Generalized Cross Correlation: New Tools for Receiver and Source Array Processing

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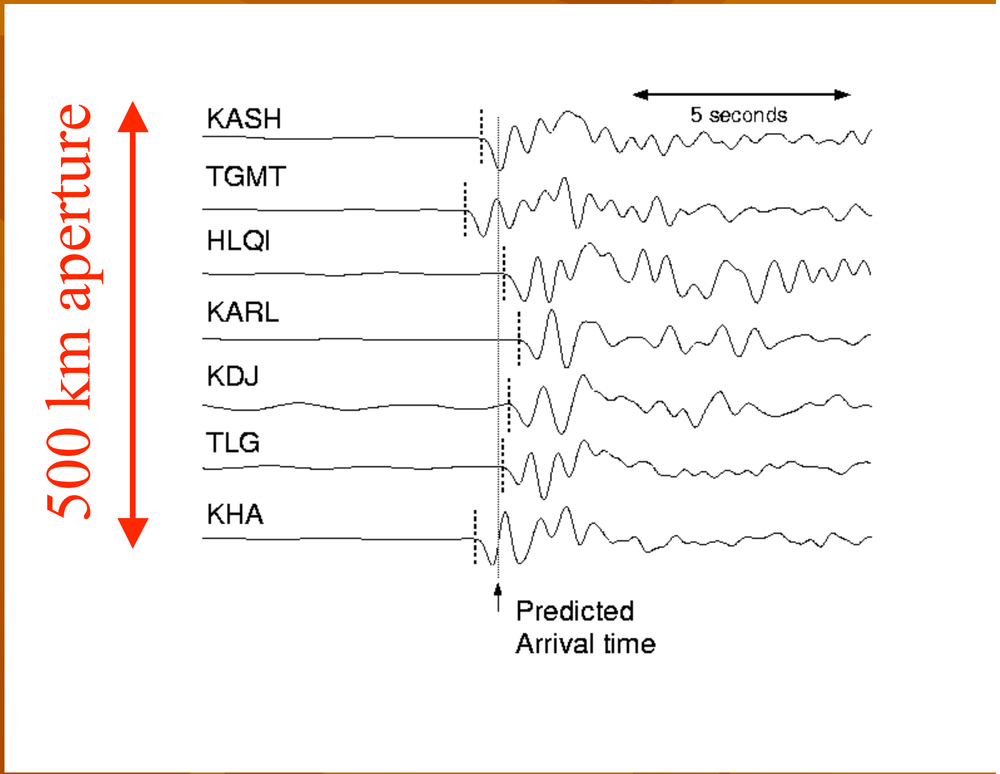
Array Processing

- Historical focus colored by nuclear monitoring
  - Plane wave processing of small arrays
  - Signal enhancement of small events
  - High frequency vertical instruments
- Modern challenge
  - Broadband instruments
  - Three-component instruments universal
  - Large aperture arrays (USArray)

Problem 1: Alignment

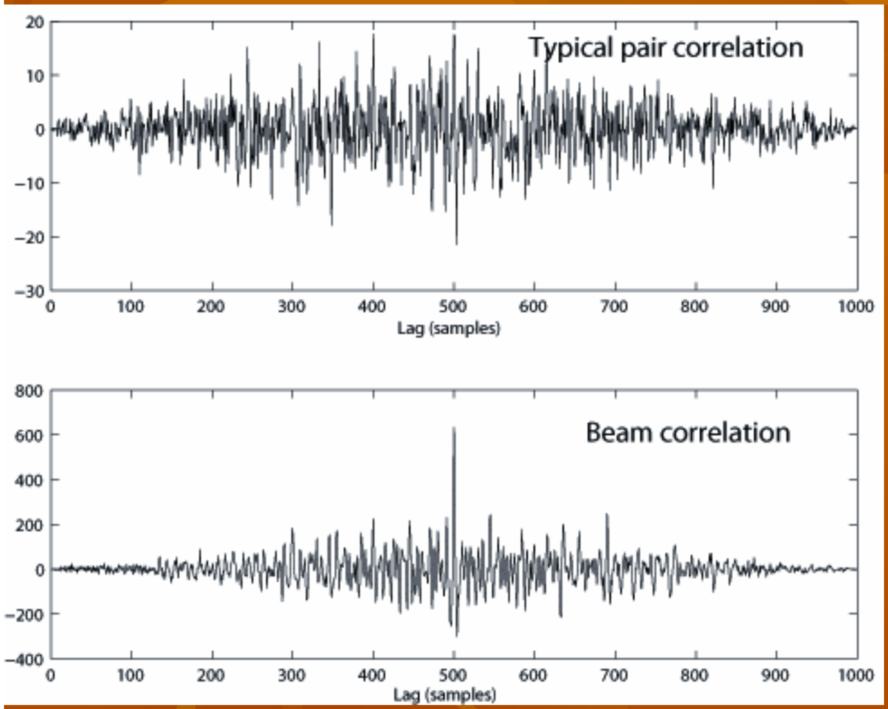
- Plane wave approximation fails when aperture gets large
- Conversely data are coherent over distances of more than 1000 km
- For large arrays stacks do not align
- Alignment lags = residuals for body wave tomography

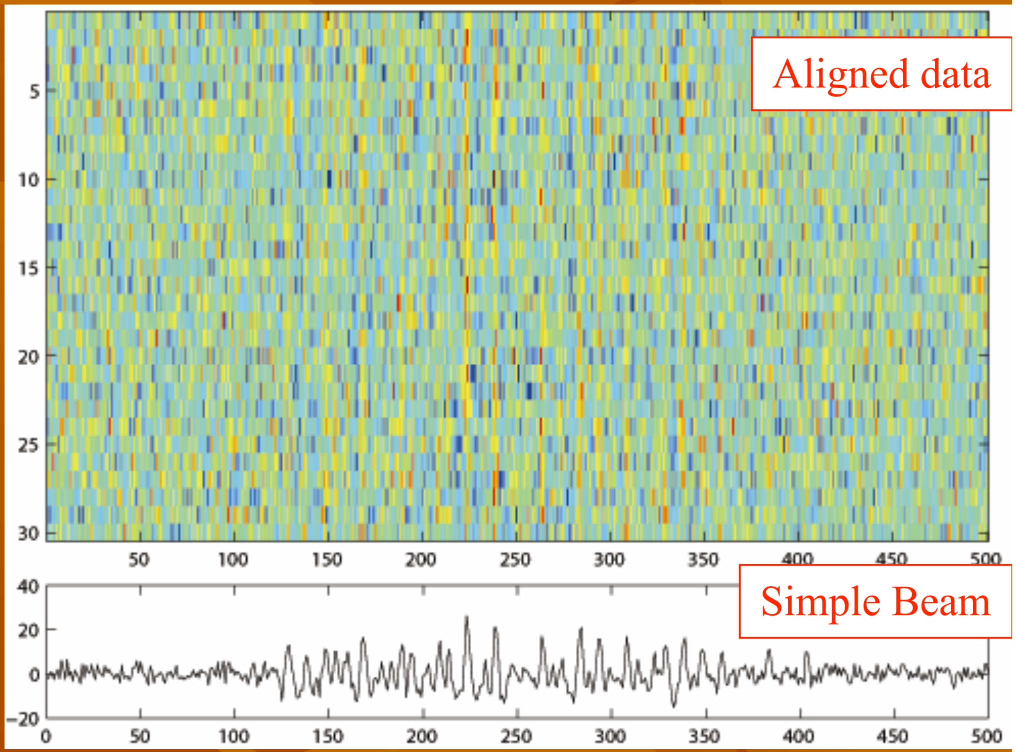


Solution?

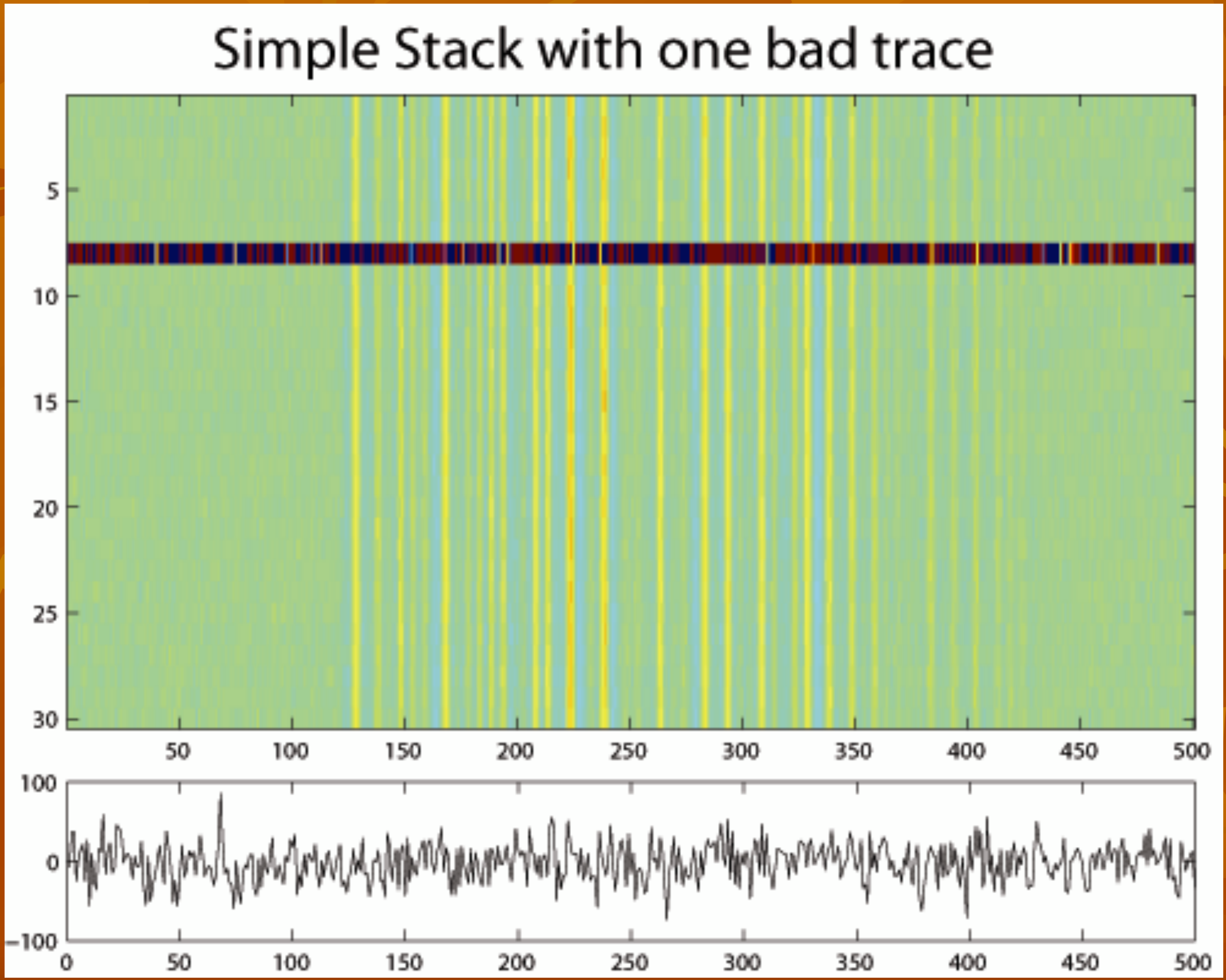
- Pair-wise correlation
  - Commonly used for P and S wave tomography residual measurements (VandeCarr and Crosson, 1990)
  - Commonly used for “source array” (Shearer and others)
- Beam correlation – obscure capability of dbap

