Homework #2: Normal mode observations, polarization analysis and component rotation **Due: 5:00 PM 2017-02-13**

Please read the following questions carefully and make sure to answer the problems completely. In your MATLAB script(s), please include the problem numbers with your answers. Use the *Publish* function in MATLAB to publish your script to a *pdf* document; find something similar if not using MATLAB. LaTeXwith *mcode.sty* or some other language will work. For more on the *Publish* functionality within MATLAB see `http://www.mathworks.com/help/matlab/matlab_prog/publishing-matlab-code.html`. Upload your *pdf* file to Blackboard under Assignment #2. Your filename should be *GEOPH677_HW2_Lastname.pdf*. Hint: You can achieve this automatically by calling your MATLAB script *GEOPH677_HW2_Lastname.m*.

Intended Learning Outcomes

Students will be able to:

1. Apply the Discrete Fourier Transform to seismic data time series
2. Identify normal modes of the Earth in the amplitude spectra of a seismic trace
3. Determine the azimuth and ellipticity of a 3-component seismic trace using coherency analysis
4. Download broadband seismic data for a particular earthquake and station using the IRIS web-based tool WILBER3.
5. Rotate 3-component seismogram from EN to RT coordinates

Part 1: Normal mode observations *(35 pts.)*

In this section you will work to identify the normal modes excited by the 2004 Sumatra-Andaman Earthquake. The file *sumatra.txt* is the vertical-component Sumatra-Andaman seismogram, as recorded at broadband station PAS in Pasadena, CA. The seismogram shows a time period of 144 hours, slightly before and after the earthquake. The time sampling interval is 10 s (0.1 Hz). There are a total of 51841 samples. The text file can be easily read into MATLAB or R. Please complete or answer the following.

1. Plot the raw time series; use dimension *hours* on the time axis. *(5 pts.)*
2. Fourier transform the time series and plot amplitude and unwrapped phase spectra; use dimension *mHz* on the frequency axis. *(5 pts.)*
3. What is the Nyquist frequency for this signal? *(2 pts.)*
4. In the paper *"Free Oscillations: Frequencies and Attenuation"*, Masters and Ridmer give a table of all the normal mode observations of the Earth up to the time of writing (1995). Identify as many normal modes as you can in your spectrum[1]. *(10 pts.)*
5. Pick the frequencies of the normal modes you identified and compare the values to the ones given in the table by Masters and Ridmer. Are there any large discrepancies? Are any spheroidal modes missing that should have been observed? Explain potential discrepancies and hypothesize what might be causing these differences. *(10 pts.)*

[1]You will only be able to observe spheroidal modes, those denoted ${}_xS_x$ because we are looking at the vertical component. See section 2.9 of the book "An introduction to seismology, earthquakes and earth structure" for the description of normal modes we covered in class. Also, make sure to look at the peaks in the spectrum that occur above 0.2 mHz; peaks lower than this are diurnal effects.

6. What is the highest frequency normal mode that you found? What effects limit the maximum normal mode frequencies that can be observed? *(3 pts.)*

1) Plot the raw time series; use dimension *hours* on the time axis. *(5 pts.)*

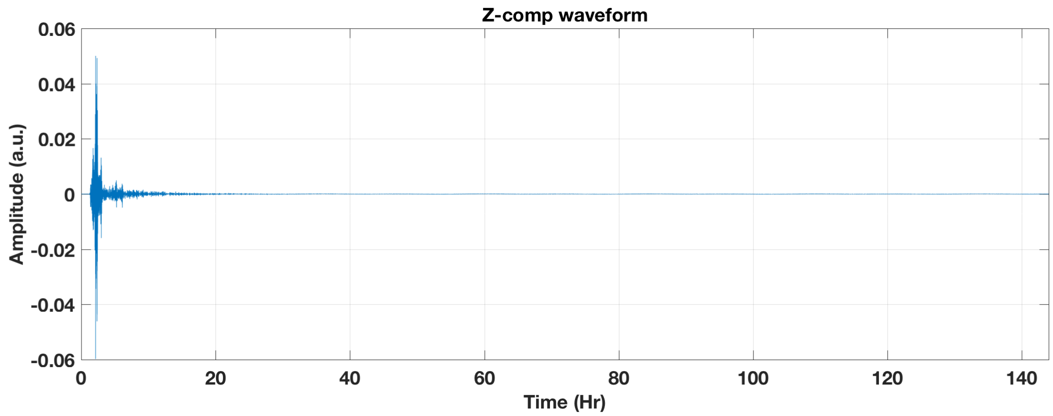

Figure 1: Raw Sumatra data.

2) Fourier transform the time series and plot amplitude and unwrapped phase spectra; use dimension *mHz* on the frequency axis. *(5 pts.)*

