Slowness-Enhanced Back-Projection

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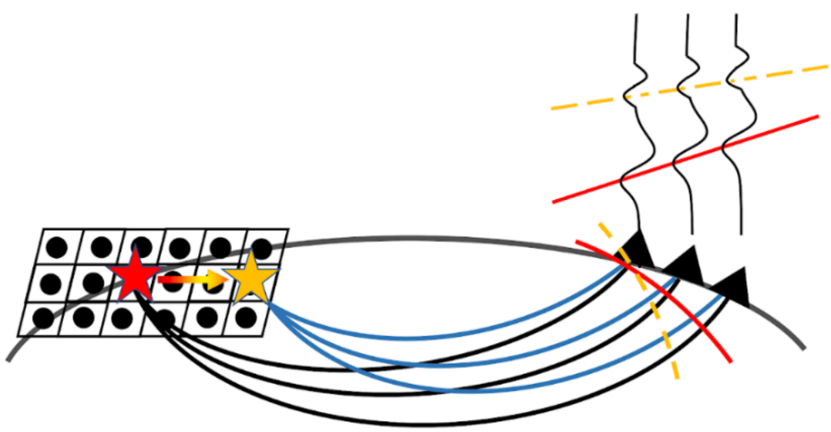
The objective of this lab is to perform the Slowness-Enhanced Back-Projection Imaging on the seismograms of large earthquakes recorded by large-scale dense arrays. The instruction is performed on the 2021 Mw 7.4 Maduo Earthquake. The results have been published in JGR: Solid Earth (https://doi.org/10.1029/2022JB025936).

Back-Projection is an earthquake-rupture imaging technique utilizing the coherent teleseismic P wavefield based on seismic array processing. Back-tracking of seismic waves recorded by dense arrays allows Back-Projection to determine the spatio-temporal properties of the rupture (length, direction, speed, and segmentation). Over recent decades, the development of large-scale dense seismic networks has enabled the Back-Projection imaging of the rupture process of major large earthquakes.



The sketch above shows the concept of Back-Projection. The black dots in the center of the rectangular grids indicate the locations of testing sources on a fault plane. The red star is the hypocenter. The moveout of recorded seismograms is shown with the red line. In principle, the moveout of the actual source locations brings the seismograms in phase; thus, the waveform stack along the moveout reaches the maximum. When the rupture front migrates to a new location, represented by the yellow star, the moveout of seismograms shift from the red line to the yellow dashed line.

MUSIC BP is performed in the frequency domain based on the orthogonality between the noise and signal subspace of the covariance matrix. Compared with Beamforming, MUSIC has the advantage of detecting multiple closeby sources simultaneously. More details about Back-Projection and MUSIC could be found in the following papers:

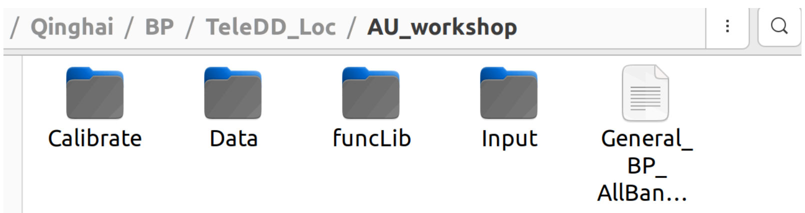
Kiser, E., & Ishii, M. (2017). Back-projection imaging of earthquakes. Annual Review of Earth and Planetary Sciences, 45, 271-299.
Meng, L., A. Inbal, and J.-P. Ampuero. 2011. “A window into the complexity of the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake”, Geophys. Res. Lett., 38, L00G07, doi:10.1029/2011GL048118.

Backprojection imaging is also performed routinely by IRIS for all new large earthquakes: https://ds.iris.edu/ds/products/backprojection/

1. Prepare the data

Firstly, we need a BP result of MUSIC BP. Here we use the 2021 Mw 7.4 Maduo earthquake as an example to illustrate the procedure. Note that MUSIC BP is a Matlab-based package requring the Signal Processing, Mapping and Imaging Processing tool boxes.

Download the “AU_workshop.zip” and “Calibrate.zip”. Unzip them and place them in the same folder. In my project, it is “/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop”:



“Calibrate” is for aftershock calibrations. “Data” contains the mainshock waveforms recorded by Australia stations. “funcLib” has all required functions. All generated data and figures will be saved in the “Input” folder. We will operate the mainshock BP in “General_BP.m”.

