Array Processing of Teleseismic Body Wave Phases Recorded by the Transportable Array

Gary L. Pavlis, Dept. of Geol. Sci., Indiana University, Bloomington, IN (pavlis@indiana.edu)
Frank Vernon, IGPP, Scripps Inst. of Oceanography, Univ. of Calif. San Diego, La Jolla, CA (flvernon@ucsd.edu)

Questions we addressed:

* How can we use the TA for coherent wavefield processing?
* What are the limits of coherent processing?
* How to adapt standard methods?
* What phases can be analyzed this way?

Issues:

Standard plane wave methods used in array processing need to be adapted to account for two fundamental issues with a broadband array the scale of the TA:

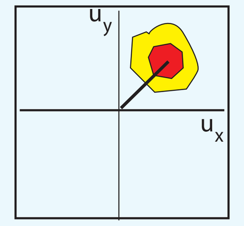
1. Alignment: we cannot use the conventional plane wave approximation due to scale and large statics problems.
2. Data volume: the data volume is so large we need ways to automatically handle noisy and bad stations

Alignment: Part 1

Conventional array processing like that used in nuclear monitoring focuses on detection and enhancement of small signals with marginal signal-to-noise conditions. The standard method is to assume a grid of possible plane wave slowness vectors and stack the array to produce a figure like this

The problem with this approach for the TA is:

1. plane wave approximation is a poor one
2. upper mantle structure cause "static" shifts that make the problem worse.

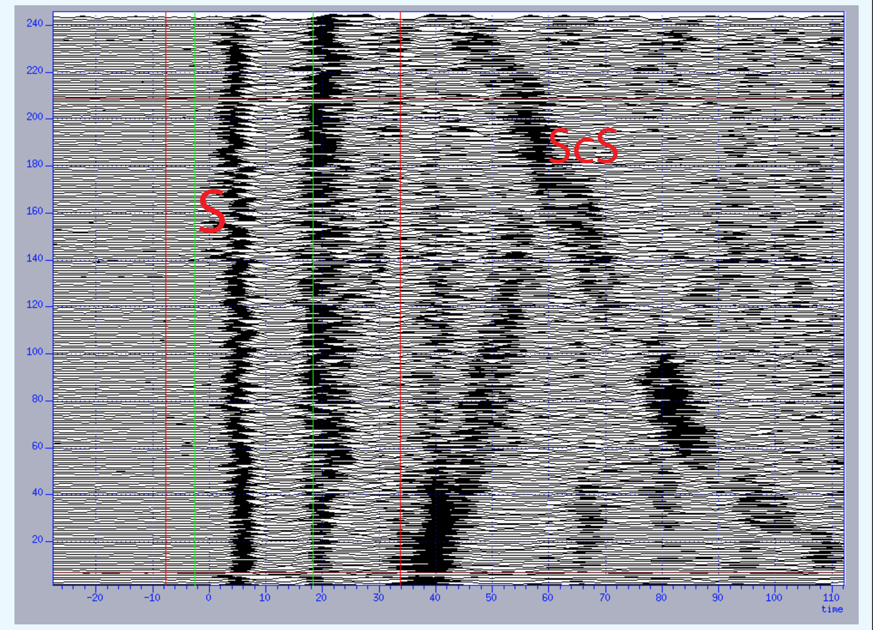


Standard slowness analysis finds best fit plane wave that maximizes stack semblance

Alignment: Part 2

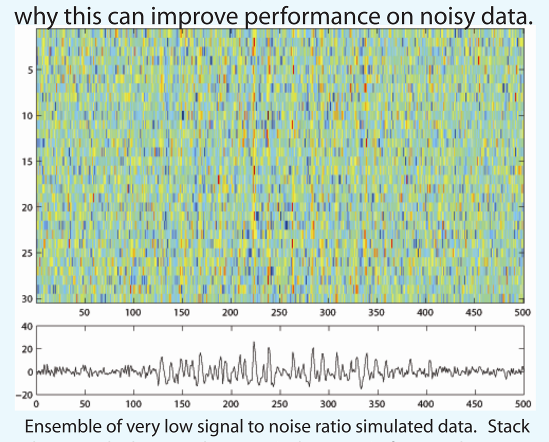
The key to broadband array processing is a change of objectives. For a facility like the Transportable Array we choose to drop the objective of finding small events buried in noise and focus on the problem of enhancing signals from known events. In the process we produce useful data in it's own right: residuals that can be used for seismic tomography.

Our procedure assumes immediately that an estimate of the hypocenter of any event is know. We then compute travel times from a standard earth mode to correct for the first order movout across the array. Below is an example for the S phase from a shallow event in South America. The zero line in this display is the predicted arrival time. Note the residual misalignment.