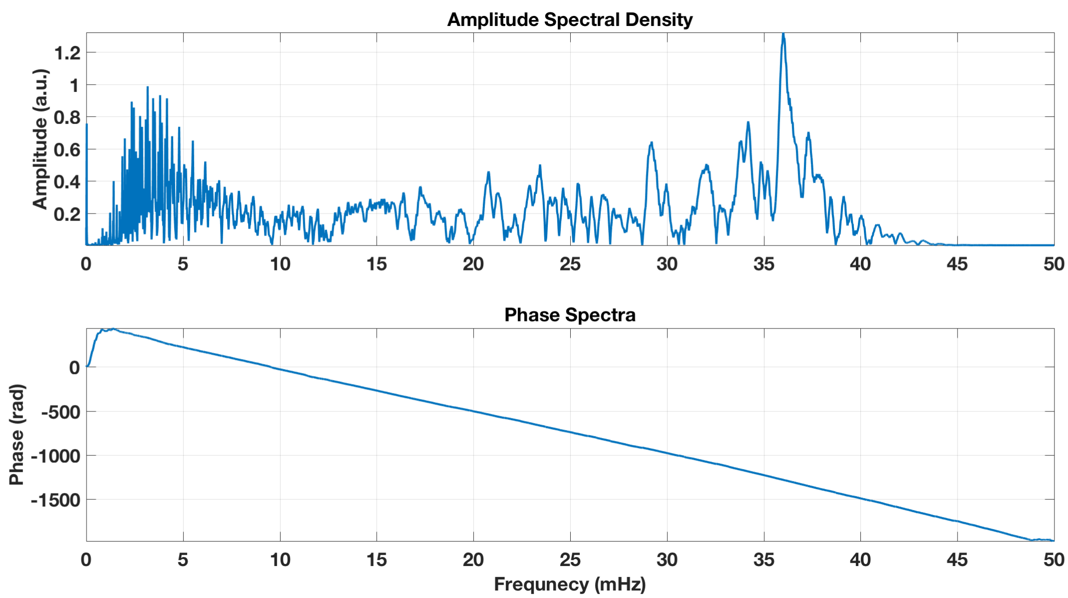

Figure 2: Sumatra data spectral data.

What is the Nyquist frequency for this signal? *(2 pts.)*

Nyquist frequency is solely determined by the sample rate of the raw time series data. In this case, the time sampling interval is 10 s (0.1 Hz). Therefore, the Nyquist frequency f_N is computed as follows:

$$f_N = \frac{1}{2dt} = \frac{1}{2 * 10} = \frac{1}{20} = 0.05\ Hz = 50\ mHz.$$

In the paper *"Free Oscillations: Frequencies and Attenuation"*, Masters and Ridmer give a table of all the normal mode observations of the Earth up to the time of writing (1995). Identify as many normal modes as you can in your spectrum. *(10 pts.)*

The first thing to do is find a function to locate peaks automatically (e.g. *findpeaks.m* in MATLAB). If there is not a code to do this already, we should write our own. Peaks are defined by zero slopes; so we can use that knowledge to write an automated picker. Here I used *findpeaks.m*.

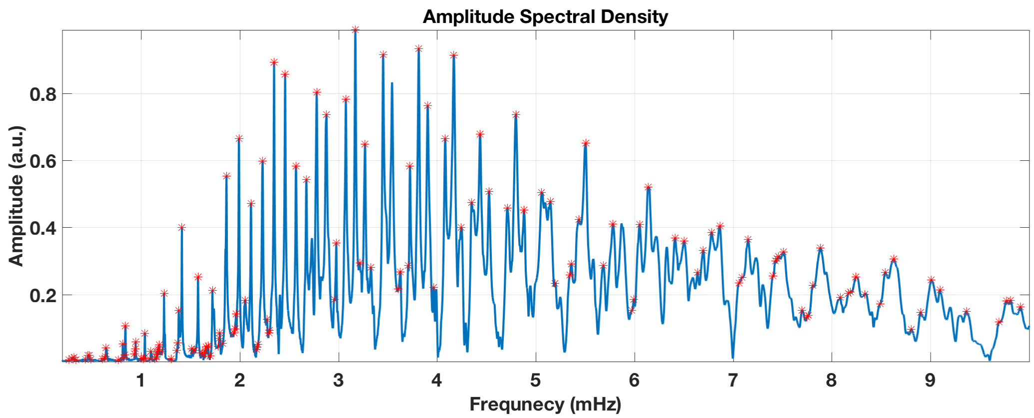

Figure 3: Sumatra peaks using *findpeaks.m* with a constraint that peaks must be different in amplitude from one to the next by 0.003 (a.u.). This constraint helps remove false peaks at the chance that some peaks may not be picked.

Pick the frequencies of the normal modes you identified and compare the values to the ones given in the table by Masters and Ridmer. Are there any large discrepancies? Are any spheroidal modes missing that should have been observed? Explain potential discrepancies and hypothesize what might be causing these differences. *(10 pts.)*

Missing modes might be because:

- 3D structure of Earth (e.g. anisotropy, attenuation, density)
- Moment tensor of source did not excite particular mode
- Depth of source influences the mode amplitudes as well
- Related to the first item, the station recordings come from different places on Earth
- We might not have the frequency resolution needed to distinguish two modes; The frequency resolution is a function of the total time, here 140 hours

What is the highest frequency normal mode that you found? What effects limit the maximum normal mode frequencies that can be observed? *(3 pts.)*

There are a number of things e.g.

- Are we observing modes or propagating waves at the high frequencies?
- Are the modes far enough apart that we can distinguish individual peaks any more.

Part 2: Polarization analysis *(30 pts.)*

Recordings of three component seismograms allow one to investigate the polarization, if any, of the particle motion of individual wave arrivals. In this section, we are going to investigate the particle motion.

You can download existing polarization code from https://github.com/dylanmikesell/Polarizemic.git. You can run the *polariz.m* example and read/skim the paper referenced in the README.md file.

Using the WILBER3 site at IRIS (Incorporated Research Institutions for Seismology) we will download some 3-component data. Let's study the recent *mb* 5.4 in Central Alaska. The WILBER3 page for this event is here. Play with the station filter settings to see how you can 1) add stations in different networks, 2) select a distance range, 3) select an azimuth range and 4) select different channels (e.g. components (E,N,Z) or types of seismometers (e.g. high-gain)). To learn more about station channel naming convention, have a look at Appendix A of the SEED Reference Manual.

Please complete or answer the following.