2. Perform MUSIC BP

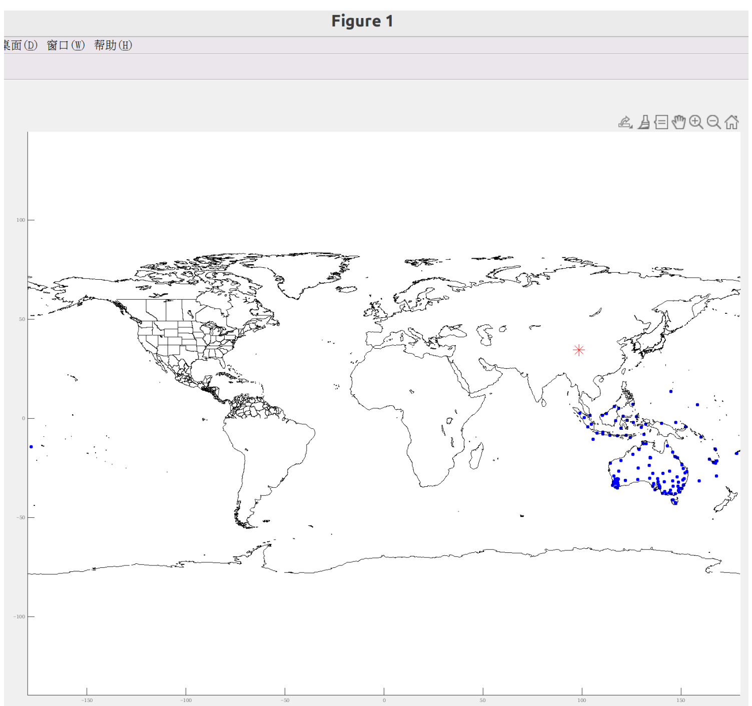
Step 1: open the General_BP.m file with Matlab. This file controls all the steps of the program. The following figure shows 6 flags to enable each processing step. When the flag is set to 1, running the script would implement the corresponding functions. You should only set one flag to 1 and other flags to zero each time.

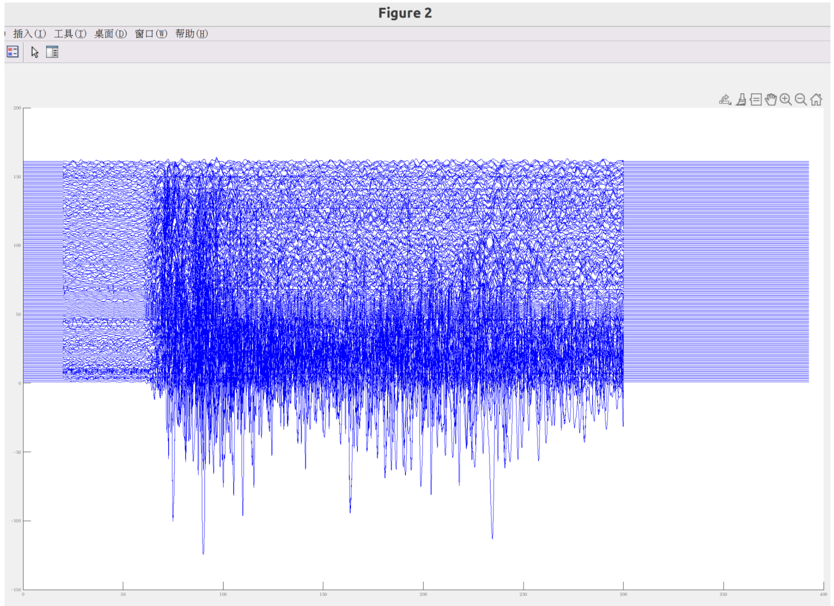
```
%% Work to do (do=1, not_do=0)
Initial_flag=0;      % Initialize a project
readBP_flag=0;       % Read seismogram from .SAC files
alignpara_flag=0;    % Get parameters for alignment
alignBP_flag=0;      % Hypocenter alignment
runBPbmfm_flag=0;    % Beamforming Back-projection
runBPmusic_flag=0;   % MUSIC Back-Projection
```