We strongly prefer beam correlation for reason seen here



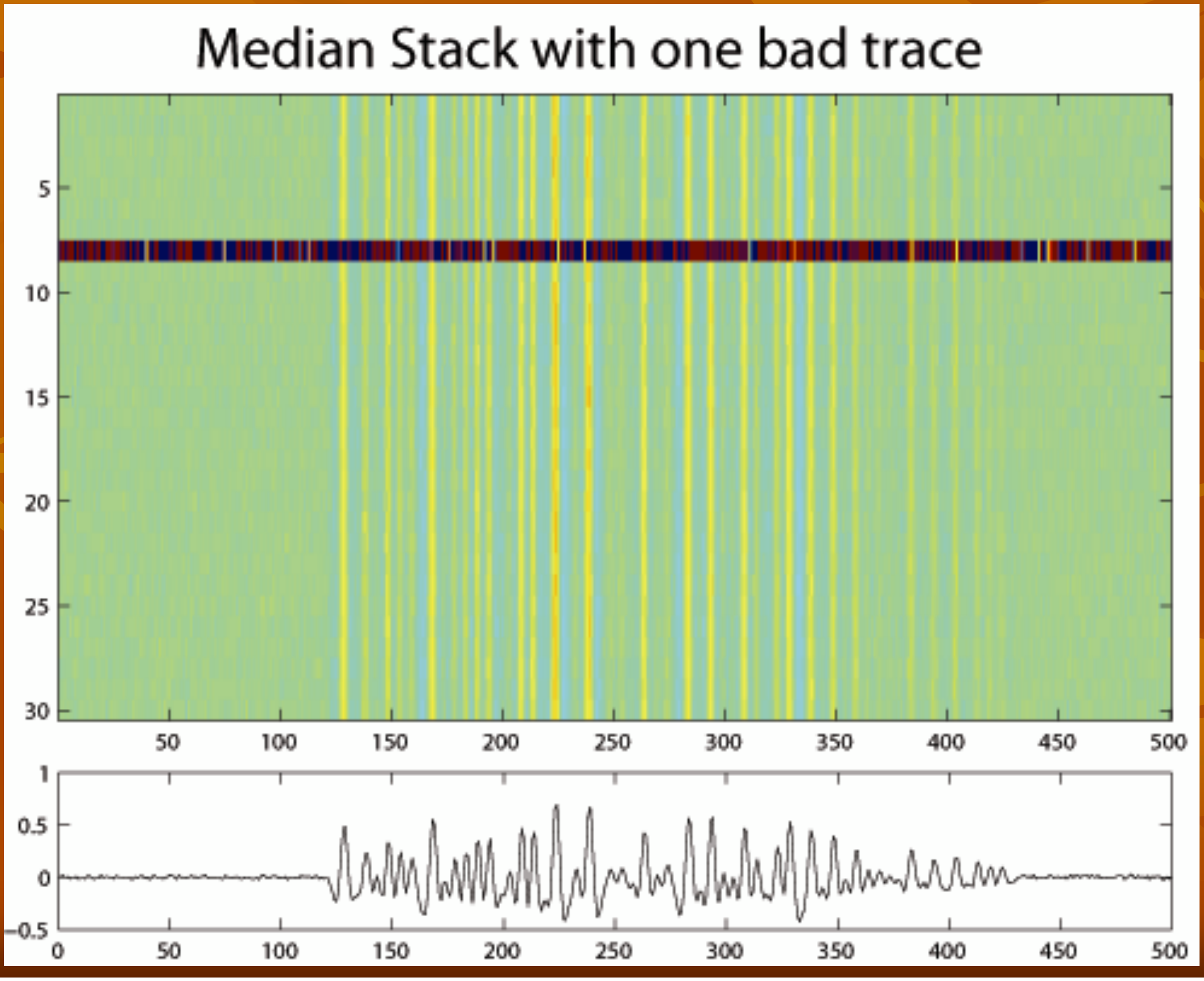


Problem 2: Bad channels

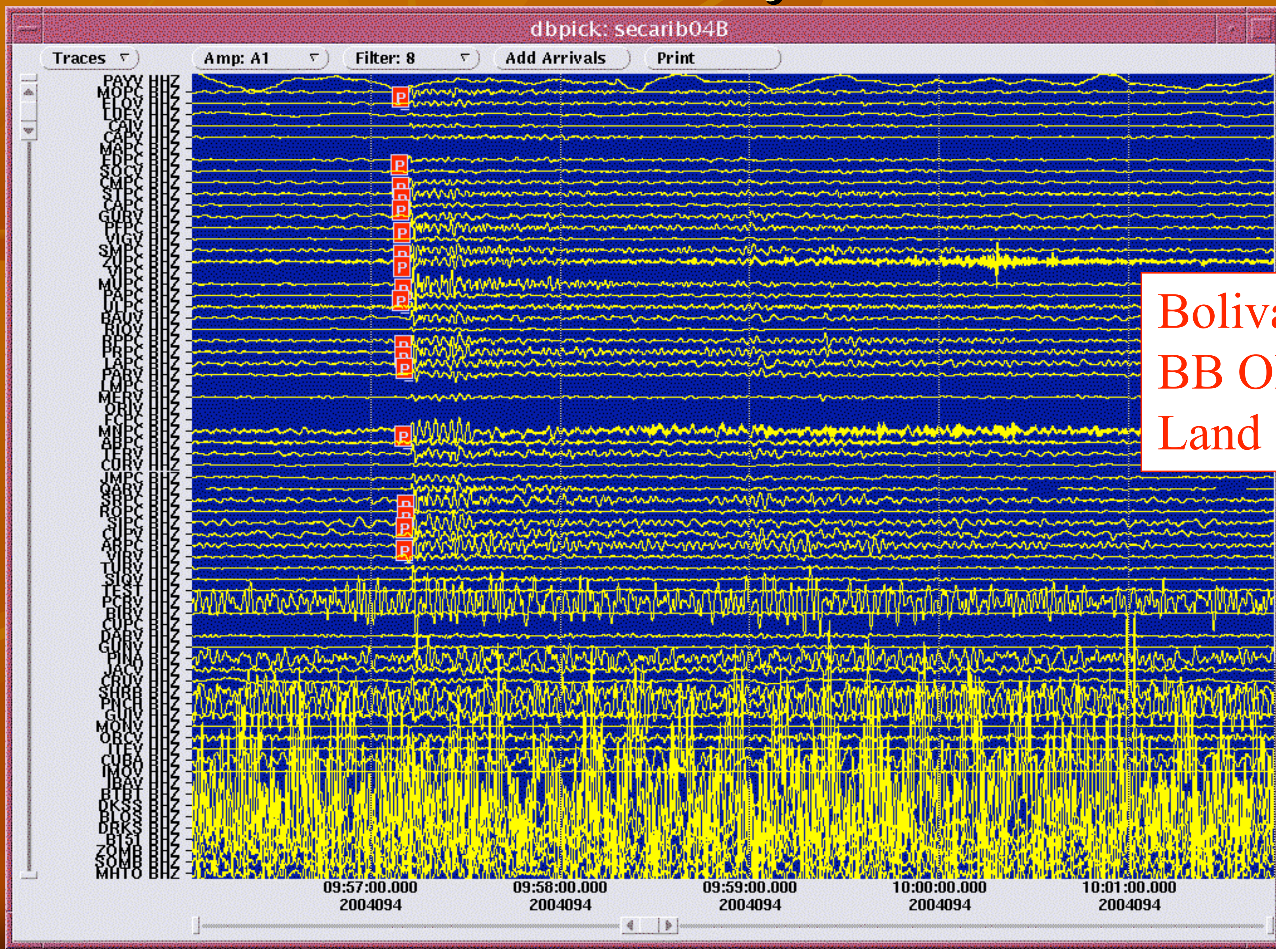


Solution

- Robust stack algorithm

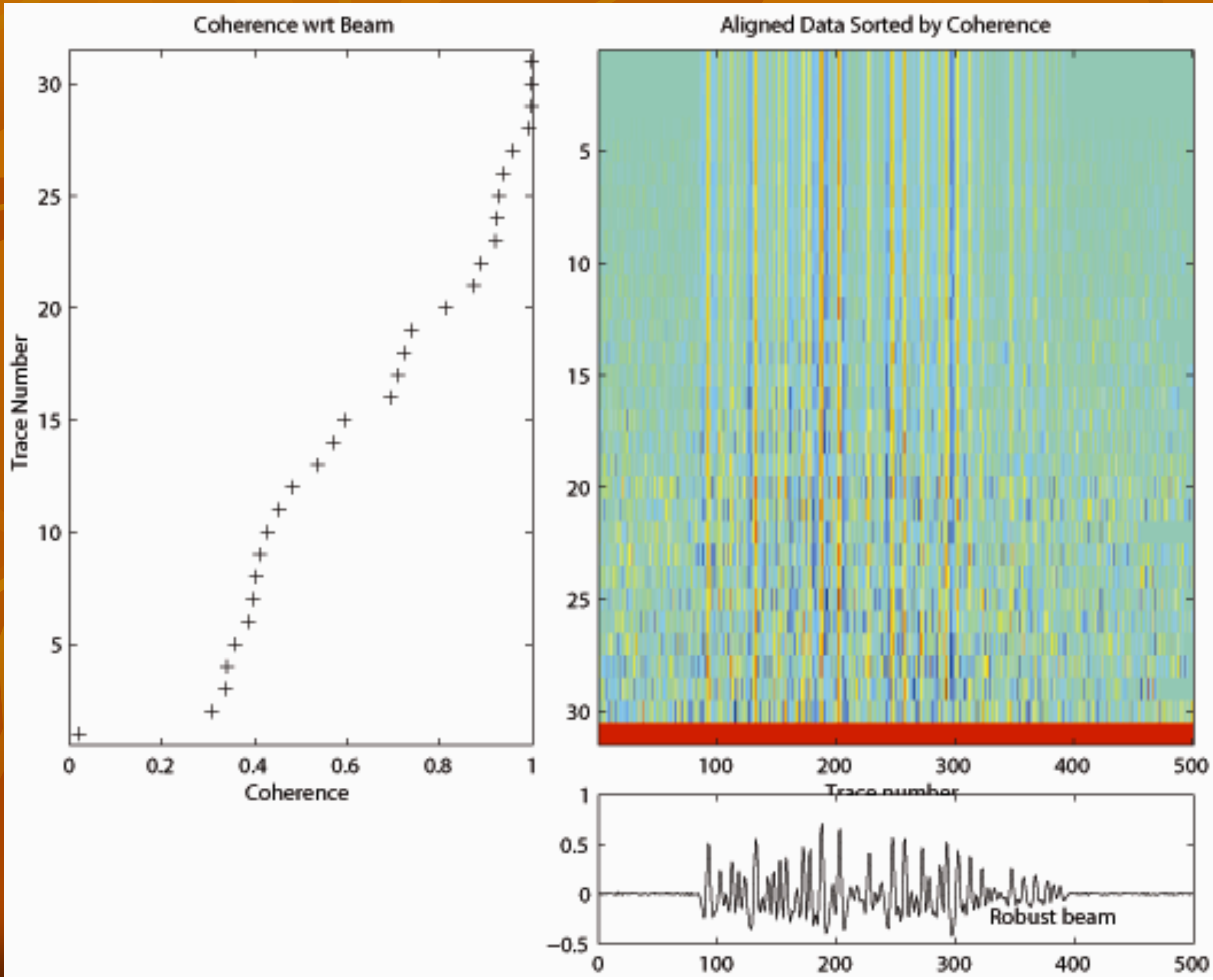


Problem 3: Wildly variable noise



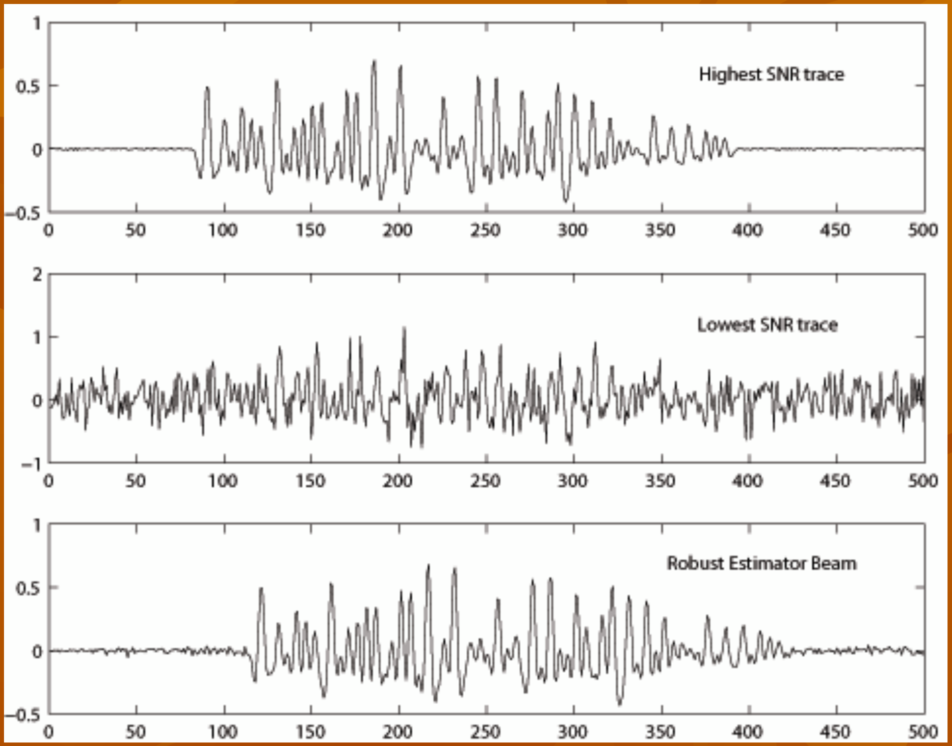
Bolivar exp:
BB OBS and
Land stations

Solution: Robust stacking Combined with Correlation



Motivation for Methodology

- “Hot” station is common with real data
- Want marginal data to contribute, but not degrade beam SNR
- Want to automatically discard bad data



Robust Method

- Initialize beam with pick of best station
