THE DIRECTORIES TO CODES, DATA, AND UNPUBLISHED PREVIOUS WORK OF

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Chapter

CHAPTER 1 USAGE OF CODES

All the codes mentioned in this Chapter are working fine on CHPC when this document is being written (July 2019). If they are not working or cannot be compiled, contact CHPC (issues@chpc.utah.edu) for help and support.

1.1 Remove instrument response

You do not have to remove instrument response if you are cross-correlating nodal noise data with the same geophone. If all instrument and components have the same response function, the cross-correlation should not be affected. But if you are cross-correlating between data from different instruments (e.g., between a nodal geophone and a broadband seismometer), you have to remove response before calculating cross-correlations. Note that even if you are cross-correlating between the same type broadband seismometers, you may still need to remove responses because different components of the broadband seismometers may have different responses. To remove instrument response, you could use this code:

/uufs/chpc.utah.edu/common/home/flin-group4/yadong/REMOVE_RESPONSE/remove_response.csh

This is also an example in the folder. After running the "remove_response.csh", you should have files ending with ".rs" in the folder "06291993".

1.2 Cross-Correlations

The codes to obtain multi-channel cross-correlations are in this directory:

/uufs/chpc.utah.edu/common/home/flin-group4/yadong/SYN_CUT_CC

(I). The $1^{st}$ step is to synchronize ambient noise data:

In the folder "DATA":

Use:

>> syn_data_v2.csh          //to synchronize the starting time of day-long noise data.
You may need to change the line "foreach date ( `ls -d ????2016` )" according to the your dataset. Check the files to make sure the format of your file names is compatible with the code.

(II). The $2^{nd}$ step is to cut the noise data into segments.

Use:

>> cut_min.csh          //to cut the noise data into 5-min segments. You can change the length in the code by changing the line "set wlen = ( 300 )". The "300" means 300 seconds.

(III). The $3^{rd}$ step is the remove the mean and trend of the noise data for each segment.

Use:

>> rmean_rtrend_taper.csh          //to remove mean and trend.

If all the above codes work, the data preparation is done.

(IV). After the data preparation, the next step is to calculate cross-correlations.

Go to the folder "CC":

Use:

>> run_cor.csh          //to calculate cross-correlations. In this code, you may need to change:

"nohup ./cor_whiten_nor_stack time.test 0 10 station.test 1000
/uufs/chpc.utah.edu/common/home/flin-group4
/yadong/SYN_CUT_CC/DATA/noise_data_5min"

"time.test" is the list of time segments

"station.test" is the list of stations

"0 10" means using the first 10 stations (station 1-10) in the station list as center stations to do the cross-correlation

"1000" means only calculating cross-correlation if the inter-station distance < 1000 km.

"/uufs/chpc.utah.edu/common/home/flin-group4 /yadong/SYN_CUT_CC/DATA/noise_data_5min" is the path to the noise data segments.

In the cross-correlation code "cor_whiten_nor_stack.c", you may need to change:

```
#define numsts 100    //number of stations
#define numcents 100    //number of center stations
#define seg 10400    //number of your time segments (length of the file "time.test")
#define LAG 2000    //Time lags of the cross-correlation in points.
#define SAMP_DEL 0.02    //Sampling rate of your noise data
#define SAC_NPTS 15000    //NPTS of you noise segment
int      nthreads= 15;  //number of threads for parallel computing
```

After you run this code, you should have cross-correlations in the "stack_all" folder. The names of the cross-correlations are like "001-002_ZZ_stacked.SAC". Here "001" is the source station, "002" is the receiver station, "ZZ" is the component of the cross-correlation.

(V). Move auto-correlations

Auto-correlations are used for different purpose with cross-correlations. Therefore, they are usually placed in a different folder. Go to the folder "stack_all" and use code "mv_auto.csh" to move the auto-correlations to the folder "AUTO".

(VI). Rewrite cross-correlations

The SAC files produced by the cross-correlation code does not have complete header information. Thus, it is better to rewrite them with the software "SAC". In the foler "stack_all", use code "rewrite.csh" to rewrite the cross-correlations. After running this code, you should have files ending with "_rw" in the folder of each components (e.g., EE, NZ, ZZ …).

(VII). Rotate to R and T components.

This step is to rotate EE, EN, EZ, NE, NN, NZ, ZE, ZN, and ZZ component cross-correlations to vertical, radial, and transverse components. First, in the folder "stack_all", use code "make_rotatlist.csh" to make a list. Then do "./rotate rotation.lst" to rotate the cross-correlations. After running this code, you should have radial and transverse component cross-correlations (e.g., file "001-002_RR_stacked.SAC" in the folder "RR").

(VIII). Obtain symmetric components.

To obtain symmetric components of the cross-correlations, you could use the code "symmetric.csh" in the folder "stack_all". This script simply calls the software "SAC" to reverse a cross-correlation and stack with itself, then divide by 2. After running this code, you should have symmetric component cross-correlations (e.g., file "001-002_RR_stacked.SAC_s" in the folder "RR").