1. Download the three-component data for two different stations. Make sure the stations are at different epicentral distances and azimuths[2]. Plot the 3-component data for each station; set the time axis to units *minutes*. *(10 pts.)*
2. Apply the three component polarization analysis to your data. You can use the covariance or coherency methods, or both. Plot the results for both stations. *(5 pts.)*
3. Based on what you read in the Vidale paper, make some observations about the polarization analysis[3]. What do you see? Do you notice changes in azimuth, incidence or ellipticity at different times in the seismogram? What could cause these variations? *(15 pts.)*

[2] Make sure to record the distance, azimuth and station lat/lon from the data table when you select your stations. You can choose any format you would like for the data download; you just need to be able to read it. Make sure to start the data 1 minute prior to the "event time" and ending 20 minutes after the "S arrival."

[3] You may want to apply frequency filters and/or time window around certain arrivals in the seismogram. There is no need to compute the polarization after the arrival the surface waves.

1) Download the three-component data for two different stations and plot.

Here is my example with using GISMOTOOLS

```
 % start time from IRIS WILBER
start = '2017-01-31T09:37:37.000';

% create MATLAB datetime object
a = datetime(start,'InputFormat','uuuu-MM-dd''T''HH:mm:ss.SSS','TimeZone','UTC');

timePre = datenum(0,0,0,0,1,0); % subtract 1 minute from start time

timeSpan = datenum(0,0,0,0,20,0); % add 20 minutes to start time

ds = datasource('irisdmcws');
% get some TA-network data
scnl = scnlobject({'G23K','G24K'}, 'BH*', 'TA', '--');
% download from IRIS
startTime = datestr(datenum(a)-timePre,'yyyy/mm/dd HH:MM:SS.FFF');
endTime   = datestr(datenum(a)+timeSpan,'yyyy/mm/dd HH:MM:SS.FFF');
w = waveform(ds, scnl, startTime, endTime);
```

I plot the data below after applying a zero-phase bandpass Butterworth filter. The filter has two poles and is in the range 0.1-5 Hz.

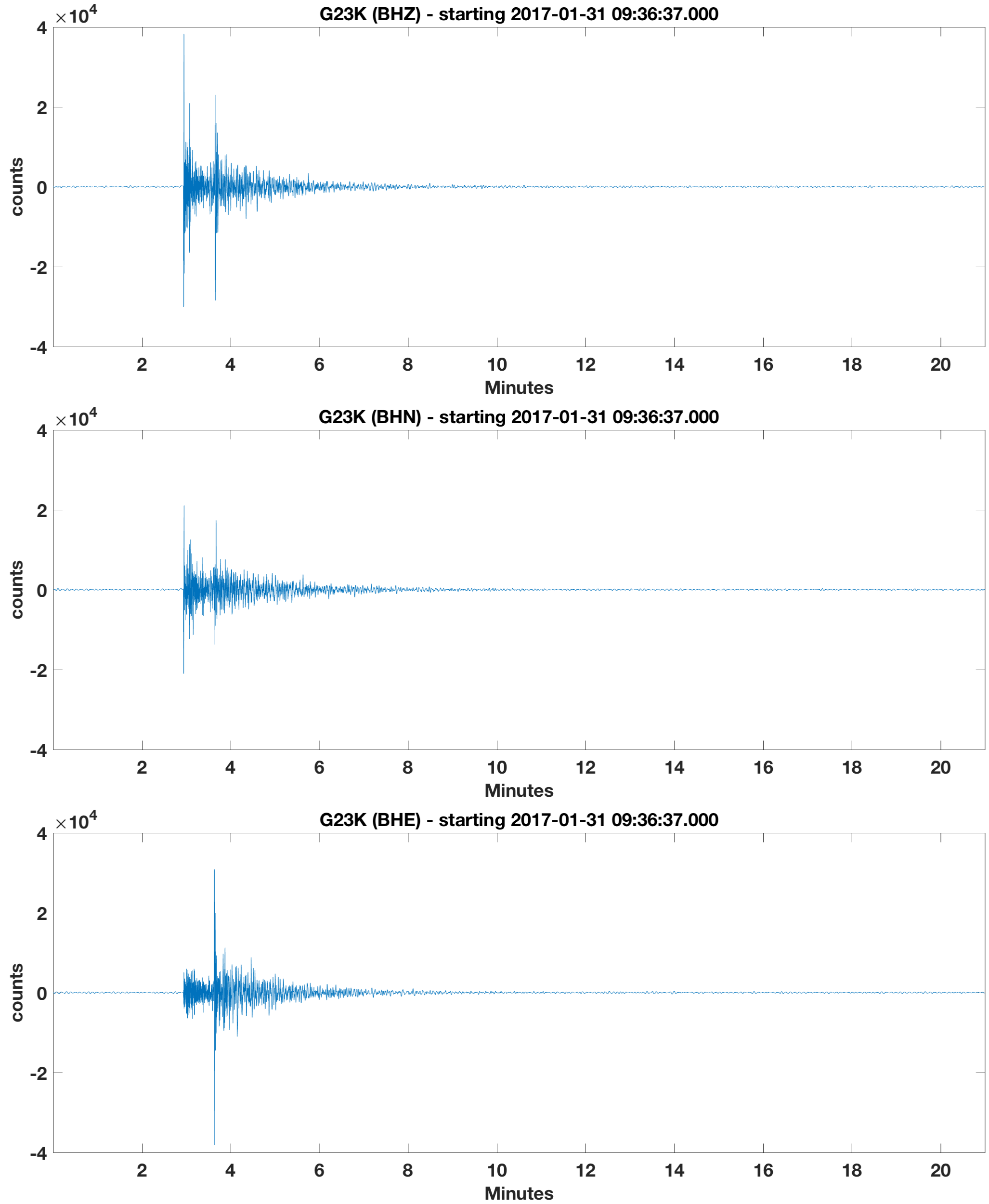

Figure 4: Station G23K, az=5.27°, distance 407 km.