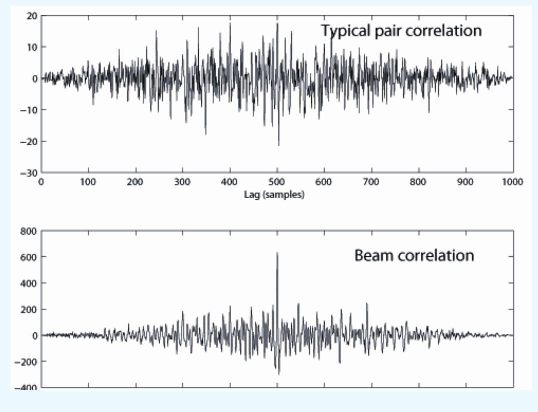


Alignment: Part 3

Previous efforts have mostly utilized pairwise cross-correlation (all pairs are correlated and sorted out with a least squares algorithm). We instead use a correlation with an array beam. This example shows why this can improve performance on noisy data.



Ensemble of very low signal to noise ratio simulated data. Stack shown at the bottom shows typical array gain for a stack.



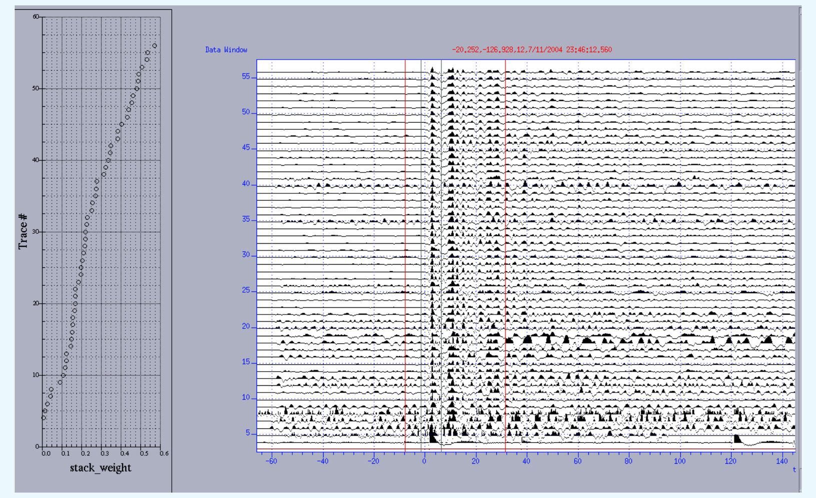
Comparison of typical pairwise cross-correlation with correlation by the array stack for this example. We find we can align lower snr data with an array correlator than pairwise correlation.

Handling Large Arrays: A lesson in the use of robust estimators

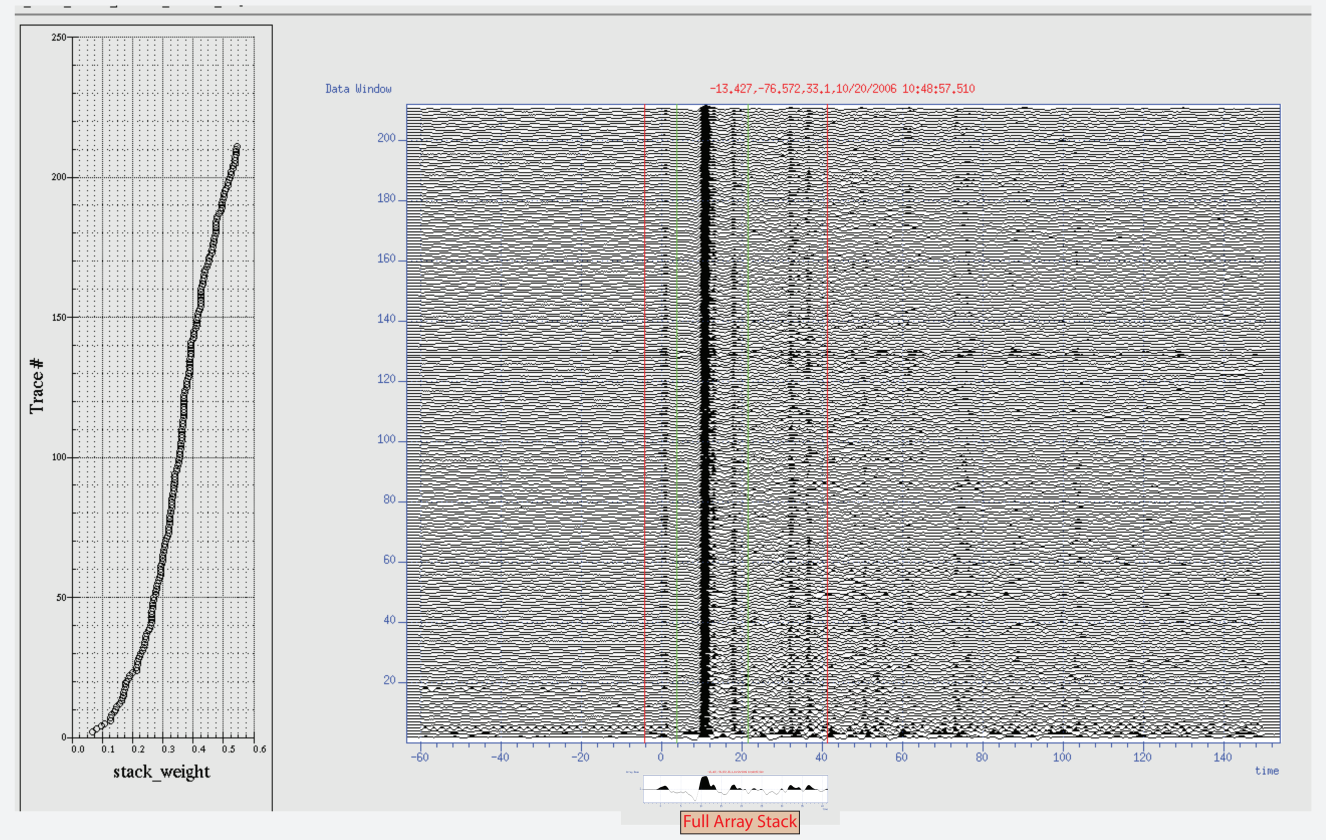
We have developed a nonlinear stacking algorithm to address the issue of array processing TA data. We use a robust stacking algorithm in combination with cross-correlation. The basic algorithm is the following:

1) Read data and align by predicted arrival time
2) Select processing time gates
3) Select trace to use as starting estimate of the beam b(t)
4) do
   i) Align data by correlation with current b(t)
   ii) if(first pass)
      b(t)=median stack
    else
      b(t)=robust weighted stack
5) while (computed correlation lags change)

Below is an example showing variable snr data after processing. These data are sorted by the computed robust weight in the final stack illustrating how the algorithm separates the wheat from the chaff.

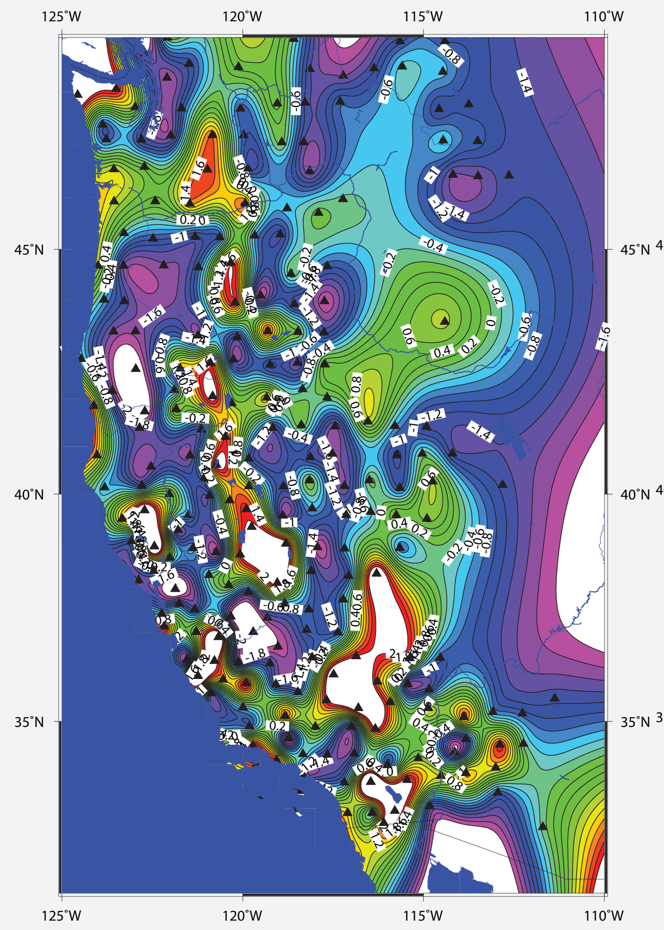


Application 1: Teleseismic P wave residuals and amplitudes

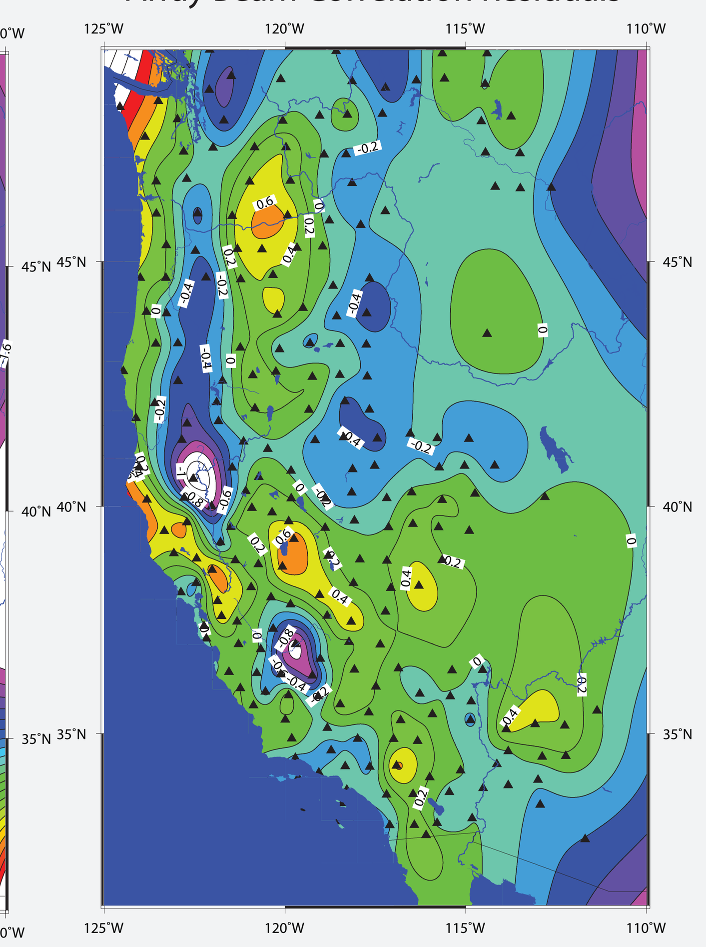


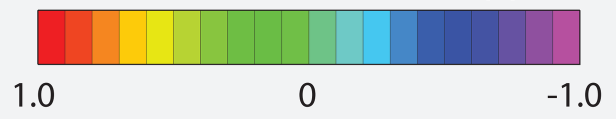
These figures show an example application of our new array processing method to estimate P wave residuals and relative amplitudes. Above is is a gather of vertical component seismograms recorded by the transportable array from an event in South America. Each seismogram was aligned to peak cross correlation with the final array stack shown above. The display shows this procedure does an outstanding job of aligning seismograms and normalizing the amplitudes. On the left is a plot of the stack weight. This shows that for this real data example the weighting function does a sound job of ranking the data in terms of signal-to-noise ratio and penalizing poorer quality traces. Note that in this display the red lines define the time gate used for cross-correlation and the green lines define the time gate for defining the robust weights.