1.3 Stack by distance

This code can stack cross-correlations by distance. The code is at:

/uufs/chpc.utah.edu/common/home/flin-group4/yadong/STACK_DIST

Please read the "readme" file for the usage of the code.

1.4 Beamforming

This code performs beamforming analysis to cross-correlations. The code is at:
/uufs/chpc.utah.edu/common/home/flin-group4/yadong/BEAMFORMING_SLOW_BAZ

Please read the "readme" file for the usage of the code. Note that the current setup of the code is to stack waveforms within 1 degree back-azimuth bins. This bin width is tiny and is only suitable for large-N arrays. It is recommended to change the bin width to 5 degree or larger in the code if you do not have a lot of stations (>500).

<u>1.5 Frequency-time analysis (FTAN)</u>

FTAN can measure surface wave dispersions from cross-correlations. The code is at:

/uufs/chpc.utah.edu/common/home/flin-group4/yadong/FTAN_SNR_RAY_INV

Please read the "USAGE_FTAN" file for the usage of the code.

1.6 Signal-to-Noise Ratio (SNR)

This code can calculate signal-to-noise ratios of surfaces waves in cross-correlations. The code is at:

/uufs/chpc.utah.edu/common/home/flin-group4/yadong/FTAN_SNR_RAY_INV

Please read the "USAGE_SNR" file for the usage of the code.

1.7 2D surface wave velocity inversion with Barmin's code

This code can invert for phase or group velocities with surface wave travel-time measurements. For details, please refer to *"Barmin, M., Ritzwoller, M. & Levshin, A. Pure appl. geophys. (2001) 158: 1351. https://doi.org/10.1007/PL00001225"*, and "http://home.chpc.utah.edu/~u0942911/MANUAL/tomo_Barmin_et_al_2001_man.pdf".

Before using this code, you need to run FTAN and SNR codes first.


(I). The first step is to prepare the travel-time data. Use the code: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/FTAN_SNR_RAY_INV/get_good_measurement.csh"

After running this code, you should have a file "3.0_ph_snrcri_4_distcri_9.0.txt" in the folder "3.0s_snrcri_4_9.0km".

There are detailed explanations in the comments of the script. Please read the comments.

If you are measuring phase travel-times, you have to correct for ambiguity (2-pi jumps). There are multiple ways to do it. A simple approach is: (1). Estimate a reference velocity (plotting travel-times vs. distance may give you a hint). (2). Calculate a reference travel-time using distance/reference-velocity. (3). If the measured travel-time is more than half period larger/smaller than the reference travel-time, add/minus one period to the measured travel-time. (4). Repeat (3) until the difference between the measured travel-time and the reference travel-time is smaller than half period. s

After obtaining the file "3.0_ph_snrcri_4_distcri_9.0.txt", you need to use another code: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/FTAN_SNR_RAY_INV/prepare.csh".

After running this code, you should have a file "data3.0s.txt". This file is ready to be used for Barmin's inversion code.

The two codes, "get_good_measurement.csh" and "prepare.csh", use some files containing station names, station locations, and inter-station distances. Please check the formats of these files and change your data to the same formats.


(II). The 2nd step is to run Barmin's inversion code.

The code is at: /uufs/chpc.utah.edu/common/home/flin-group4/yadong/TOMO_BARMIN_ET_AL

You need to have a "data" folder. In this folder, there are "contour.ctr" and "data3.0s.txt".

In the file "contour.ctr", the first line is a point outside of your tomography area. Any point outside would be fine. The second line means using 4 points to determine the tomography area. Then you need to set the locations of the 4 points. The 4 points should be in the order of northwest-southwest-southeast-northeast. You don't have to change the rest of the file.

The file "data3.0s.txt" has the data at 3.0 sec period. The first column is the sequence number; the second to the fifth column are the locations of the two stations; The $6^{th}$ is the velocity; The 7th and $8^{th}$ should be all "1", don't need to change them; the $9^{th}$ is the names of the two stations connected with underlines; The $10^{th}$ is the distance between the two stations.

Use "run_RUN.csh" to do tomography. This code calls "RUN_tomo_RA_noweight_64_.1.csh". You need to set period and three parameters (alpha, sigma, and beta). Alpha and Sigma are smoothing parameters and beta is damping parameters. Please refer to *"Barmin, M., Ritzwoller, M. & Levshin, A. Pure appl. geophys. (2001) 158: 1351. https://doi.org/10.1007/PL00001225"* for the theory of this tomography method and the meanings of these parameters. Briefly speaking, alpha controls how hard you want to smooth the velocity maps, and beta controls the smoothing radius. If you don't want damping, set beta as 1. If you would like to use higher damping, use a larger number.

The code "RUN_tomo_RA_noweight_64_.1.csh" sets up input parameters for "tomo_sp_cu_s_shn_.1" to do tomography.

You can run "tomo_sp_cu_s_shn_.1" step by step without using "RUN_tomo_RA_noweight_64_.1.csh", and have a better understanding of what the code "RUN_tomo_RA_noweight_64_.1.csh" does. You could do the followings (% signs represent comments):

```
>> ./tomo_sp_cu_s_shn_.1 data/data3.0s.txt test 3.0
>> me
%enter menu
>> 4
% We select option 4 in the menu. (Path density & azim. coverage?)
```

>>v

% review menu, we can see option 4 becomes "1" from "0".

