Robust Estimation of Fracture Directions from 3D Converted Waves

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VERITAS
Geophysical Integrity

Outline

- Introduction
- The polarity method
- Synthetic example of geometry problem
- The least-squares method
- Synthetic results
- Real data example
- Conclusions

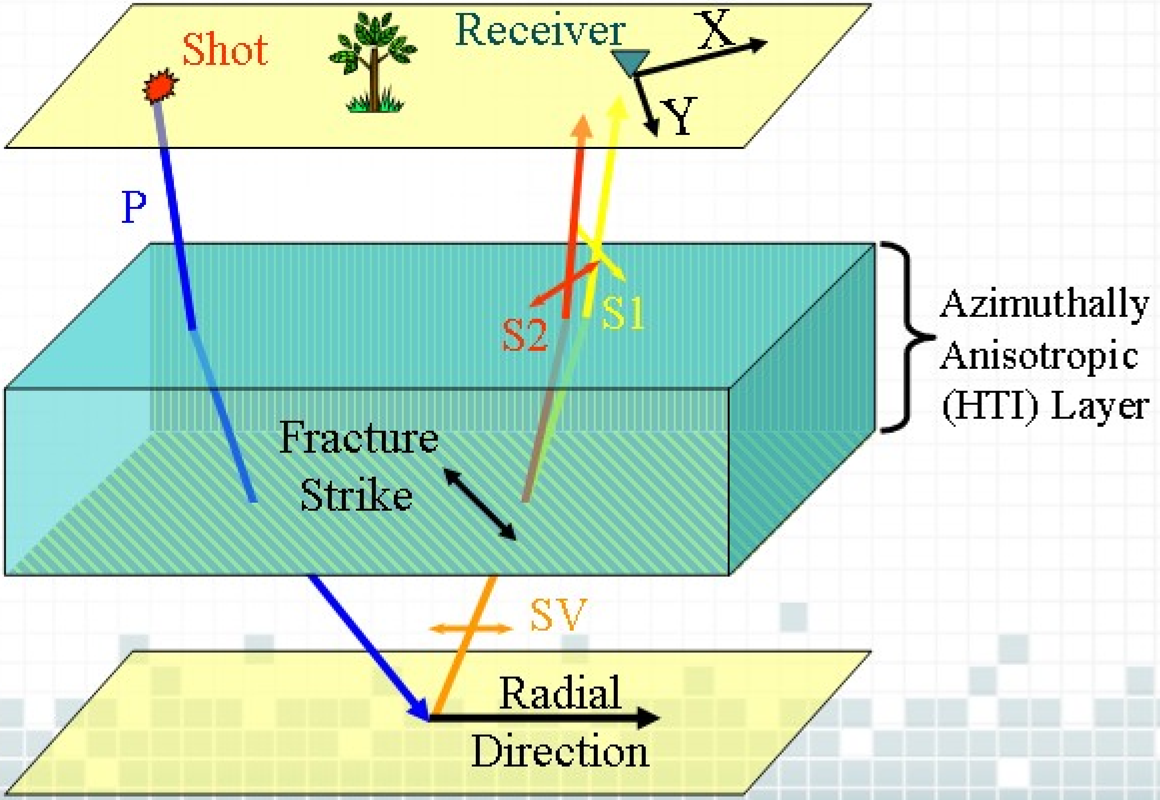
Introduction

- **Azimuthal anisotropy, principle causes**
  - fractures
  - stress

- **Azimuthal anisotropy, seismic signatures**
  - VVAZ (Velocity Variation with Azimuth)
  - AVAZ (AVO Variation with Azimuth)
  - ➢ Shear-wave splitting

Introduction

- **Shear-wave Splitting**
  - "If two S-waves travel in the same direction with different polarizations and speeds they are split." (Winterstein, 1989, Geoph. **55**, 1070)



Introduction

- **Shear-wave splitting requires two analysis/processing steps**
  1. Estimation of the anisotropy directions and magnitude.
  2. Correction for shear-wave splitting within the imaging process.

- **Estimation methods**
  – Radial-transverse ratio (Garotta, 1989)
  – Transverse polarity flip detection (Li, 1998)
  – 3-D Alford rotation (Gaiser, 2000)
  ➢ Least-squares method (this talk)

Geometry assumptions

Method	Azimuth Distribution Requirement
Radial / transverse energy ratios	Regular
Polarity flip	Regular
3-D Alford rotation	Orthogonal pairs
Least-squares	At least 2 different azimuths

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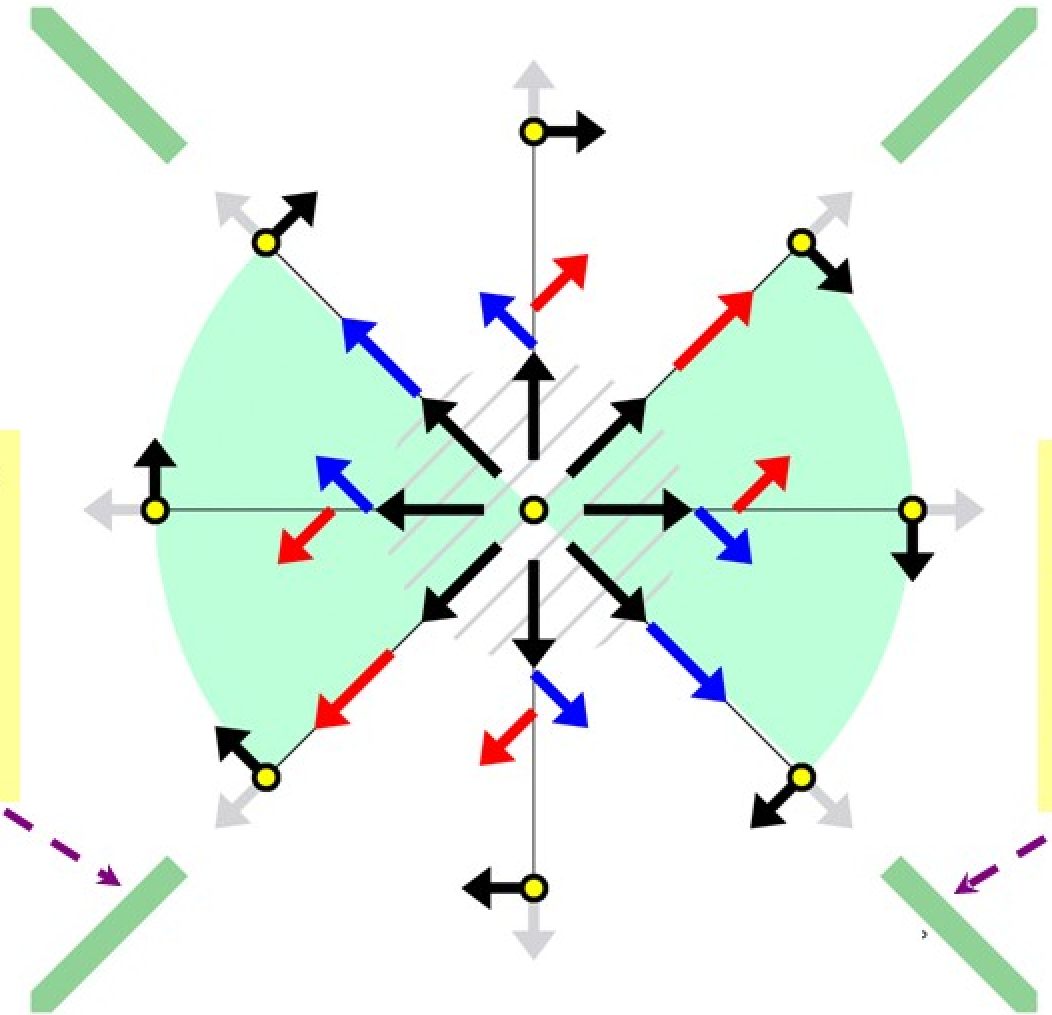
Azimuthal polarity variation