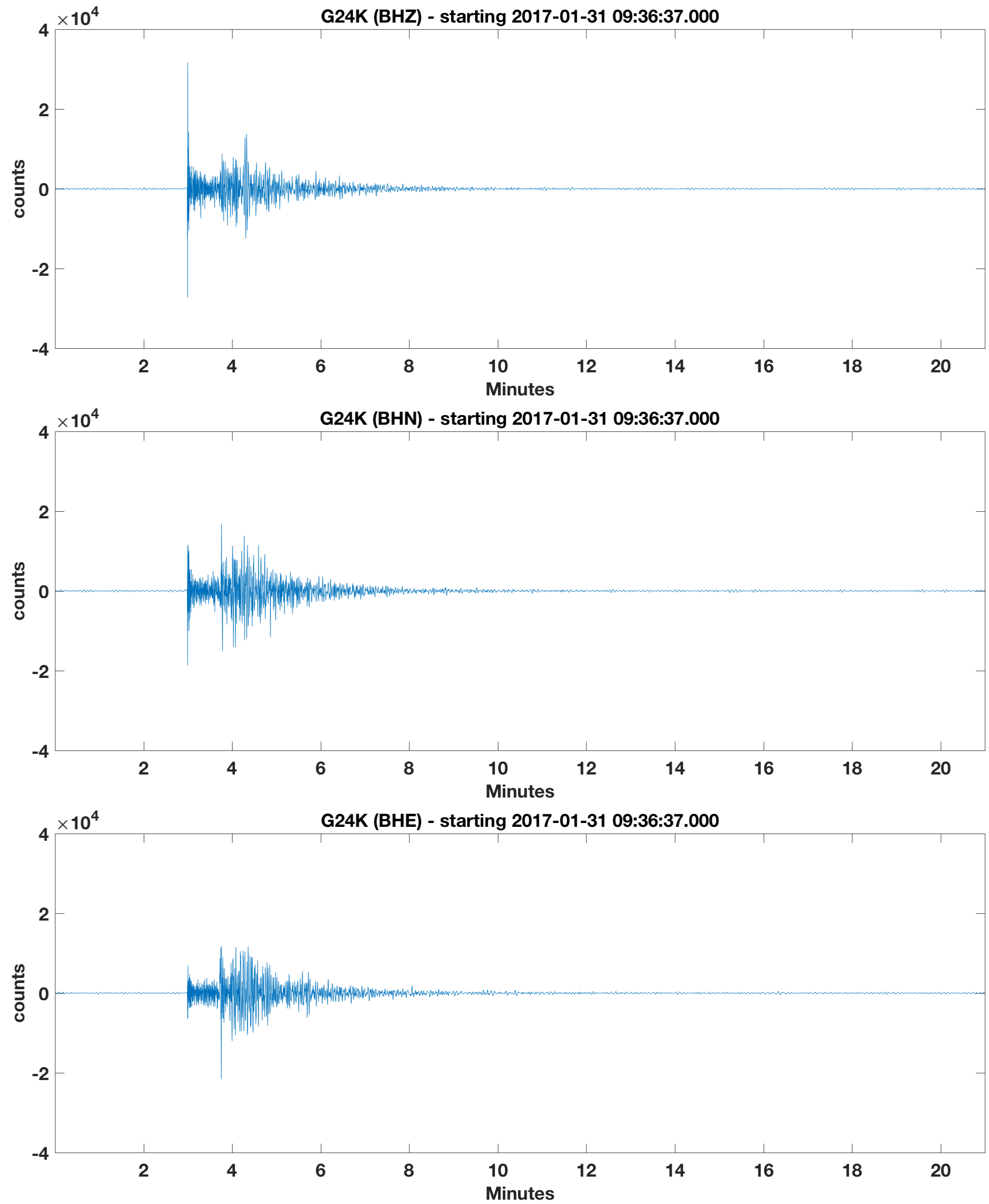

Figure 5: Station G24K, az=20.56°, distance 435 km.

Apply the three component polarization analysis to your data. You can use the covariance or coherency methods, or both. Plot the results for both stations. *(5 pts.)*

I applied a more narrow bandpass filter (3-5 Hz) and windowed around the P-wave arrival (i.e. the very first arrival). I then applied the coherency method of polarization analysis to this window of data using a 30 sample (0.75 second) window length. Below I plot the Z-data window and the coherency results. You can see that right when the first P wave arrives, the azimuth is actually not too far from the calculated azimuth for both station examples.

The other thing to note is the chance in the incidence angle. The incidence angle increases as the station get further from the source. That makes sense given that incidence angle is degrees from vertical. The closer one is to this 133 km deep earthquake, the more vertical (i.e. incidence near 0) the arrival should be.