>> 11

>> 0

% this means no anisotropy

>> 12

>> $alpha

>> $beta

>> $sigma

>> $sigma

% set up inversion parameters.

>> 5

>> 46 50 0.1

% set the latitude range: Here it is from 46 to 50 with a grid size of 0.1 degree

>> 6

>> -122.4 -118.4 0.1

% set the longitude range and the grid size

>> 10

% set step of integration

>> 0.016

set X_zone

>> 0.1

% the ration of step of integration and X_zone should remain 0.016/0.1

>> R

% "R" means Rayleigh waves

>> P

% "P" means Phase velocities

>> 0.1

% length of main cell

>> 7

% anisotropy parameter. Because we set up no anisotropy, this value doesn't matter.

>> 19

% We require the residuals output

>> 25

% We require the resolution output

>> v

% review menu, make sure everything is correct.

>> q

% quit menu

>> go

% start running the inversion

After you run "run_RUN.csh", the file "CA_5000_20_1_3.0.1" in the folder "3.0/5000_20_noweight/" will be the tomography result. There is an official manual of the code "tomo_sp_cu_s_shn_.1" at "http://home.chpc.utah.edu/~u0942911/MANUAL/tomo_Barmin_et_al_2001_man.pdf".

## 1.8 Double beamforming

Please go to "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/DOUBLE_BEAMFORMING_TOMO_USAGE" and read the "workflow.txt" for the usage of double beamforming tomography codes.

1.9 Shear velocity inversion with Herrmann's code

This code can invert for a 1D shear velocity model from surface wave dispersions. To use this code, you need to install a software package. Please go to this website "http://www.eas.slu.edu/eqc/eqccps.html". This package is free to use and there are instructions about how to install the package on the website. If you successfully install the programs, you should be able to use the command "surf96".

After you install the programs, go to "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/VS_INV_HERRMANN". Please read the "readme" file in the folder for the usage of the code.

### 1.10 H/V

Here you can find the usage of the codes to do double beamforming stacking for ZZ, ZR, RZ, and RR component cross-correlations and measure Rayleigh wave ellipticities. The path to the code is: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/HV_DB_USAGE". Please read the "readme" file carefully. Some of the codes are not 100% completed (e.g., the process to calculate the standard deviation of the mean). You may need to modify the codes.

CHAPTER 2 DATA

2.1 Mount St Helens Project

(I). Raw data

The origin data of the Mount St. Helens (MSH) array is at: "/uufs/chpc.utah.edu/common/home/zland1/yadong/dataMSH/data/MSH_bin". The data are in matlab format.

I have converted the data to SAC format with the help of Eli Workman. The SAC data are at: "/uufs/chpc.utah.edu/common/home/zland1/yadong/dataMSH/datasac/rwdata"

The data only have vertical components with a sampling rate of 250 points/second.

(II). Cross-Correlations

The vertical-vertical cross-correlations are at: "/uufs/chpc.utah.edu/common/home/flin-group2/yadong/MSH_project_group2/cor2_for_Rayleighwave".

2.2 Cascadia

2.2.1 ZO2017 array

(I). Raw data

The "FCNT" files are at: "/uufs/chpc.utah.edu/common/home/zland1/wardk/ZO".

The day-long ambient noise data are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_2017/SAC_DATA".

The synchronized hour-long ambient noise data are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_2017/SAC_DATA/noise_data_1hr".

(II). Cross-correlations

The nine-component cross-correlations are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_2017/CC_remove_bad_days_correct_para_correct_syn/stack_all".

2.2.2 CACS93 array

(I). Raw data

The "seed" files downloaded from IRIS are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_Broad_Band/data/seed_file".

The day-long SAC files are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_Broad_Band/data/syn_and_cut_data_resp_removed".

The hour-long instrument-response-removed noise data are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_Broad_Band/data/syn_and_cut_data_resp_removed/noise_data_1hr".

(II). Cross-correlations

The nine-component cross-correlations are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/Cascadia_Broad_Band/CC_correct_syn_rm_resp/stack_all".

2.3 San Jacinto Fault Project

2.3.1 RR array

(I). Raw data

The "FCNT" files are at:

"/uufs/chpc.utah.edu/common/home/zland1/allam/RR/RAW_DATA".

The day-long SAC files are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/RR_array_cc/SAC_DATA".

The 5-min noise data are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/RR_array_cc/SAC_DATA/noise_data_5min".

(II). Cross-correlations
The nine-component cross-correlations are at: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/RR_ARRAY/CC/stack_all".

2.3.2 BS array

(I). Raw data

The "FCNT" files are at:
"/uufs/chpc.utah.edu/common/home/zland1/allam/BS/RAW_DATA".

The day-long SAC files are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/BS_array_cc/SAC_DATA".

The 5-min noise data are at: "/uufs/chpc.utah.edu/common/home/flin-group3/yadong/BS_array_cc/SAC_DATA/noise_data_5min".