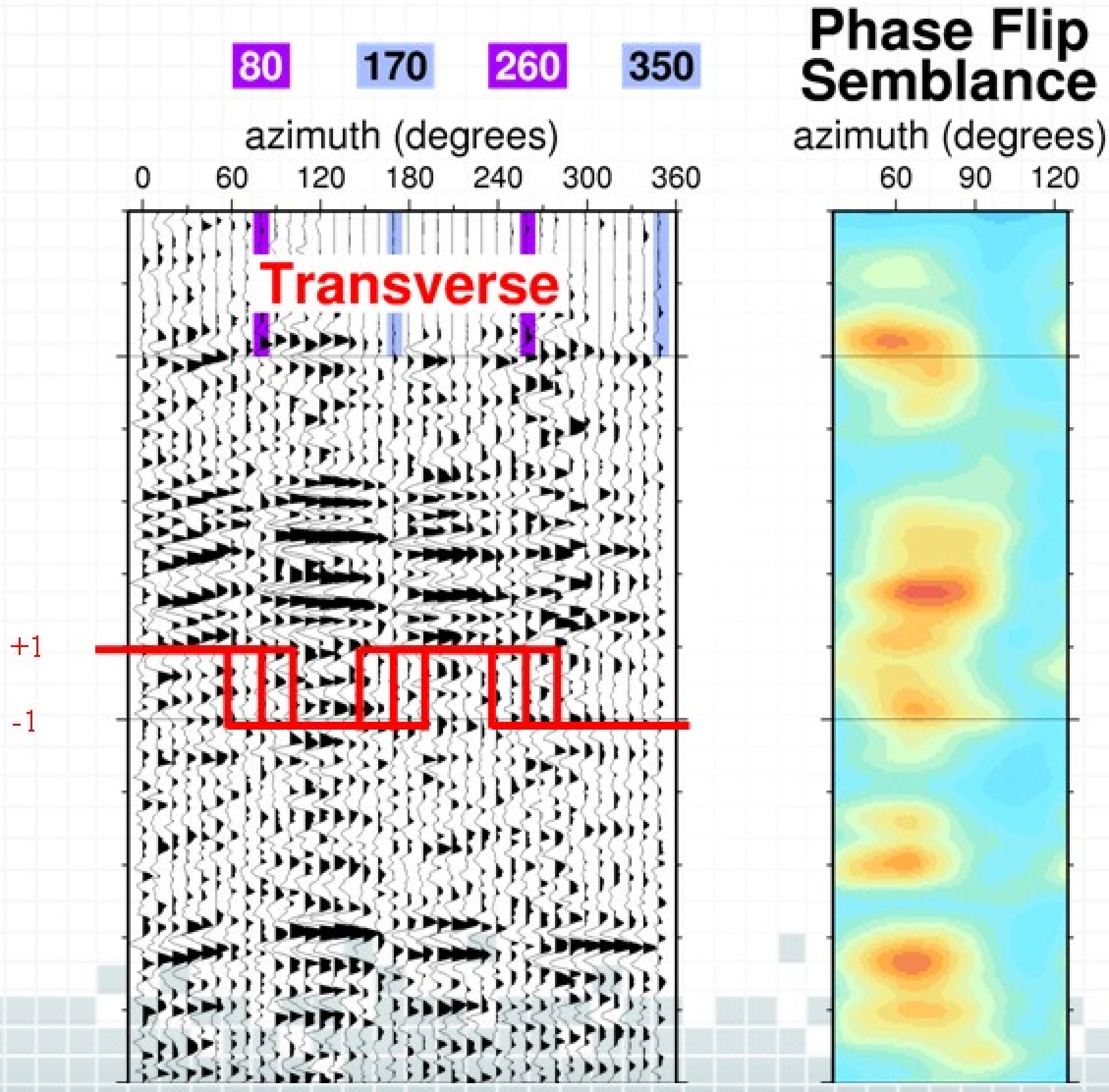
Polarity reverses across isotropy plane

(fracture strike, or S1 direction)

Polarity reverses across symmetry plane

(fracture normal, or S2 direction)

Transverse polarity flip detection



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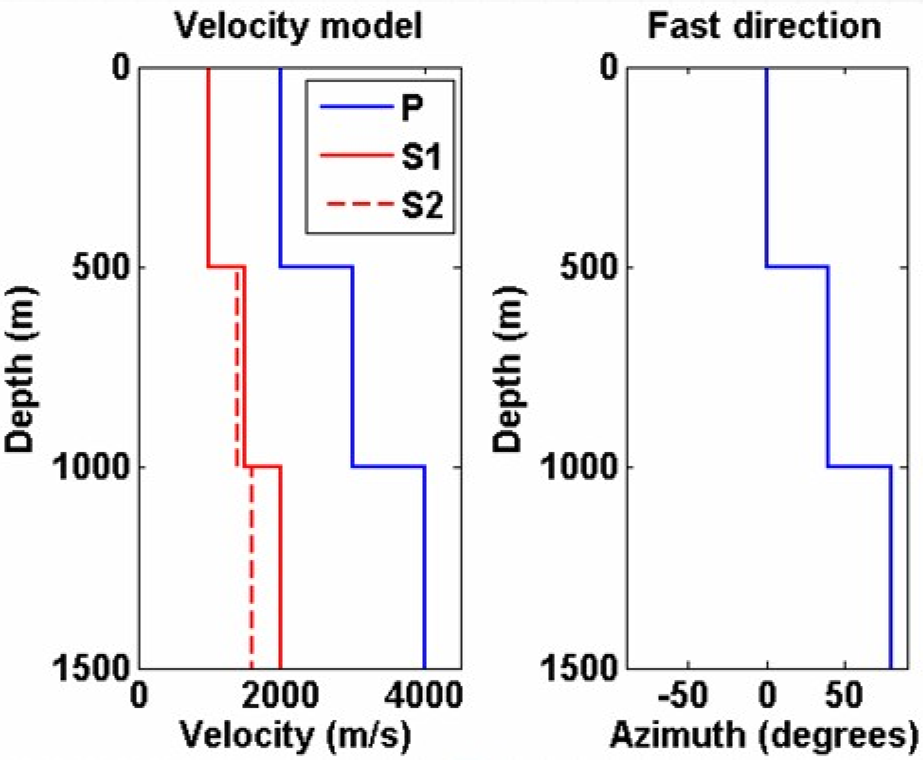
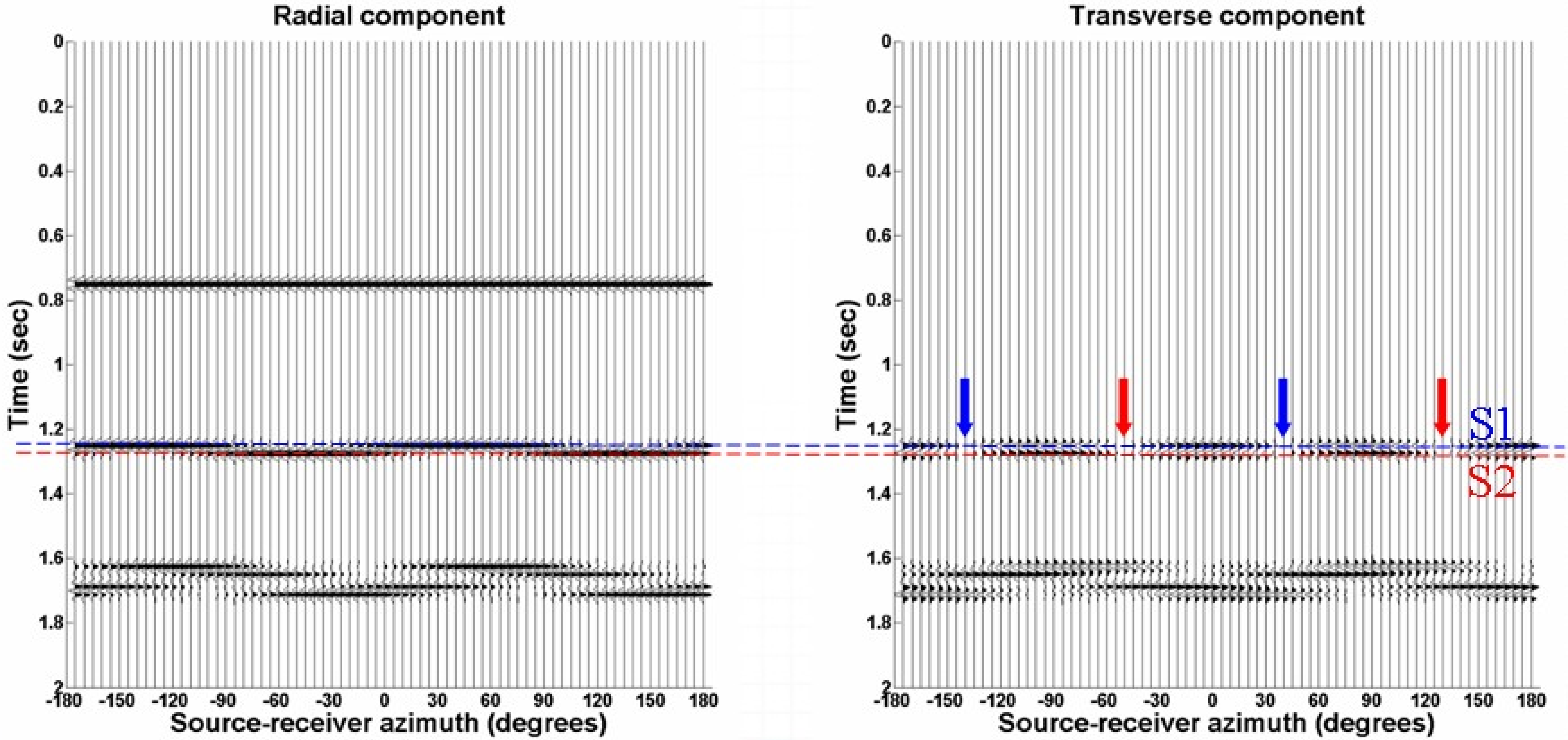
Model

