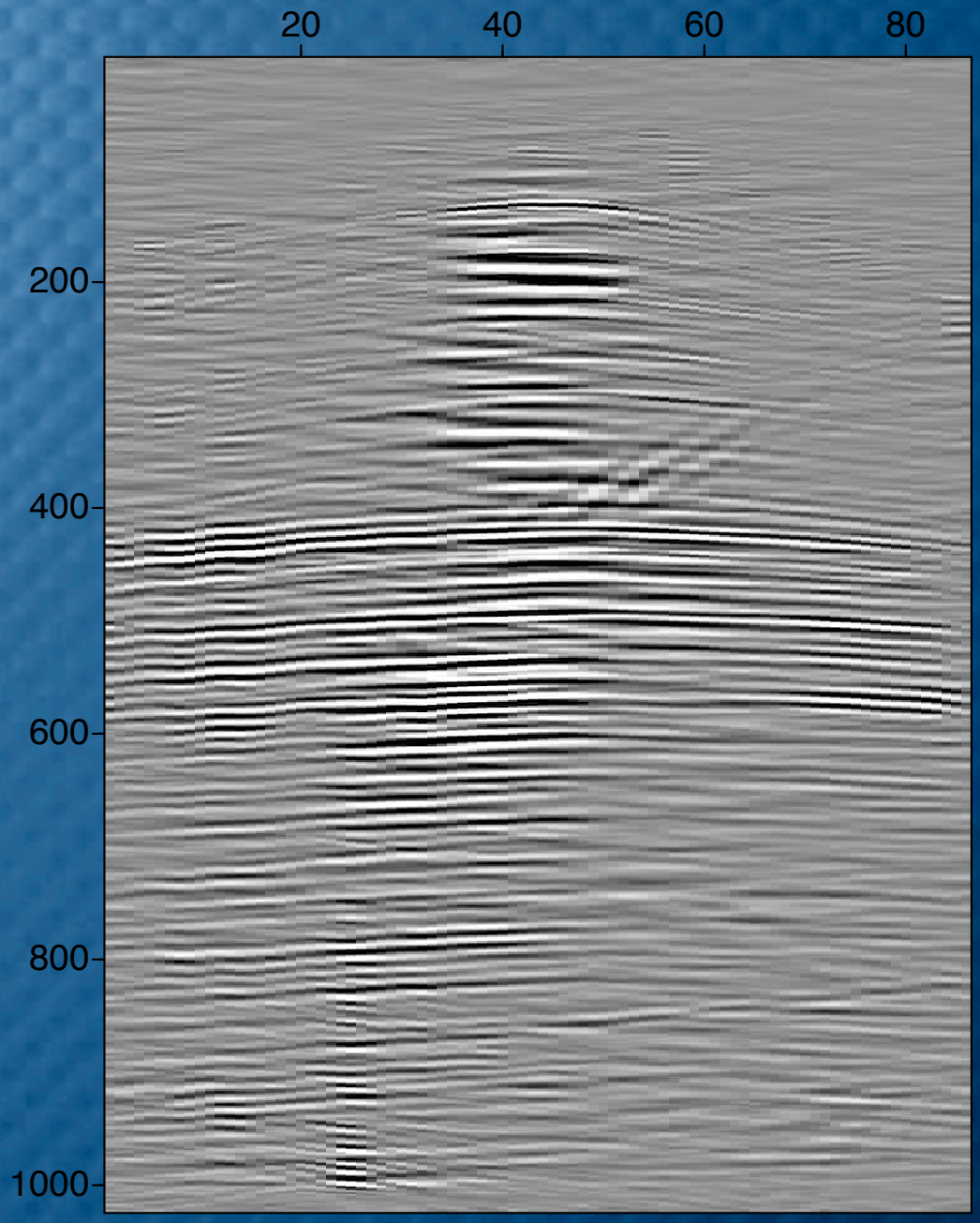


Predicted Noise

Iterative Result

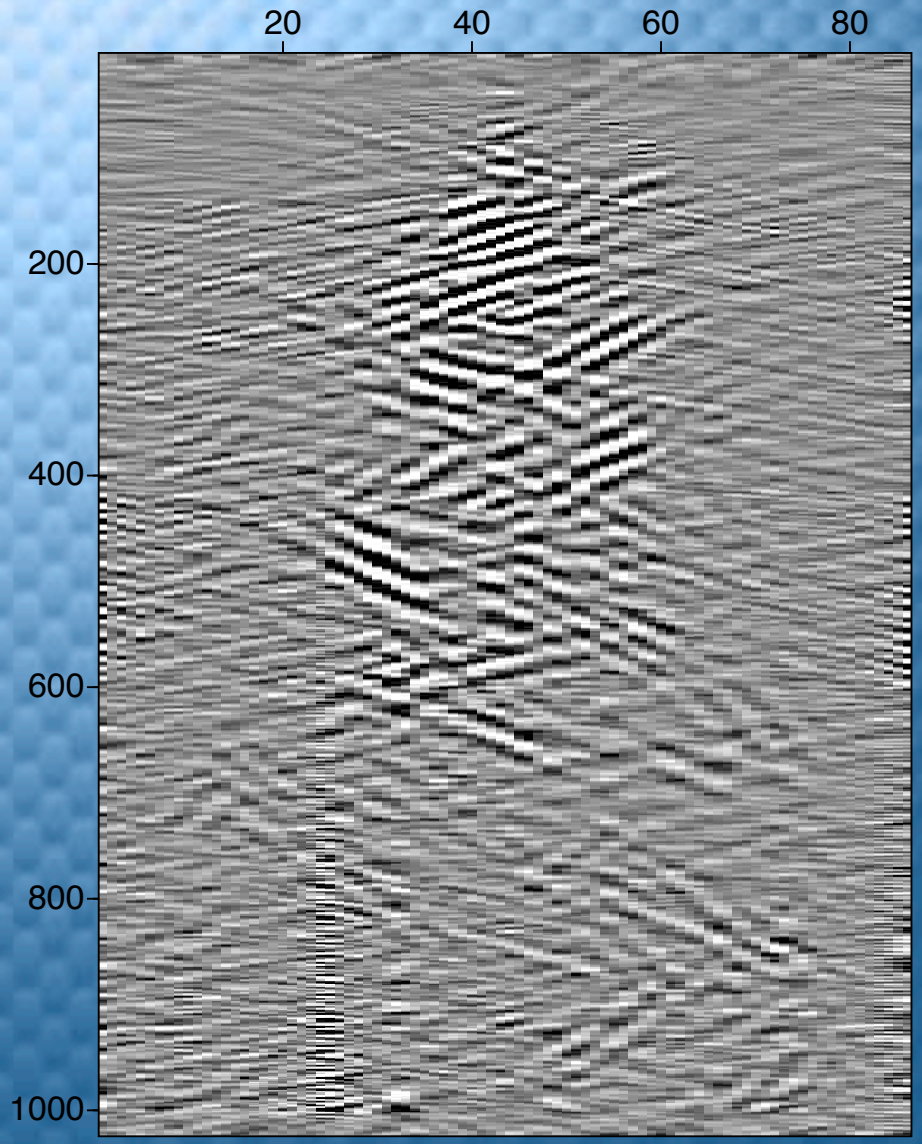


0 Iterations

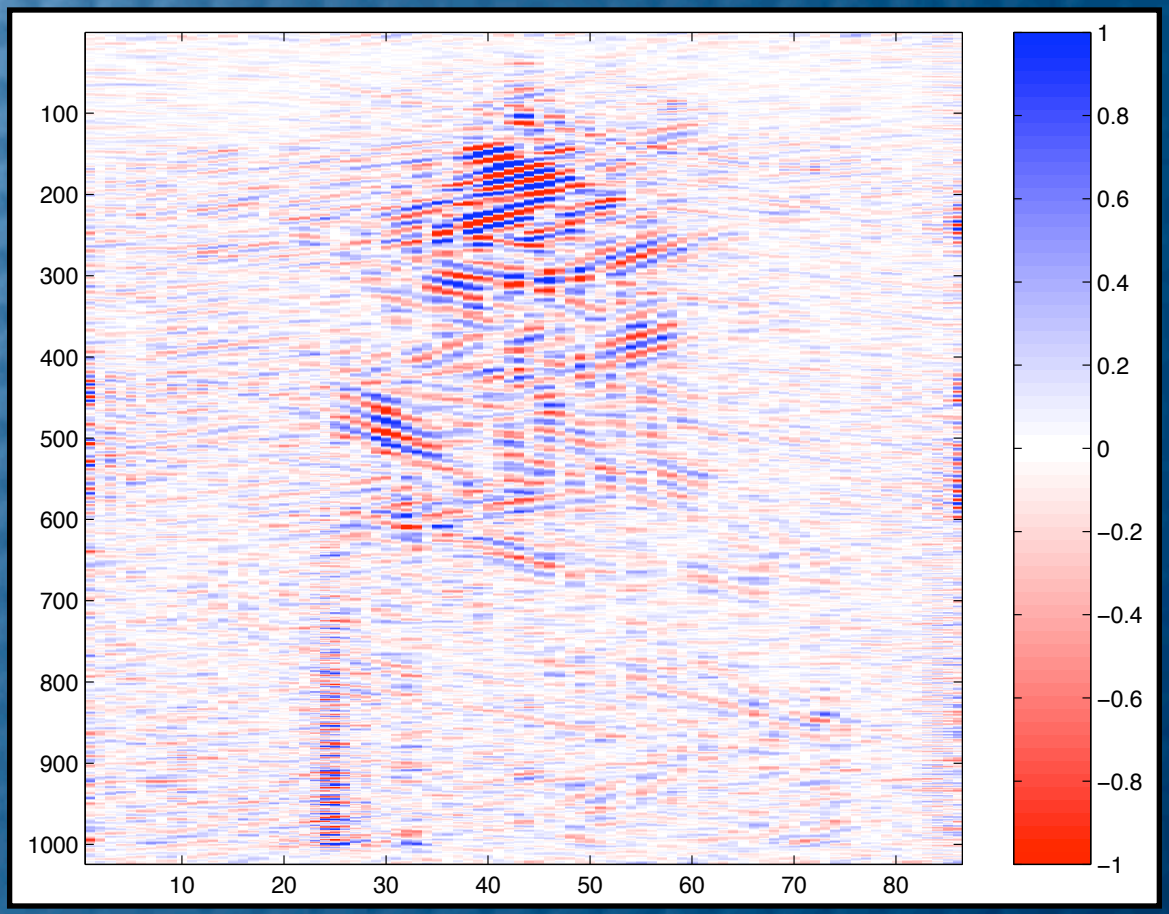


3 Iterations

