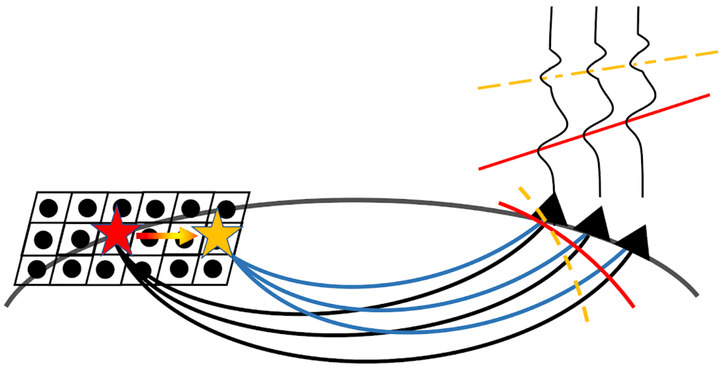
MUSIC Teleseismic Back-Projection

Instruction prepared by Tian Feng and Lingsen Meng
Dept. of Earth, Planetary and Space Sciences, UCLA

1. Introduction

The objective of this lab is to perform the Back-Projection Imaging on the seismograms of large earthquakes recorded by large-scale dense arrays. The instruction is performed on the 2018 Mw 7.5 Palu Earthquake, and you will complete the Back-Projection Imaging on the 2011 Mw 9.0 Tohoku Earthquake on your own.

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.

In this lab, we will perform two versions of Back-Projection: Beamforming and Multiple Signal Classification (MUSIC). Beamforming stacks the seismograms directly in the time domain, while MUSIC 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 simutaneously. 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/

2. Practice on 2018 Mw 7.5 Palu Earthquake

We start by downloading the zip file MUSICBP on github. Once the source files aredownloaded,unzip MUSICBP.ZIP. Note that MUSICBP is a Matlab-based package requring the **Signal Processing, Mapping and Imaging Processing** tool boxes.

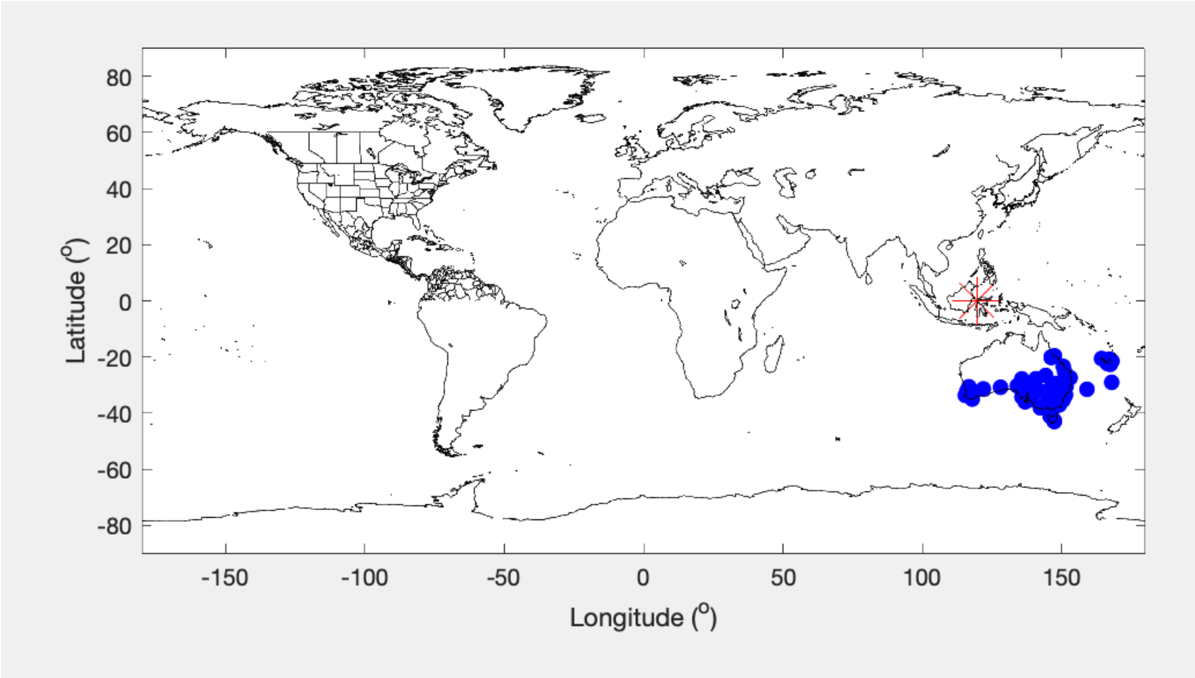
Step 1: open the General_BP.m file with Matlab in the folder of MUSICBP. This file controls all the steps of the program. The following figure shows 5 flags to enable each processing step. When the flag is set to 1, running the script would implement the corresponding functions. You should only set one flag to 1 other flags to zero each time.