(II). Cross-correlations

The nine-component cross-correlations are at: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/BS_ARRAY/CC/stack_all".

### 2.3.3 DW array

(I). Raw data

The "FCNT" files are at: "/uufs/chpc.utah.edu/common/home/zland1/allam/BW".

The day-long SAC files are at: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/BW_ARRAY/DATA".

The 5-min noise data are at: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/BW_ARRAY/DATA/noise_data_5min".

(II). Cross-correlations

The nine-component cross-correlations are at: "/uufs/chpc.utah.edu/common/home/flin-group4/yadong/BW_ARRAY/CC/stack_all".

CHAPTER 3 TOMOGRAPHY FOR THE RR ARRAY – TWO METHODS

Apart from the double beamforming tomography method, I also applied other two tomography methods to measure the Rayleigh wave phase velocities across the RR array (see chapter 4 in my dissertation for the introduction of the array). The two methods will be described below and preliminary results will be presented.

The first method used is referred as FTAN&2D Inversion method. I applied Frequency-Time Analysis to the vertical-vertical cross-correlations across the RR array to measure travel-times of the Rayleigh waves at each period. Then I corrected the phase travel-times ambiguities. The travel-time measurements are shown in Figure 3. Next, I performed a 2D phase velocity inversion.

The second method I used is referred to as Neighborhood Cross-Correlations and Eikonal Tomography Method. At a certain period, I used the cross-correlations $Z_{S_i,R_j}(t)$ between station $S_i$ and station $R_j$ and the cross-correlations $Z_{S_i,R_{j+1}}(t)$ between station $S_i$ and station $R_{j+1}$. Station $R_j$ and $R_{j+1}$ were geometrically next to each other. Then I cross-correlated $Z_{S_i,R_j}(t)$ and $Z_{S_i,R_{j+1}}(t)$ and obtained $ZZ_{S_i-R_j,R_{j+1}}(\tau)$, where $\tau$ is the lag time of the cross-correlation. The amplitude of $ZZ_{S_i-R_j,R_{j+1}}(\tau)$ reaches its maximum at $\tau_{S_i-R_j,R_{j+1}}$, where $\tau_{S_i-R_j,R_{j+1}}$ represents the travel time difference between the ray path $(S_i,\ R_j)$ and the ray path $(S_i,\ R_{j+1})$. Then the phase velocity between station $R_j$ and station $R_{j+1}$ was determined as the distance between the two stations $(D_{j,j+1})$ divided by the travel time difference $\tau_{S_i-R_j,R_{j+1}}$:

$$V_{j,j+1} = \frac{D_{j,j+1}}{\tau_{S_i-R_j,R_{j+1}}}.$$

By using other stations as the source stations, I obtained multiple phase velocity measurement between station $R_j$ and station $R_{j+1}$. Then I calculated the mean of those measurements as the final velocity and the standard deviation of the mean as the uncertainty.

Figure 1 demonstrated the process of measuring the velocity between two stations using the neighborhood cross-correlation method. Note that the apparent period of the measurement could be computed as the time difference between two points on each side of the maximum amplitude where the cross-correlations equal to zero.

Figure 2 presents multiple phase velocity measurements at a particular location with all the source stations in the top panel, all the measurements at all locations in the bottom panel.