- Initial alignment by cross-correlation
- Median stack
- Repeat until convergence:
  - Foreach ensemble member
    - Residual=data – current_beam
    - Weight(i) = penalty_function(residual);
  - current_beam = weighted stack
  - Realign data by cross-correlation with beam

Penalty Function

Amplitude Normalization

$$w_i = \frac{\mathbf{d}_i \bullet \mathbf{b}}{\| \mathbf{d}_i \| \| \mathbf{r}_i \|} = \frac{\mathbf{d}_i \bullet \mathbf{b}}{\| \mathbf{d}_i \| \| \mathbf{d}_i - (\mathbf{d}_i \bullet \mathbf{b})\mathbf{b} \|}$$

Controlled by Signal to Noise AND coherence

where

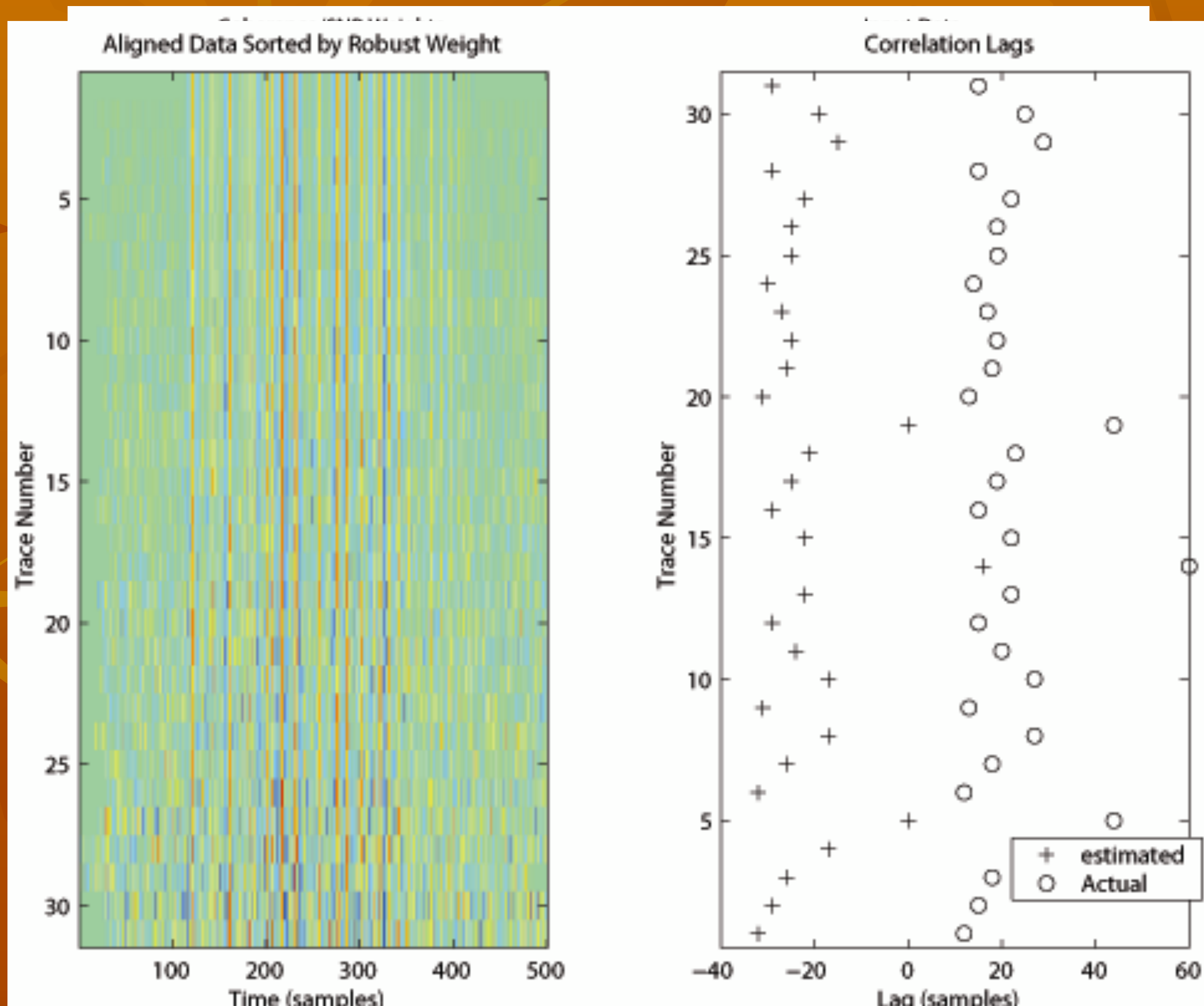
w_i is the robust weight computed for the i^{th} seismogram,