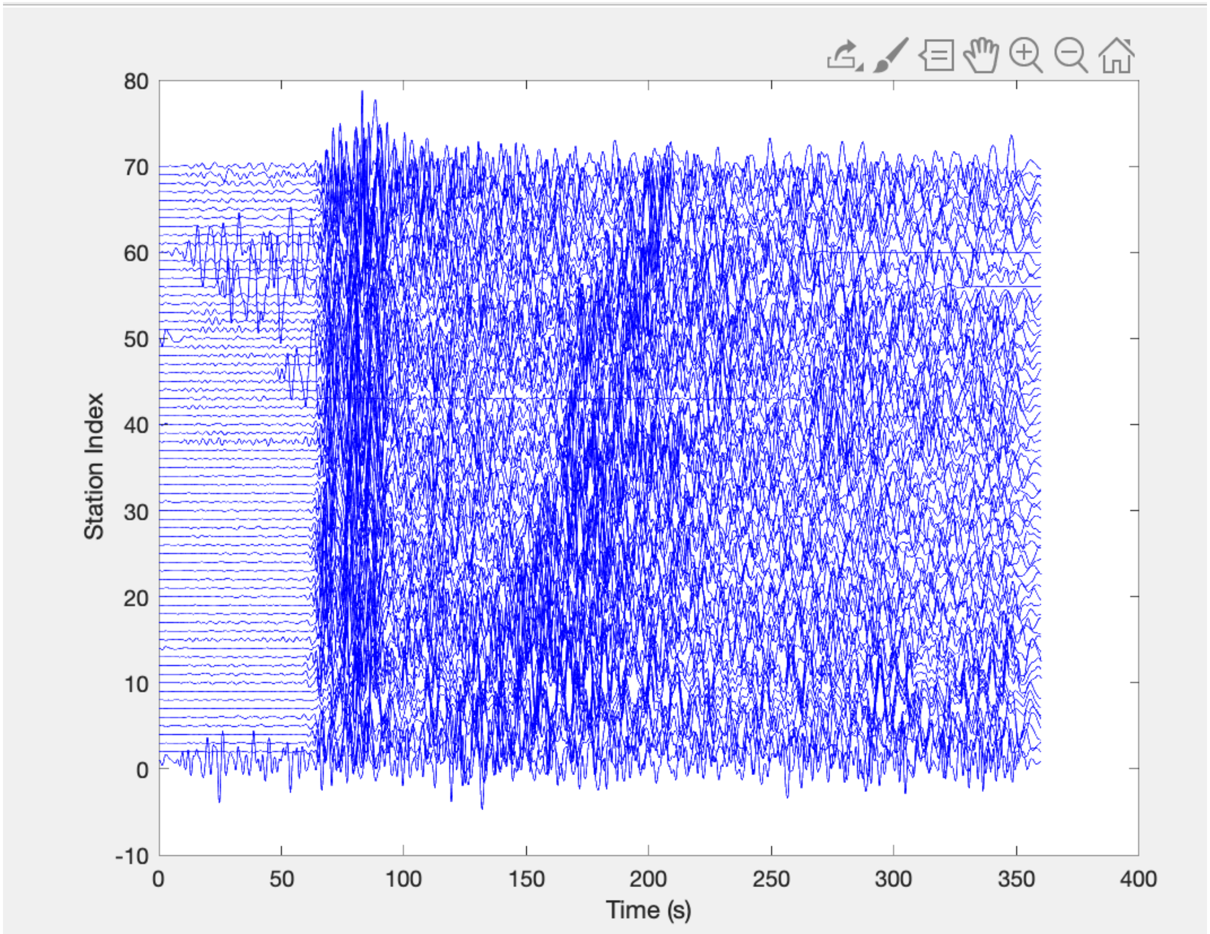
```
%% *** Set here the processing steps to perform (positive=1, negtive=0)****
Initial_flag=0;      % Initializing a new project
readBP_flag=0;       % Reading seismogram from .SAC files
alignBP_flag=0;      % Hypocenter alignment
runBPbmfm_flag=0;    % Beamforming Back-projection
runBPmusic_flag=0;   % MUSIC Back-Projection
```

