ATTEMPTS TO ENHANCE ARRAY DETECTION CAPABILITY: A SEARCH FOR SYSTEMATIC ARRAY RESIDUALS

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ABSTRACT

We investigate the performance of array beams formed using the observed slowness and azimuth of arrival for large, well located events. For this study, we use event locations from the United States Geological Survey (USGS) Earthquake Data Reports (EDR). The deviations of the observed azimuths of arrival from the predicted azimuths of arrival based on a suite of events are used to estimate correction surfaces to be applied for improved azimuth estimation for phase association and event location. We have begun an exploratory effort to study the residual waveforms for seismic array elements. The individual seismic traces from array elements are shifted to a common geographic reference point using delays based on the observed slowness and azimuth of arrival, and then averaged to form the array beam. We then compute the residual seismograms by subtracting the beam from the time shifted traces for each element and study the residual traces for systematic effects. Any systematic effects in the residuals point to deviations from the assumed ideal array behavior. If we can identify and correct for systematic array deviations, we hope to improve array detection capability, as well as array estimates of azimuth and slowness.

OBJECTIVE

We evaluate and attempt to improve the performance of array beams formed using the observed slowness and azimuth of arrival for large, well located events. The deviations of the observed azimuths of arrival from the predicted azimuths of arrival based on a suite of events will be used to estimate correction surfaces to be applied for improved azimuth estimation for phase association and event location. Similarly, deviations in predicted and observed slowness of phases across the array are tabulated for correction surfaces. In addition to these efforts aimed at location and association, we are also closely examining the residuals of the beam forming process looking for systematic errors. Any systematic errors that can be explained and corrected (such as static delays or other variations from a simple plane wave propagation across the array) may improve the performance of the array for all events. If we can improve the array beam or FK performance for large well located events, we hope to lower the detection threshold for smaller events where the array enhancement of the signal to noise will be far more important.

RESEARCH ACCOMPLISHED

Seismic arrays have a long history in seismic verification and monitoring (Blandford 1974, Capon 1969, Capon 1970, Capon et. al. 1969, Capon et. al. 1968, Capon et. al. 1969, Green et. al. 1966, Mykkeltveit et. al. 1990). Techniques for processing array data are based on the assumption that the seismic wave field propagates as a plane wave across the array, allowing a simple prediction of the time of arrival of a wave front at each station for a given azimuth of arrival and phase velocity of propagation (or the reciprocal of phase velocity typically called slowness). For body waves, non-dispersive propagation is also assumed, so a seismic phase propagates without dispersive distortion. For typical arrays, this means the seismic phase is virtually unchanged as it propagates from element to element. In addition, arrays are designed with an element spacing that tries to preserve the correlation of the signal and exploit a lack of correlation of noise at frequencies of interest so that simple time shifting and summation will cause the signal to add constructively and the decorrelated noise to add destructively, increasing the signal-to-noise ratio (SNR). Deviations from the assumed model will cause degradation of performance of the array beam forming and estimation of azimuth of arrival and slowness. We are conducting an exploratory effort to evaluate seismic arrays for systematic deviations from the assumed model and are searching for possible simple corrections that may be applied to improve array performance.

Our initial efforts are applied to the Makanchi array, which is expected to be typical of future monitoring arrays. We have acquired data for the Makanchi array in Kazakhstan and extracted waveforms for events listed in the USGS