$\mathbf{d}_i$ is the i^{th} seismogram in the ensemble,

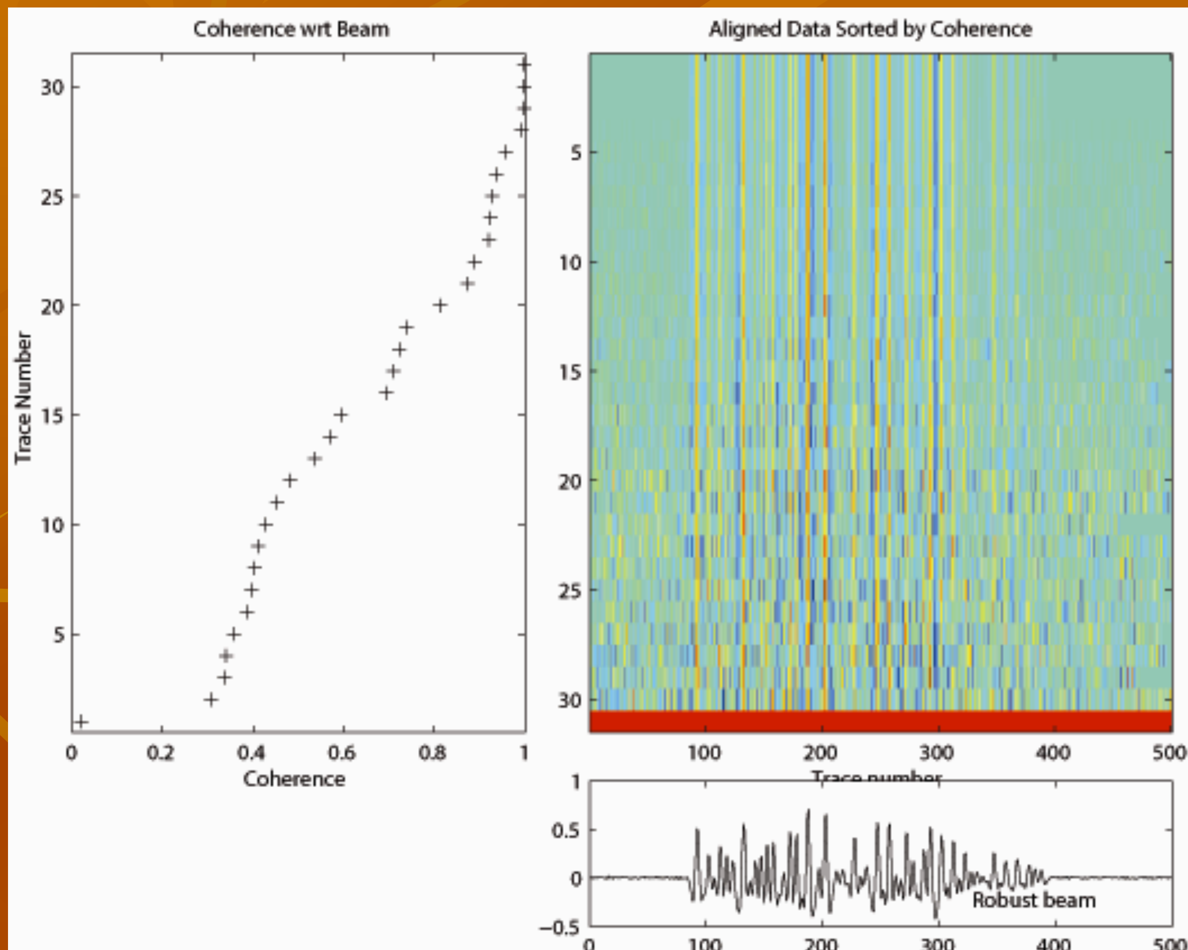
$\mathbf{b}$ is the normalized beam (i.e. $\| \mathbf{b} \| = 1$) and,

$\mathbf{r}_i$ is the residual seismogram.

Synthetic Example1



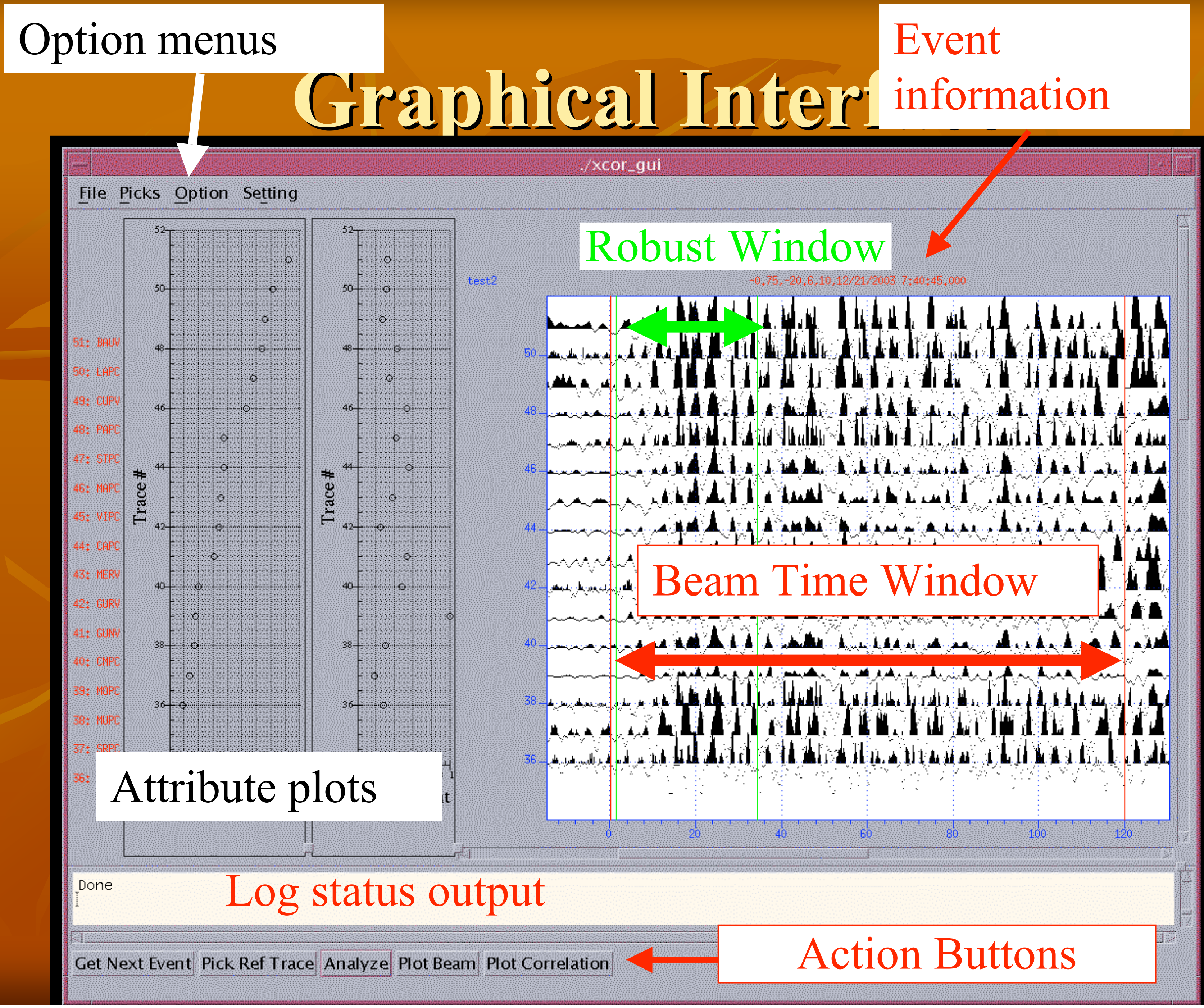
Synthetic Example 2: one dead trace



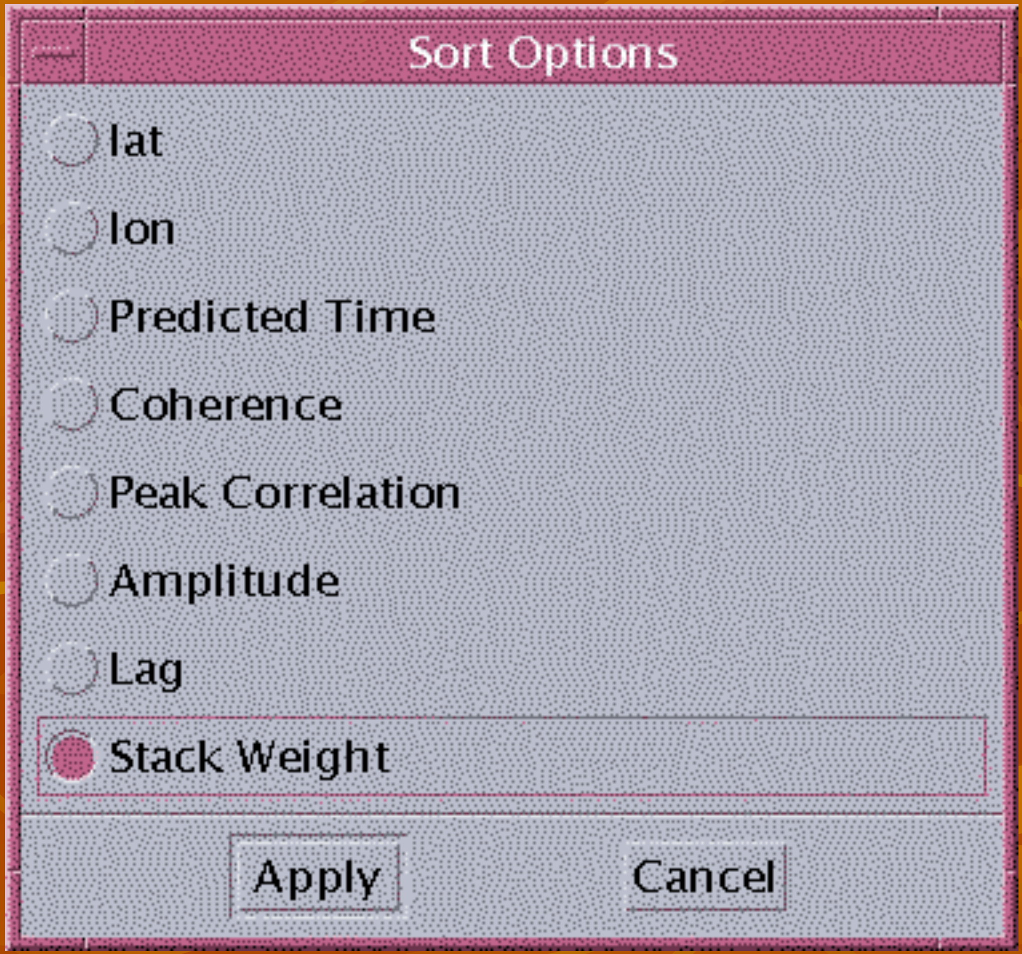
New Implementation

- X Windows (Motif) graphical user interface written by Peng Wang
  - Developed Seismic Plot Widget
  - Trace plot from Seismic Unix (SU)
  - Used open-source tool to do an attribute display
  - Picking abstracted as SeismicPick object
- Analysis code
  - C++ processing object called a "MultichannelCorrelator"
  - Implements algorithm I just described
  - Could be equally applied to source array ensemble, but new program is focused on teleseismic phase picking