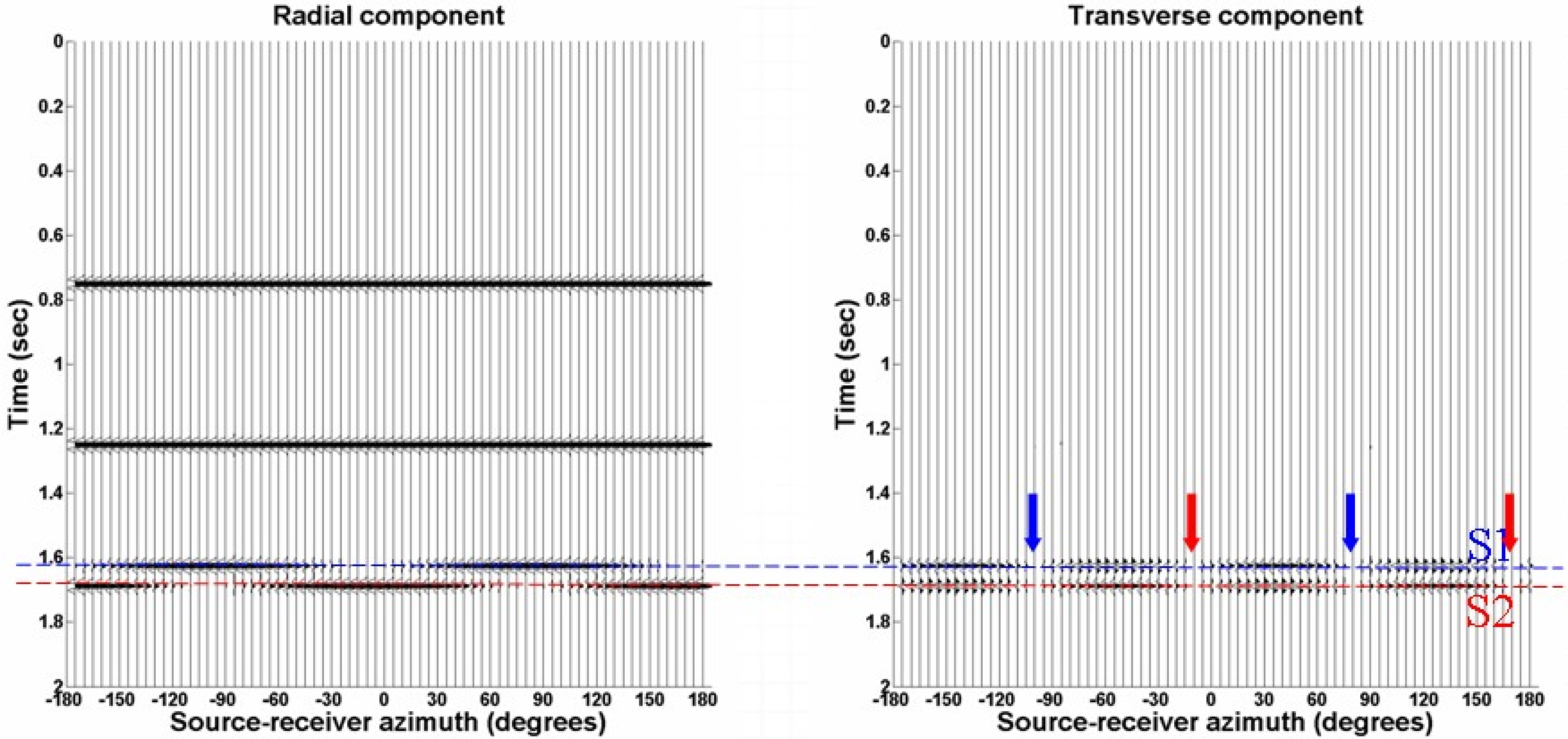
- **Model: 3 layers each 500m thick**
  - isotropic top layer
  - HTI layer: S1 azimuth 40°
  - HTI layer: S1 azimuth 80°
- **Modeling assumptions**
  - near vertical incidence shear-wave propagation.
  - vector decomposition occurs
  - neglect other variations with azimuth for the S1 and S2 modes
- **Wavelet**
  - Zero phase 30Hz Ricker