Iterative Effects

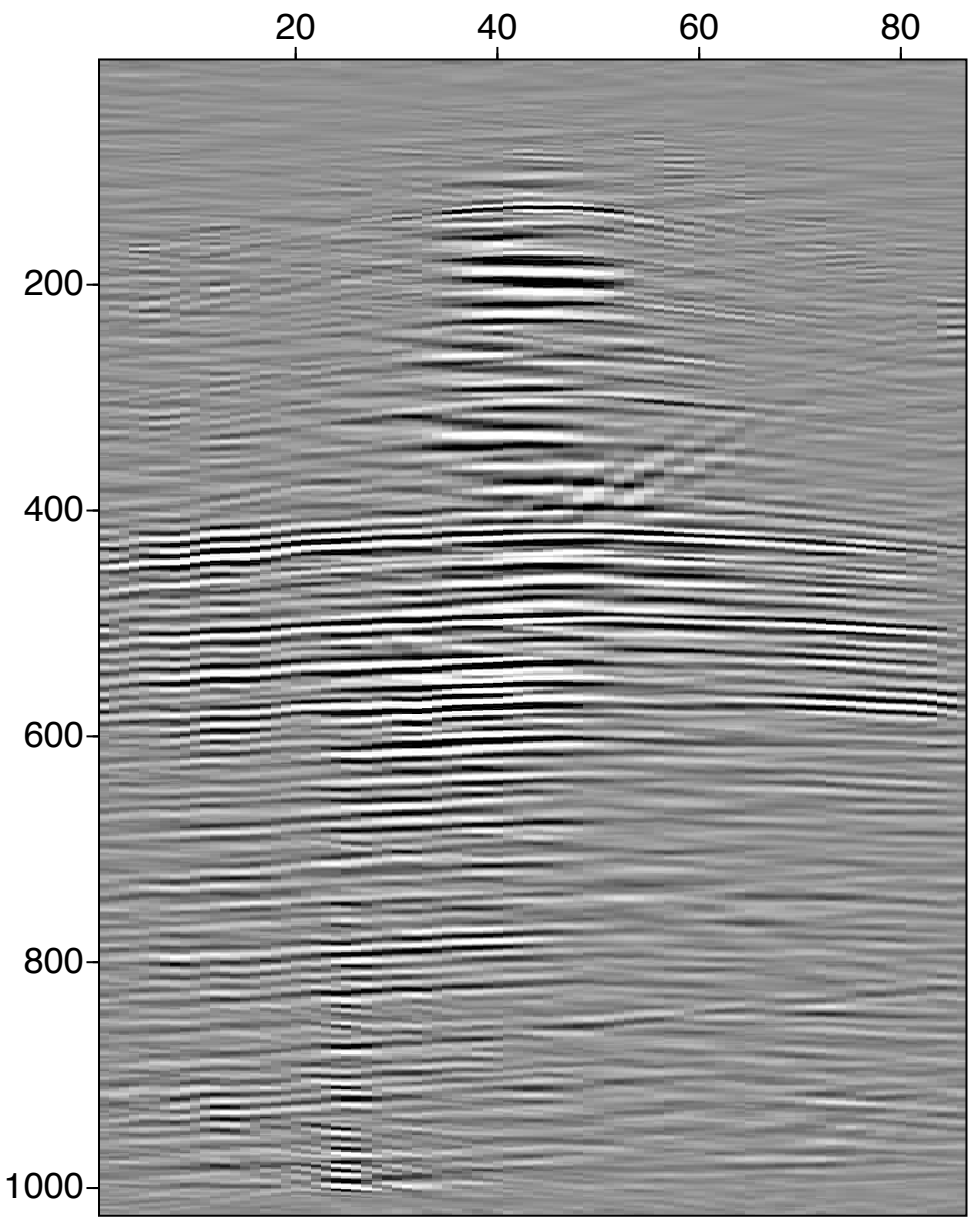


Difference Between Iterative Result and Initial Result

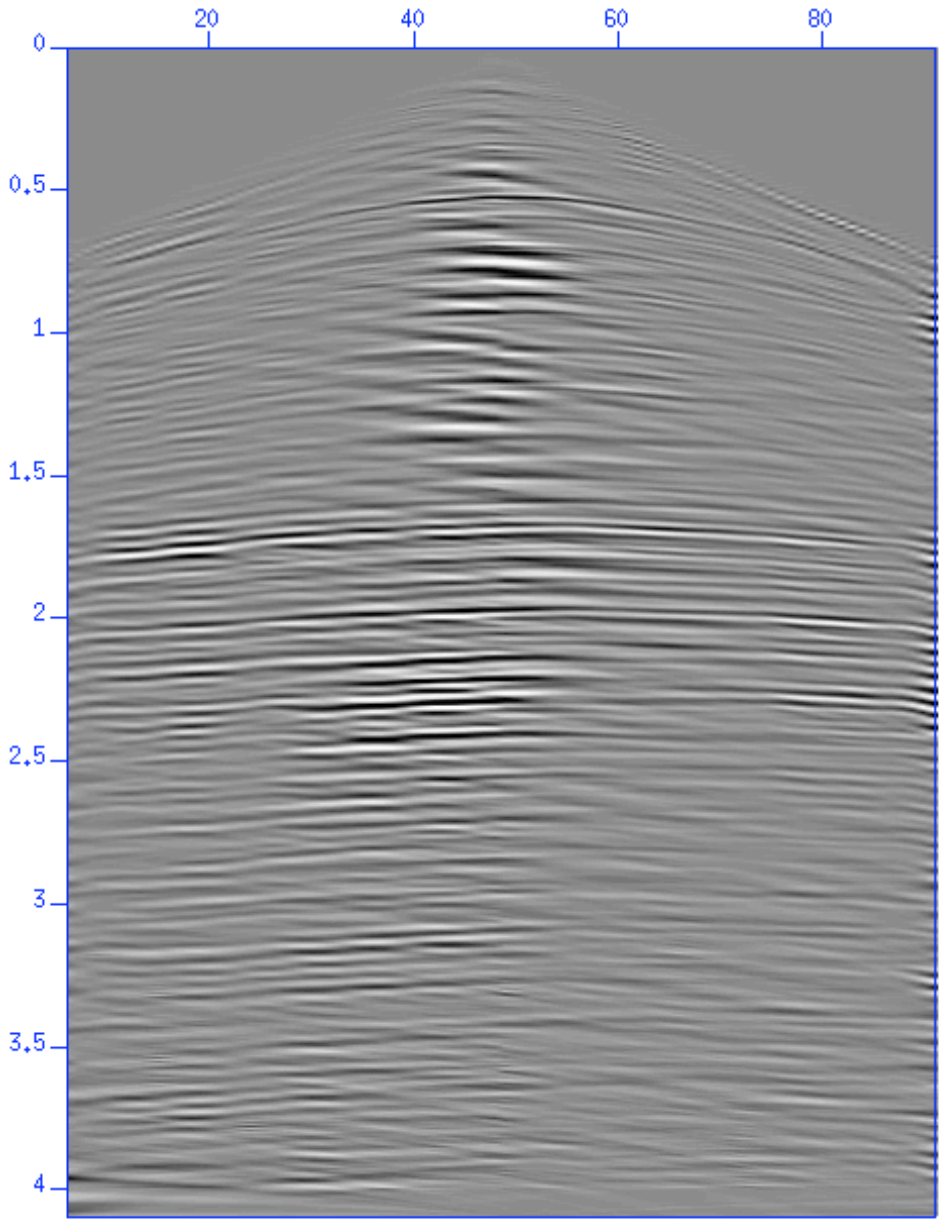


- Improves overall signal by removing