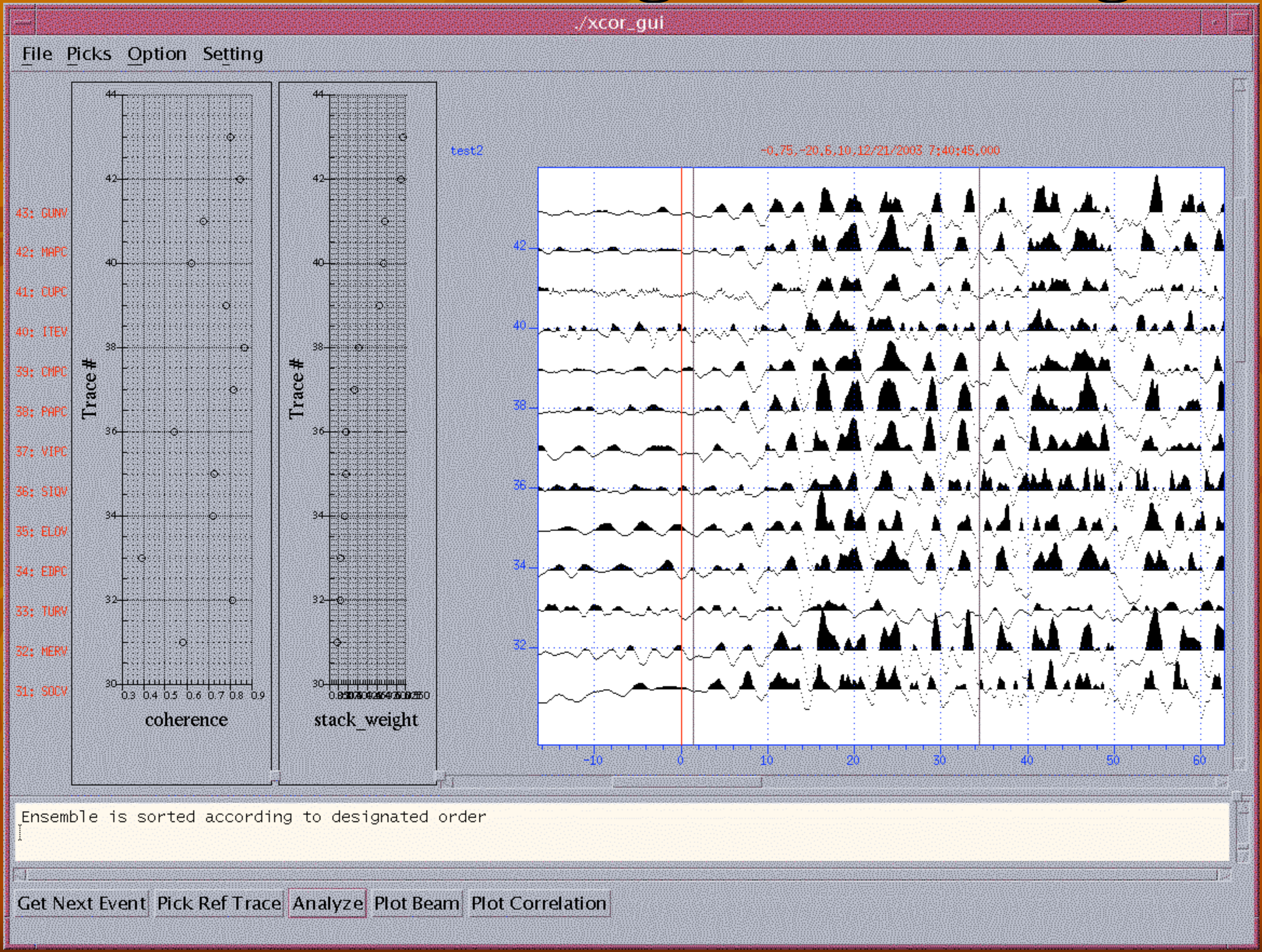
Graphical Interf



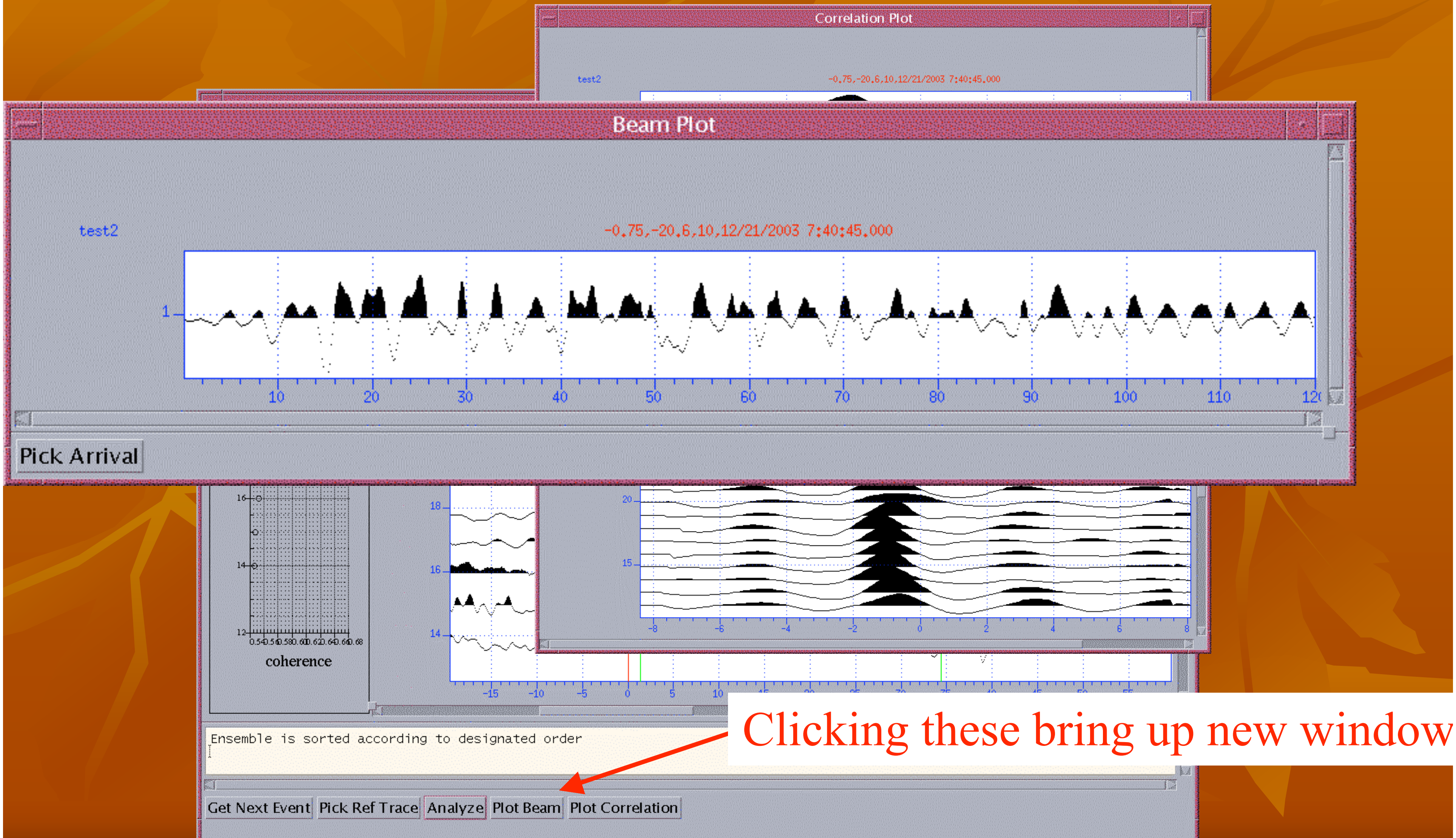
Sort Options



Result of selecting "StackWeight"

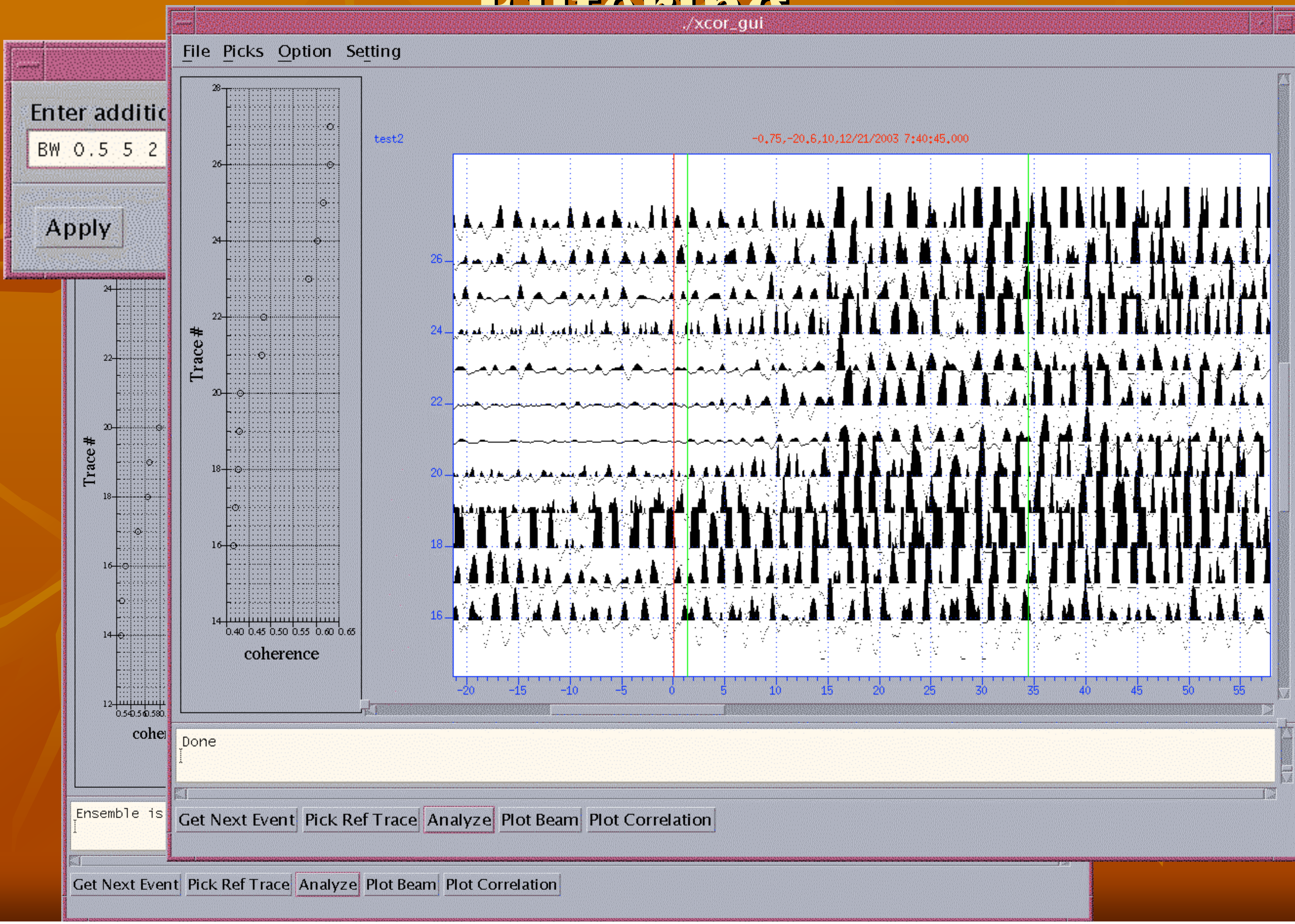


Beam and Correlation plots



Clicking these bring up new window

Filtering



./xcor_gui
File
Picks
Option
Setting
Enter additic
BW 0.5 5 2
Apply
test2
-0.75,-20.6,10,12/21/2003 7:40:45.000
Trace #
coherence
Done
Ensemble is
Get Next Event
Pick Ref Trace
Analyze
Plot Beam
Plot Correlation