Step 2: Initialize the working project by setting Intial_flag = 1. After clicking the run button, you will create a folder named “Palu_2018”. The hypocenter parameters of latitude, longitude, depth, and magnitude should also be set before running the script. After initialization, you could find three subfolders in your project folder: “Data”, “Fig”, “Input”. Then you should copy all the data files (.SAC) into the subfolder “Data”.

```
%% *** Set here the parameters to initialize the project and read the SAC files***
project = 'Palu_2018';% name of the project, e.g. Tohoku_2011
lon0=119.840;         % hypocenter longitude
lat0=-0.178;          % hypocenter latitude
dep=10.0;             % hypocenter depth
Mw=7.5;               % magnitude
sr=10;                % sampling rate in Hz (the frequency that seismograms are down-sampled to)
ori=60;               % length of seismograms before P-arrival time in seconds
displayLength=360;    % length of waveforms (in seconds) to be displayed
plotScale=1.5;        % amplitude scaling factor of seismograms for display purpose
```

Step 3: Then you will start to import seismograms by setting readBP_flag = 1 and other flags = 0. After running the script, you will see two figures: one is the map of stations and the earthquake, the other is the original waveforms.In the folder “Input”, you will see data0.mat file storing the raw waveforms and other metadata.





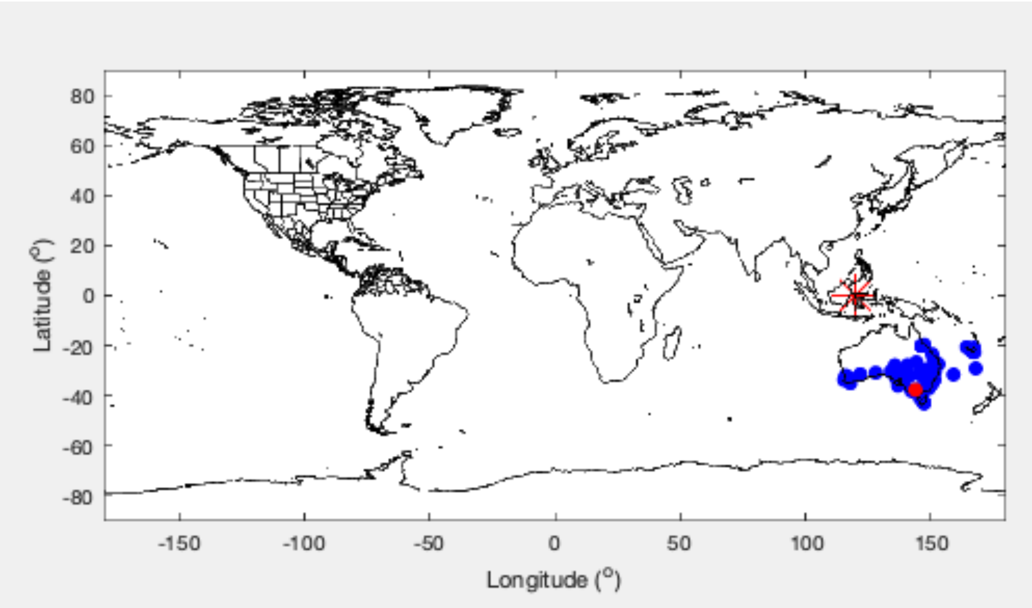
Step 4: Then align the seismograms **(This is the Most important step!!!)** by setting alignBP_flag = 1, and other flags = 0. You will align the seismograms 4 times, from low to high frequency bands.The comments after each line of “align()” list the frequency range and corresponding window length of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

