

DATA AND CODE REPOSITORY

prepared by

Sin-Mei Wu

University of Utah

May 2021

Chapters

1. DATA	2
1.1 2015 Upper Geyser Basin Array	2
1.2 2016 Upper Geyser Basin Array	3
1.3 2017 Upper Geyser Basin Array	4
1.4 2018 Hawaii Rapid and Permanent HVO Arrays	5
1.5 2019 Hawaii Post Eruption Array	7
1.6 2018–19 Steamboat Geyser Array	7
1.7 2018 Utah Mine Array	8
1.8 2020 Yellowstone Array Plus Nearby Permanent Stations	9
2. CODE PACKAGE	10
2.1 Cross-Correlation (CC)	11
2.1.1 Stacked Single-Component CC	11
2.1.2 Stacked Nine-Component CC	11
2.1.3 Short Window Nine-Component CC	11
2.1.4 Whole Array Normalized Stacked Nine-Component CC	12
2.1.5 Whole Array Normalized Short Window Nine-Component CC	12
2.2 Cutting the continuous data into small windows	13
2.3 Polarization Plus Backprojection	13
2.3.1 Old Faithful (Single Source Station)	13
2.3.2 Steamboat (Entire Array)	14
2.4 Temporal Change in Seismic Velocity (dv/v)	15
2.4.1 Moving Window Cross-Spectral Method	15
2.4.2 Stretching Method	15

2.5 Frequency Dependent Polarization Analysis	15
2.6 Doublet Pool Detection and Periodicity	16
2.7 Old Faithful Detection, Classification, and Prediction	16

CHAPTER 1

DATA

For this chapter, I provide the access to the seismic data including continuous data and cross-correlations that I have processed. Note that all the continuous nodal data of vertical component would never be reversed (i.e., those data remain the original nodal polarity). Please feel free to contact me if there are any questions (a06859a35@gmail.com).

1.1 2015 Upper Geyser Basin Array

The 2015 Upper Geyser Basin array consists of ~133 nodal stations from November 2 to November 14 2015. In this repository, I provide the location of cross-correlations (CC) on University of Utah CHPC server. For raw data, please contact Jamie Farrell. For some of the detail processing, I refer to the published work (Wu et al., 2017) shown below.

Published work:

Wu, S.-M., Ward, K. M., Farrell, J., Lin, F.-C., Karplus, M., & Smith, R. B. (2017). Anatomy of Old Faithful from subsurface seismic imaging of the Yellowstone Upper Geyser Basin,

Geophysical Research Letters, 44(20). doi:10.1002/2017GL075255.

Data (cross-correlations) used in the paper:

/uufs/chpc.utah.edu/common/home/flin-group3/icemax/UGB_DATA_GRL

Main Directory:

/uufs/chpc.utah.edu/common/home/flin-group3/icemax/OLD_FATH_DATA

Based on the main directory, the stacked 9-component cross-correlations can be found here:
Decimated_to_100Hz/ccf_5min_9comp/stack_all_new

The individual 5-min CCs are here, this is my first version of outputting short-window CCs and hence not organized for convenient usage. I would suggest re-running the CCs (chapter 2.1) if you need a thorough study based on the data.

Decimated_to_100Hz/ccf_5min_9comp/\$sta where *\$sta* represents the desired station name

1.2 2016 Upper Geyser Basin Array

The 2016 Upper Geyser Basin array had a total of 617 nodal stations location and each of the subarray lasted for ~2 days between November 7 to November 16 2016. The published work only used the 80-station array situating on top Old Faithful geyser's sinter. In this repository, I document the stacked CC for the entire array, and short-window CCs for the published study.

Published work:

Wu, S.-M., Lin, F.-C., Allam, A., & Farrell, J. (2019). Imaging the deep subsurface plumbing of

Old Faithful geyser from low-frequency hydrothermal tremor migration, Geophysical Research Letters, 46. <https://doi.org/10.1029/2018GL081771>.

Data (cross-correlations) used in the paper:

/uufs/chpc.utah.edu/common/home/flin-group3/icemax/UGB_DATA_2016

Main Directory:

/uufs/chpc.utah.edu/common/home/flin-group3/icemax/OLD_FATH_DATA_2016

Based on the main directory, the processed (synchronized, high-passed 0.05 Hz) continuous data are here: [\\$mon\\$day2016](#)

The stacked 9-component cross-correlations can be found here: [stack_all_new](#)

For the short-window (1 min) CCs, I have only done for a few source stations (029, 554, 561, and 562) for the tremor polarization and back projection study (Wu et al., 2019). Please go to [tremor_\\$sta/\\$sta](#) for the 9-component 1-min CCs. The CCs are undergone whole array normalization and you can find the stacked CCs based on the time of Old Faithful eruption here: [tremor_\\$sta/stack_who_1-5_\\$sta_pair](#)

1.3 2017 Upper Geyser Basin Array

I don't have much work done for the 2017 data besides taking a look of CCs (source station: 029, 066, 071, 130, and 554) and plotting the movies to see wave propagation.