Figure 4 shows the three phase velocity profiles obtained with the FTAN and Inversion method, the Neighborhood Cross-Correlation and Eikonal tomography method, and the double beamforming method.
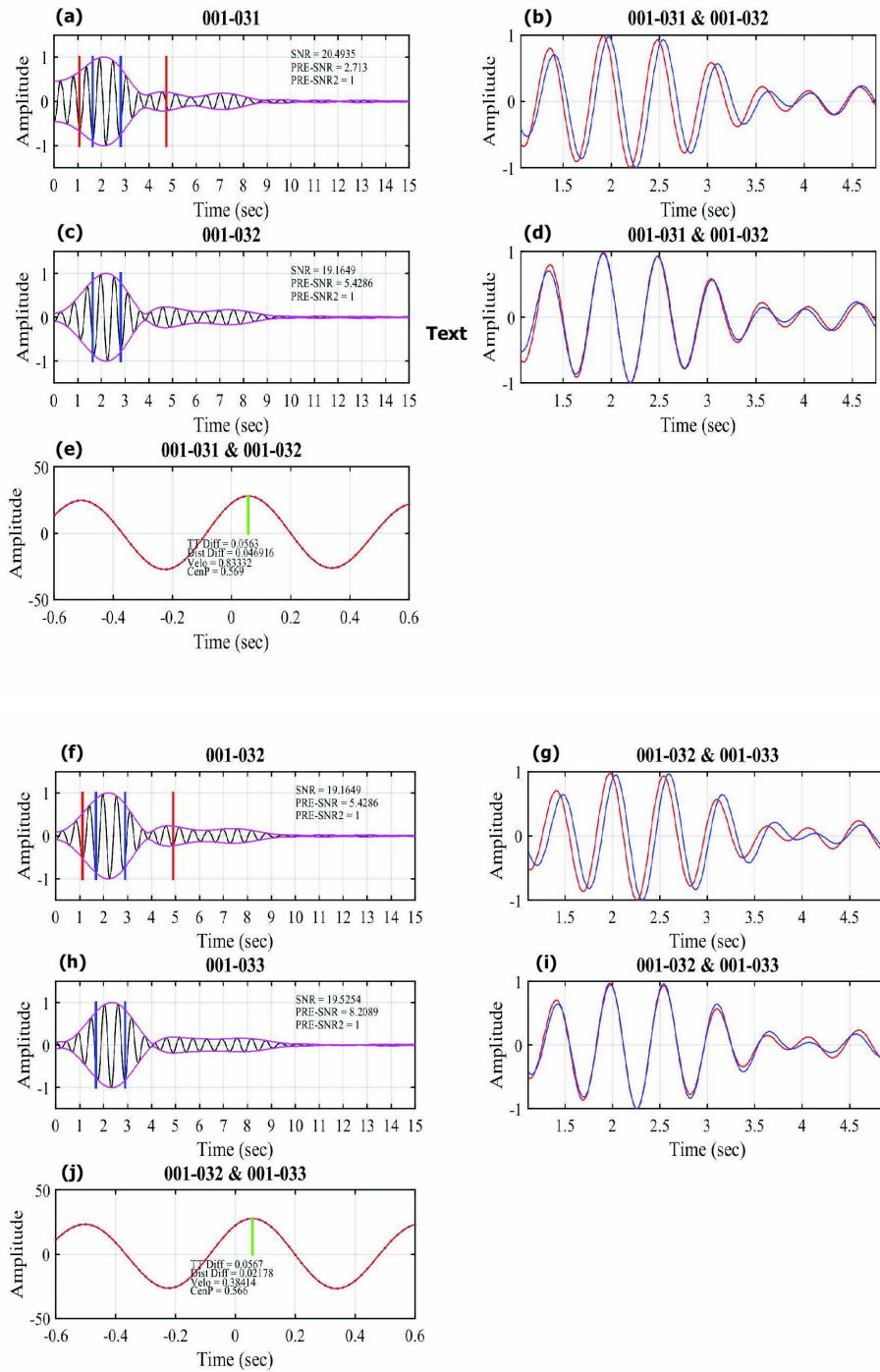
Figure 1. Neighborhood CC method demonstration with RR array. (a) and (c). ZZ cross-correlation at 0.6 sec period between station 001 and station 031, and station 031, respectively. (b). The waveforms in (a) and (c) plotted on top of each other. (e). the cross-correlation function between the two waveforms in (b). The green bar shows where the maximum