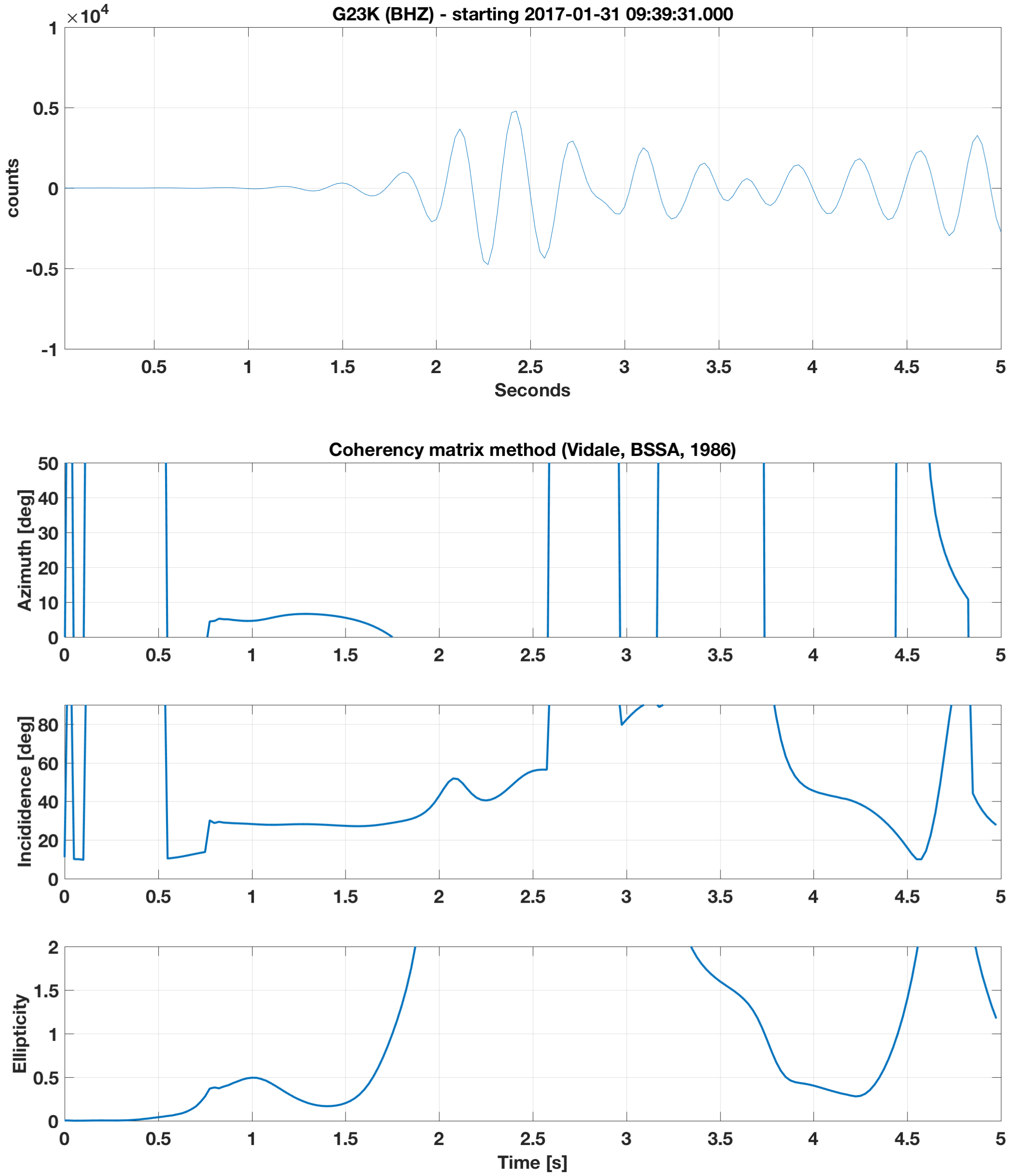

Figure 6: Station G23K, az=5.27°, distance 407 km.