Main Directory:

/uufs/chpc.utah.edu/common/home/flin-group3/icemax/OLD_FATH_DATA_2017

The processed (synchronized, high-passed 0.05 Hz) continuous data are here: [\\$mon\\$day2017](#)

Stacked CCs for the listed source stations are here: *stack_all_new_old* and *stack_all_new_029*

I will suggest recalculating the CCs directly for new studies.

For the movies for wave propagation, please go to the directory called *Movie*. It is not well organized yet but you can look at the script called *prepare.csh* to see how it has been done.

1.4 2018 Hawaii Rapid Nodal and Permanent HVO Arrays

The Hawaii data that I have processed for three topics. 1) One is for a general tomography on the Hawaii big island that includes permanent HVO stations, 2) one is for the linear array that deployed along the highway 130, and 3) the last one is the published work (Wu et al., 2020) that utilizes auto-correlation functions (ACFs) to look for the temporal changes in seismic velocity (dv/v) across the Kilauea volcanic system. Below I describe the data access in the order of the listed topics.

For tomography and the linear array, here is the main Directory:

/uufs/chpc.utah.edu/common/home/flin-group3/icemax/Hawaii_2018

The processed (response removed to velocity, decimated, synchronized, high-passed 0.05 Hz) continuous nodal data are here: [\\$mon\\$day2018](#)

The data from permanent HVO stations that were processed to be compatible with the nodal data are here: [HV_2018/\\$sta/xxx.bp](#)

The stacked CCs including the FTAN and SNR results for tomography are here:

TOMO_example/DATA

The stacked CCs used for the linear array: *CCF_YD_night* and *CCF_YD_wholearray*

The relative amplitude across the line is preserved in *CCF_YD_wholearray* but I am unsure about *CCF_YD_night* which is using the nighttime windows only.

Published work:

Wu, S.-M., Lin, F.-C., Farrell, J., Shiro, B., Karlstrom, L., Okubo, P., & Koper, K. (2020). Spatiotemporal Seismic Structure Variations Associated with the 2018 Kīlauea Eruption based on Temporary Dense Geophone Arrays, *Geophysical Research Letters*. 47, e2019GL086668. <https://doi.org/10.1029/2019GL086668>

For dv/v , here is the main Directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/KILAUEA_VARIATION

Based on the main directory, the 5-min ACFs for each of the stations are here:

\$sta/\$sta-\$sta/\$comp

You also can find hourly stacked ACFs one layer up.

Same thing for the HVO permanent stations, go to */uufs/chpc.utah.edu/common/home/flin-group5/icemax/KILAUEA_VARIATION_BB*

1.5 2019 Hawaii Post Eruption Array

Main Directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/KILAUEA_2019

The processed (response removed to velocity, decimated, synchronized, high-passed 0.05 Hz) continuous nodal data are here: [\\$mon\\$day2019](#)

Stacked CCs with whole array normalization along the line: *stack_all_line_reduced* and *stack_all*

The linear line was extended towards north and south (compared to 2018), so the ‘reduced’ represents I tried to keep the line as the same as 2018 array.

You can check out the station file for the exact stations used in the CCs: *station_line.lst* and *station_line_reduced.lst*

1.6 2018–19 Steamboat Geyser Array

The way I processed the data was only for one major direction – the 4D tremor location similar to what I did for the 2016 Old Faithful data. The outcome is one publication based on the 2019 data but I did a similar process so the all data should be consistent and are distributed in three main directories (STEAMBOAT_2018, STEAMBOAT_2019, and STEAMBOAT_2019_Final). The CCs are all done with the whole array normalization, using 5-min window then stacked to hourly.

Published work:

Wu, S.-M., Lin, F.-C., Farrell, J., Keller, W., White, E., & Hungerford, J. (2021). Imaging the Subsurface Plumbing Complex of Steamboat Geyser and Cistern Spring with Hydrothermal Tremor Migration using Seismic Interferometry, *Journal of Geophysical Research: Solid Earth*, 126, e2020JB021128. <https://doi.org/10.1029/2020JB021128>.

