Homestake Mine Project
Second Progress Report

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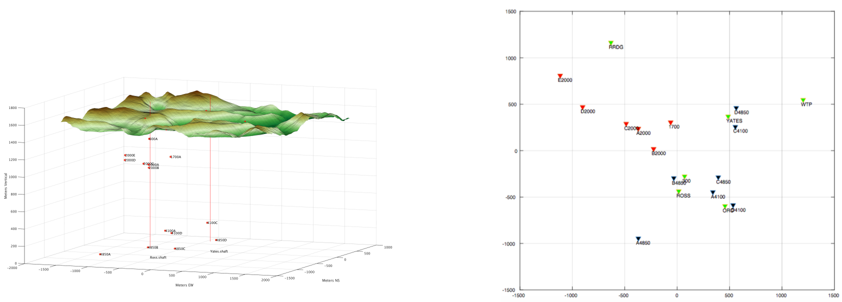
1. Background

For next generation of LIGO, which aims to probe the gravitational waves with a lower frequency, how to identify the signals from the universe with those caused by the seismic event or density fluctuations (Newtonian noise) is the foremost challenge to guarantee the sensitivity of the observation [Harms et al. 2006]. This motivated the seismic study of the former Homestake mine in Lead, South Dakota, a very promising candidate site. It is being transformed gradually into a scientific laboratory which now is known as the Sanford Laboratory. It lies far from the oceans and has the deepest reaching tunnels in North America (8000 ft) which provides an optimal stage for monitoring the seismic signals with a three dimensional network of seismometers.

In recent two years, the experiments in Homestake cooperated by several research groups have constantly provided unprecedented data in different depth, much wider than normal boreholes, for researchers to shed light on the wave propagation in shallow structure (Figure1). Also, the complex geology at Homestake has made it an ideal place to study the seismic wave propagation through layers with strong lateral heterogeneity, attenuation, scattering and interaction with free surface.

Variations and fluctuations caused by lateral heterogeneity in near surface always bring great difficulties to seismologists who want to make use of the signals from distant and deep sources (e.g. back projection). Accordingly, how to analyze the noise or irregular, messy signals mostly due to the shallow structure and make corrections of these signals is a challenging problem we are interested in.



(a) 3D view (b) Plane view

Figure 1. Seismometer distribution. [Color code: Deep(black), Middle(red), Surface(green)]

2. Ongoing Work Progress

2.1. Analyzing the velocity structure of Homestake area

As mentioned in the previous progress report, I continue dealing with the active source data using the joint inversion of H/V spectral ratios and phase-velocity dispersion. I have finished the dispersion curves picking of Mill St, Grandview St, Sunnyhill St and 1000a part. The figure below shows part of our result:

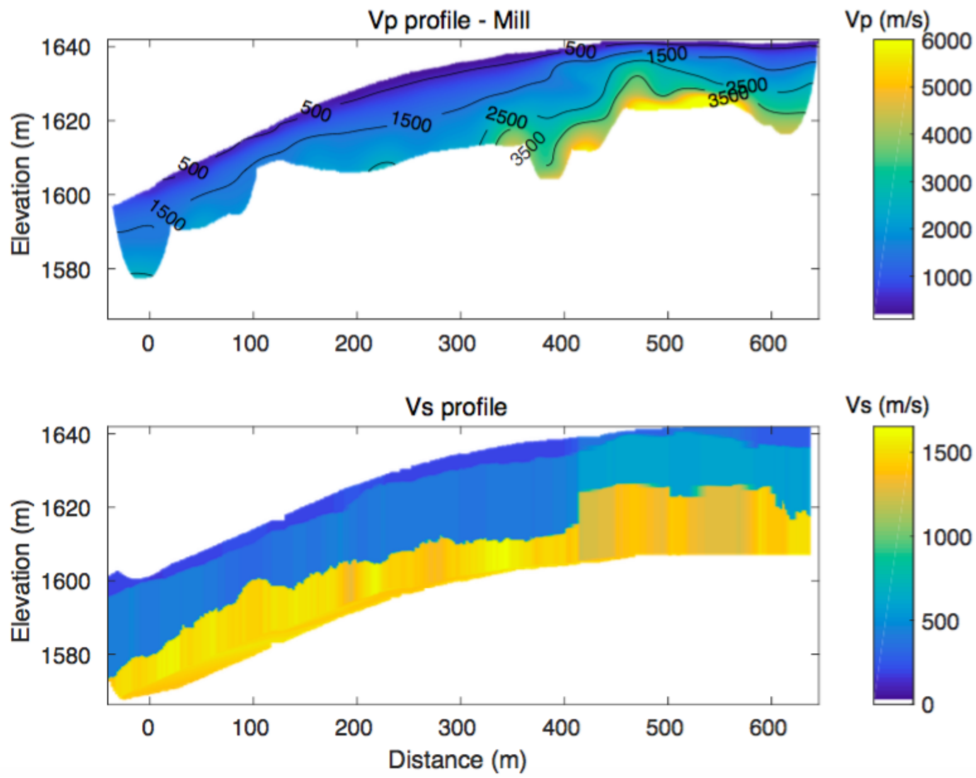


Figure 2. P wave and S wave velocity profile of Mill Road

Our result (Figure2) shows S wave velocity profile agrees very well with the P wave velocity profile.