Hand Picked P Residuals



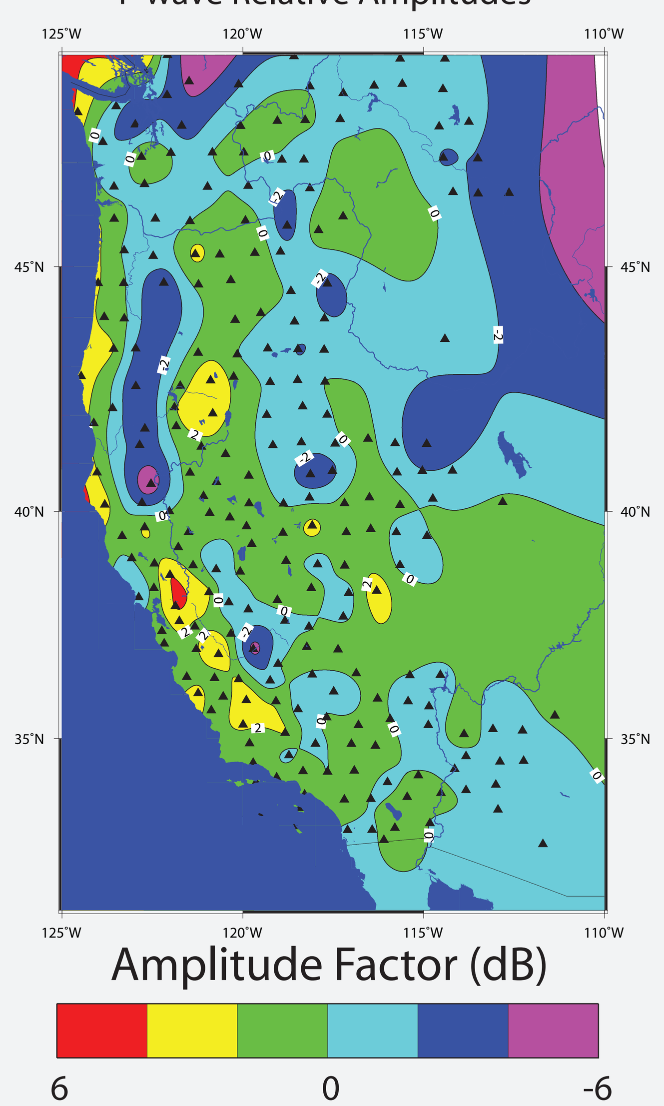
Array Beam Correlation Residuals





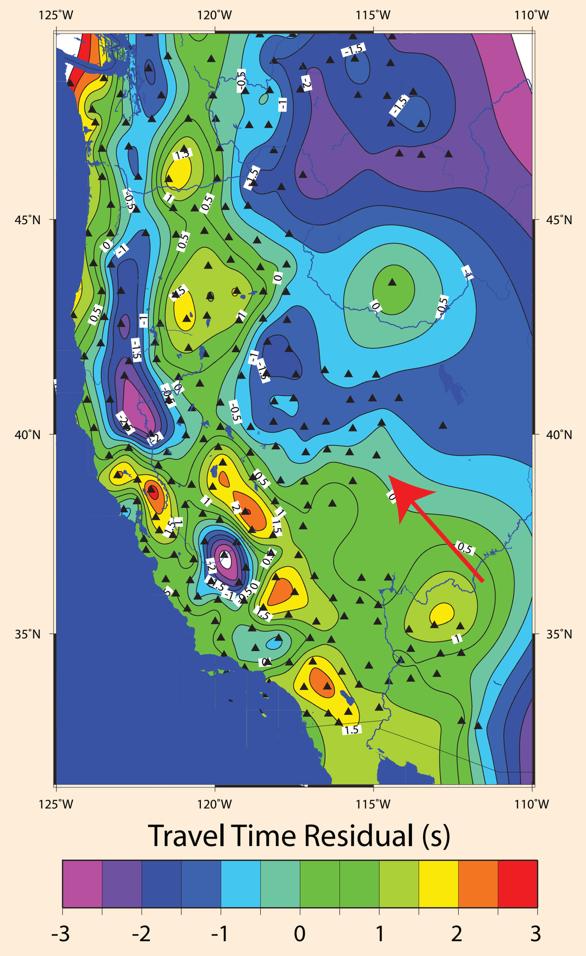
These figures show contour plots of relative residuals derived from the seismic data shown to the left. The left panel shows results of phase picks made at the ANF using conventional interactive (hand picked) graphics. On the right we show the results of the cross-correlation (shifts used to align the seismic display to the left). The correlation data are clearly more internally consistent and