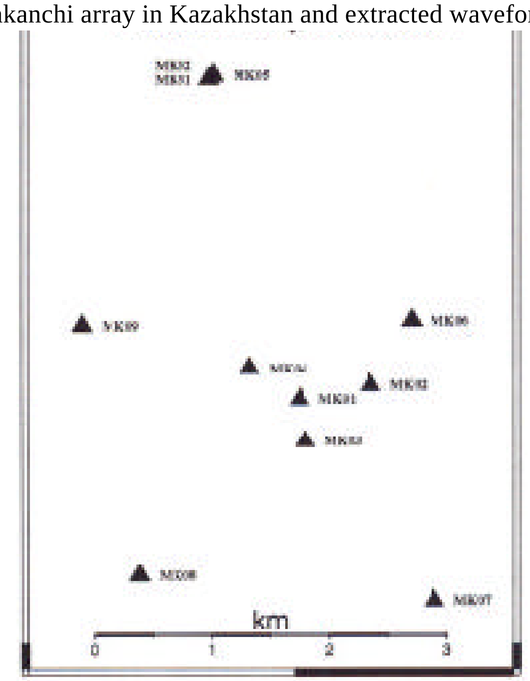

Figure 1. Map of Makanchi Array showing array geometry and scale.

EDR seismic event catalog.We have chosen large well located events so that we can expect clear arrivals with good signal to noise. These larger events should produce the best possible results from the array, and we hope any systematic residuals will lead us to correction terms that can be applied for smaller events. For the purpose of illustration in the paper, we are using a single event 361 km from the array at an azimuth of 149 degrees. The event has a USGS body wave magnitude of 4.8 and is recorded with good SNR. It has clear Pn, Pg, and Lg arrivals. We begin with simple linear delay and sum beam forming, evaluating both time domain and frequency domain beam forming. The slowness, or PseudoFK spectrum, based on simple delay and sum beam forming for a two-dimensional (2-D) grid of horizontal slownesses, defines the distribution of beam formed energy as a function of horizontal slowness. Each 2-D slowness point can be interpreted as a slowness and azimuth of arrival, and we evaluate the region of maximum beamed energy to estimate the slowness and azimuth. We scale the energy of the region vs. slowness for energy less than a simple fraction of the maximum energy to unit volume, and compute the first and second central moments. This gives us a useful estimate of the observed slowness and azimuth of approach as well as an analog to covariance describing the width of the peak and a measure of the uncertainty of the estimates of the arrival.

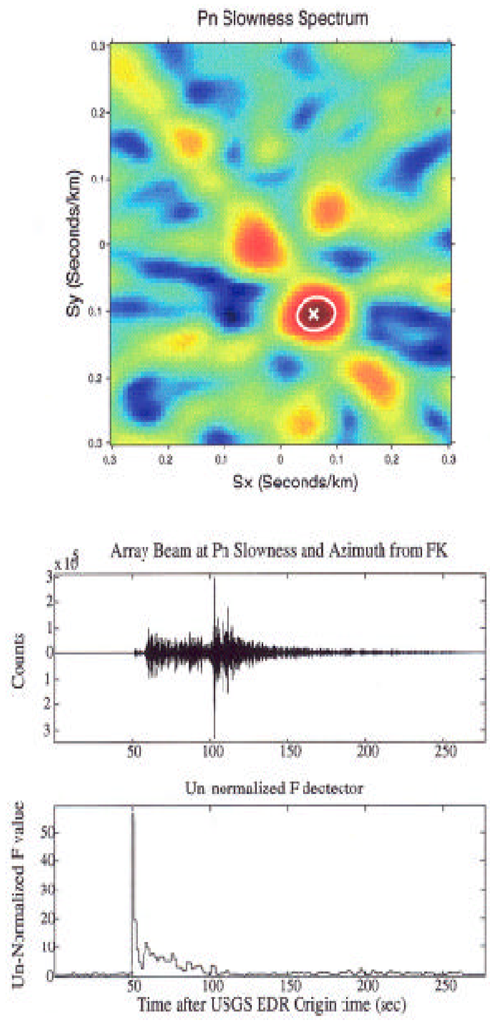

Figure 2. Slowness Spectrum of Pn arrival (at approximately 50 seconds) shown in upper colored panel. The cross represents the peak amplitude measured. The white oval is the 70% of peak amplitude contour bounding the region used to estimate averaged slowness and azimuth as well as confidence bounds. The lower panel shows the entire waveform beamed at the estimated Pn arrival parameters and the unscaled F detector.