Synthetic receiver gather

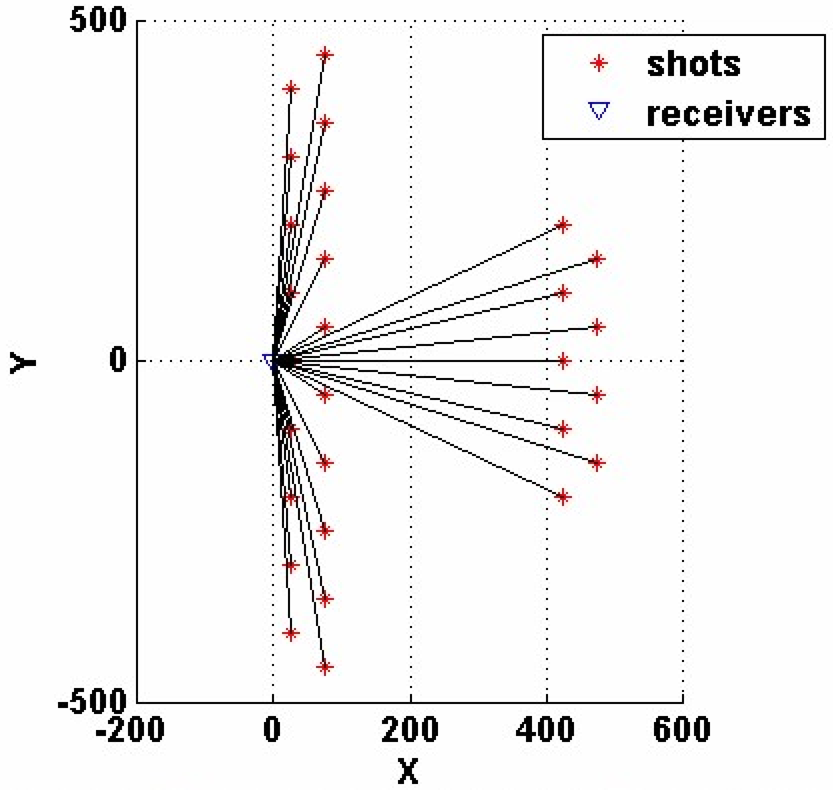


After stripping layer 2

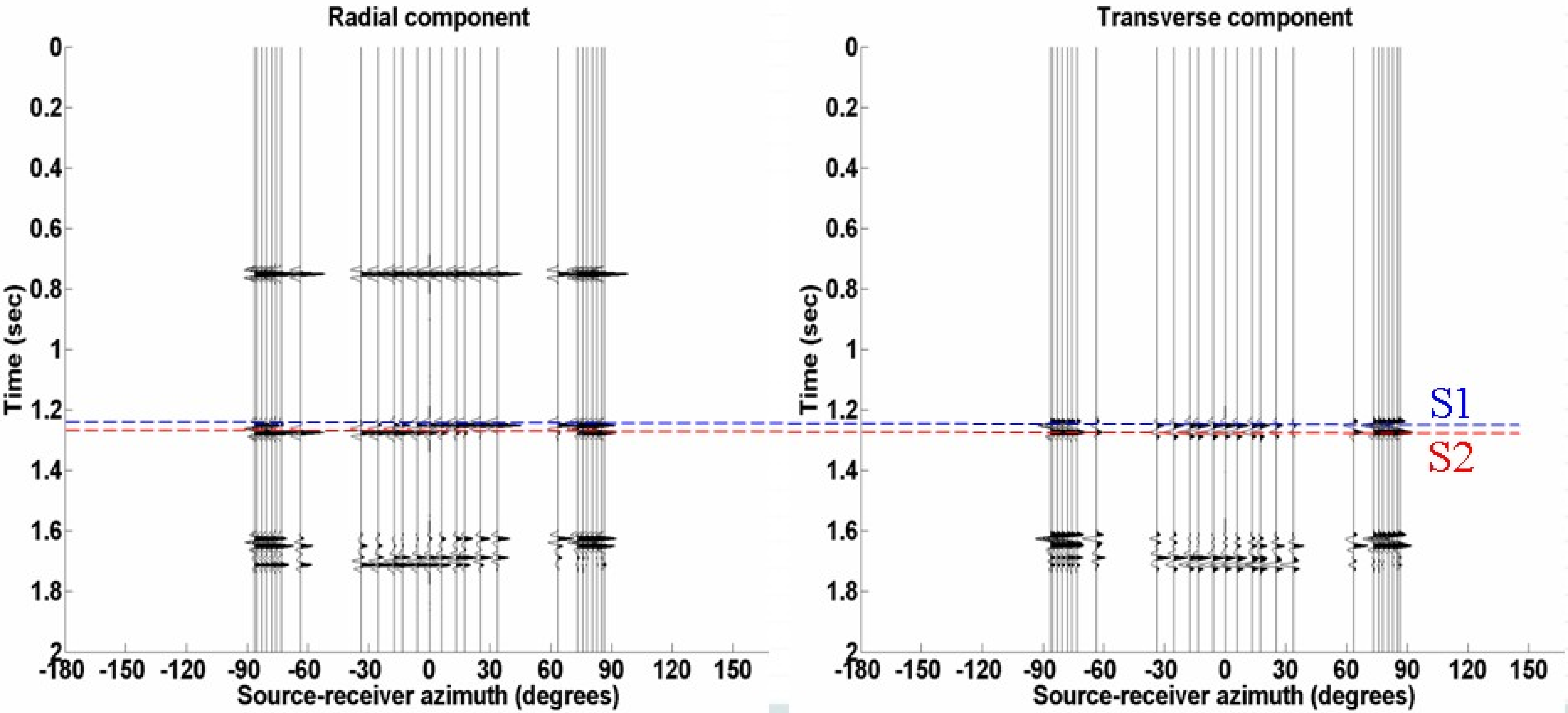


Geometry for synthetic

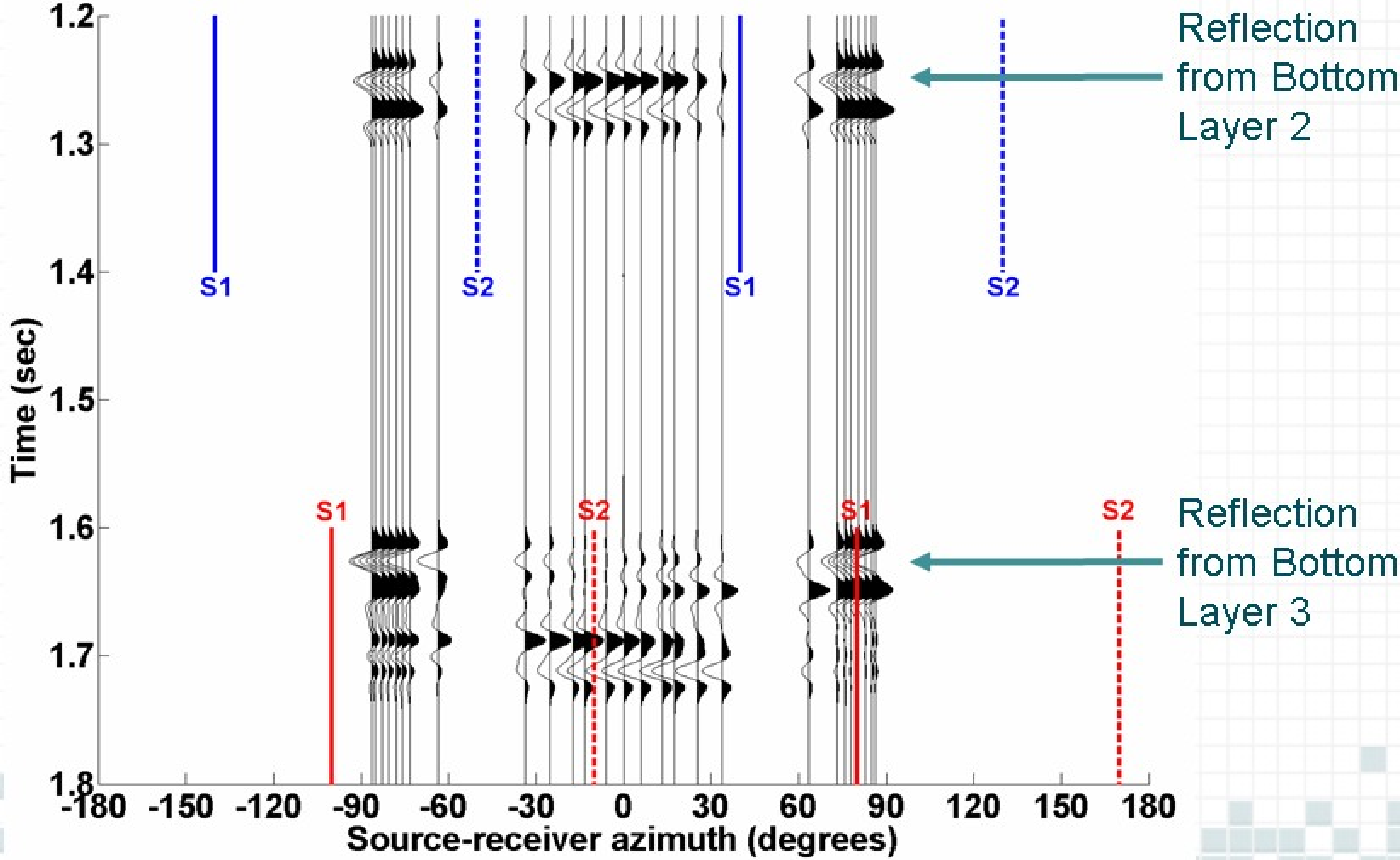
- Derived from an actual OBS survey
- Shot line dropped to the left
- Offsets limited to a maximum of 500m



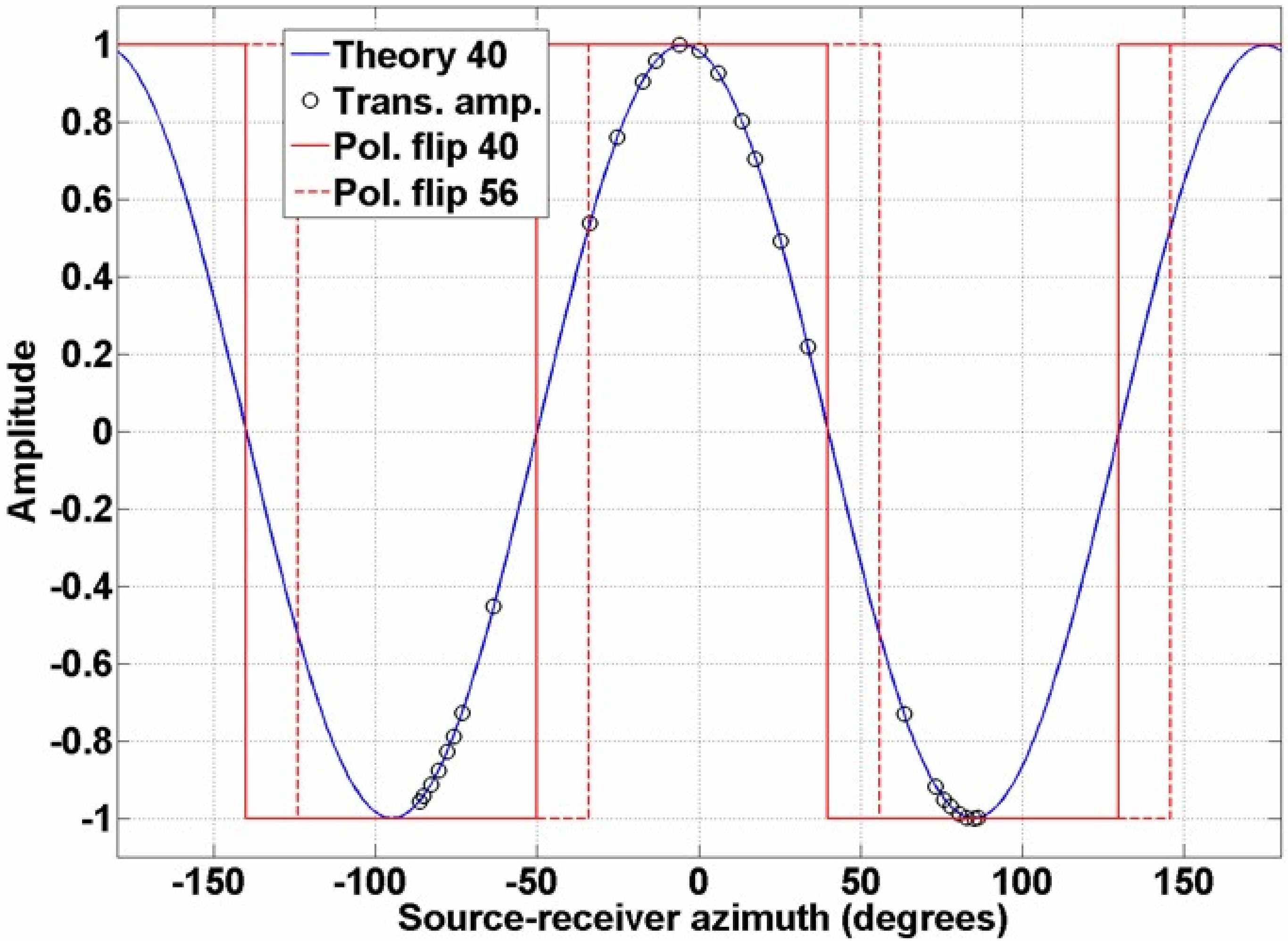
Synthetic receiver gather



Transverse component



Transverse component amplitude
Top event



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Transverse amplitude

Under our assumptions, amplitude of an event (either S1 or S2 arrival) on the transverse component is

$$A_T(\theta_i) = C \sin[2(\phi - \theta_i)]$$

$$i = 1, \ldots, N$$

N traces with azimuths θ_i

ϕ: S1 direction

C : constant scale factor for the event at a given time.

Least-squares algorithm

Recall: $A_T(\theta_i) = C\sin[2(\phi - \theta_i)]$ $i = 1,\ldots,N$

Rewrite: $A_T(\theta_i) = C\begin{pmatrix}\sin(2\theta_i) & \cos(2\theta_i)\end{pmatrix}\begin{pmatrix}-\cos(2\phi) \\ \sin(2\phi)\end{pmatrix}$

Only depends on Geometry

Only depends on Fracture Direction

Least-squares algorithm

Recall:

$$A_T(\theta_i) = C\sin\left[2(\phi - \theta_i)\right] \qquad i = 1,\ldots,N$$

Rewrite:

$$\underbrace{\begin{pmatrix} A_T(\theta_1) \\ A_T(\theta_2) \\ A_T(\theta_3) \\ \vdots \\ A_T(\theta_N) \end{pmatrix}}_{\mathbf{A}_T} = C \underbrace{\begin{pmatrix} \sin(2\theta_1) & \cos(2\theta_1) \\ \sin(2\theta_2) & \cos(2\theta_2) \\ \sin(2\theta_3) & \cos(2\theta_3) \\ \vdots & \vdots \\ \sin(2\theta_N) & \cos(2\theta_N) \end{pmatrix}}_{\mathbf{L}} \begin{pmatrix} -\cos(2\phi) \\ \sin(2\phi) \end{pmatrix}$$

Least-squares algorithm

Recall: $A_T(\theta_i) = C\sin\left[2(\phi - \theta_i)\right]$ $\quad i = 1,\ldots,N$

Rewrite: $\mathbf{A}_T = C\mathbf{L}\begin{pmatrix} -\cos(2\phi) \\ \sin(2\phi) \end{pmatrix}$

Least-square solution:

$$C\begin{pmatrix} -\cos\left(2\hat{\phi}\right) \\ \sin\left(2\hat{\phi}\right) \end{pmatrix} = \left(\mathbf{L}^T\mathbf{L}\right)^{-1}\mathbf{L}^T\mathbf{A}_T$$

Least-squares method

- **Advantages**
  - No scanning required
  - Doesn't require regular azimuthal sampling
- **Drawback**
  - Neglects effect of AVO, therefore best applied in limited offset ranges
- **Note**
  - In special case of 2 orthogonal azimuths, $\mathbf{L}^T\mathbf{L}$ is the identity matrix, so get a simple rotation