show good correlation with expected tectonic features. Note the strongly early arrivals that correlate with subduction zones in the Pacific Northwest.

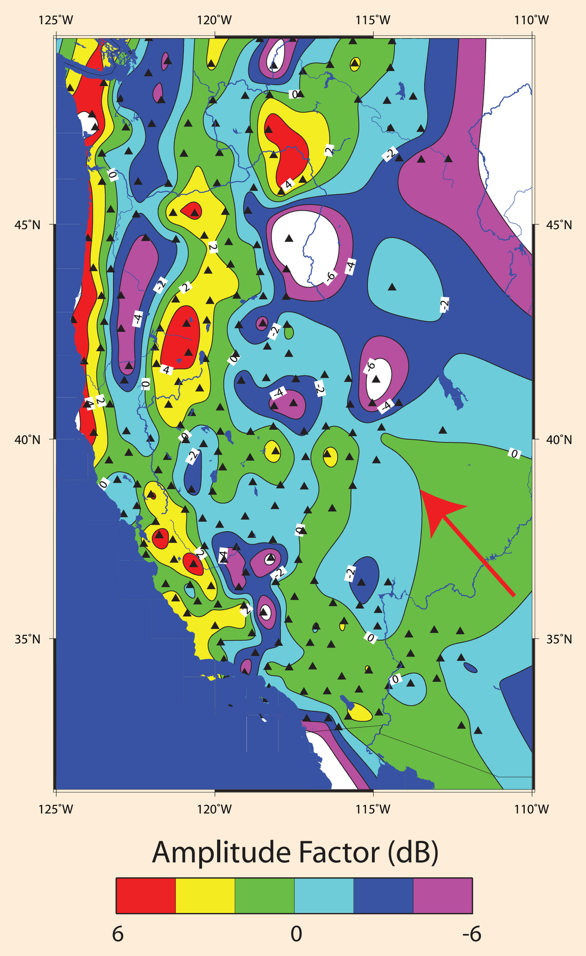
P wave Relative Amplitudes



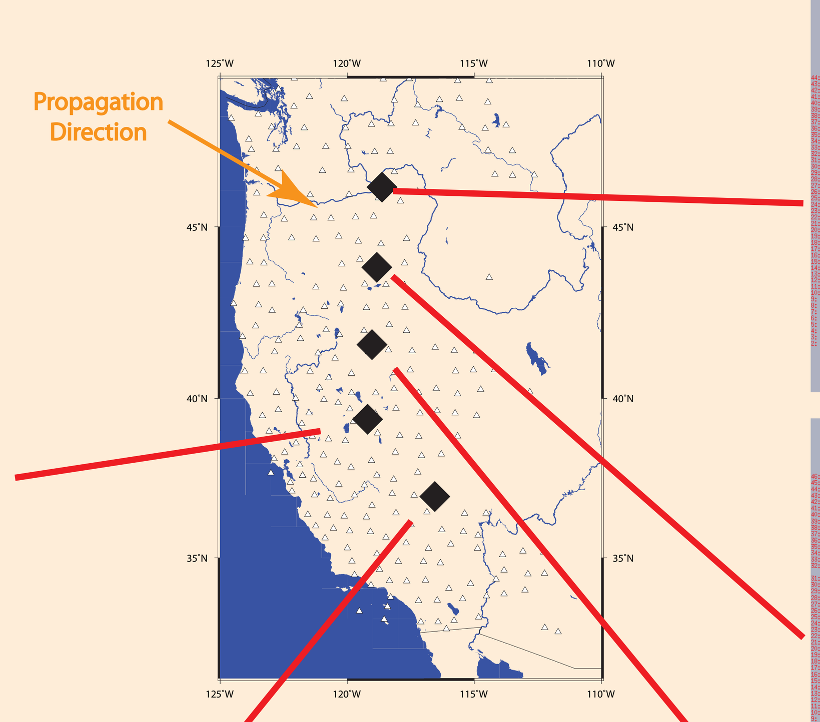
Relative amplitude factors for P waves computed from the seismograms at the left. Amplitude are computed by using a dot product between the array beam and the aligned signal on the time gate defined by the red lines. Note the strong correlation between amplitudes and residuals.