The slowness spectrum is computed for a time window that is presumed to contain a seismic phase. The seismic traces for the time window for each of the nine short period vertical array elements have the mean removed and are tapered prior to Fourier transforming. The transforms are then phase shifted with delays that correspond to the travel time predicted by a plane wave propagation across the array to a reference point for a suite of horizontal slownesses in the North-South and East-West directions. At each two dimensional slowness point the energy of the summation of the phase shifted transforms is computed and plotted (Figure 2a) as a surface. The peak of the surface is found, and a region that is greater than 70% of the peak is identified as the main lobe of the array response for the arrival. The volume of the region is normalized to unity, so that it can be treated as a density function. The mean and covariance are computed as a measure of the interpolated peak arrival and an estimate of the elliptical shape and orientation of the peak as a function of slowness. The peak is converted from 2-D slowness to a polar vector of slowness for the arrival and the azimuth of approach to the array. The slowness is useful for phase identification based on the characteristic slowness values of regional phases. The azimuth is useful for associating phases into events and location. The deviations of observed slowness from travel-time model predictions, and azimuth from great circle arc propagation are used along with the estimates of the width of the slowness spectrum peak in slowness and azimuth about the arrival, to build correction surfaces for location.

Once a slowness and azimuth of arrival are estimated, a beam is formed using those parameters. A beam computed by phase shifting in the frequency domain and inverse transforming to the time domain is shown (Figure 2b) along with a trace that is the F detector (Blandford 1974). In the beam forming process, the individual station traces are shifted into the alignment predicted by the estimate based on peak energy of the slowness spectrum, and then averaged in the frequency domain. This frequency domain beam is then subtracted from the shifted station spectra to compute the residual spectra. The beam and residual spectra are all inverse Fourier transformed to the time domain. The F detector is computed by using a sliding 3-sec. window, shifted by 1.5 seconds. The ratio of the energy in the beam is divided by the energy in the residual waveforms, which, when properly normalized, is Blandford's F detector. The F detector grows as the coherent beam grows, and also grows as the energy in the residuals is minimized. In the example, the data are already of ample signal to noise to permit an analyst to pick the arrival. The F detector has been very useful in this study for finding coherent phases, but only when the data are high pass filtered prior to the process of beam forming and computation of the F detector. The coherence of the microseismic noise across the array at frequencies near 0.2 Hz seems to be the most likely problem for the degraded performance of the F detector on raw array data.

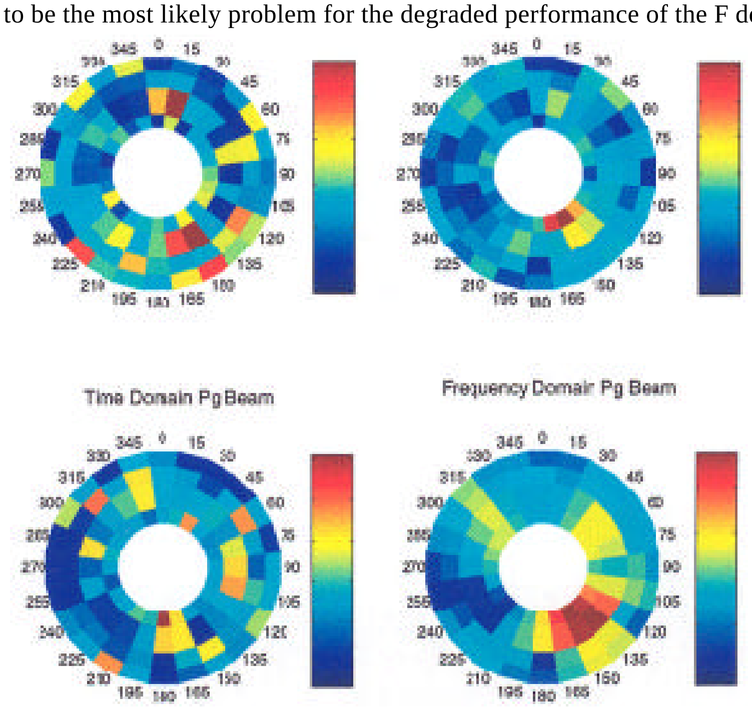

Figure 3. Comparison of time domain beams in the left column and frequency domain beams in the right column for Pn arrivals in the top row and Pg arrival in the bottom row.