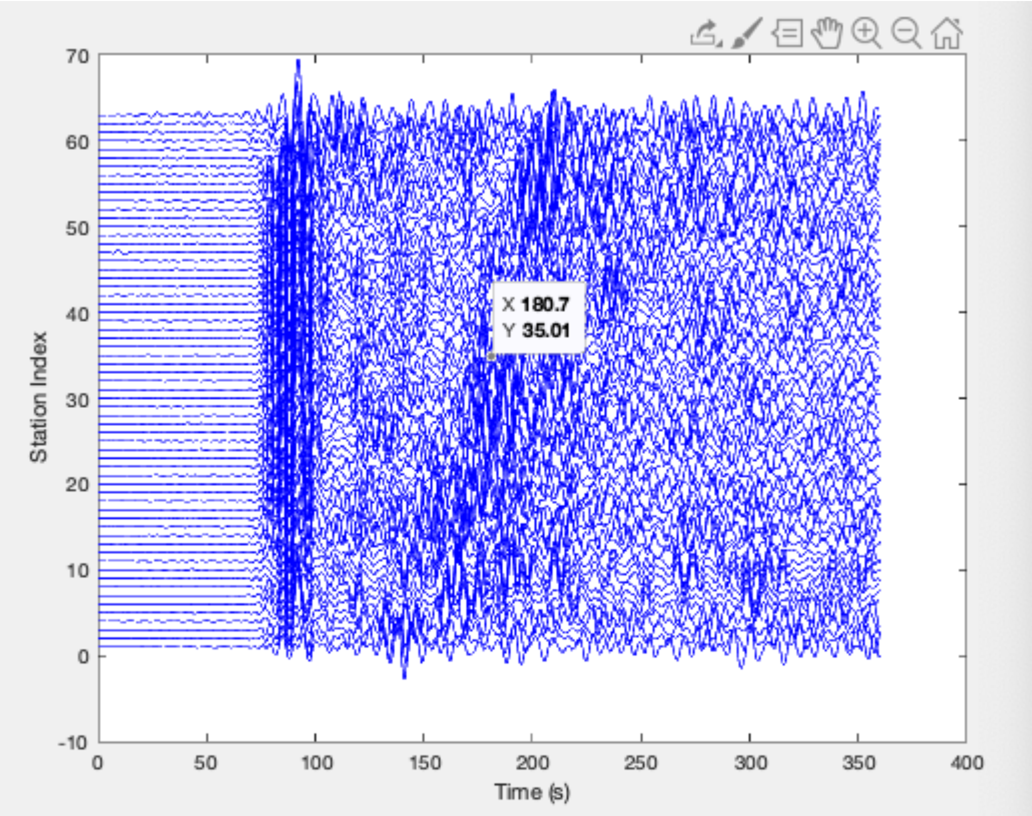
different frequency band, please modify “alignband.m” accordingly. After filtering the raw seismograms with different frequency bands, the script will align the seismograms in selected windows by cross-correlation. You can find details about cross-correlation through the link: https://www.mathworks.com/help/signal/ug/align-signals-using-cross-correlation.html

The essence of this step is to find the right starting time of the window and the reference seismogram. You should choose a represetative seismogram with clear first arrival as the reference seismogram. For example, # 40 seismogram in the above figure is a good choice while the # 60 seismogram is not suitable to be a reference seismogram due to large noise before the P wave arrivals. 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,:)=[54,40,0.7]. This means the alignment window is from 54 sec to 84 sec, since the window length corresponding to the first filter is 30 sec. The reference seismogram is #40 and the threshold is 0.7.

```
%% *** Set here the Parameters for Hypocenter alignment ***
bandChoice=4;       % Choice of the alignment frequency band.
align(1,:)=[54,40,0.7]; % 1st align: freq band=[0.1, 0.25](Hz) windowLength=30(sec) maxShift=5(sec)
align(2,:)=[61,40,0.6]; % 2nd align: freq band=[0.25,0.5]  windowLength=15 maxShift=0.6
align(3,:)=[64,40,0.6]; % 3rd align: freq band=[0.5, 1.0]  windowLength=8  maxShift=0.1
align(4,:)=[64,0, 0.6]; % 4th align: freq band=[0.5, 1.0]  windowLength=8  maxShift=0.1
ts  = align(bandChoice,1); % start of the alignment window
refSta = align(bandChoice,2); % No. of the reference seismogram, set to zero for the stacked seismogram
cutoff= align(bandChoice,3); % cutoff threshold of the cross-correlation coefficient
```

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.