amplitude locates. (d). The waveforms shifted by the travel-time difference determined by (e). (f-j). same as (a-e) but for cross-correlation 001-032 and 001-033.
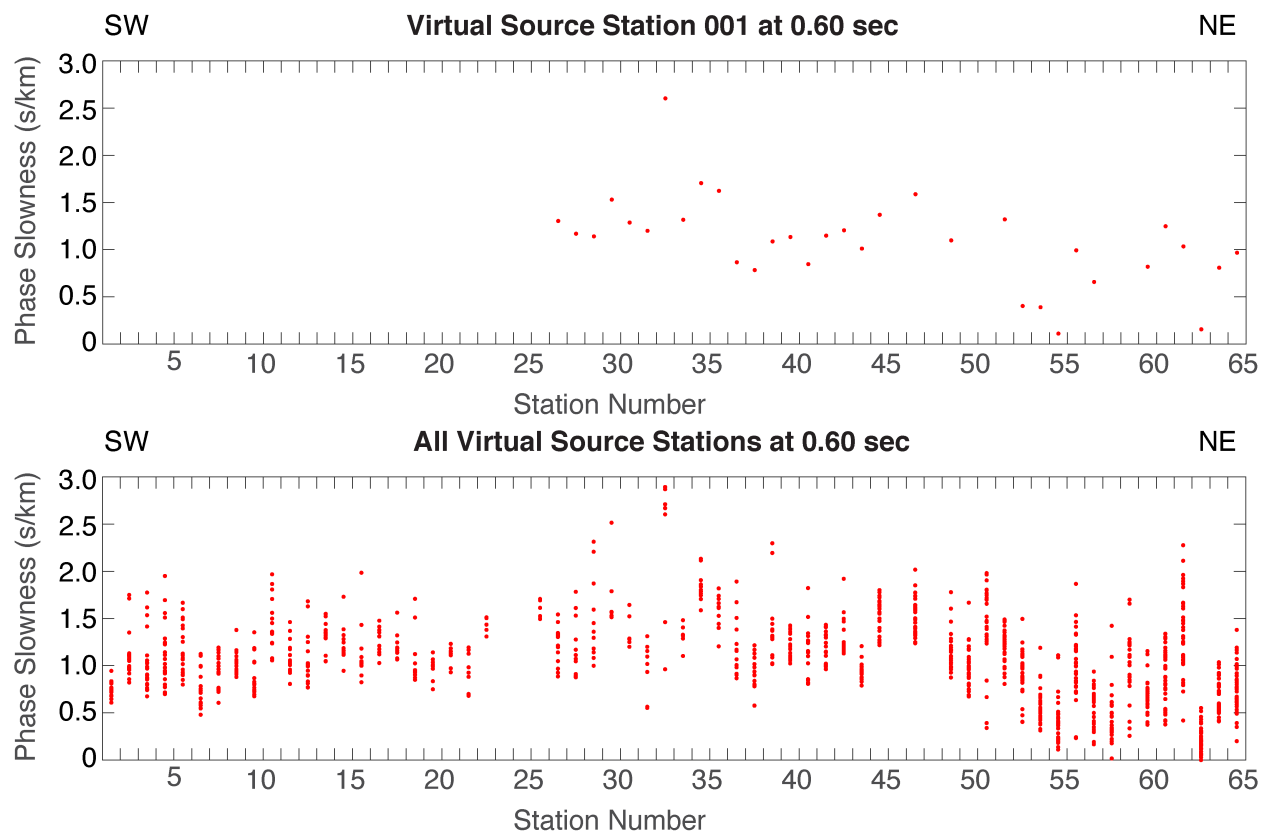
Figure 2. Phase slowness measurements from neighborhood cross-correlation methods. Top: the measured slowness at 0.6 second period between all the receiver stations with one common source station 001. Bottom: all slowness measurements at 0.6 second period with all the source and receiver stations.
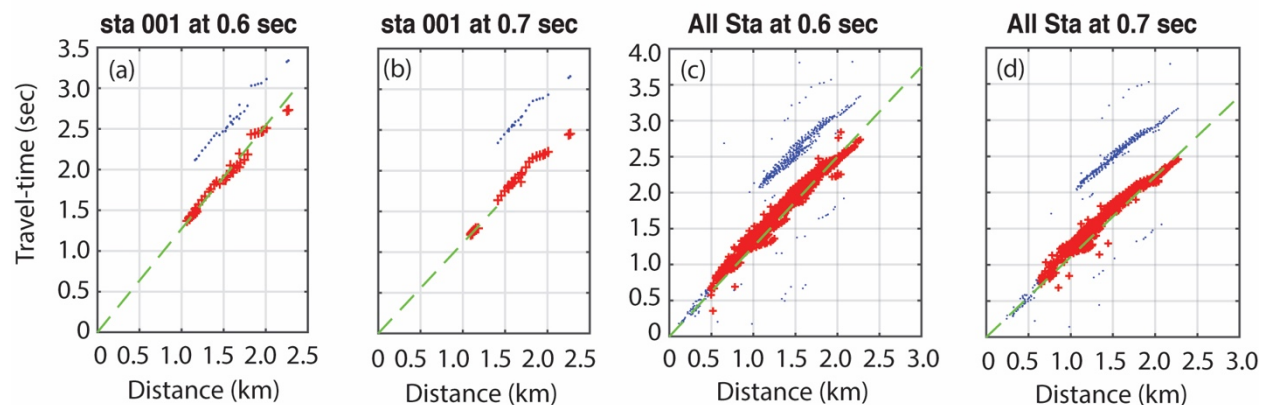
## RR Array Travel-time Measurements