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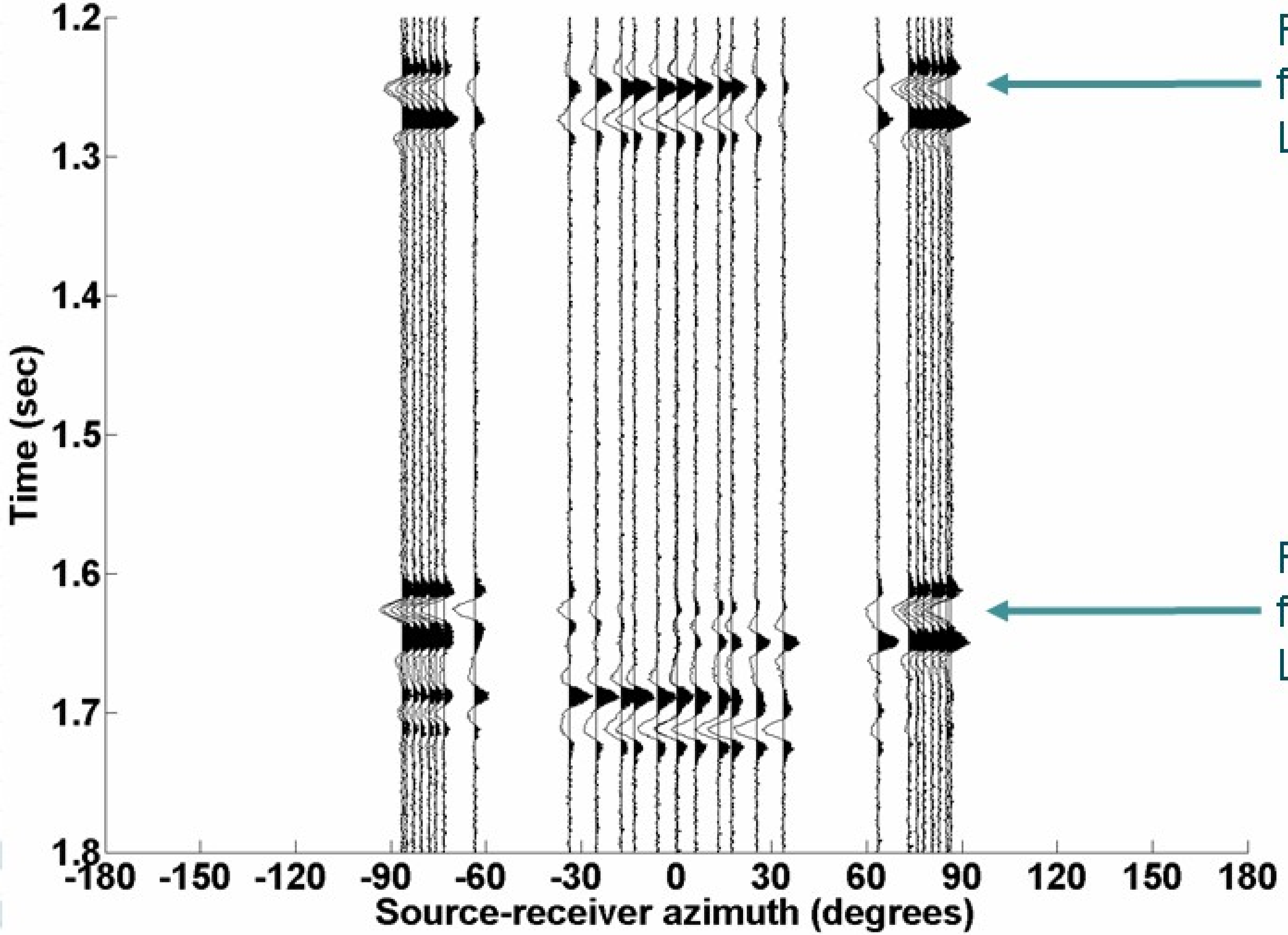
Results on synthetic data

- **Noise added to synthetic data**
  - RMS amplitude 3% of peak signal
- **Layer stripping procedure**
  - Estimate S1 direction for first HTI layer
  - Remove effects of layer
  - Estimate S1 direction for second HTI layer
  - Remove effects of layer

Comparison of Polarity Flip results vs. Least-squares:

	HTI 1		HTI 2	
Model	40°		80°	
Polarity Flip	33.75°	6.9%	76°	4.4%
Least-squares	39.81°	0.2%	79.41°	0.7%