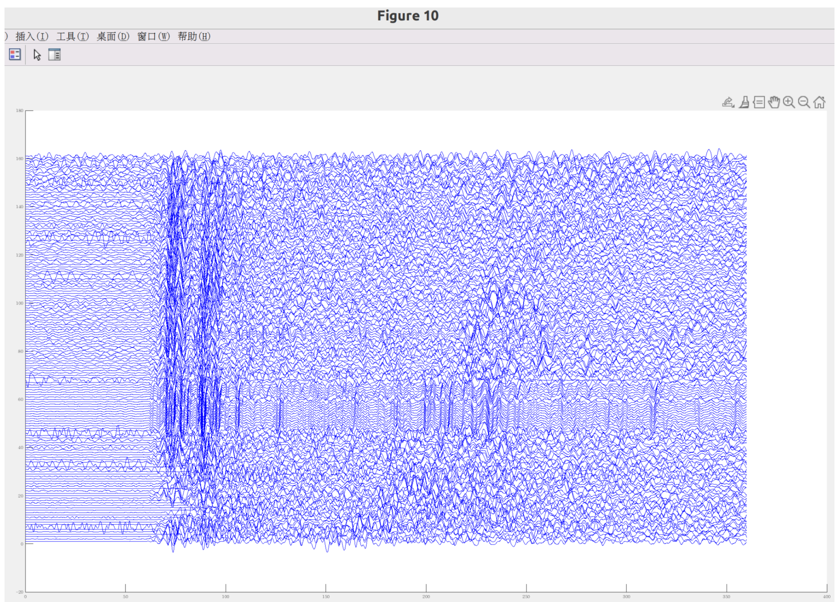
Step 2: Since we already prepared the data and folder manually, we will start with reading seismograms. We set readBP_flag = 1 and other flags = 0, and set earthquake information:

```
%% Parameters for read
workPath= '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/';
cd(workPath);

dep=7.607;                % depth
lon0=98.3622588499;       % lontitude
lat0=34.6202641954;       % latitude
Mw=7.4;                   % magenitude
strike1=0;                % strike 1, not used in the code
strike2=0;                % strike 2, not used in the code

sr=10;                    % sample rate
ori=60;                   % how long the data start before P-arrival
display=360;              % time length of waveform showing by plotAl
plotscale=1.0;            % plotscale:  scaling of the amplitudes of
```

After running the script, you will see three figures: one is the map of stations and the earthquake (Figure 1), one is the original waveforms (Figure 2), and the other one is the waveforms filtered to 0.1-2 Hz and normalized (Figure 10). In the folder “Input”, you will see data0.mat file storing the raw waveforms and other metadata.





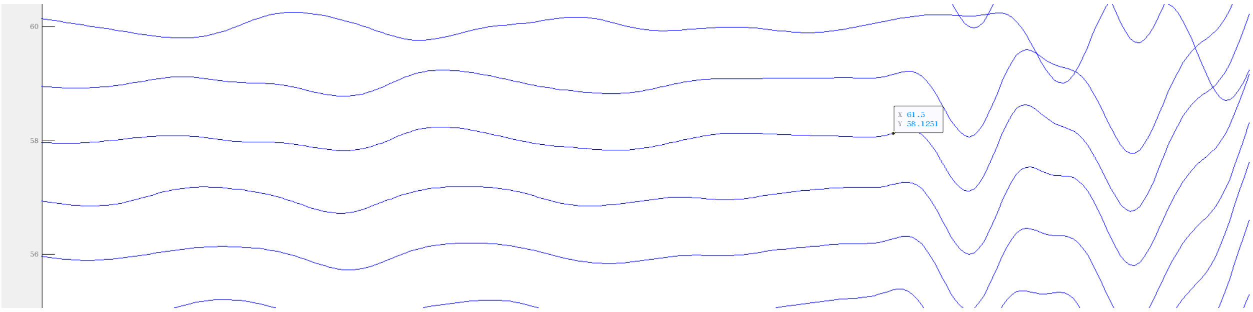


Step 3: Then align the seismograms (This is the Most important step!!!) by setting **alignBP_flag** = 1, and other flags = 0. You will align the seismograms 4 times, from low to high frequency bands. The comments after each line of “align()” list the frequency range and corresponding window length of each alignment. These settings are suitable to align any first P arrival recorded at teleseismic distance. If you wish to change them for alignment in a different frequency band, please modify “alignband.m” accordingly.

After filtering the raw seismograms with different frequency bands, the script will align the seismograms in selected windows by cross-correlation. You can find details about cross-correlation through the link:

https://www.mathworks.com/help/signal/ug/align-signals-using-cross-correlation.html

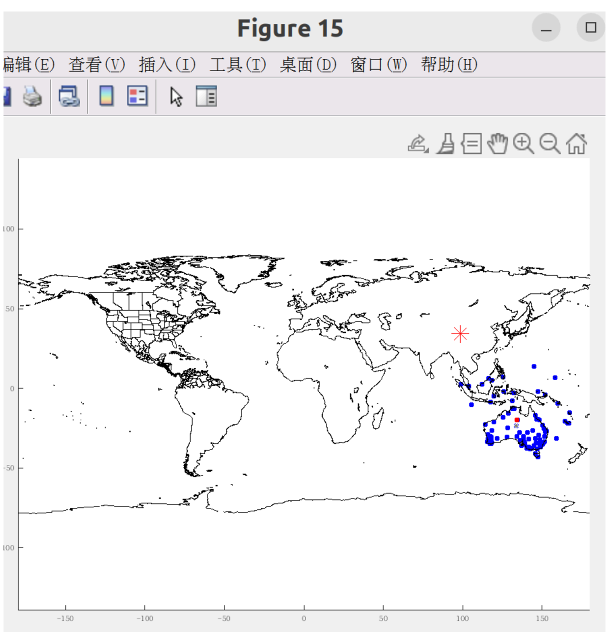
The essence of this step is to find the right starting time of the window and the reference seismogram. You should choose a representative seismogram with clear first arrival as the reference seismogram. For example, #58 seismogram in the above figure is a good choice.