Figure 3. Travel time measurements by FTAN. (a). travel-times of the Rayleigh waves in the cross-correlations from station 001 to all the receiver stations at 0.6 second period. The blue dots are raw measurements and the red crosses are after phase ambiguity correction. The green line shows the reference velocity to correct the travel-time for the shortest ray path. (b). same as (a) but at 0.7 second period. (c) same as (a) but for all the source and receiver stations. (d). same as (c) but at 0.7 second period.
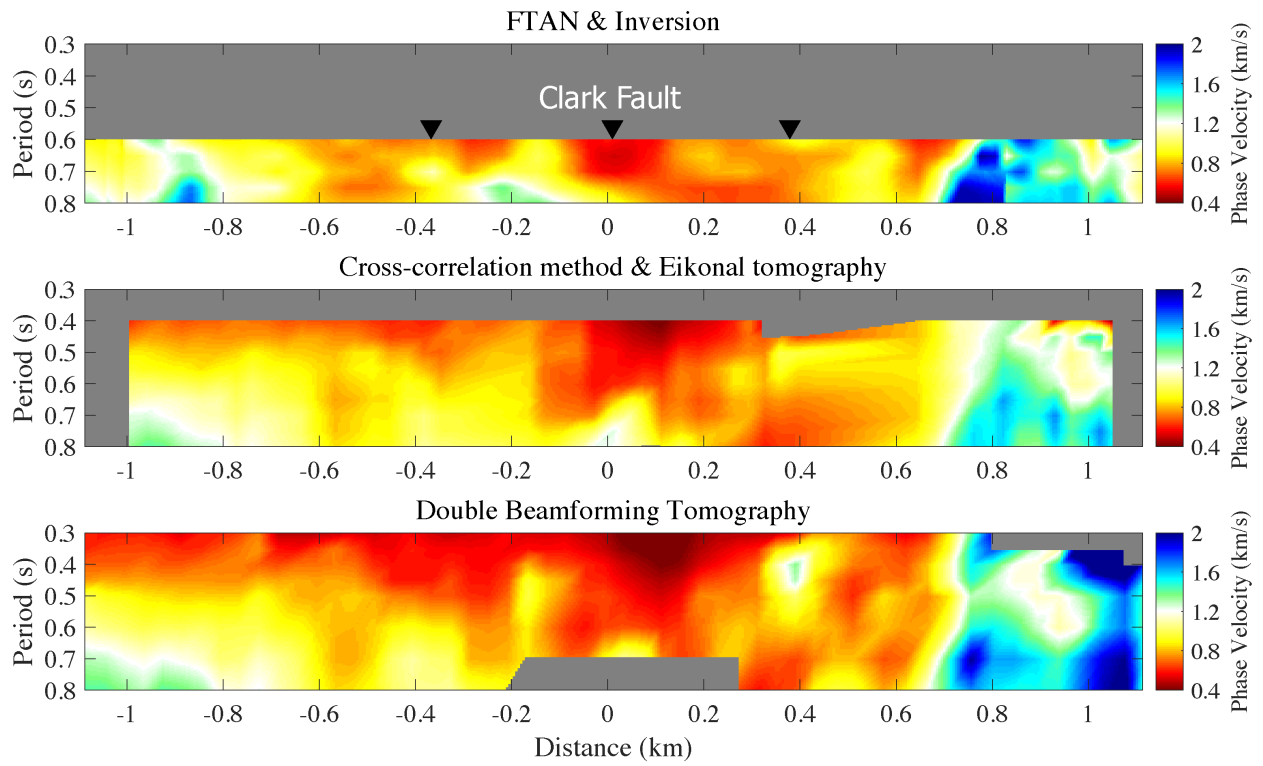
Figure 4. RR array phase velocity profiles with three methods: FTAN & 2D inversion (top), Neighborhood CC & Eikonal (middle), and double beamforming (bottom).