artifacts though phase scanning

High Quality Radon Comparison

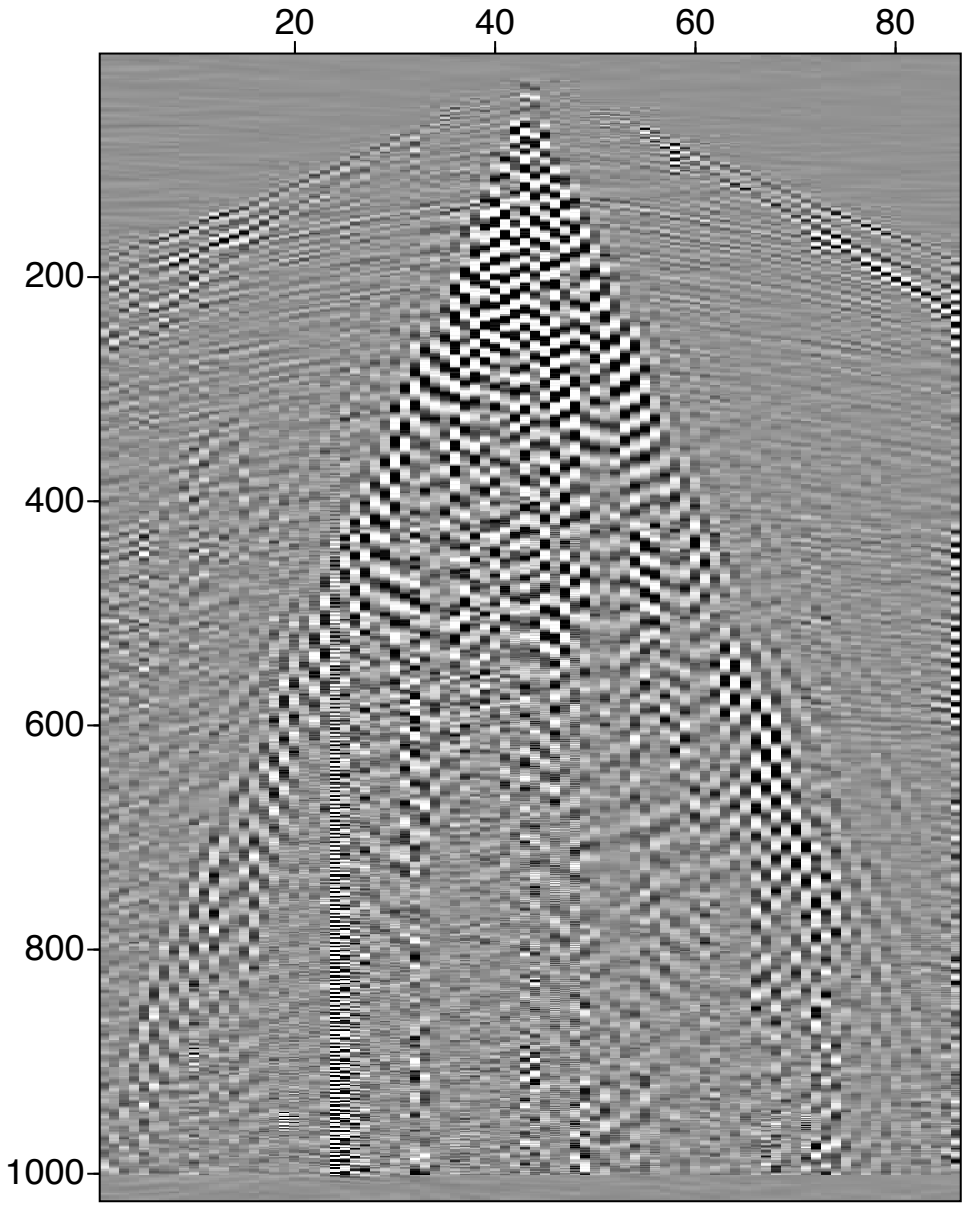


CAS Result

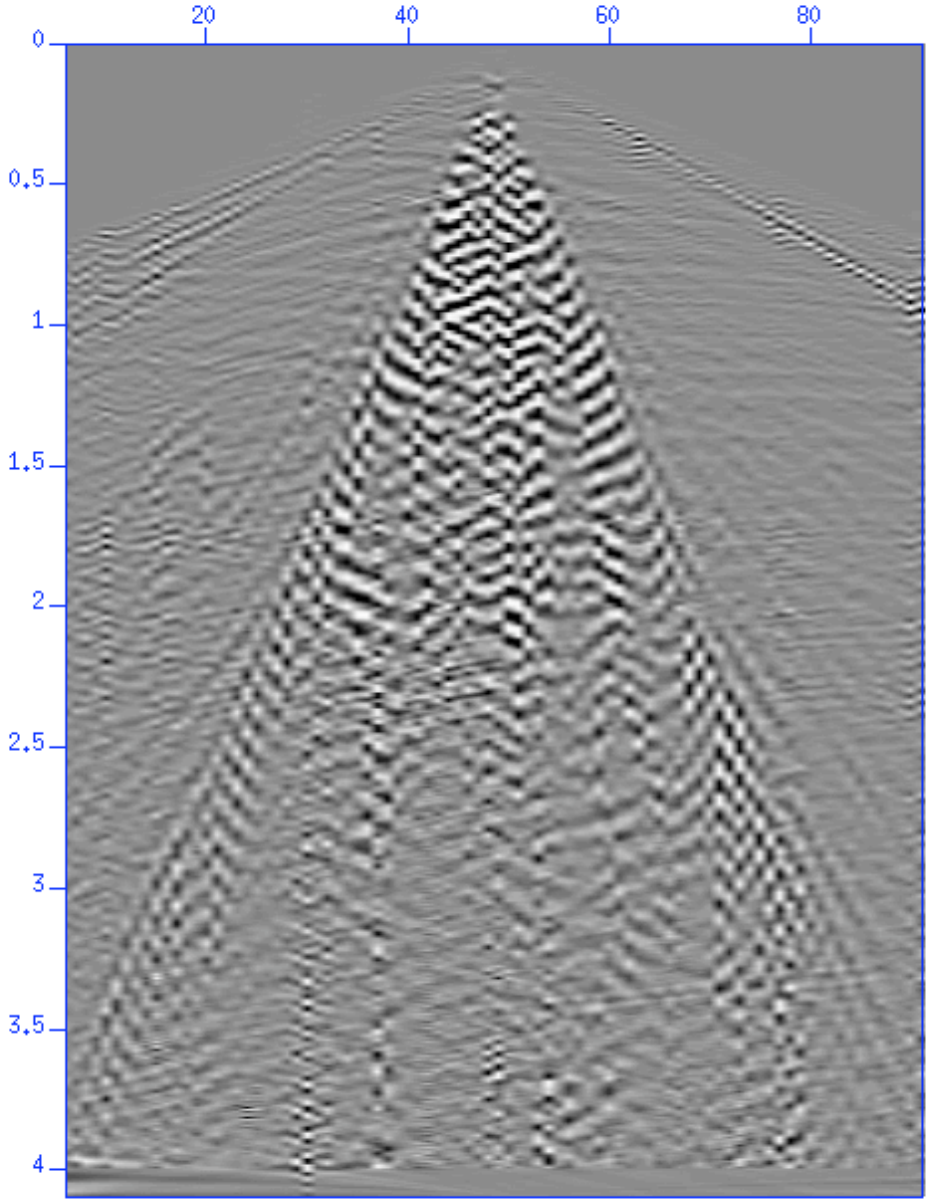


High Quality Radon Result

High Quality Radon Comparison



CSA Noise



High Quality Radon Noise

Conclusions

- Curvelet Adaptive Subtraction can effectively remove Ground Roll and preserve reflectors
- Adaptive Subtraction works even with less than optimal noise modeling
- Curvelet flexibility allows for robust adaptive subtraction which is relatively phase independent
- Iterative process can further improve signal to noise ratio

Acknowledgments

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- Tadeusz Ulrych and the sponsors of the Consortium for the Development of Specialized Seismic Techniques (CDSST).