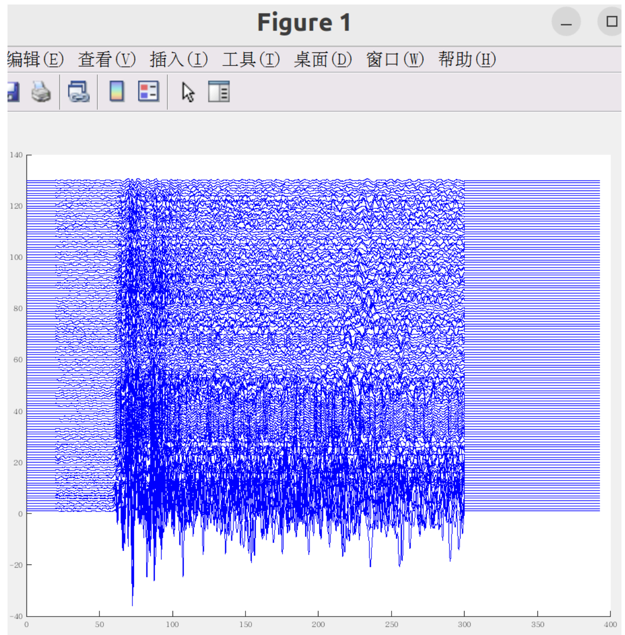


In the following figure, we set the alignment requirement through the variable named align. The first element is the starting time of the window, the second element is the reference seismogram index, and the third number is the cutoff threshold of the cross-correlation coefficient (usually set it from 0.6 - 0.8). Seismograms with cross-correlation coefficient below the threshold will be removed. For the first round of alignment, we set align(1, :)=[61.5-15, 58, 0.7]. This means the alignment window is from 46.5 sec to 76.5 sec, since the window length corresponding to the first filter is 30 sec. The reference seismogram is #58 and the threshold is 0.7.

```
%% Parameters for alignment
Band_for_align=4;       % different freqency choice for alignment t
align(1,:)=[61.5-15,58,0.7];    % 1st align: freq band=[0.1,0.25];w
align(2,:)=[60.3-7.5,48,0.6]; % 2nd align: freq band=[0.25,0.5];wir
align(3,:)=[59.9-4,39,0.6]; % 3rd align: freq band=[0.5, 1.0];windc
align(4,:)=[59.9-4,0,0.6];  % 4th align: freq band=[0.5, 1.0];windc
align(5,:)=[0 ,0, 0.0]; % 5th align: freq band=[1.0, 4.0];windowLer
ts11  =align(Band_for_align,1);                    % how long the data
refst =align(Band_for_align,2);                    % the number of refe
cutoff=align(Band_for_align,3);                 % threshold of the cros
```

After setting the parameter and running the script, you will see new figures of remaining stations and aligned and filtered seismograms. You may find fewer seismograms because the seismograms with the cross-correlation coefficient (between the reference seismogram) below the threshold are removed. You can also find the data1.mat in the input folder. Make sure the seismograms are visually aligned near the P arrivals, otherwise redo the alignment.



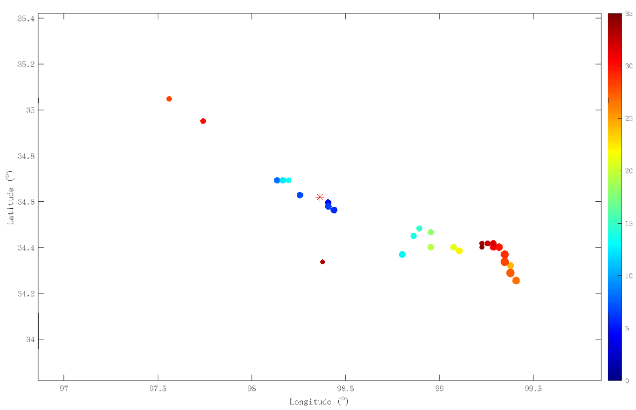


You will then change the Band_for_align=i and align(i,:) to run the ith alignment (i=2,3,4). Please note the window length when you perform the alignment. Note that the parameters of the last alignment is the same as the third alignment except that the reference seismogram number is set to zero, which means the fourth alignment is done with respect to the “mean” (stacked over all stations) seismogram from the third alignment.