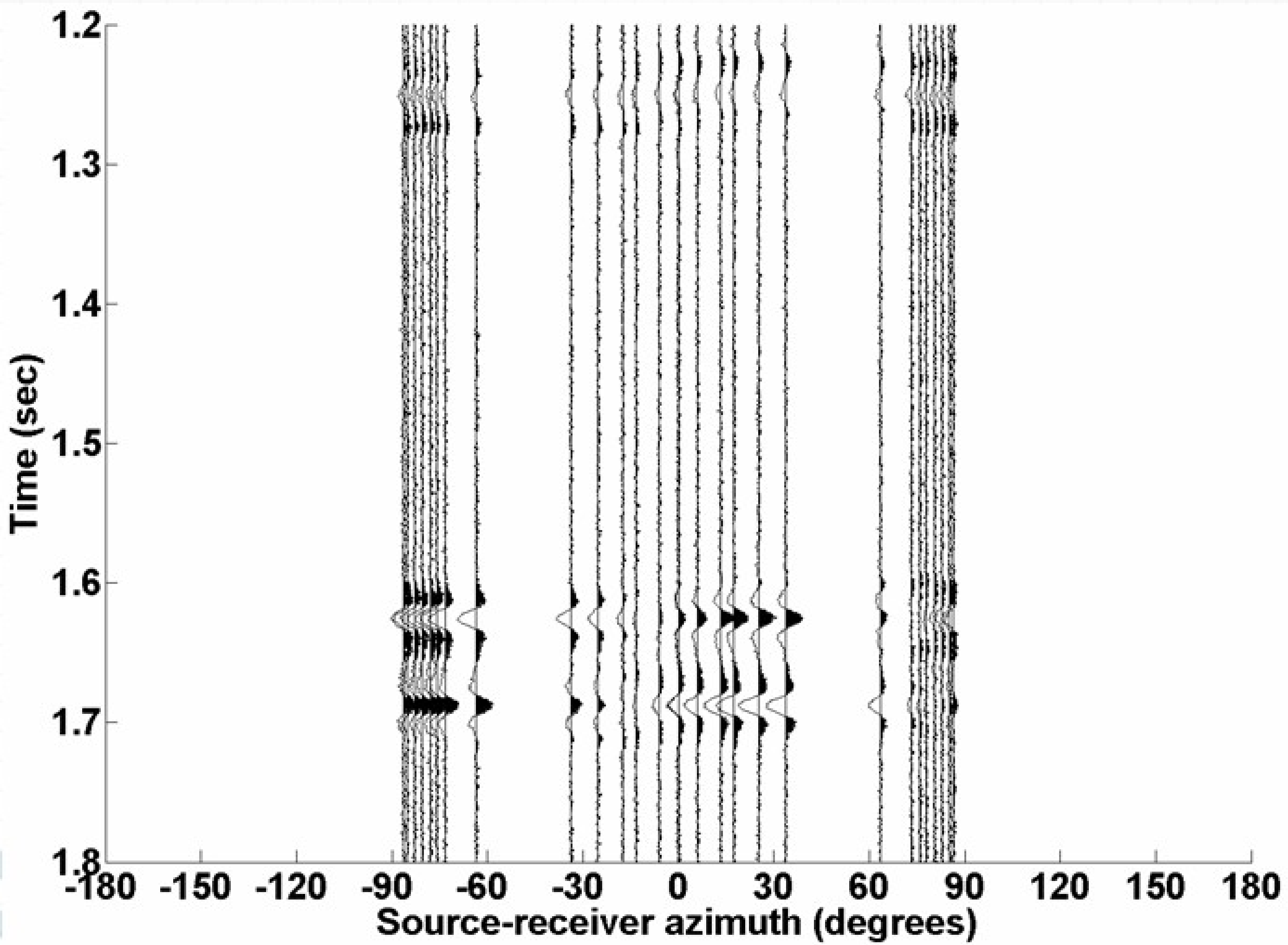
Transverse component, 3% noise



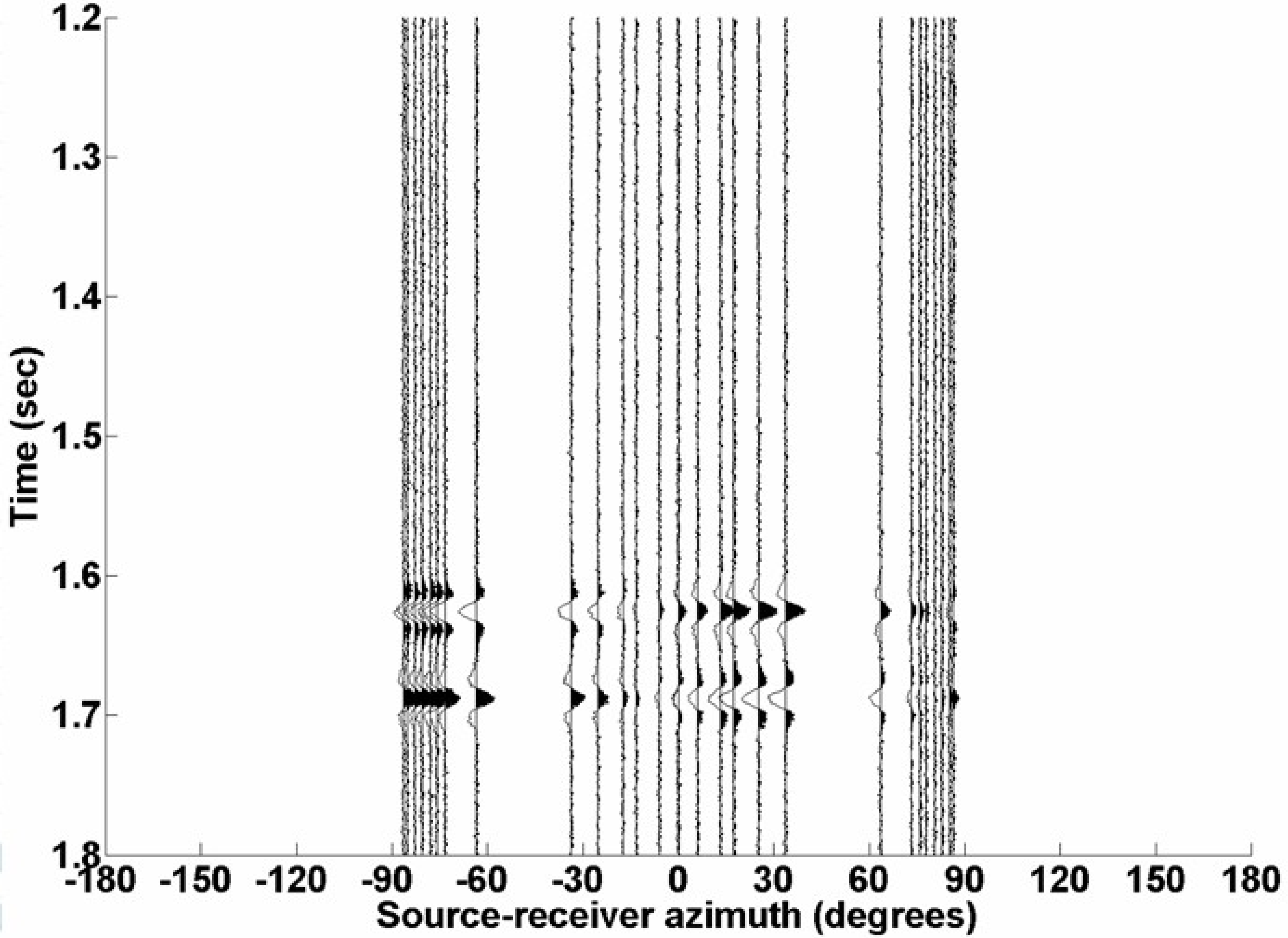
Reflection from Bottom Layer 2

Reflection from Bottom Layer 3

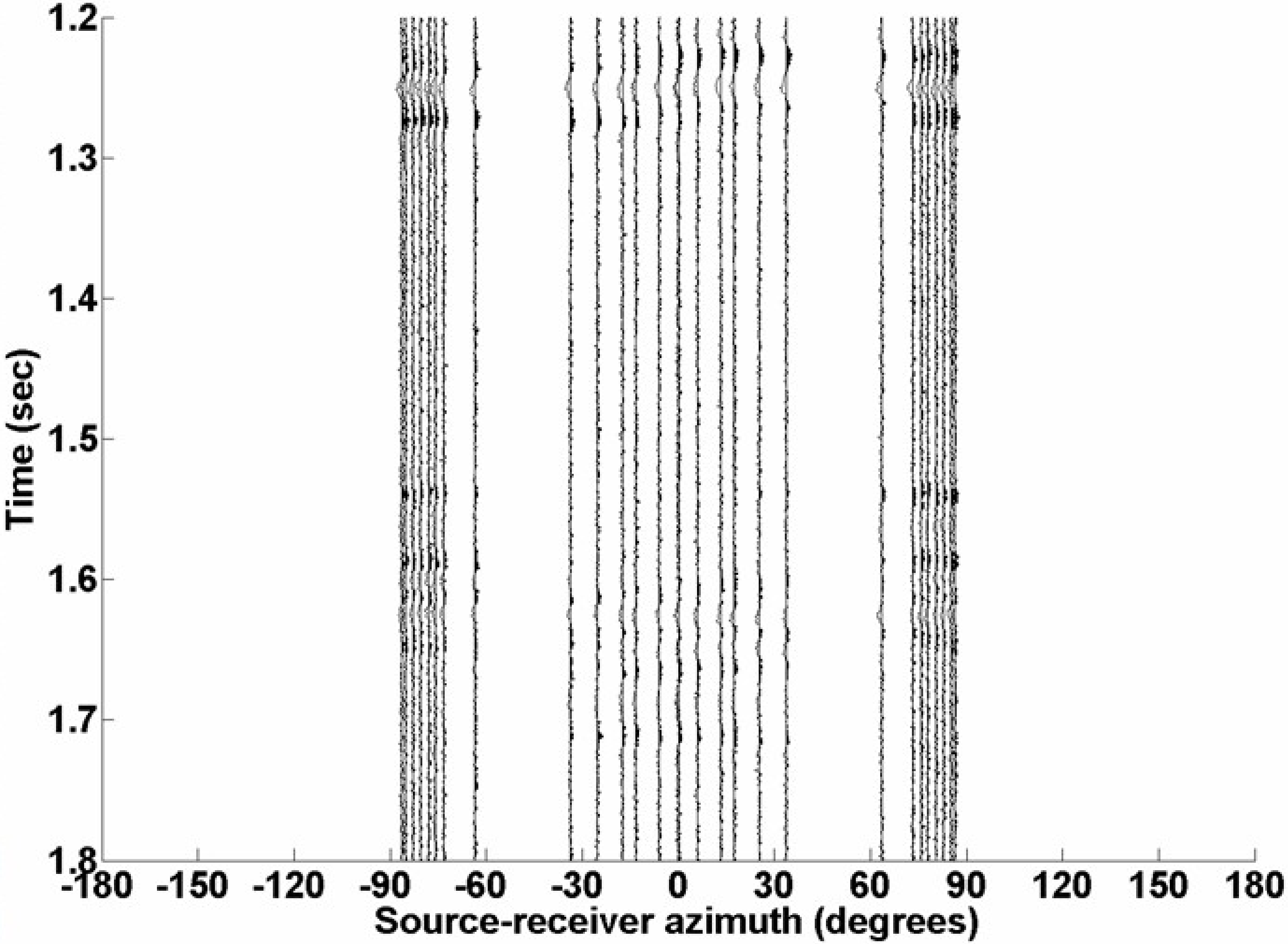
1st layer stripped: polarity flip estimate



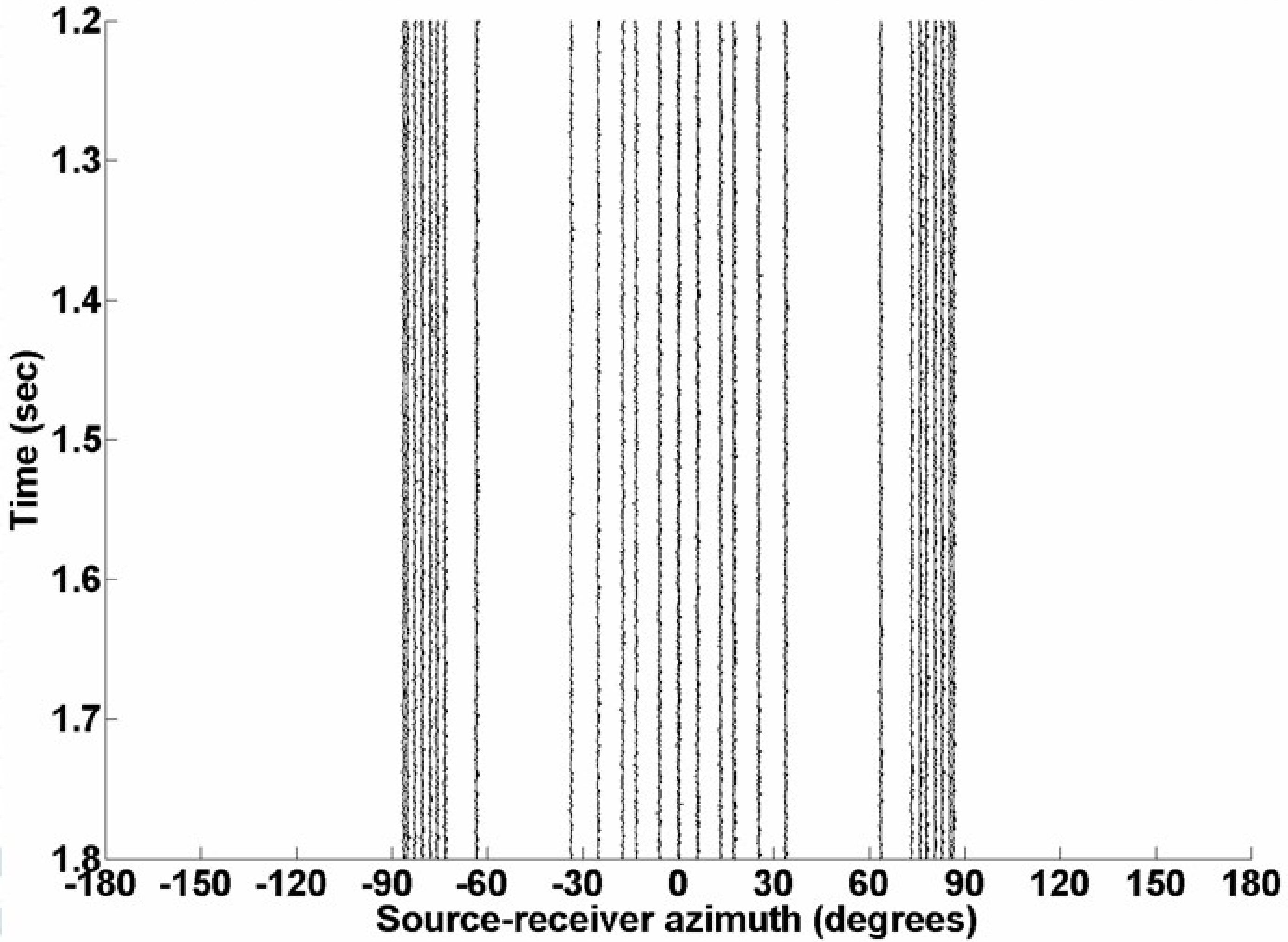
1st layer stripped: least-squares estimate