Extension to Three-components

Three-component correlations:

$$\mathbf{c}_1 = \mathbf{e} \otimes \mathbf{b}_e$$
$$\mathbf{c}_2 = \mathbf{n} \otimes \mathbf{b}_n$$
$$\mathbf{c}_3 = \mathbf{v} \otimes \mathbf{b}_v$$

Combined to give vector correlation:

$$\| \mathbf{c}(\tau) \| = | \mathbf{c}_1 | + | \mathbf{c}_2 | + | \mathbf{c}_3 |$$

This is a generalization of complex form:

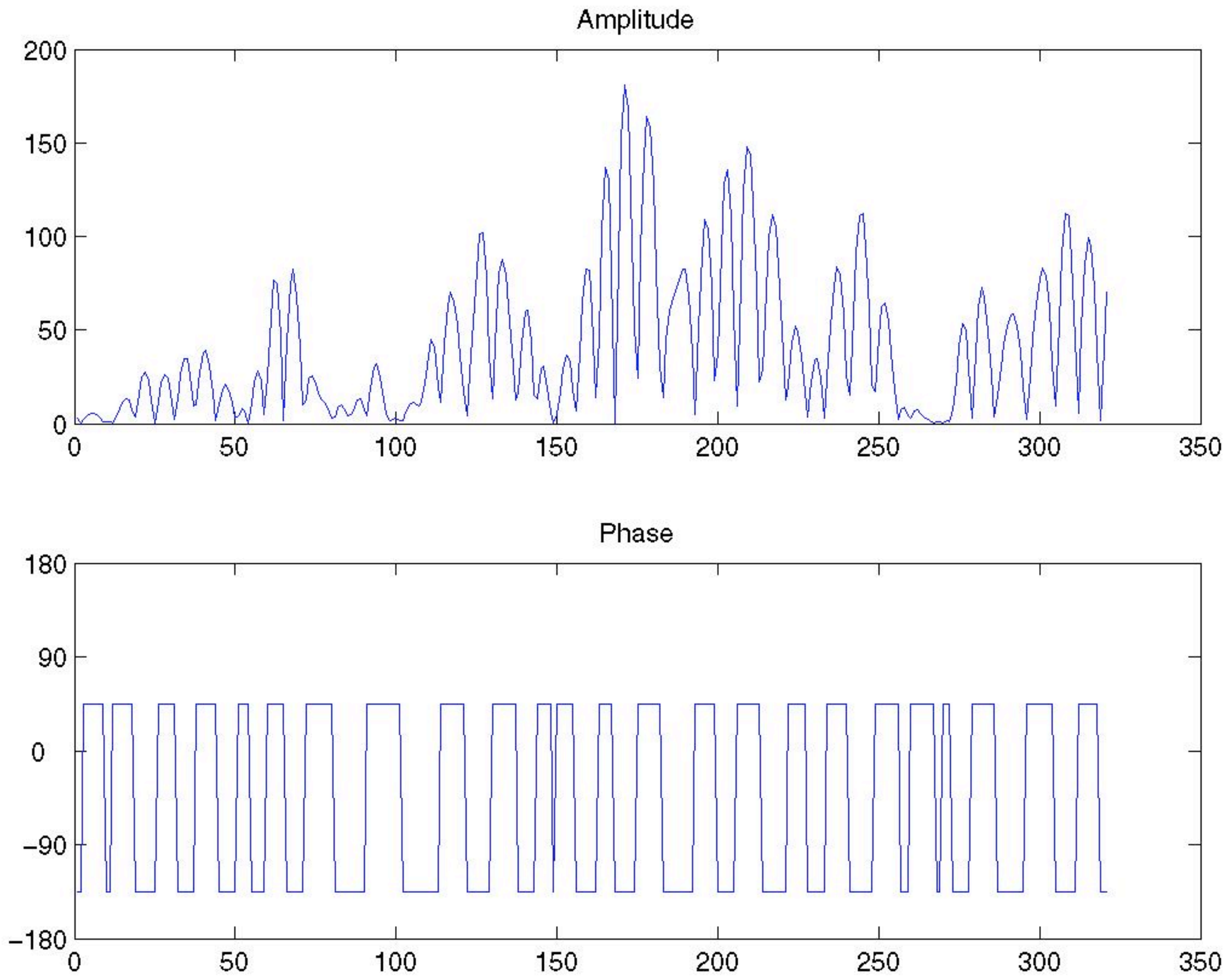
$$\mathbf{z}(t) = \mathbf{e}(t) + i\mathbf{n}(t)$$

where the complex cross-correlation function is

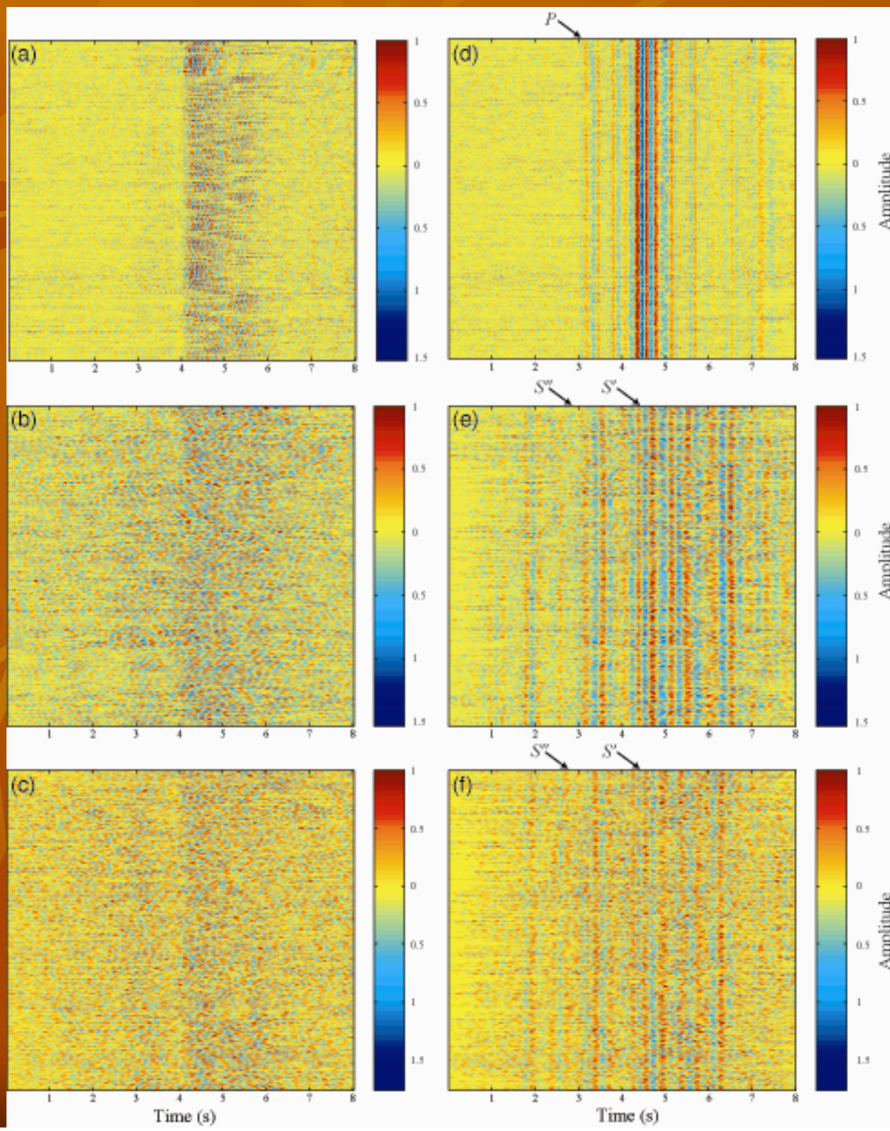
$$\mathbf{c}(\tau) = \mathbf{z} \otimes \mathbf{b}_z$$

Both amplitude an phase of $\mathbf{c}(\tau)$ are potentially useful

Example: Eagar (2005)



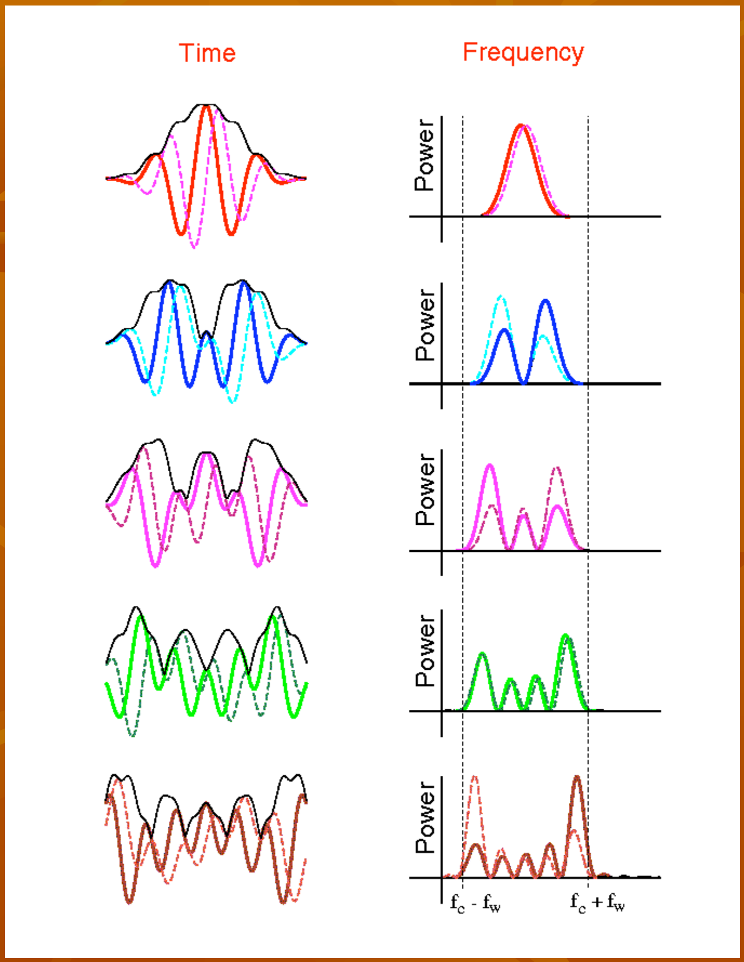
Application to source array: (Eagar, 2005)