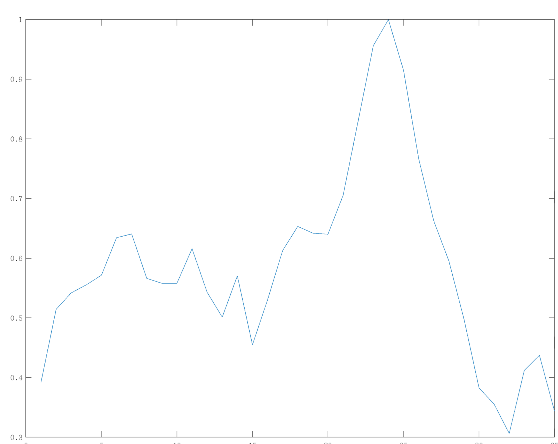
Step 4. Perform the MUSIC Back-Projection by setting runBPmusic_flag = 1. Please modify the range of latitude and longitude to the potential source area of the earthquake(units are in degrees). The variable “parr”is the starting time of the Back-projection (typically P wave arrival time). The variable “duration”is the time span of the Back-projection (units are in second).

```
%% Parameeters for setpar/runteleBP
inputband=4;              % number of align_data used for runteleBP
parr=55;                  % P arrival time, could be same as tsll
over=45;                 % duration of runteleBP
qs=100;                   % longitudinal griding
ps=100;                   % latitudinal griding
latrange=[-0.8 0.8];          % latitudinal range
lonrange=[-1.5 1.5];          % longitudinal range
    %%% Band choice
    Band=4;               % frequency choice for setparBP/runteleBP
                          % for details, look at function 'band_selec
        % Band=1 [0.05,0.25]; Band=2 [0.25,1.0]; Band=3 [0.5,1]
        % Band=4 [0.5,2]    ; Band=5 [1,4]
```

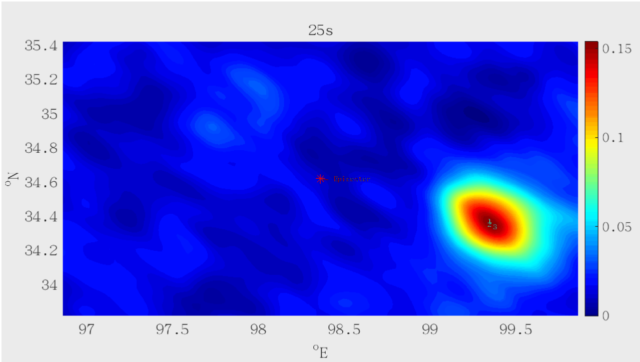
After running the General_BP.m with runBPmusic_flag = 1, you will see a Back-Projection movie and get three figures as follows. In the Input folder, you will find a Par0.5_2_10.mat file and a Par0.5_2_10_MUSIC_Dir folder (you are automatically navigated to this folder after running General_BP.m). Here, you can find movie.gif storing the Back-Projection movie and .mat files storing BP snapshots of each time step. A text file “HFdots” contains the BP peak timing and locations (the four columns in the file are time, lat, lon, power). You can plot the BP results with this file in GMT for better display quality. A few figures are also saved as pdfs in this folder. The “summary_BP.pdf”displays the spatial distribution of the peak power at each time step. The “power_BP.pdf” is the normalized Back-projected power of the earthquake as a function of time. If you can’t see any concentrated energy in the Back-Projection movie, please redo step 3.



Summary plot



Power plot



Movie plot

3. Calibrate with aftershocks

Step 1: prepare aftershocks.

In the “Calibrate” directory, create folders for all aftershocks. In my example, they are “afXX_Myy”, where XX is the arbitrary event number and yy could be the magnitude of aftershocks:

In each directory, create a “Data” folder and copy seismic data (in “sac” format) of each aftershock to the corresponding data folder (in this example, they have already been prepared).

Run “create_ev.m” to create the necessary Matlab file storing aftershock names. A mat file named “evtlst.mat” is created. This file stores the folders’ names for later aftershocks BP.

```
evtlst_char=['af04_M51';'af06_M52';'af08_M52'];
evtlst_name=['af04_M51';'af06_M52';'af08_M52'];

save evtlst.mat evtlst_char evtlst_name
```

Open “AU102_Auto_read_and_match.m”. The input parameters:

```
%% INPUT
mother_loc = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Calibrate';
main_mat   = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Input/Par0.5_2_10.mat'
address= '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/';            % address of
addpath(genpath(strcat(address,'funcLib/')));   % directory of Back-Projection functions
ori       = 60; % please refer to your request on IRIS
display   = 360; % please refer to your request on IRIS
Preshift = false;    % no change! About readBP
plotscale= 1.5;      % plotscale:  scaling of the amplitudes of seismograms
```

“mother_loc” is the directory of SEBP. “main_mat” is the directory of the BP file for MUSIC BP. “address” is the directory of MUSIC BP. Please make sure the directory has funcLib of MUSIC in it. Run the script, we will have the aftershock waveforms read in and the time shifts are assigned based on the mainshock time shift.