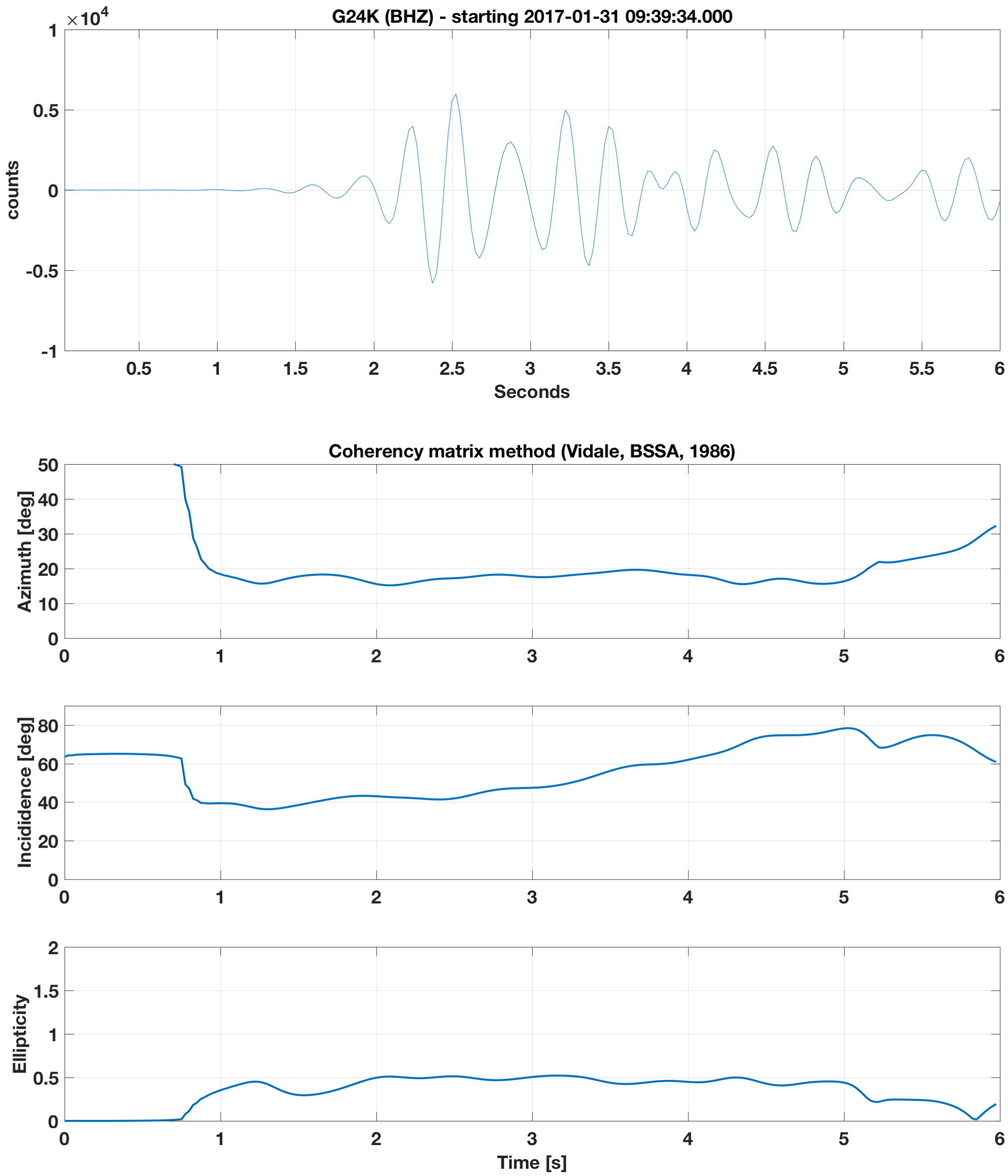

Figure 7: Station G24K, az=20.56°, distance 435 km.

Based on what you read in the Vidale paper, make some observations about the polarization analysis[4]. What do you see? Do you notice changes in azimuth, incidence or ellipticity at different times in the seismogram? What could cause these variations? *(15 pts.)*

What did you write?

Part 3: Component rotation *(35 pts.)*

Now we will investigate the influence of component rotation and how that affects our ability to analyze waveforms.

Please complete or answer the following for both of the stations you used in *Part 2*.

1. Compare your estimate of azimuth from the polarization analysis in *Part 2* to the azimuth given on the WILBER3 site. *(5 pts.)*
2. Using the source lat/lon and the station lat/lon, compute the back-azimuth. How does this compare with the azimuths from the WILBER3 site and the polarization analysis? *(10 pts.)*
3. Using the rotation equation defined in class, transform your data from the NE to RT directions. Plot a comparison of the ENZ and RTZ data for both stations. *(10 pts.)*
4. Redo the polarization analysis on the rotated RT data. Does anything change? Describe the differences and similarities that you observe. *(10 pts.)*

Compare your estimate of azimuth from the polarization analysis in *Part 2* to the azimuth given on the WILBER3 site. *(5 pts.)*

I did a number of things. 1) I took the azimuth from IRIS. 2) I computed the azimuth in MATLAB using the *distance.m* function that actually computes azimuth and distance on an ellipsoid rather than a sphere. I used the *WGS84* model for the ellipsoid. 3) I eyeballed the azimuth from the polarization plots.

For G23K that gave me:

1. 5.72 [deg]
2. 5.7230 [deg]
3. 6-7 [deg]

For G24K that gave me:

1. 20.56 [deg]
2. 20.5889 [deg]
3. 18-19 [deg]

[4]You may want to apply frequency filters and/or time window around certain arrivals in the seismogram. There is no need to compute the polarization after the arrival the surface waves.

Using the source lat/lon and the station lat/lon, compute the back-azimuth. How does this compare with the azimuths from the WILBER3 site and the polarization analysis? *(10 pts.)*

See previous. I computed azimuth on the ellipsoid. G23K gives back-azimuth 186.5555 [deg]. G24K gives back-azimuth 203.7303 [deg].

Using the rotation equation defined in class, transform your data from the NE to RT directions. Plot a comparison of the ENZ and RTZ data for both stations. *(10 pts.)*

$$\begin{pmatrix} U_R \\ U_T \end{pmatrix} = \begin{pmatrix} \cos\theta & sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} U_E \\ U_N \end{pmatrix}, \tag{1}$$

where $\theta = 3\pi/2 - \zeta'$ and ζ' is the back-azimuth.

It is worth noting that another way to write this is using the forward-azimuth.

$$\begin{pmatrix} U_R \\ U_T \end{pmatrix} = \begin{pmatrix} \cos\zeta & sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} U_N \\ U_E \end{pmatrix}, \tag{2}$$

where ζ' is the forward-azimuth.