Attempts at simple time domain beam forming as used in MatSeis proved to be a failure. The time domain beam forming uses a quantized time shifting process that computed the nearest array index offset to the predicted time shift and retrieves the time domain samples, then averaging as in the spectral technique. No attempt was made to compute the residuals or the F detector. The frequency and time domain beam formers were computed for Pn and Pg arrivals for azimuths in steps of 15 degrees, and the expected slownesses for Pn, Pg, Sn, and Lg starting with Pn as the inner ring and stepping outward one phase at a time. The rose plots are shown in Figure 3. The color bars indicate the energy color coding with the reds largest and the blues smallest. The frequency domain beams show peak energy near the 150 degree azimuth as predicted by the slowness spectrum and show a distribution of energy that falls away smoothly from the peak. The time domain beam former shows a poor distribution of false peaks and erratic energy distribution. We conclude that the time domain beam forming process is not reliable although it may be worth investigating linear interpolation to estimate the time shifted amplitude for the time domain beam forming.

After gaining confidence in the frequency domain beam forming, we started to look for systematic problems in the array residuals with the hope of interpreting any deviations from the plane wave propagation model. We beamed the entire waveform for the event at the estimated Pn slowness and arrival from the slowness spectrum. The results in Figure 4 show a number of features. The top panel shows the entire waveform for the beam and the individual station residual traces show large residuals in the Lg phase compared to the beamed Lg. The beam for Pn arrival parameters is far from the correct slowness for Lg, so the Lg phase is not reinforced by beam forming, and the averaging process then reduces the beamed amplitude of Lg, and the energy is captured by the residuals, which show the poor fit of the Lg beam using Pn arrival parameters. In the lower panel, we show an expanded version of the Pn portion of the beam. Several interesting features are visible. First, the residuals start with low amplitude at the Pn arrival but grow fairly rapidly to become larger than the beam. Second, the amplitudes of the residual tend to stay larger than the beam, which shows a general diminishing amplitude with time. Third, the residuals show what appears to be a slightly higher frequency content than the beam. Fourth, the residuals show a range of amplitudes; some are significantly large and some smaller. This leads us to conclude that only the initial Pn arrival appears coherent across the array, and the rapid growth in the residuals indicates a higher fraction of scattered energy at slightly higher frequencies relative to the Pn arrival. This Pn coda may be a candidate of coda analysis, comparing average of the coda analyses of the individual elements to the coda of the beam. More scrutiny of the residuals is required to determine the effective coherent bandwidth of the signal and what frequency bands are dominated by scattered energy. We also need to try a slowness spectrum analysis of the residuals in an attempt to identify any systematic errors from local heterogeneity or perhaps static delays.