Step 2: run BP for aftershocks.
Open “AU103_Auto_run_music.m” and set some directories:

```
%% INPUT
mother_loc = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/
address= '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/';
addpath(genpath(strcat(address,'funcLib/')));   % directory of Back

```

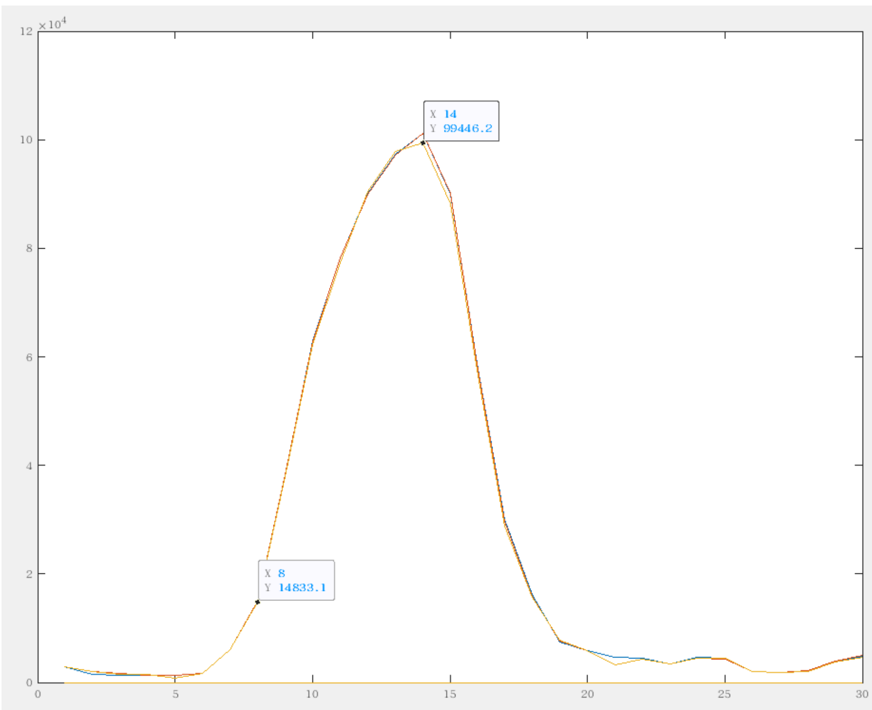
“mother_loc” and “address” are the same as in the previous step.

```
%% Loop for all events
% for j=1:2
for j = 1 : n_evt

    load 'evtlst.mat'
    evtlst_name(j,:)
    cd (evtlst_name(j,:))
        % mother_loc = '/home/liuwei/HPSSD/Qinghai/Tele_Cali/TeleDD
        % Parameter set for runBP
            lon0=98.3622588499;     % MAINSHOCK lontitude
            lat0=34.6202641954;     % MAINSHOCK latitude
            dep0 = 7.607;    % MAINSHOCK depth
            sr=10;          % sample rate
            parr=45;        % start time
            begin=0;        % always 0
            over=30;        % end time
            step=1;         % time step
            ps=120;          % number of grids for lat
            qs=120;          % number of grids for lon
            latrange=[-0.8,0.8]; % lat range
            lonrange=[-1.5,1.5]; % lon range
            fl=0.5;        % frequence low of bandpass
            fh=2;           % frequence high of bandpass
            win=10;         % window length for BP

            inputband=5;    % i.e. data5.mat
            Band = 4; % band4: [0.5,2]
```

The “lat0, lon0, dep0” is the hypocenter of the mainshock and should be the same as used in the MUSIC BP for the mainshock. “parr” is the beginning time for the aftershocks BP, and “over” is the duration. In my project, the theoretical P arrival is 60 s, so I use 45 and 30 to make sure the

time window covers the possible aftershocks time (45 s < 60 s < 75 s). Other parameters could be the same as those used in mainshock BP.
Run the script, and it will perform the MUSIC BP for aftershocks. The output files will have the same style as mainshock BP but for three aftershocks.

Step 3: Pick the BP inferred locations for aftershocks
In Matlab, cd the directory of aftershock BP results. In my project, it is "/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Calibrate/af04_M51/Input/Par0.5_2_10_MUSIC_Dir". Open "movieBP.mat", and input "plot(Power(:,:))". Matlab will plot a figure for the BP power of aftershock:



Pick the rising time of the BP power. In this example, it is 7 to 13 s. In this time window, the aftershock is imaged by MUSIC BP. Open the "bux" and "buy" variables in Matlab, and read the mean x and y values in the 8 to 14 s time window:

bux buy

30x10 double

	1	2	3
1	34.3312	34.3177	34.3312
2	35.4203	34.4925	34.3043
3	35.4203	34.4119	35.4068
4	35.4203	35.4203	35.4068
5	35.0976	35.0976	34.3312
6	34.9631	34.9497	34.9631
7	34.4791	34.4656	34.4656
8	34.4656	34.4791	34.4522
9	34.4656	34.4522	34.4656
10	34.4388	34.4253	34.4388
11	34.4388	34.4253	34.4388
12	34.4388	34.4388	34.4253
13	34.4388	34.4388	34.4253
14	34.4253	34.4119	34.4388
15	34.4253	34.4119	34.4253
16	34.3984	34.3850	34.3984

bux buy

30x10 double

	1	2	3
1	98.2992	98.2992	98.2740
2	99.4085	99.8623	98.2992
3	99.3833	97.9463	99.4085
4	99.3833	99.3581	99.3833
5	99.6606	99.6354	97.3160
6	97.3665	97.3665	97.3413
7	98.8791	98.9043	98.8791
8	98.9799	98.9547	99.0051
9	99.0051	99.0051	98.9799
10	99.0303	99.0303	99.0051
11	99.0555	99.0555	99.0303
12	99.0807	99.0555	99.0807
13	99.0807	99.0555	99.0807
14	99.0555	99.0555	99.0303
15	99.0555	99.0555	99.0303
16	99.1060	99.1060	99.0807

In this example, the average bux could be 34.44, and the average buy could be 99.05. So (34.44N, 99.05E) is the BP inferred location for the first aftershock. Repeat the procedure for all three aftershocks.

Copy the "create_ca.m" to the "Events" directory. Open the script:

```
lat_ap=[34.44;34.42;34.65];
lat_ca=[34.49;34.43;34.70];
lon_ap=[99.05;99.30;98.09];
lon_ca=[98.91;99.14;98.03];
lat_cali=[];
lon_cali=[];

save ca_ap_loc.mat lat_ca lat_ap lon_ca lon_ap lat_cali lon_cali
```

Use "lat_ap" to record the latitude for BP inferred locations, and use "lon_ap" to record the longitude for BP inferred locations. Use "lat_ca" and "lon_ca" to record the catalog locations. Run the script, and a file named "ca_ap_loc.mat" will be created. The file stores the BP inferred locations and catalog locations for all aftershocks.

Step 4: calibrate the aftershocks

Open “AU104_Auto_cali_music.m”, and set some parameters:

```
%% PRE-SET

address= '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/';            % address of
addpath(genpath(strcat(address,'funcLib/')));   % directory of Back-Projection functions
%%% INPUT
mother_loc = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Calibrate';
ap_ca_loc  = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Calibrate/ca_ap_loc.mat
ref = 25;
```

“ap_ca_loc” is the directory of “ca_ap_loc.mat” file. The “ref” is the reference station. We can keep it as default.

Run the script and we will get the calibrated aftershock BP. In the calibration directory (mine is “/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Calibrate/af04_M51/Input/Par0.5_2_10_music_Cali2Dplus_Dir”), open “movieBP.mat” by Matlab. Again, read the rising time for aftershocks and pick the mean bux and buy in the corresponding time interval.

bux buy

30x10 double

	1	2	3
1	34.3984	34.3984	34.3850
2	34.3984	34.4119	34.3984
3	34.8959	34.8152	34.8824
4	34.8959	34.9093	34.8959
5	35.3396	35.3530	34.7211
6	34.9900	34.9900	34.9766
7	34.5060	34.5194	34.5060
8	34.4925	34.5060	34.5060
9	34.4925	34.4925	34.4791
10	34.4791	34.4791	34.4656
11	34.4791	34.4656	34.4791
12	34.4791	34.4656	34.4656
13	34.4791	34.4656	34.4656
14	34.4791	34.4656	34.4791
15	34.4656	34.4791	34.4656
16	34.4522	34.4656	34.4388

bux buy

30x10 double

	1	2	3
1	99.7362	99.7110	99.7362
2	99.7110	99.6858	99.6858
3	99.2320	99.8118	99.2572
4	99.2320	99.2068	99.2068
5	97.2404	97.2152	99.4841
6	98.9295	98.9043	98.9295
7	98.7782	98.7530	98.7530
8	98.8791	98.8539	98.8286
9	98.8791	98.8539	98.9043
10	98.9043	98.8791	98.9295
11	98.9295	98.9547	98.9043
12	98.9295	98.9547	98.9295
13	98.9295	98.9547	98.9295
14	98.9295	98.9295	98.9043
15	98.9295	98.9043	98.9043
16	98.9547	98.9295	98.9799

In the example, mean x and mean y are 34.48 and 98.93, respectively. They are very close to the catalog location (34.501097N, 98.930649E). This proves that our calibration is valid. Repeat the procedure for all aftershocks.