Main Directory:

</uufs/chpc.utah.edu/common/home/flin-group4/icemax>

The processed (decimated and synchronized) continuous nodal data are here: *STEAMBOAT_2018/\$mon\$day2018* and *STEAMBOAT_2019/\$mon\$day2019*

The CCs are in *STEAMBOAT_2018/\$sta* and *STEAMBOAT_2019_FINAL/\$sta*

The hourly-stacked CCs can be found as:

STEAMBOAT_2019_FINAL/\$sta/\$pair/Hours12-cgf-norm_who-CGF_\$pair

1.7 2018 Utah Mine Array

The Utah mine array only has 17 stations. I computed 5-min CCs with the whole array normalization.

Main Directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/UTAH_MINING_2

The raw data from Derrick is a zip file: *DATA/lw_coal_node.zip*

The unzip and organized file that shown as daily sac is here: *DATA/2018. \$mon. \$day*

The CCs *\$sta*

1.8 2020 Yellowstone Array Plus Nearby Permanent Stations

This is an ongoing work that I am combining both dense nodal array and nearby permanent stations for producing Yellowstone tomography. Here I just listed the major working directories and I may update this repository after the project is published.

The main directory for the nodal data:

/uufs/chpc.utah.edu/common/home/flin-group5/icemax/YELLOWSTONE_NODAL_WY_2020

The main directory for permanent station data (network: MB, PB, US, and WY):

/uufs/chpc.utah.edu/common/home/flin-group5/icemax/YELLOWSTONE_NODAL_WY_2020/WY_DATA/Data

The stacked 9-component CCs for all data: *stack_all_new*

FTAN and tomography results for 2020 data: *TOMO*

FTAN and tomography results from Jamie's sparse data: *TOMO_Jamie*

Combined both sparse and dense data for tomo: *TOMO_combined_weight*

Hsin-Hua's 3D joint inversion with ray tracing for surface wave: *HH_Joint_Inversion*

Movie for wave propagation: *Movie*

CHAPTER 2

CODE PACKAGE

I have organized the code to be individual package for particular usage, usually it comes along with an example data to run, a README or a usage file showing you how to run it. I did in this way for the simplicity of the code usage, so that the code is not tied to/buried in the complicated directories and I hope the code can be leaned with its core function and readily adaptable for the desired, further analyses.

2.1 Cross-Correlation (CC)

There are many versions of cross-correlations in our group but the core function and the script (in C) is the same. The major differences are the computing channels (single component or 9-component), normalization (preserve relative amplitude between component or among whole array), and the output CCs (stacked or individual segment). The codes are developed and modified mostly for nodal data format (applicable to permeant station data just need to organize the data structure). For applying the code to different dataset, you need to modify the C script to make sure the parameters (e.g., data point, sampling, data length, and stations) are changed based on your current dataset.

2.1.1 Stacked Single-Component CC

Main directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/4_share_1comp

This is the code closest to the original code from Fan-Chi. The difference is that I modified it to read SAC data as input. I don't think the example in the directory is effective here so I put it here just as a reference of the access to the code. The C script is similar to the rest of CC scripts as those scripts are built up based on this one. If you do want to use the code, remember to change the sampling (delta) in the output sections.

2.1.2 Stacked Nine-Component CC

Main directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/4_ShiouYa_9Comp

You will find an example including the detailed workflow here. This package includes the process from organizing data structure, cutting into small windows, to calculating the 9-component stacked cross-correlations.

2.1.3 Short Window Nine-Component CC

The only difference from 2.1.2 is this code outputs individual short-window (e.g., 5min) CCs. I don't have an example package as the input is the same. Note that the parallel computation is no longer effective as the output is written within the parallel section. The source code can be found here: /uufs/chpc.utah.edu/common/home/flin-group3/icemax/useful_tool/widget/cor_whiten_1min_1000Hz_newdir

Please make sure the output directory (\$sta/\$pair/\$comp) is made before the CC calculation. This code shows how to make it: */uufs/chpc.utah.edu/common/home/flin-group4/icemax/STEAMBOAT_2019_FINAL/ccf_5minute_wha.csh*

2.1.4 Whole Array Normalized Stacked Nine-Component CC

I don't often use this because the concern of nonlinear normalization based on the apparent dominant frequency. There's an example that I calculated for 2019 Kilauea data (section 1.5) and you can code the source code here:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/KILAUEA_2019/wholearray_ccf