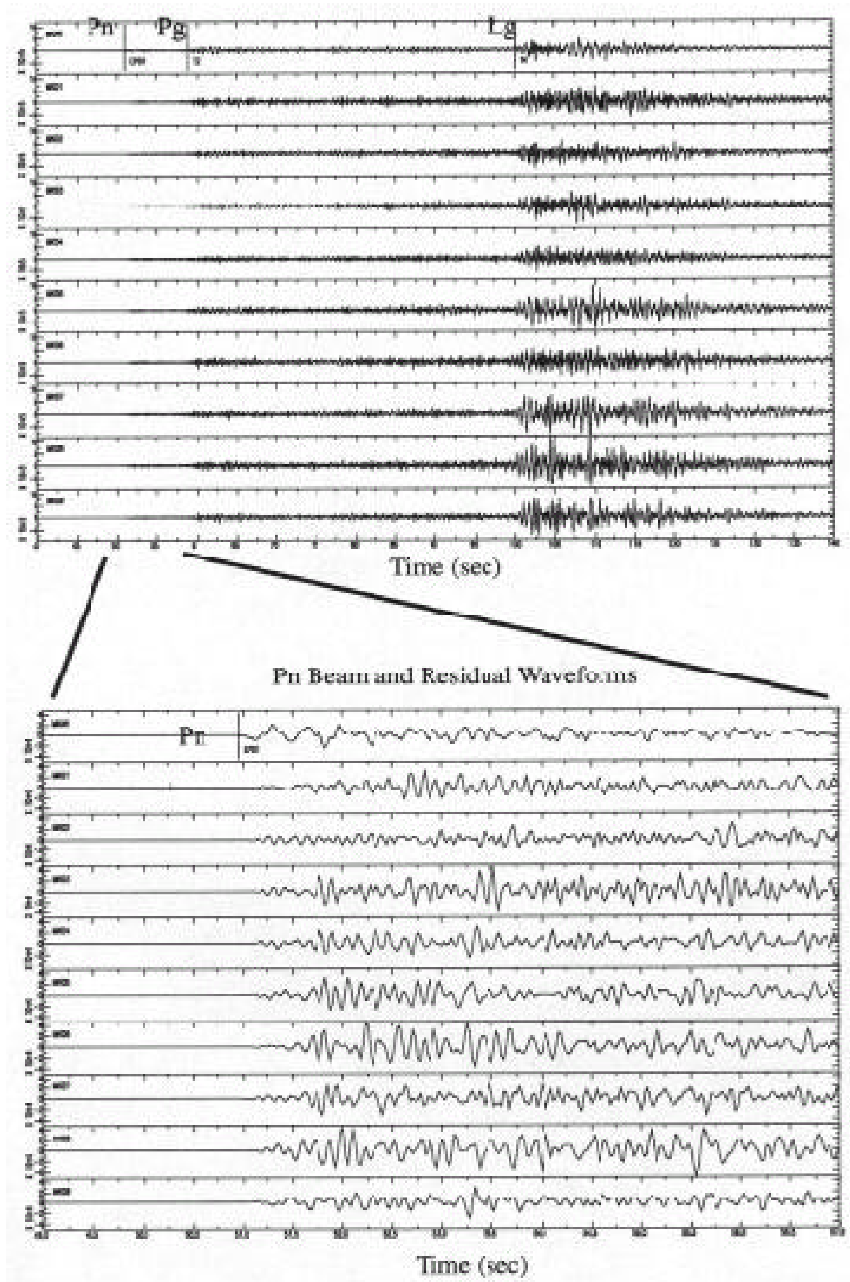

Figure 4. Comparison of the Pn beam and the residuals for each short period vertical array element. The entire trace is shown in the top panel and the Pn phase is shown in the lower panel.

CONCLUSIONS AND RECOMMENDATIONS

Our initial attempts to use time domain beam forming were deemed a failure as the distribution of energy as a function of slowness and azimuth was disturbingly poorly correlated to the azimuth and slowness for event with good signal-to-noise ratio and clear arrivals. We implemented a frequency domain beam former, using complex exponential terms to phase shift in the frequency domain, and found the results produced a distribution of energy as a function of slowness and azimuth consistent with other techniques, and basically consistent with the expected values. Time domain beam forming may need to be upgraded to use interpolation to shift between samples of the waveforms, but frequency domain beam forming appears to be simple, straightforward and accurate. While we were developing the frequency domain beam forming routines, we added additional capability to generate residual seismograms and Blandford's (1974) F detector. The residual seismograms are simply the difference between the beam (computed by shifting all the seismograms for the individual arrays elements to a common location and averaging) and the shifted seismograms. The residual seismograms are potentially useful for analyzing the deviations from simple plane wave propagation. The F detector has potential as a phase detector, but at least for this dataset, we found that the detector had to be run on high-passed data even for events with good signal to noise. We suspect that the microseismic noise is still correlated across the array, and the high pass filter helps to further suppress the microseismic correlated noise, allowing the F detector to primarily respond to the arriving seismic phase and the higher frequency noise.

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