CHAPTER 4 TOMOGRAPHY FOR THE BS ARRAY

From November to December 2015, a nodal geophone array (BS array) was deployed across the San Jacinto Fault to study the fault zone structure. Figure 5 shows the location of the array. The array had 134 three-component 5Hz geophones deployed for about a month. Although the ideal configuration of the array was a straight line perpendicular to the fault trace, locations of the stations were limited by the accessibility of the area. Consequently, the actual array was not strictly linear. I have computed 9-component cross-correlations with the noise data of the array.

Figure 6 shows the cross-correlation record sections bandpassed 0.2 to 2 second periods between station 001 (red star in Figure 5) and all other stations. Clear Rayleigh waves can be observed on ZZ, ZR, RZ, and RR components, while Love waves can be observed on TT components.

I used FTAN to measure the Rayleigh wave phase travel-times on the ZZ cross-correlations and inverted for phase velocities with the inversion method of Barmin et al. (2001). The phase velocity profile is shown in Figure 7.
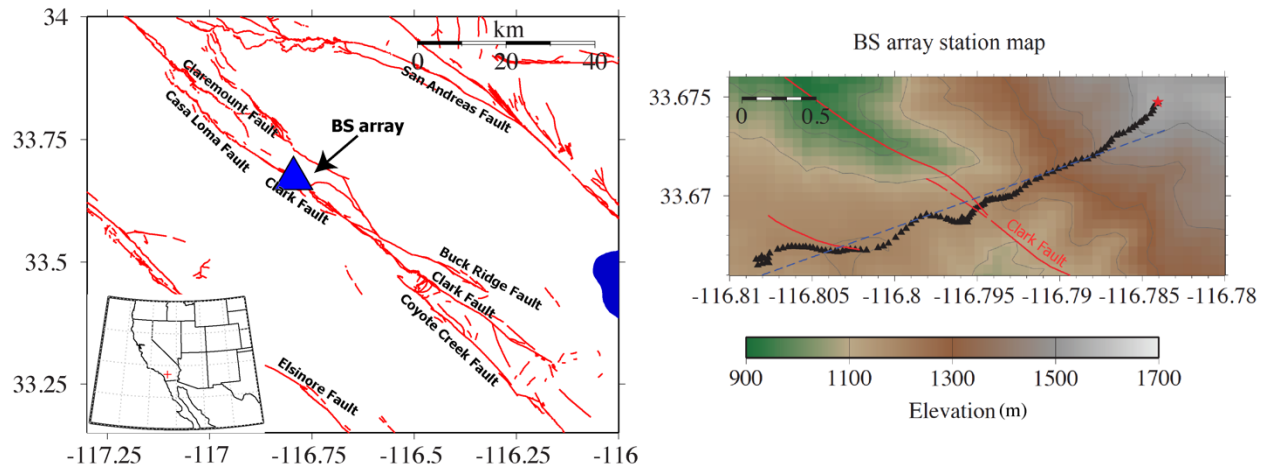
Figure 5. BS array configurations. Left: regional map including faults in Southern California. The BS array location was labeled as a blue triangle. Right: BS array station map. The black triangles represent nodal geophone stations. The red star on the northeast is the source station used in Fig. 6. The faults are plotted as red lines. The blue is a straight line fitting the locations of all the stations that is used as the tomography cross-section (Fig. 7).
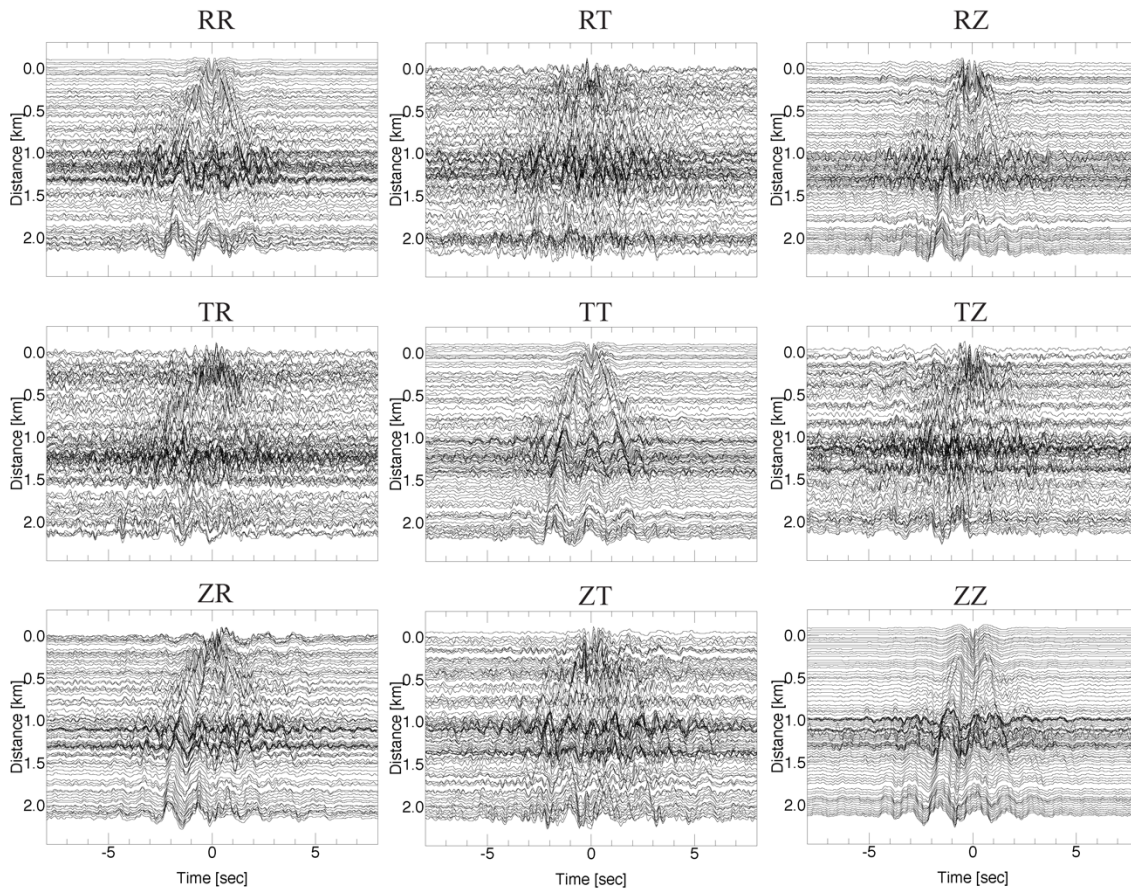
Figure 6. Record section of 9-components cross-correlations between station 001 (red star in Fig. 5) and all other stations in the BS, bandpassed 0.2-2 second periods.
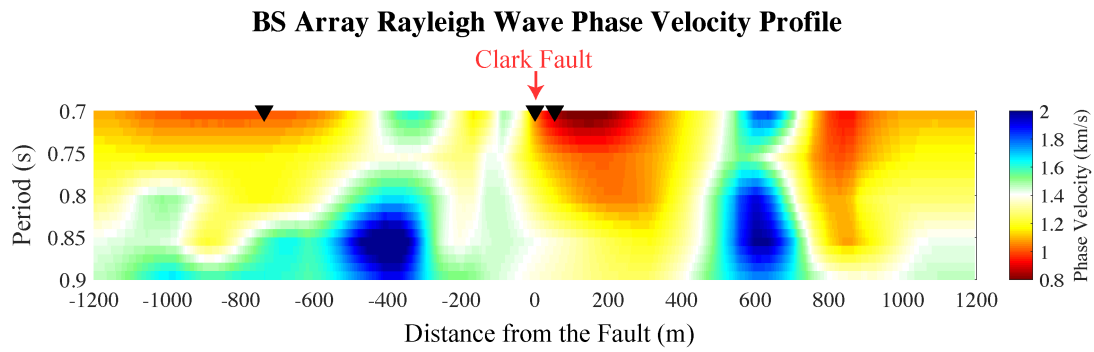
Figure 7. BS array phase velocity profile with FTAN and 2D inversion. The fault traces are labeled as reverse triangles.