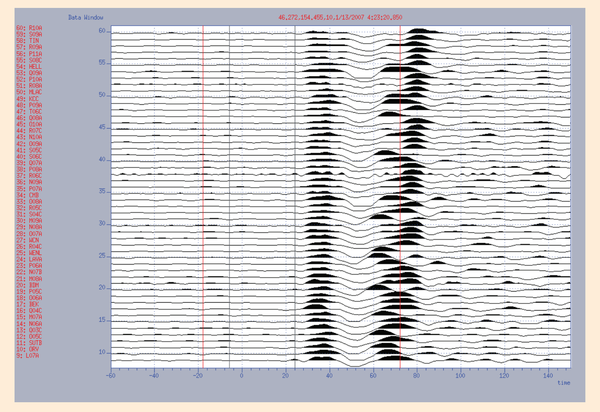
Application 2: Teleseismic S phase processing

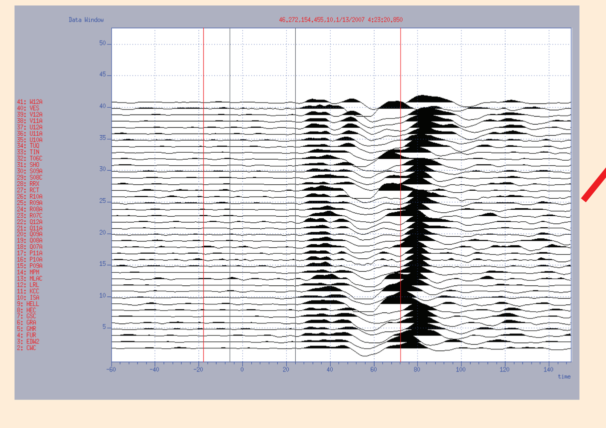




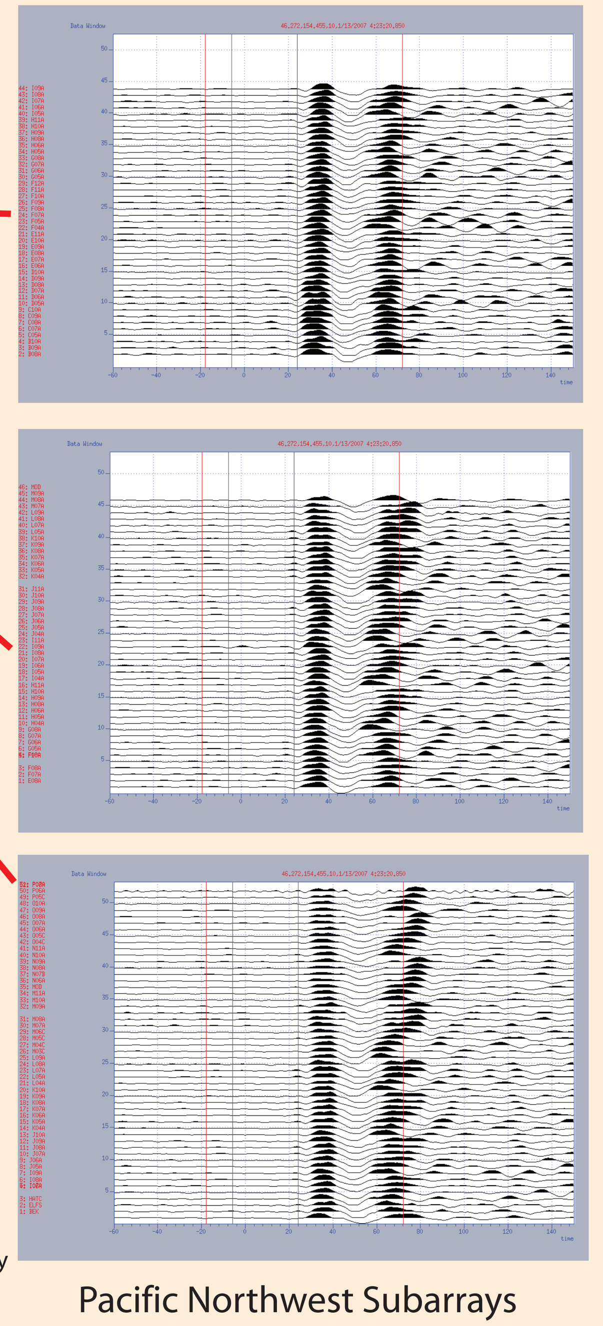
Here we show results processing the S phase for the same event for which P wave data were analyzed in the panel to the lower left. The left figure shows S residuals computed by cross-correlation and the right shows the computed amplitude scale factor for S. These results were computed from the transverse component. Note the remarkable correlation in travel time residuals with the P wave results. In contrast the S amplitudes have a similar overall pattern, but the amplitude variations are much larger than for P and show some interesting differences from the P wave results.