2.2. Analyzing the scattering in Homestake area

[Spudich and Bostwick 1987] and [Scherbaum et al. 1991] first showed that the early S coda was dominated by multiple scattering within the shallow structure, using the the virtual seismic array (source array) deep underground with the reciprocity of the Green's function [Shearer 2007]. However, such result is doubted because the accuracy of the results depends, to a great extent, on the quality of the available information about the sources, such as location, origin times, and source mechanism [Rost and Thomas 2002]. The data collected in the 3D Homestake array do not need to use the reciprocity, thus they could provide directly the first-hand information to identify the strong scattering in the shallow layer (areas above the deepest stations).

2.2.1. Method

One way to find the propagation direction of component waves using array observations is to use a frequency-wavenumber power spectrum, also known as fk analysis [Sato et al. 2012]. The frequency–wavenumber analysis (fk analysis) is able to measure the complete slowness vector (i.e. back azimuth and horizontal slowness) simultaneously. The fk analysis calculates the power distributed among different slownesses and directions of approach. The time delays required to bring the signals into phase provide a direct estimate of the back azimuth and the slowness of the signal. When the slowness and back azimuth of a signal are unknown, a grid search for all u and combinations can be performed to find the best parameter combination, producing the highest amplitudes of the summed signal. This computation is performed in the spectral domain to save computation time.

2.2.2. Derivations for fk analysis

Assume a signal arriving at a reference point within the array with a horizontal velocity v_s and a back azimuth is described as $s(t)$. The nth seismometer with the location vector $\mathbf{r_n}$, relative to the array reference point records the signal $x_n(t)$:

$$x_n(t) = s(t - \mathbf{u} \cdot \mathbf{r_n})$$

where $\mathbf{u}$ is the slowness vector.
Then from the record of the array, we can derive the signal at the reference point:

$$y(t) = \frac{1}{N}\sum_{n=1}^{N} x_n(t + \mathbf{u} \cdot \mathbf{r_n})$$

we can calculate the erergy distribution as a function of $\mathbf{u}$ in frequency domain.
Using Parseval's Theorem, the total energy recorded at the array can be calculated by the integration of the squared summed amplitudes over time:

$$E = \int_{-\infty}^{\infty} |y(t)|^2 dt = \int_{-\infty}^{\infty} |Y(f)|^2 df$$

where $Y(f) = \mathcal{F}\{y(t)\}$.
For DFT, the form is:

$$\sum_{n=0}^{N-1} |x[n]|^2 = \frac{1}{N}\sum_{k=0}^{N-1} |X[k]|^2$$

Thus,

$$Y(f) = \int_{-\infty}^{\infty} y(t)e^{-i2\pi ft}dt = \frac{1}{N}\sum_{n=1}^{N}\int x_n(t+\mathbf{u}\cdot\mathbf{r_n})e^{-i2\pi ft}dt$$
$$= \frac{1}{N}\sum_{n=1}^{N} X_n(f)e^{i2\pi f\mathbf{u}\cdot\mathbf{r_n}}$$

$$E = \int_{-\infty}^{\infty} |y(t)|^2dt = \int_{-\infty}^{\infty} |Y(f)|^2df$$
$$= \int_{-\infty}^{\infty} |\frac{1}{N}\sum_{n=1}^{N} X_n(f)e^{i2\pi f\mathbf{u}\cdot\mathbf{r_n}}|^2df$$

So the result of fk analysis can be distributed as a function of slowness and back azimuth.

2.2.3. Result of fk analysis

For wavefield data having a finite duration in a given frequency band having center frequency f, we generate contour plots of the estimated fk power spectral density P_f in the horizontal slowness plane. We choose the highest signal within the given band as the center freqency f. Figure 4(a) shows results of an fk analysis of data recorded by 2 different seismic array, located at the deep and surface part in Homestake Mine of a Mw 7.7 earthquake in Japan. We compare the wave approaching direction at different level of depth. We show that, at deep array, the approaching wave have a certain direction (or intensed distribution Figure4(a),4(c)), while at the surface the waves are composed of wavelets in a variety of direction (Figure4(b),4(d)). The result suggests that the structure between the deep stations and the surface is the dominant factor that causes the variance.
Also, the peak being near the origin indicates that the apparent slowness $\mathbf{u}$ is small. The apparent slowness $\mathbf{u}$ is determined by v_0, the medium velocity beneath the array, and incident angel i:

$$u = \frac{1}{v_{app}} = \frac{\sin i}{v_0}$$

This shows either i is small, which means the incident waves is steep, or the medium velocity is very fast. This matches our expectation of the teleseismic event in Japan.