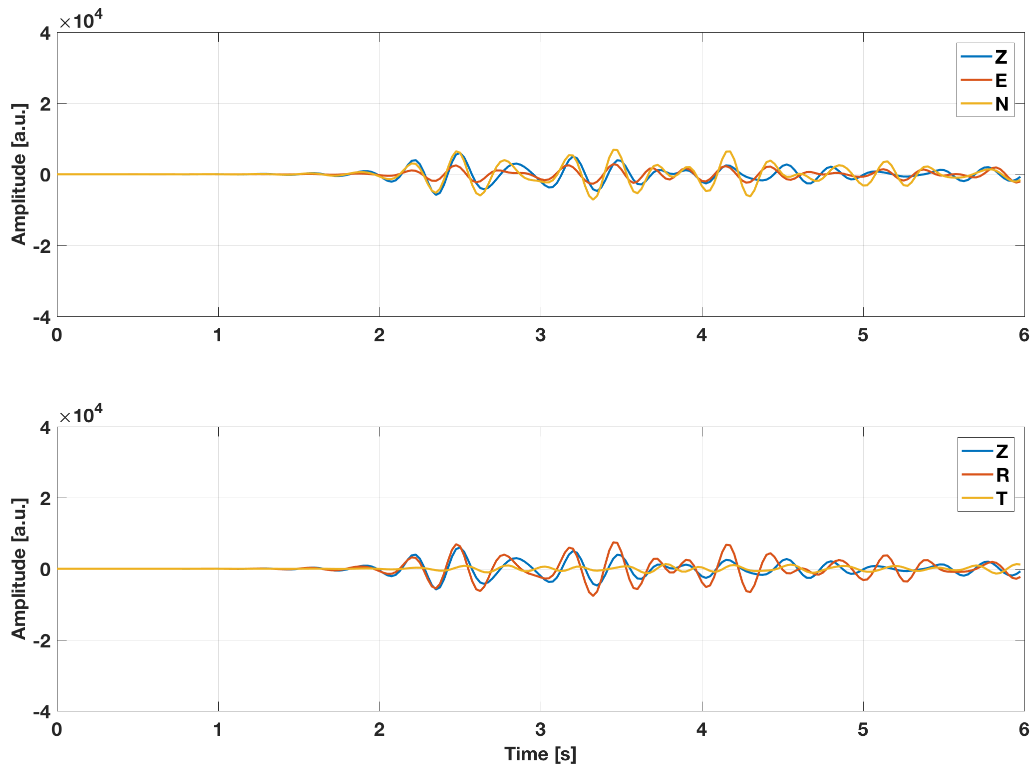

Figure 8: Station G24K, az=20.56°, distance 435 km. Rotated by θ=66.2697 [deg]. This is the P-wave arrival. This is a 3-5 Hz filtered example. Note there is no longer much energy on the T component.

I find that if I use an azimuth of 24 deg instead of 20.5 deg I get even less energy on the T component. This could be because the waves are bending due to local geology directly near the station.

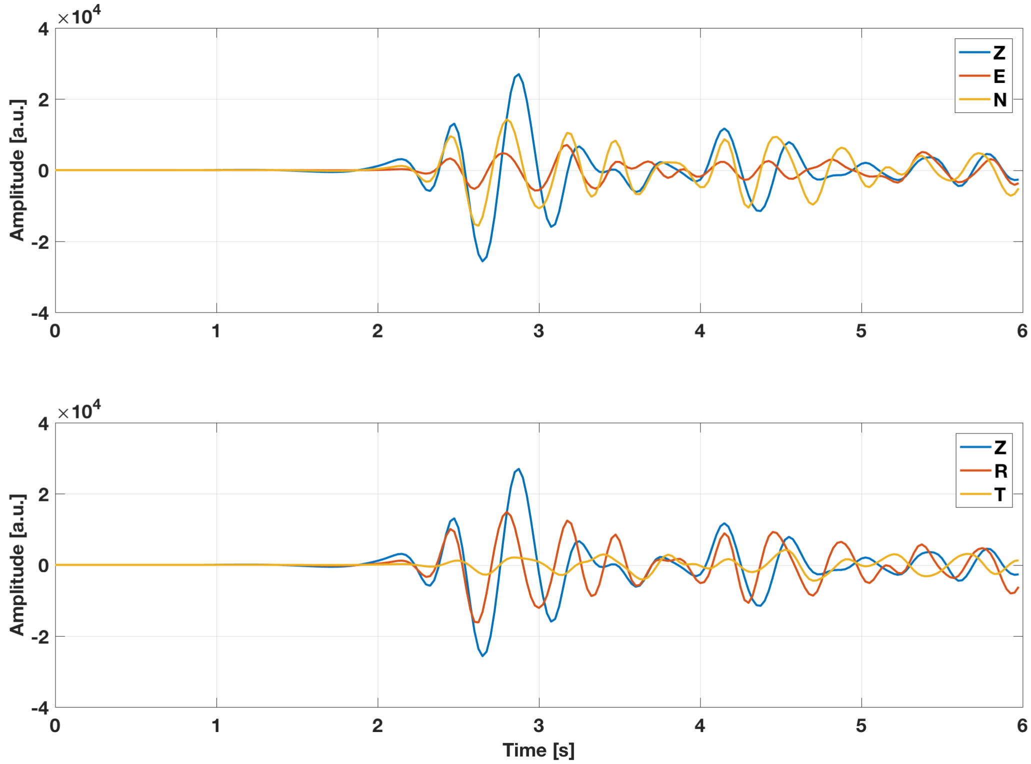

Figure 9: Station G24K, az=20.56°, distance 435 km. Rotated by θ=66.2697 [deg]. This is the P-wave arrival. This is a 1-5 Hz filtered example. Note there is no longer much energy on the T component.