2nd layer stripped: polarity flip estimate



2^{nd} layer stripped: least-squares estimate



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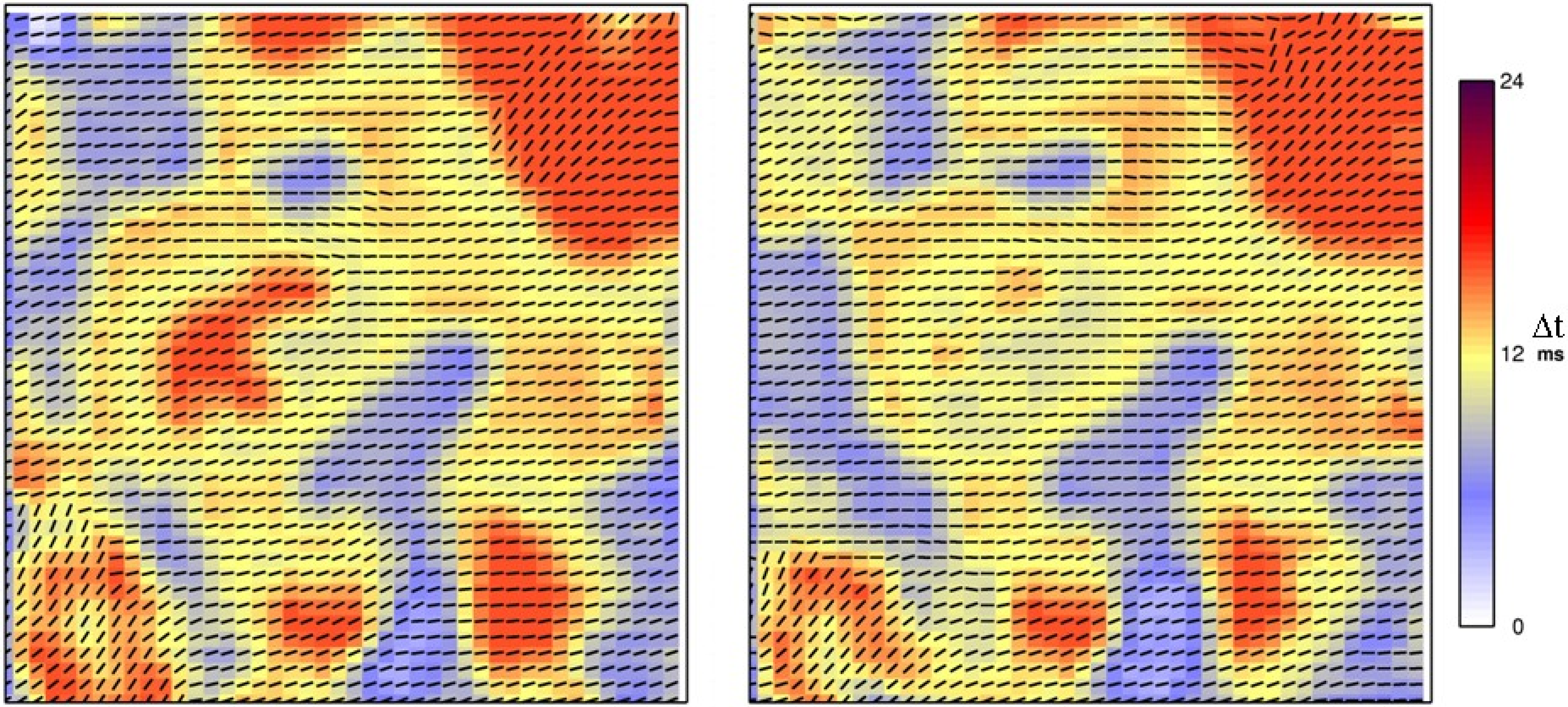
Field data example

- **Carbonate play in North America**
- **Workflow**
  - Superbinning with a radius of 2000ft.
  - Azimuthal binning into 72 sectors of 5°.
  - NMO stacking over offsets greater than 2000ft.
  - Analysis with spatial intervals of 330ft.
- **Azimuth decimation to assess robustness for poor geometry**
  - Remove half of azimuth sectors
  - Remaining azimuths: 90°-175° and 270°-355°.