2.1.5 Whole Array Normalized Short Window Nine-Component CC

This is the code that I commonly use for Old Faithful, Steamboat, and Utah Mine studies. Please find the source code here: */uufs/chpc.utah.edu/common/home/flin-*

group4/icemax/STEAMBOAT_2019_FINAL/cor_whiten_whole_array_5min

And this is an example of how I run it: */uufs/chpc.utah.edu/common/home/flin-*

group4/icemax/STEAMBOAT_2019_FINAL/run_CCFs_para.txt

The common procedures that I use are (1) pre-processing, (2) cross-correlation that outputs short-window CCs, (3) filtering to desired frequency, (4) determination of the value (amplitude) for further normalization, then 5) normalize the short-window CCs based on the value. However, the process is not efficient as the code is not in C after (2). The post-filter and post-normalization

actually cost quite amount of time. I strongly suggest modifying the C code for future usage. For (4), you can find the code here:

```
/uufs/chpc.utah.edu/common/home/flin-  
group4/icemax/STEAMBOAT_2019_FINAL/norm_wholearray_ccf.csh
```

2.2 Cutting the continuous data into small windows

You can find the example to run here:

```
/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/4_ShioiYa_9Comp/  
Package_4_ShioiYa/cut_min.csh
```

Please give the desired time window is sec (now is 300s for 5-min window). The fortran code won't output the windows that have zero amplitude.

2.3 Polarization Plus Backprojection

Following the published works (Wu et al., 2019 & 2021), the polarization + backprojection method is done with using single source station (2.3.1) and taking the entire array as potential source station (2.3.2).

2.3.1 Old Faithful (Single Source Station)

Main directory:

```
/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/Polarization_4share
```

This is for computing the dominant direction in 3D of CCs using eigen analysis, performing back projection in 3D space, then plotting out the result. I use the example using the published Old Faithful data and a step-by-step readme.

2.3.2 Steamboat (Entire Array)

Instead of the direct 3D back projection, the method applied for Steamboat data adapts a 2-step back projection scheme from 2D to 3D. The reason doing this is the source properties (quantity, location, and strength) are complicated compared to Old Faithful. Please refer to Wu et al. (2021) JGR paper for the detailed processing. I also use the example based on the published work here.

Directory for 2D backprojection demonstration:

[/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/2D_Back_Projection_Polarization_4share](#)

This package is an simplified version that demonstrates the 2D surface projection using the closest receivers, which also output the image similar to Figure 4a in the 2021 paper.

To have the full backprojection analysis, please refer to here:

Directory for 2D and 3D backprojection method:

[/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/2Dthen3D_Back_Projection_Polarization_4share](#)

This package gives an example of 2-step as well as two iteration projections. Please see the README about the structure and the instruction to run them. I also recommend to read the 2021 paper and read through the commented codes to see what are the parameters you can set for your data.

2.4 Temporal Change in Seismic Velocity (dv/v)

The core function of the dv/v is the evaluation the relative velocity, or phase changes, between any two given waveforms (CCs) that were computed at two different time windows. Therefore, the code package here demonstrates how to get the dv/v out of two waveforms based on the two common methods. There's README in the directory that will guide you how to run it, what are the parameters, and how to use the results. Please also pay extra attention to the sign of the dv/v.

2.4.1 Moving Window Cross-Spectral Method

Main directory:

[/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/MWCSM_4_share](https://uufs.chpc.utah.edu/common/home/flin-group4/icemax/4_share/MWCSM_4_share)

2.4.2 Stretching Method

Main directory:

[/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/Stretch_4share](https://uufs.chpc.utah.edu/common/home/flin-group4/icemax/4_share/Stretch_4share)

2.5 Frequency Dependent Polarization Analysis

The frequency-dependent polarization analysis is based on Koper and Hawley (2010). A direct example of the method is my Kilauea paper (Wu et al., 2020). My role here is organizing the whole procedure suitable for nodal data, including the data structure, calculation, and plotting. Here I use the example of Yellowstone Lake data and you should be able to run through it easily after taking a look of the detailed instruction: *FREQUENCY_DEPENDENT_POLARIZATION.txt*

Main directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/4_share_frequency_dependent_polarization

2.6 Doublet Pool Detection and Periodicity

I wrote a Fortran code specifically for Doublet Pool eruption detection and eruptive length determination. This is readily applicable for any day-long seismogram from the station near doublet pool. There's a readme inside the directory too.

Main directory:

/uufs/chpc.utah.edu/common/home/flin-group4/icemax/4_share/4_share_DoubletPool_detection

2.7 Old Faithful Detection, Classification, and Prediction

I wrote a series of Fortran, C, and Python codes for Old Faithful tremor detection, classification, and the prediction. Unfortunately, there are many codes that I have not had the chance to revisit and reorganize to be comfortable for sharing at this point, mainly because there are too many versions and we have not warped this project up. *I will be updating this repository for this section.*