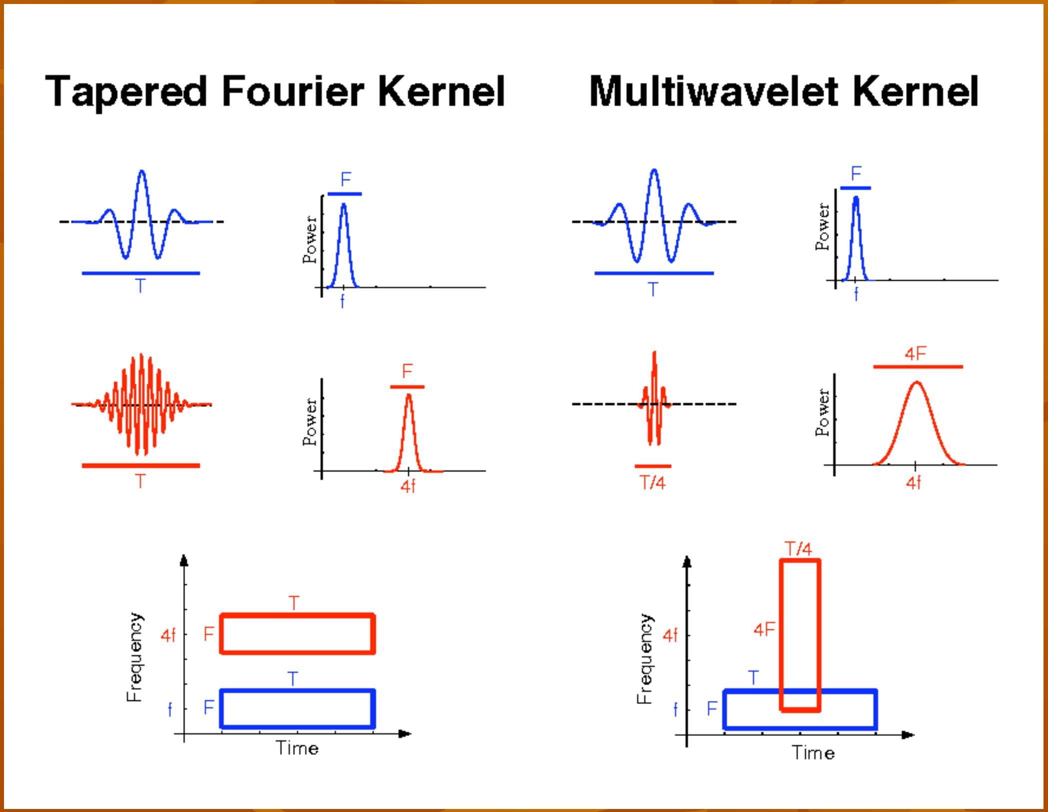


Vertical – robust single Channel algorithm

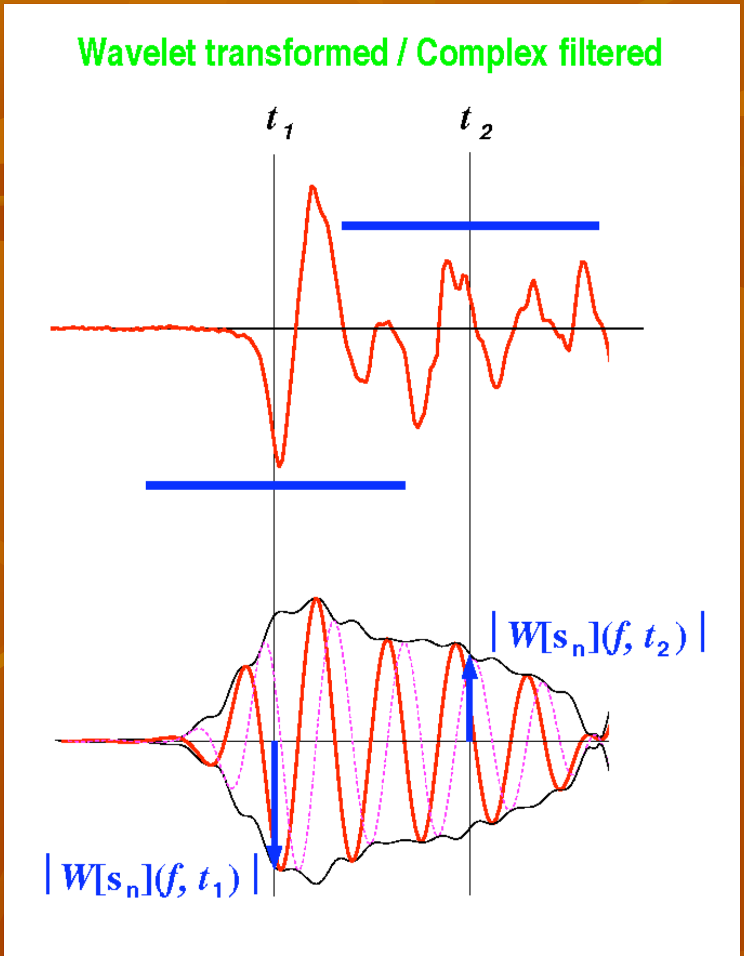
EW and NS – complex correlation algorithm