Anisotropy: S1 direction and Δt

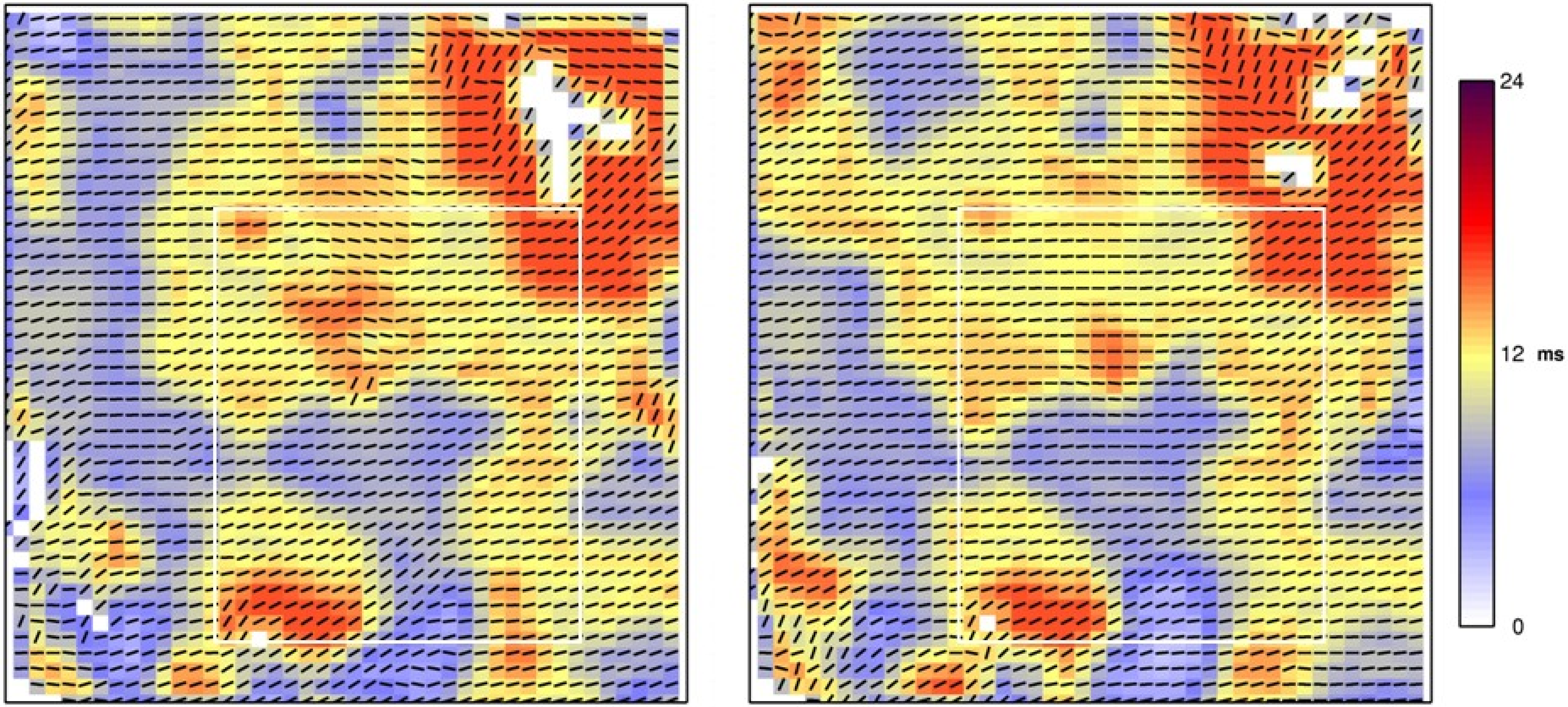


Polarity Flip

Least-squares

All azimuth sectors

Anisotropy: S1 direction and Δt

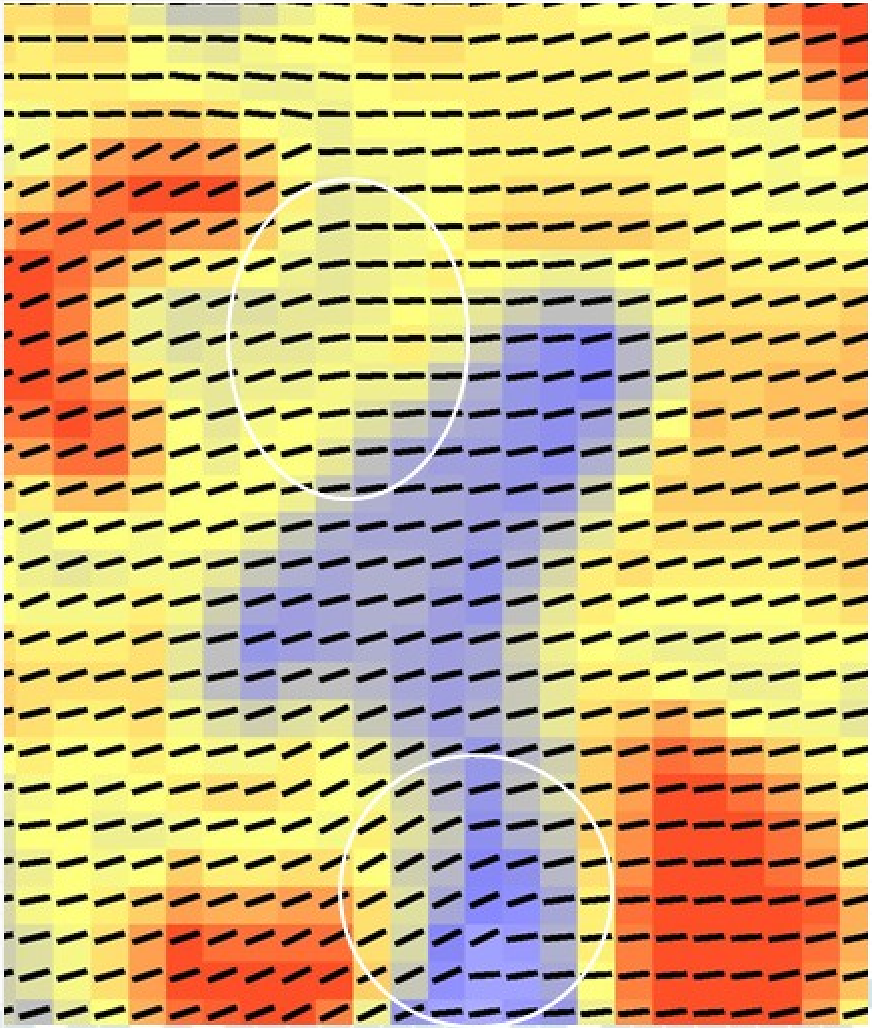


Polarity Flip

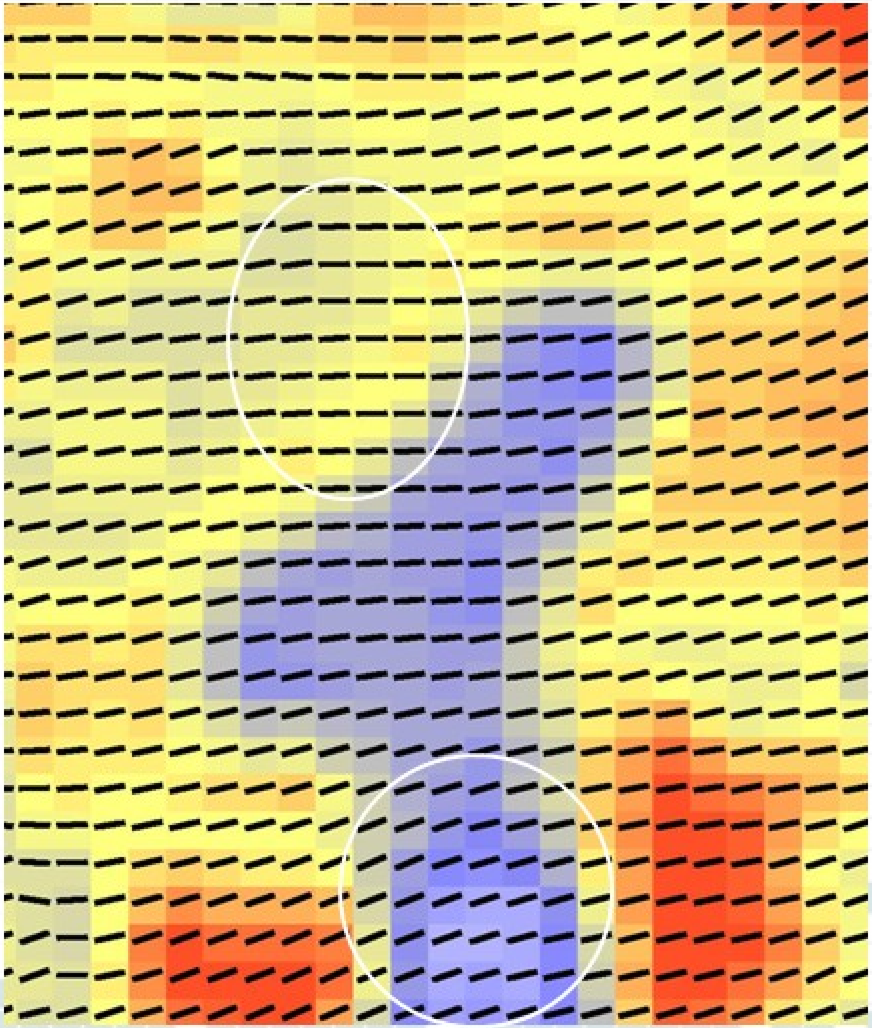
Least-squares

Half azimuth sectors

All azimuth sectors

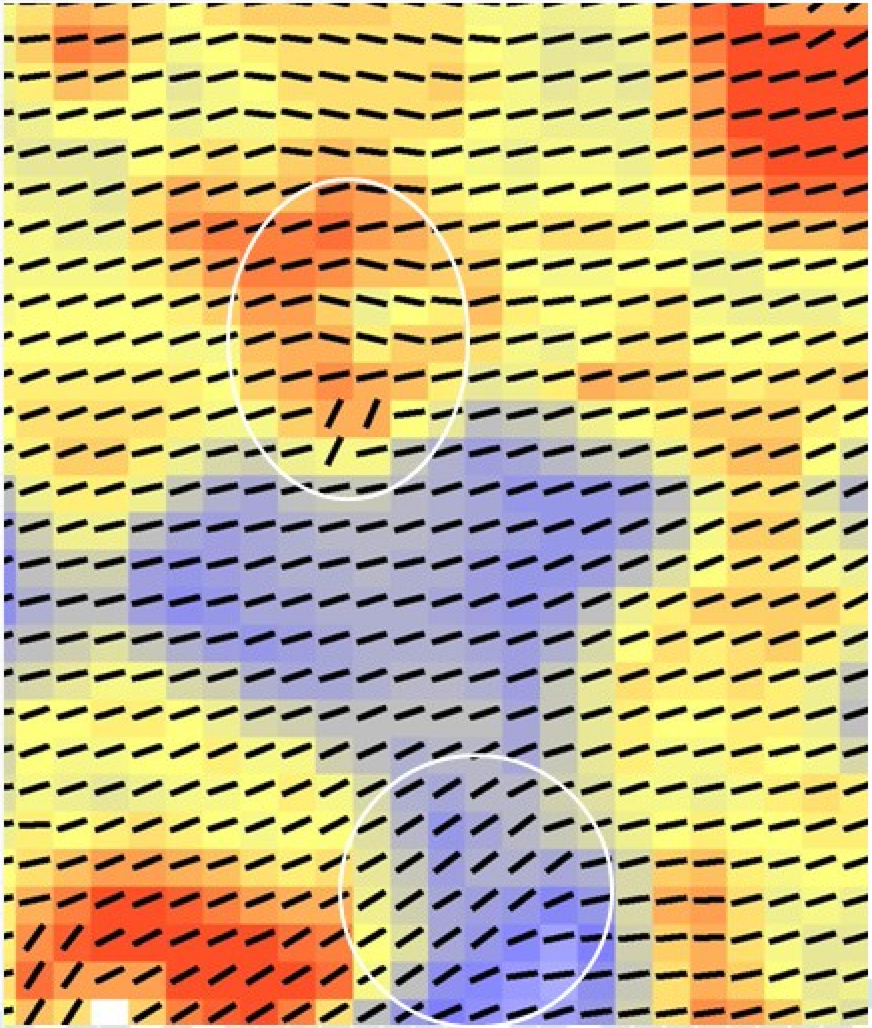


Polarity Flip

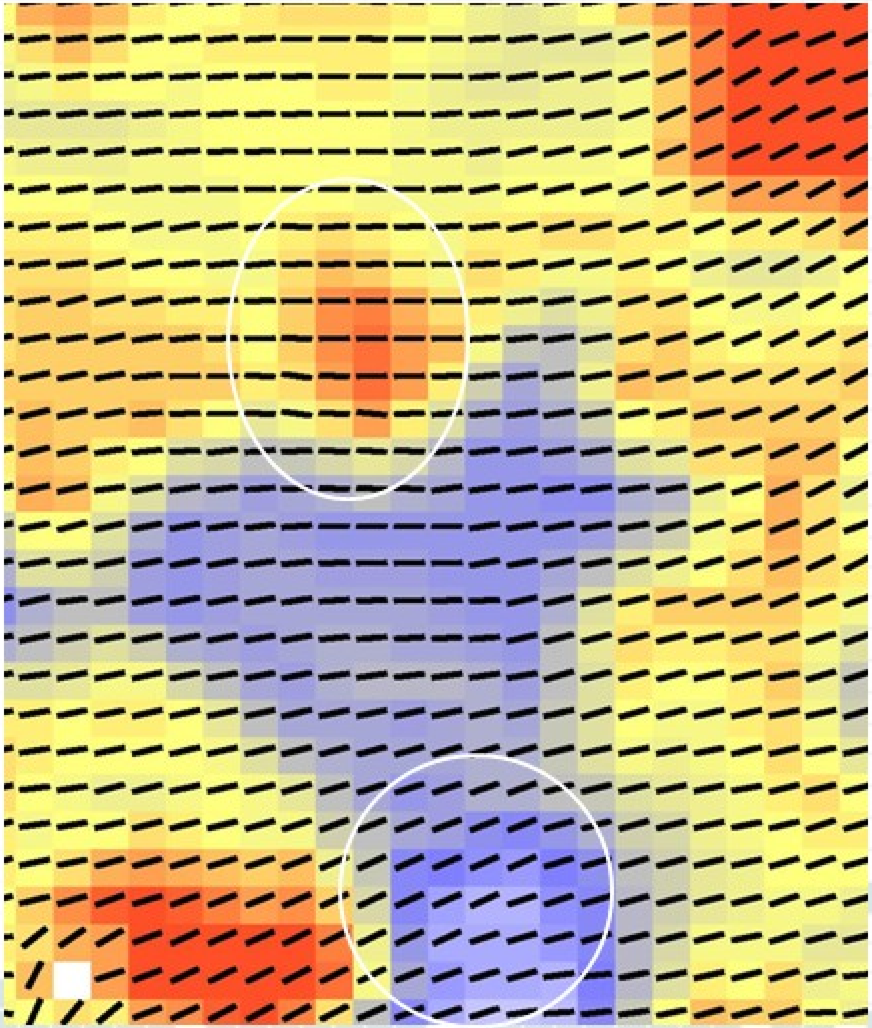


Least-squares

Half azimuth sectors



Polarity Flip



Least-squares

Conclusions

- Transverse component behavior is sensitive to azimuthal anisotropy directions
- Polarity based method works well, for adequate azimuthal sampling
- For poor azimuth sampling, polarity based method is suboptimal
- Least-squares method is robust in presence of irregular azimuth distribution
- No binning of azimuths is required

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