California Subarrays



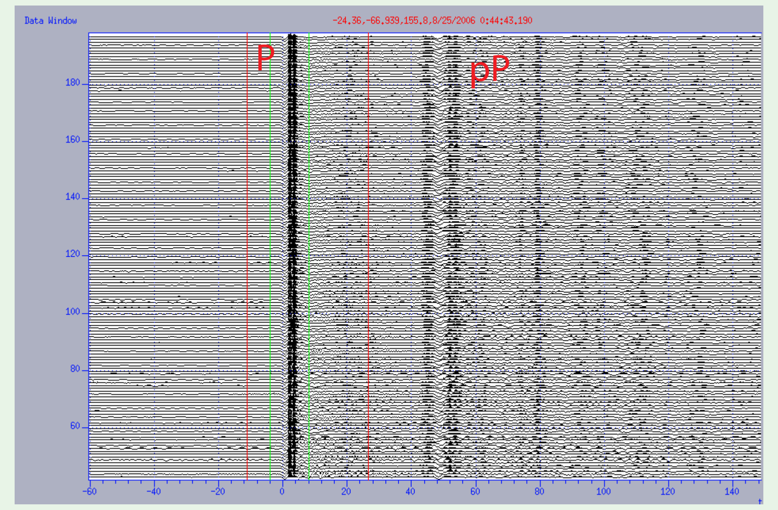
Pacific Northwest Subarrays

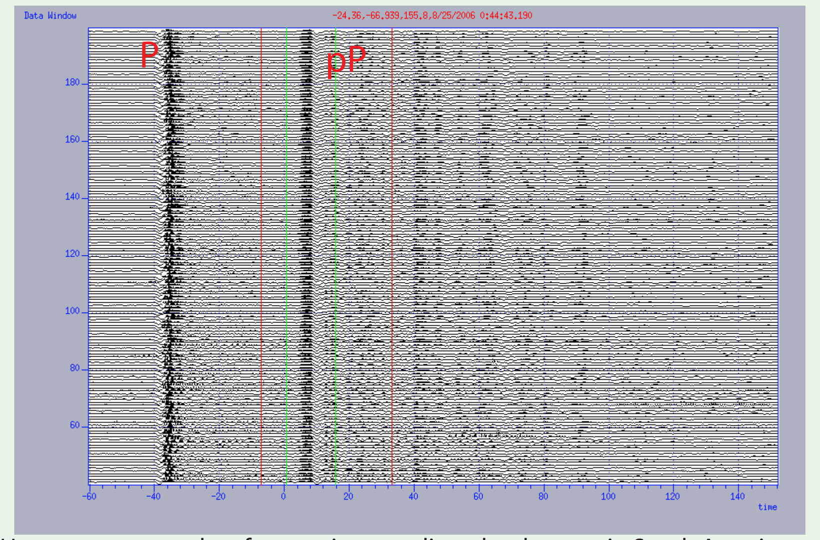
Here we show a tantalizing result from subarray analysis of S waves from the recent (January 13, 2007) Kurile Islands earthquake. Data were grouped in circular subarrays with centers shown above and processed independently. This is a useful strategy when waveforms vary strongly spatially. In this case, however, the waveform variation shows an interesting pattern. The seismograms in each panel are sorted by latitude. Note the row by row pattern of waveform variation in the Pacific Northwest subarrays that are absent from the California subarrays. The moveout of the distortion is consistent with interference by a seconday phase with a west to east moveout. The association with subduction zones in the Pacific Northwest is striking suggesting strongly this is S reflected from the top of the subduction zone.

Application to Other Teleseismic Phases

Here we show examples of array processing with this method for other teleseismic phases.