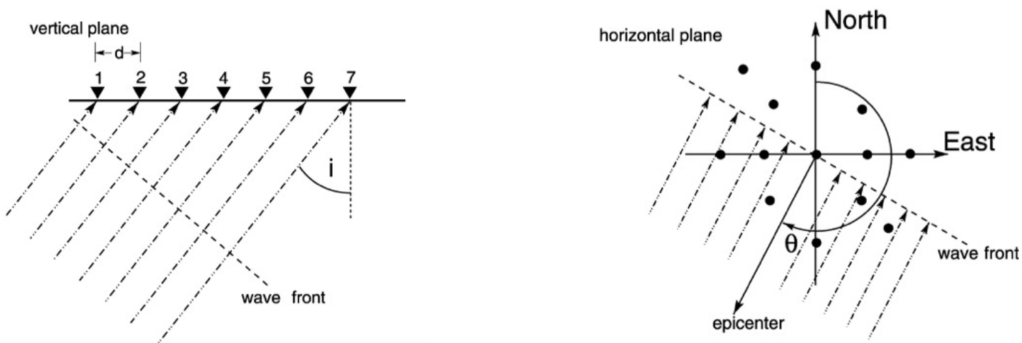
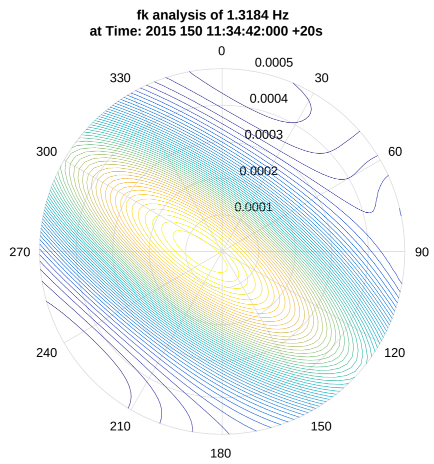
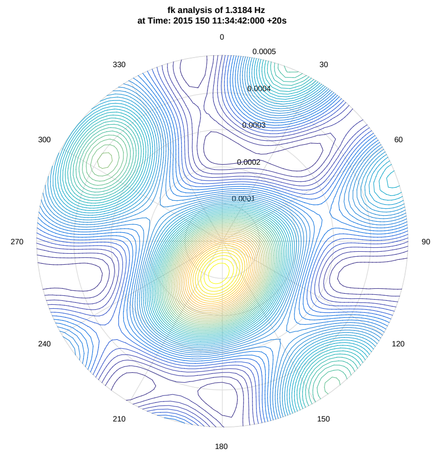


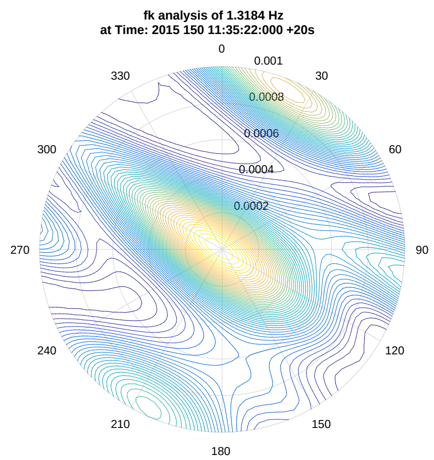
Figure 3. (a) The vertical plane of an incident wave front crossing an array at an angle of incidence i. (b) Sketch of the horizontal plane of an incident plane wave arriving with a back azimuth θ.



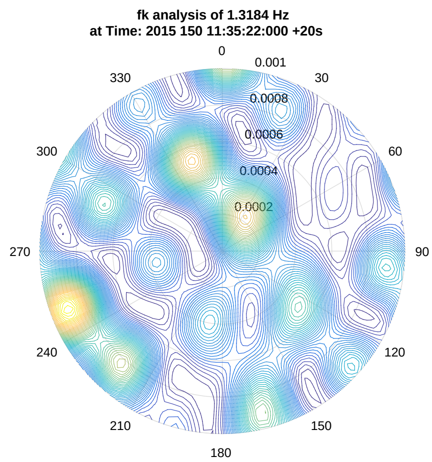
(a) Direct P Deep array



(b) Direct P Surface array



(c) P Coda Deep array



(d) P Coda Surface array

Figure 4. fk analysis of Japan Earthquake: The color in the plot means the power distribution. A peak indicates the direction of approach and the apparent propagation velocity of the plane wave that crosses the array. The analysis was performed with the raw data from 20 s time windows, one pair surrounding the direct P-arrival, and one pair beginning 40 s after the direct P-arrival.

3. Future Work

The vertical distance should be considered. And reflection, free surface effect as well;

See how much the station geometry might influence the result (Exclude other factor);

Use TauP to choose the exact time window to compare our result with the incidence angle and azimuth given from the ray tracing method;

Make the sliding-window fk analysis to see how the result varies with time.

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