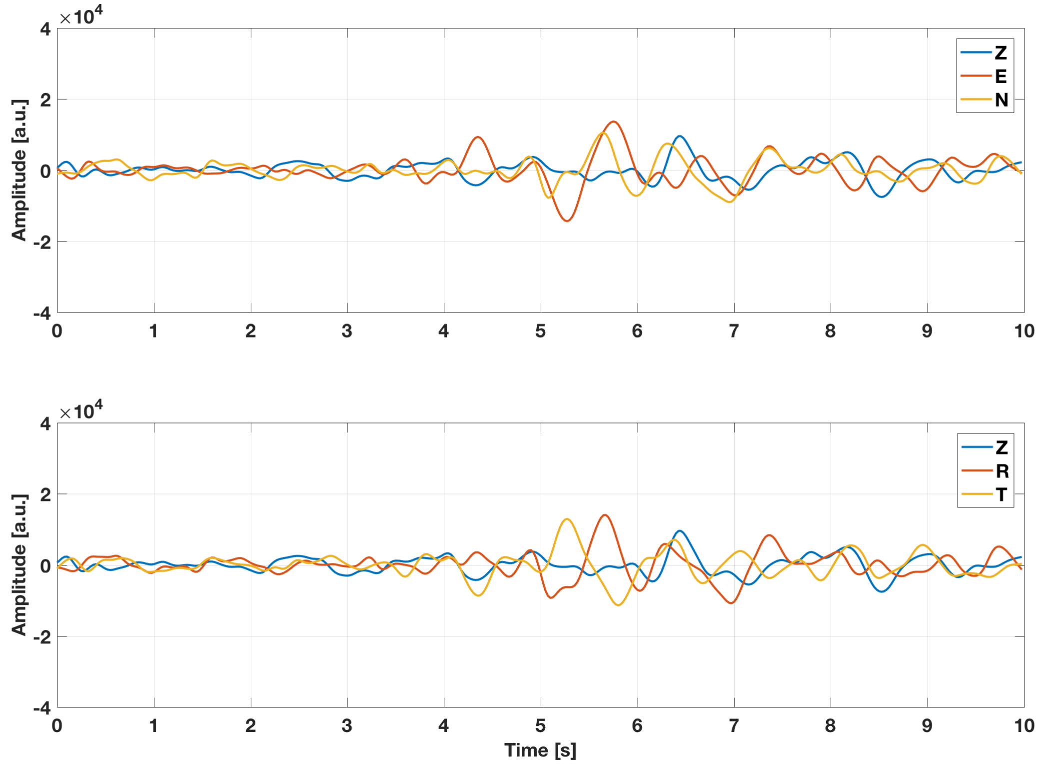

Figure 10: Station G24K, az=20.56°, distance 435 km. Rotated by θ=66.2697 [deg]. This is the S-wave arrival. This is a 0.5-5 Hz filtered example.

Redo the polarization analysis on the rotated RT data. Does anything change? Describe the differences and similarities that you observe. *(10 pts.)*

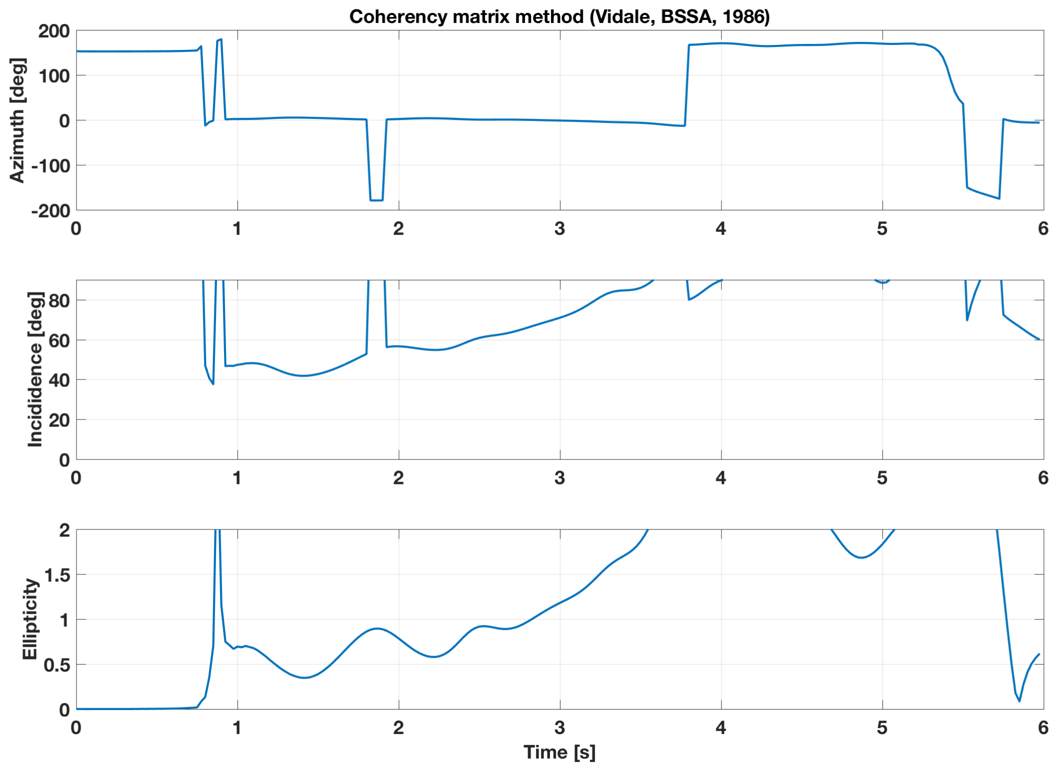

Figure 11: Station G24K, az=20.56°, distance 435 km. This is the polarization output after rotating to R and T coordinates. R is now in the North direction, so the azimuth of the arrival is zero. You also can notice that there are more jumps now. This is because the energy is properly aligned on in the proper direction so some components are zero, which leads to an unstable polarization result. The code has trouble determining if the wave is coming from 0 or 180 [deg]. This comes from the 3-5 Hz filtered P-wave arrival.

Extra credit 1: *(5 pts.)*

Use a tool that interfaces with your chosen compute language to automatically fetch the waveform data from IRIS in *Part 2*. For instance GISMO has this example.

See GISMOTOOLS example in earlier question.

Extra credit 2: *(5 pts.)*

Apply an instrument deconvolution to the data you download. For this particular homework we are not interested in absolute amplitudes and therefore the deconvolution is not required. If you would like practice with this process though, you can apply the instrument deconvolution for extra credit. The trick will be to find the RESP file for your sensor. *HINT: You may want to check IRIS and see if they have a site to download RESP files for stations in their database.*