Step 5: calibrate the mainshock

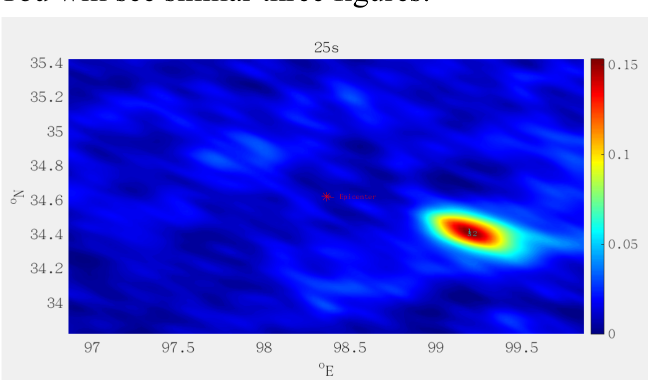
Since we validate our slowness calibration, we can now perform that on the mainshock. Open "AU105_Main_cali_music.m" (please note that "mother_loc" is the directory of mainshock):

```
%% PRE-SET
%%% INPUT
mother_loc = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/';
ap_ca_loc  = '/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU_workshop/Calibrate/ca_ap_loc.mat';
ref = 25;
```

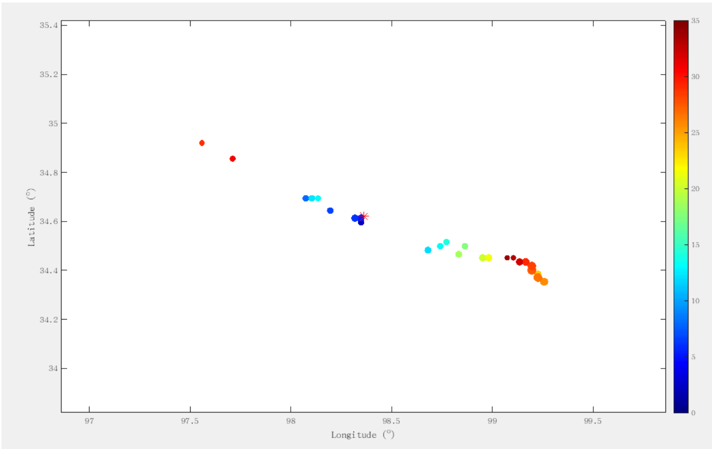
```
  n_evt=3

      load 'Input/Par0.5_2_10.mat'
      load(ap_ca_loc);    % Load ca and ap location of afteshocks


      %% STEP 1: Get slowness error for the mainshock.

          lat_sta=ret.lat; lon_sta=ret.lon;              % stations

          lat_ca = lat_ca; lon_ca = lon_ca; dep_ca(1:n_evt,1) = ret.dep0
          lat_ap = lat_ap; lon_ap = lon_ap; % AF apparent (BP inferred)

          lat_c=mean(lat_ap); lon_c=mean(lon_ap); dep_c =ret.dep0;

          dS2Dplus = get_dS_2Dplus(lat_sta,lon_sta,lat_c,lon_c,dep_c,...
                              lat_ca,lon_ca,dep_ca,lat_ap,lon_ap,ref); %
          ret.dS0 = dS2Dplus.dS0;
          ret.dSx = dS2Dplus.dSx;
          ret.dSy = dS2Dplus.dSy;

   save Input/Par0.5_2_10_cali.mat
```

"n_evt" is the number of aftershocks. Run the script, and we get the results of calibrated BP for the mainshock. It is stored in the same directory as mainshock BP before calibration and has "Cali2Dplus_Dir" at the end of the file name. In this example, it is in "/home/liuwei/HPSSD/Qinghai/BP/TeleDD_Loc/AU/Input/Par0.5_2_12_music_Cali2Dplus_Di" .

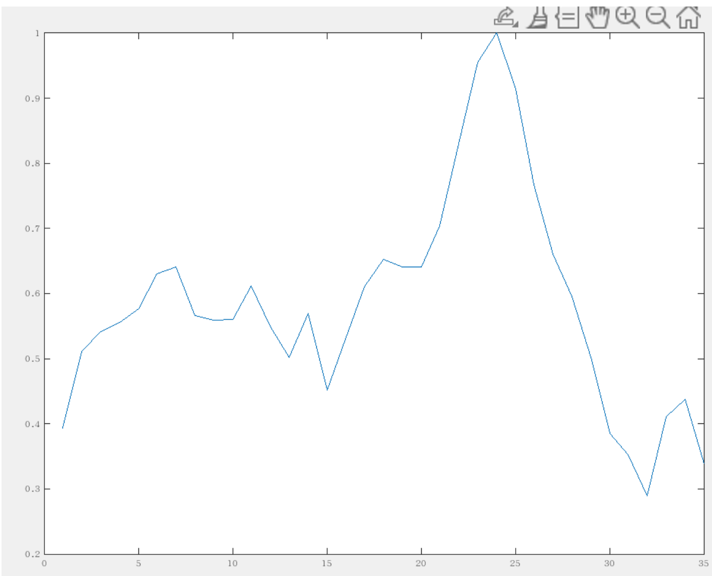
You will see similar three figures:



Movie plot



Summary plot


Power plot