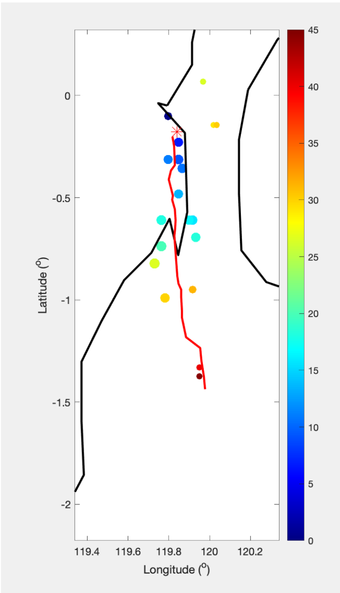


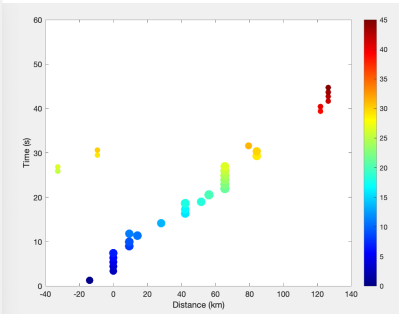
You will then change the bandChoice=i and align(i,:) to run the ith alignment (i=2,3,4). Please note the window length when you perform the alignment. Note that the parameters of the last alignment is the same as the third alignment expect that the reference seismogram number is set to zero, which means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

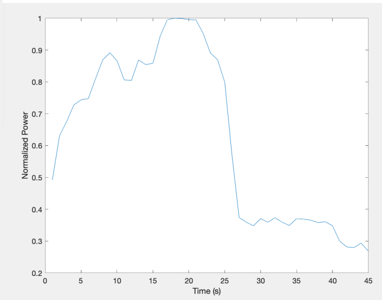
Step 5. Perform the Beamforming Back-Projection by setting runBPbmfm_flag = 1. Please modify the range of latitude and longitude to potential source area of the earthquake(units are in degrees). The variable "parr" is the starting time of the Back-projection (typically P wave arrival time). The variable "duration" is the time span of the Back-projection.

```
%% *** Set here the Parameters for back-projection runner ***
inputBand=4;         % number of aligned seismograms used as an input for the back-project:
parr=61;             % P-wave arrival time, could be the same as ts
duration=45;         % earthquake
qs=60;               % number of grids in latitude of the imaging domain
ps=60;               % number of grids in longitude of the imaging domain
latrange=[-2 0.5];   % latitude length of the imaging domain
lonrange=[-0.5 0.5];% longitude length of the imaging domain
Band=4;              % frequency band for the back-projection
% Band=1 [0.05,0.25](Hz); 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 runBPbmfm_flag = 1, you will see a Back-Projection movie and get four figures as following. In the Input folder, you will find Par0.5_2_10.mat file and a Par0.5_2_10_bmfm_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. There are two “ distance vs time” plots showing the locations of peak power as a function of epicentral distance (**dis_epi_BP.pdf)** or north-south distance (**dis_NS_BP.pdf**). You can modify the **SummaryBPbeamforming.m** or **SummaryBPmusic.m** to use other distance metric or adjust the content of the figures. The slope of these two figures could be used to estimate the rupture speed. If you can’t see any concentrated energy in the Back-Projection movie, please redo step 4.







summary plot **distance vs time plot** **power plot**

Step 6. Perform MUSIC Back-Projection by setting runBPmusic_flag = 1. **Navigate your current directory to MUSICBP before running the script again**. You will get a similar output as the previous step, please compare the difference between the MUSIC version and the Beamforming version.

3. Assignment: Perform on the 2011 Mw 9.0 Tohoku Earthquake

The Palu Earthquake is just for practice. You will perform the Back-Projection on the 2011 Mw 9.0 Tohoku Earthquake with the following parameter: Lat0=38.297; Lon0=142.373; Dep=20; Mw=9.0; and duration=150. The data is in the folder named **TohokuTAData**. Try your own alignment and station selections. Please use both Beamforming and MUSIC versions and check if there’s any difference. Also, set the latrange=[-3 3] and lonrange=[-3 3]. In the dis_NS_BP.pdf, the projection direction is set to North-South direction. If you want to change the projection direction, you could change the variable pjt_az in the summaryBPmusic.m and summaryBPbeamforming.m files.

You should complete a lab write-up containing an introduction of the Back-Projection (Beamforming and MUSIC). Please include your alignment criteria and how many seismograms you delete in each round of alignment. You will include the summary plots, distance vs time plots, and the power plots for each version in the report. Then compare your summary plots with the following paper, and **describe the rupture extent and speed** in the paragraph. ***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.*

Also, please find a source model of the Tohoku Earthquake and compare the difference of location of the highest earthquake energy. You can find many versions in this link: http://equake-rc.info/srcmod/

Please explain why they are similar or different to the BP summary plot (Bonus question)? Finally, you will only submit a pdf file of the report, including all the figures generated from the scripts.