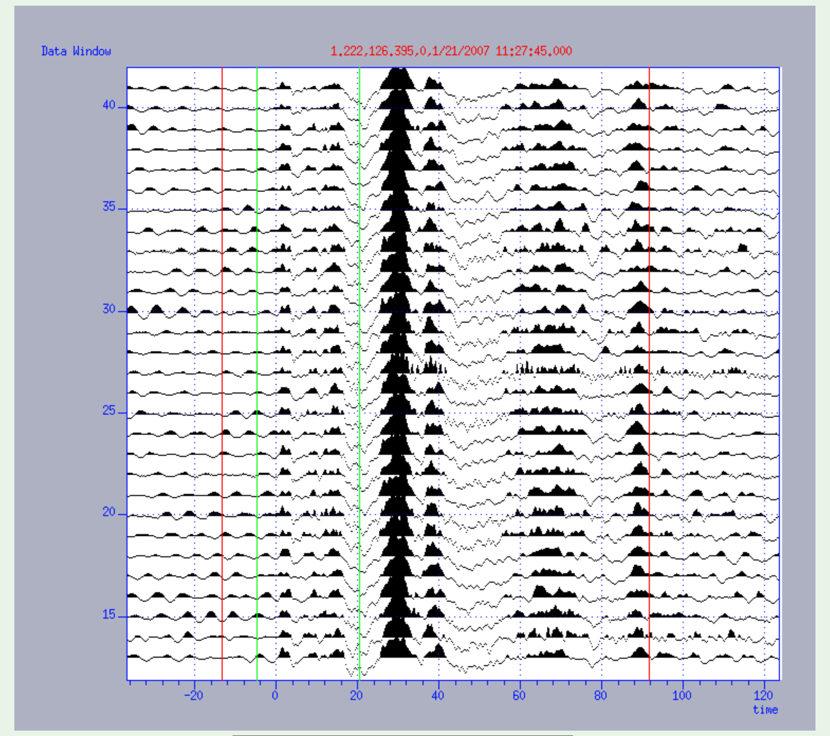
pP phase

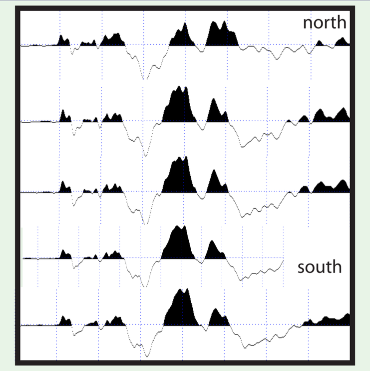




Here we compare data from an intermediate depth event in South America aligned on P (top figure) and pP (bottom figure). As we should expect aligning P or pP produces similar results because P and pP sample nearly identical paths.

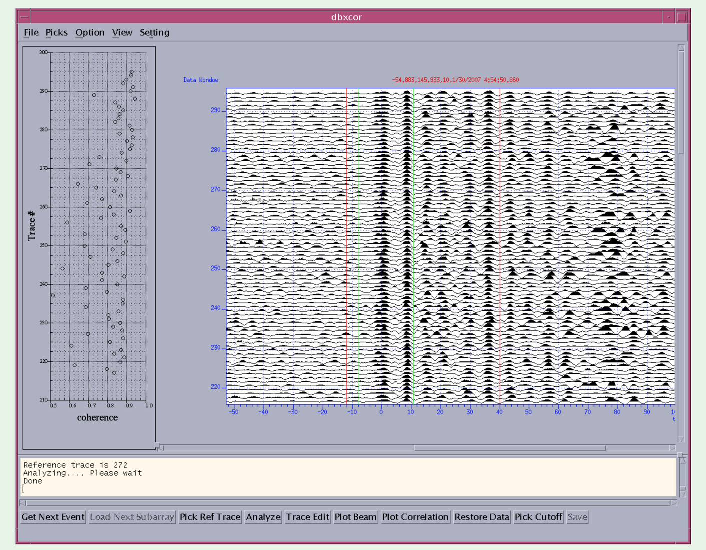
Pdiff

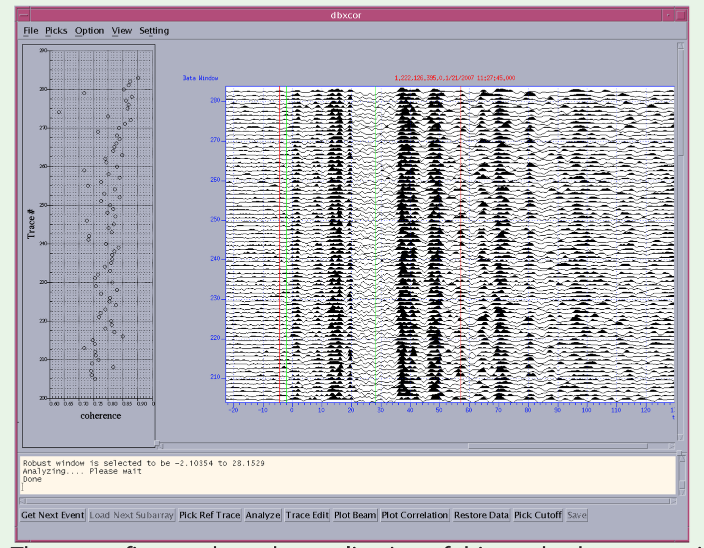




Here we show results from a subarray analysis of P diffracted from an event in Indonesia. The seismograms shown are from the northernmost subarray (see map in S wave data section). To the left we plot the beam from the five subarrays. The array spans a distance range of 101 to 118 degrees with the southernmost subarray being the most distant. The array beams are remarkably similar, but there does appear to be the expected loss of higher frequencies from north to south.

PP





These two figures show the application of this method to processing of PP phases from two events located beyond the core shadow. The top event is from New Zealand and the bottom event is the same event analyzed for Pdiff to the left. Alignment works, although the coherence of the stack members is generally lower than for P. Nonetheless this shows promise as a tool to add additional travel time measurements for teleseismic P wave tomography.

Summary

* Initial application of new array processing methodology to USArray data
* The entire array can be stacked for teleseismic P and S
* Stacking seems feasible for phases like PP, SS, PcP but more experience is needed to understand limits
* Subarrays are needed when array spans phase crossovers (e.g. S-SKS)
* Interesting observation of S suggesting reflection from top of subduction zone
* Pdiff result hints at potential applications to core-mantle boundary.