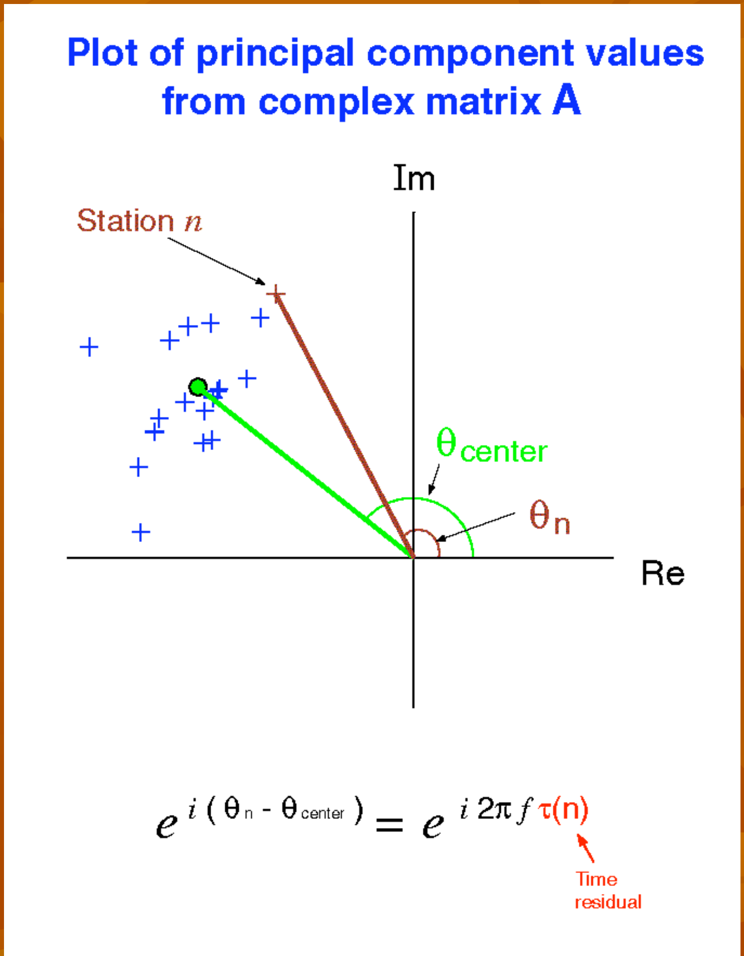
Multiwavelets



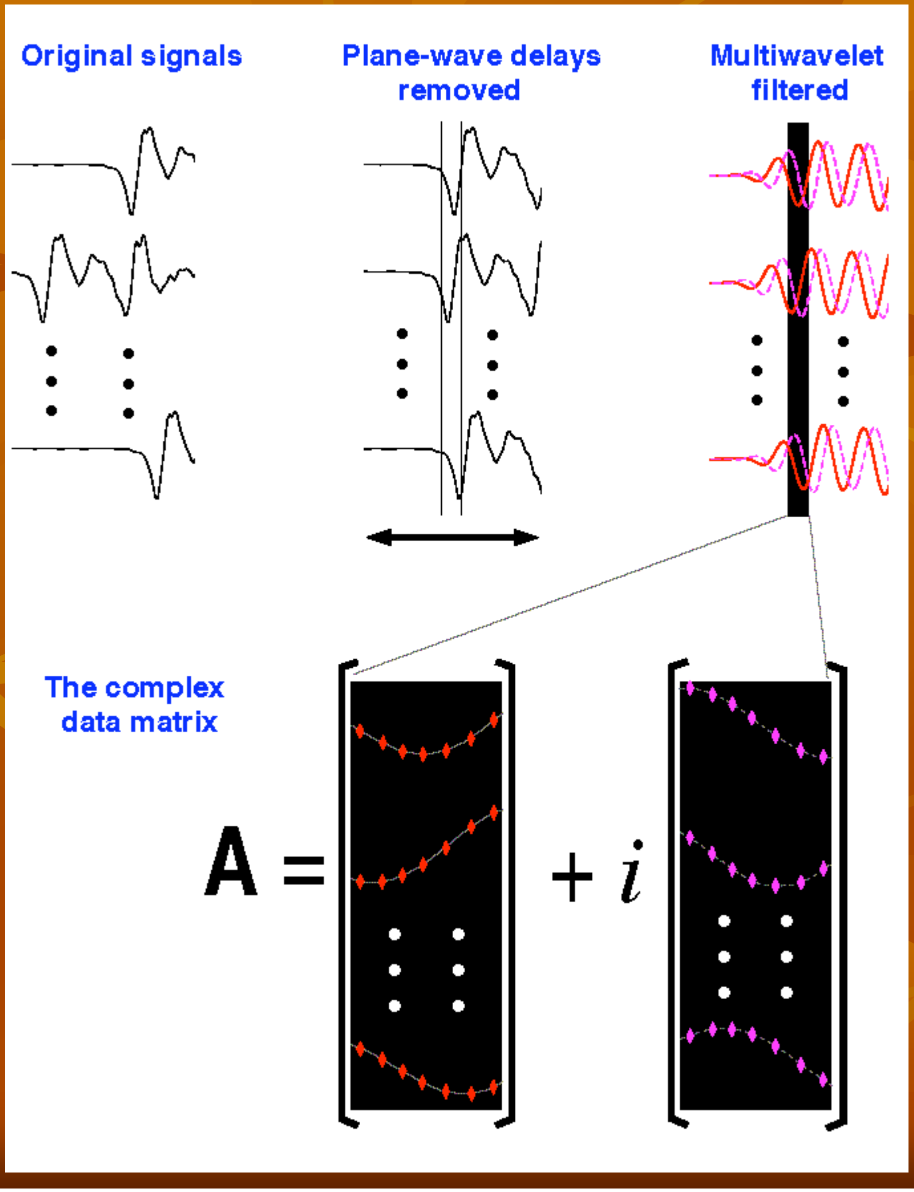


Advantage 1: subsample timing by phase measurement



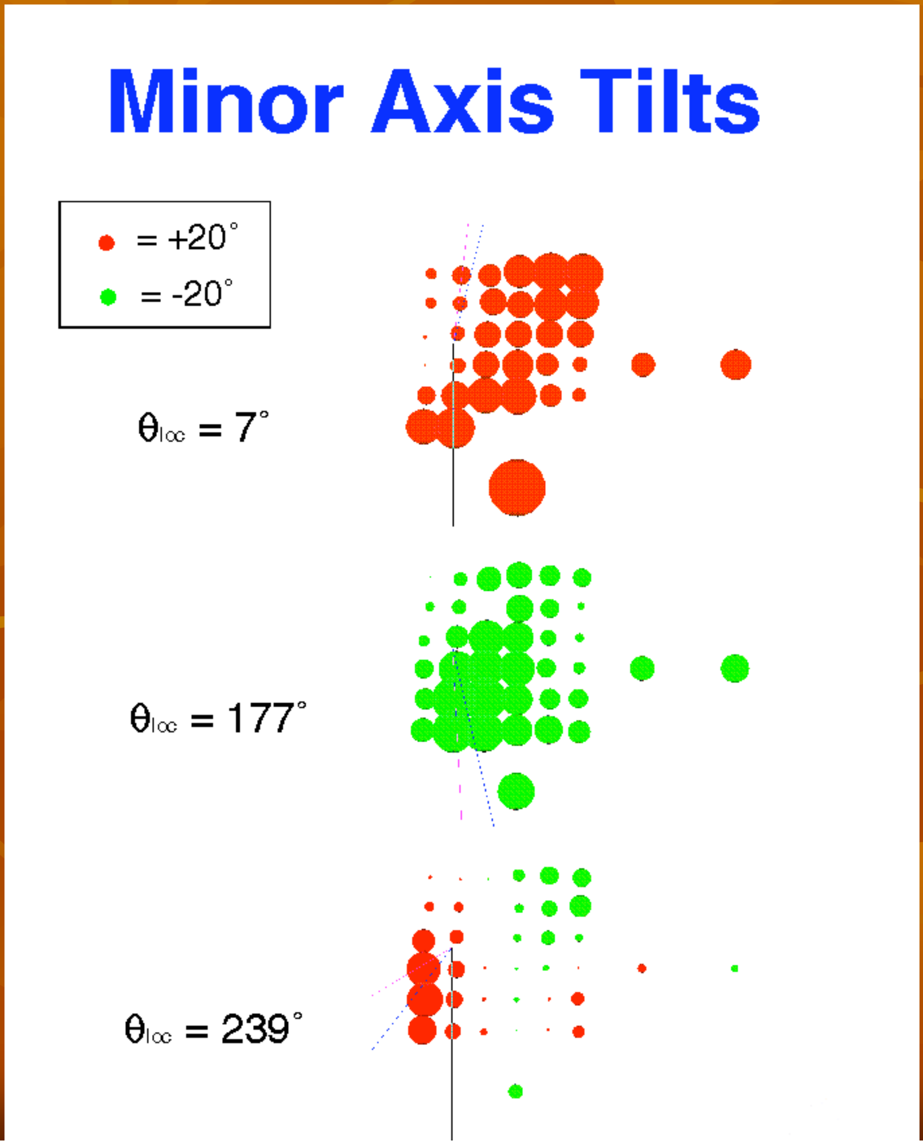


Multiwavelet Array Processing



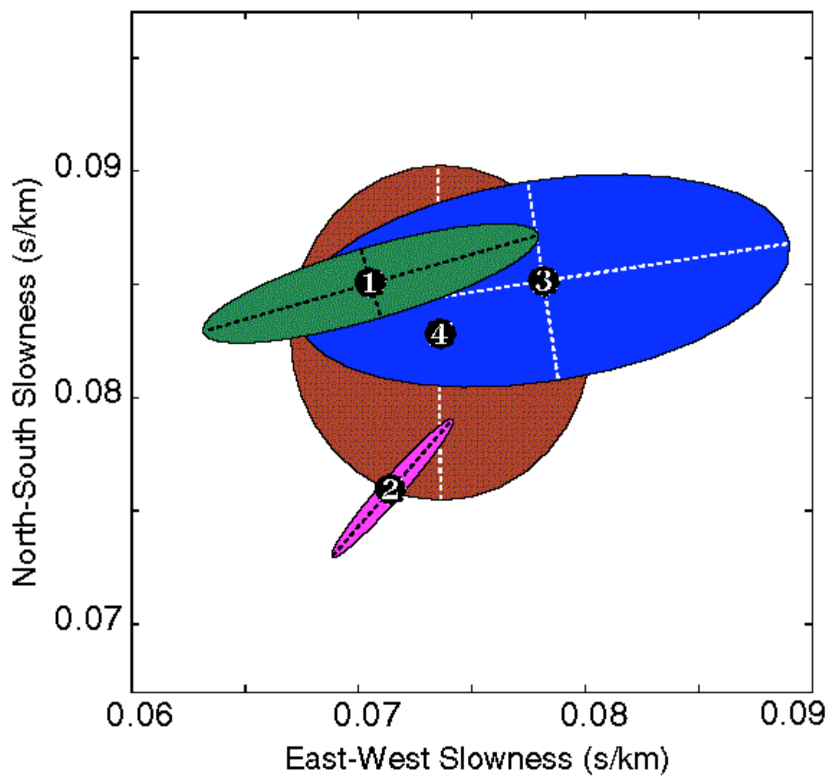
Bear and Pavlis (1999)

Advantage 2: Simultaneous particle motion estimation



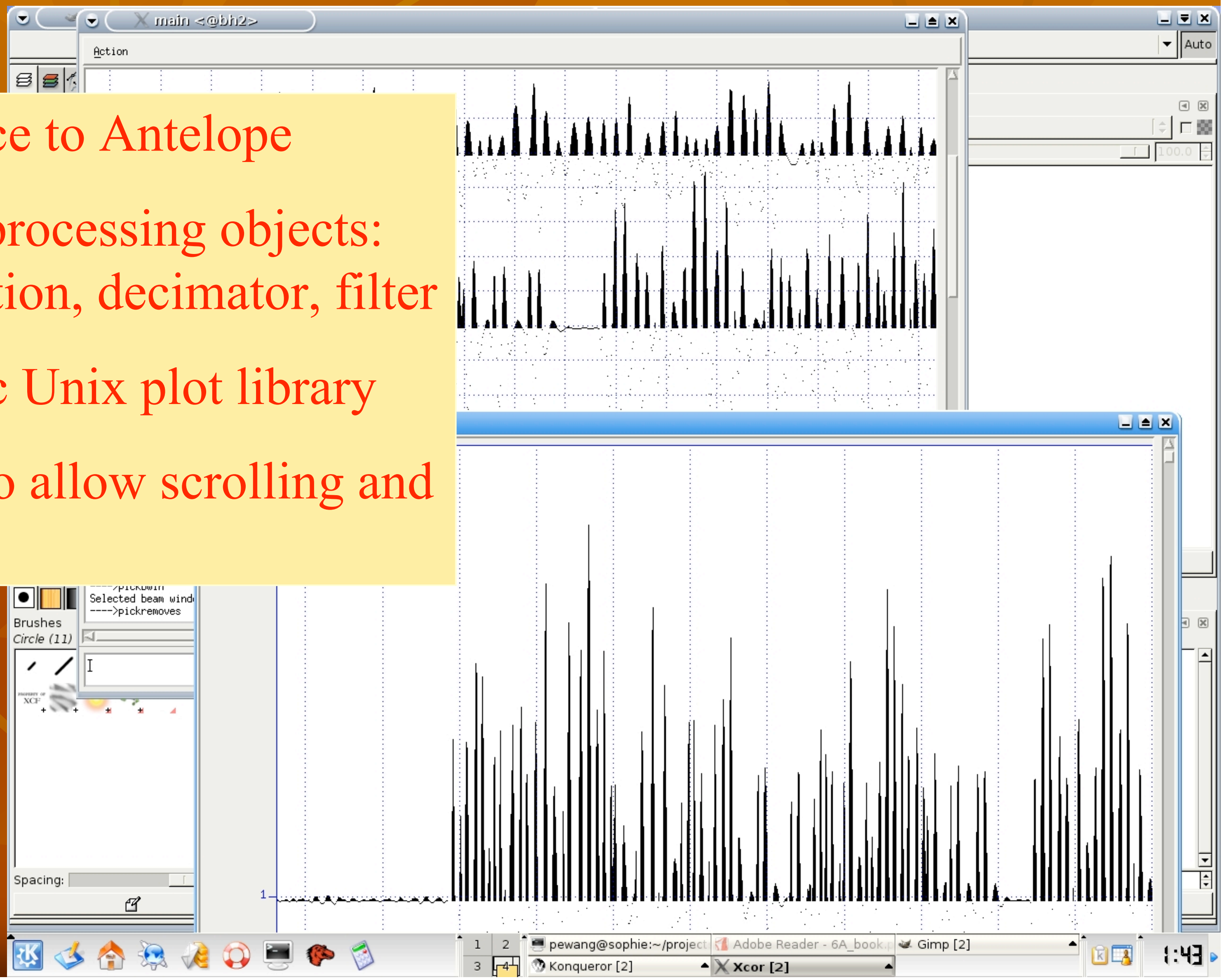
Bear et al. (1999)

Advantage 3: Nonparametric Error Estimates



Implementation

- C++ interface to Antelope
- Interface to processing objects: stack, correlation, decimator, filter
- Uses Seismic Unix plot library
- Uses Motif to allow scrolling and picking



Conclusions

- Beam correlation will always yield superior results to pairwise correlation
- Robust method
  - Robust stack using SNR/coherence-based loss function
  - Stable in presence of bad traces
  - Performs well in variable noise conditions
  - Iterative loop with beam correlation
- Three-component processing
  - Robust method penalizing each component separately
  - Complex method for horizontals only useful for orientation problems
  - Full 3C method
- Multiwavelet processing
  - Simultaneously measure slowness vector, lags, and polarization in multiple frequency bands
  - Only method known that can produce objective error estimates of above
- Code in C/C++ available at http://www.indiana.edu/~aug (Contributed Software link)