499 - Independent Study Report (Spring 2011)

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INTRODUCTION:

The goals of this project were to

1. Increase the working period range of Locy Hall seismometer.
2. Find the response of the Locy seismometer.

with covering some of the theoretical background.

Making adjustments to the seismometer has made it responsive to bigger periods as shown in the first section of this report.

In order to find the response of the Locy seismometer, a comparison has been made between the data from a seismometer with a known response (i.e. a STS-2 seismometer) *almost*[2] at the same location.

A STS-2 seismometer was installed close to the location of Locy seismometer and was recording seismic data for almost 3 weeks (22 days from May 11 to June 1, 2012), during which time recorded the Texas earthquake ($M_w = 4.8$) on May 17, 2012. This event was the only significant earthquake that was RECOGNISED on the STS-2 records.

Some data processing was done on the data of both seismometer and a comparison was made to find the response of Locy Hall seismometer.

In this report, first a demonstration of the change in the working period range of the Locy Hall seismometer will be given, which is followed by a section on data acquisition using the STS-2 seismometer. After that, some practical aspects of the theory behind this processing will be presented and finally the data processing to find the response will be discussed in some detail.

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2   These two seismometers were not placed at exactly the same location, but were located in the basement of Locy Hall with reasonably short distance from each other. The building effects and the differences in their sorrounding environments have been considered to be negligible.

1. LOCY HALL SEISMOMETER WORKING PERIOD RANGE:

Working on the Locy Hall seismometer resulted in an increase in its working period range at pushing it to higher periods. The process was done by changing the viscosity of the damper oil and the mass of the green seismometer (see 499 report for Winter 2012).

In order to make a comparison, some intervals of noise pertaining to before and after the changing process, noise records from 11 separate (1 hour) time windows before and 11 separate (1 hour) time windows after the process were chosen and stacked. For the results see Fig. 1-1 to Fig 1-3.
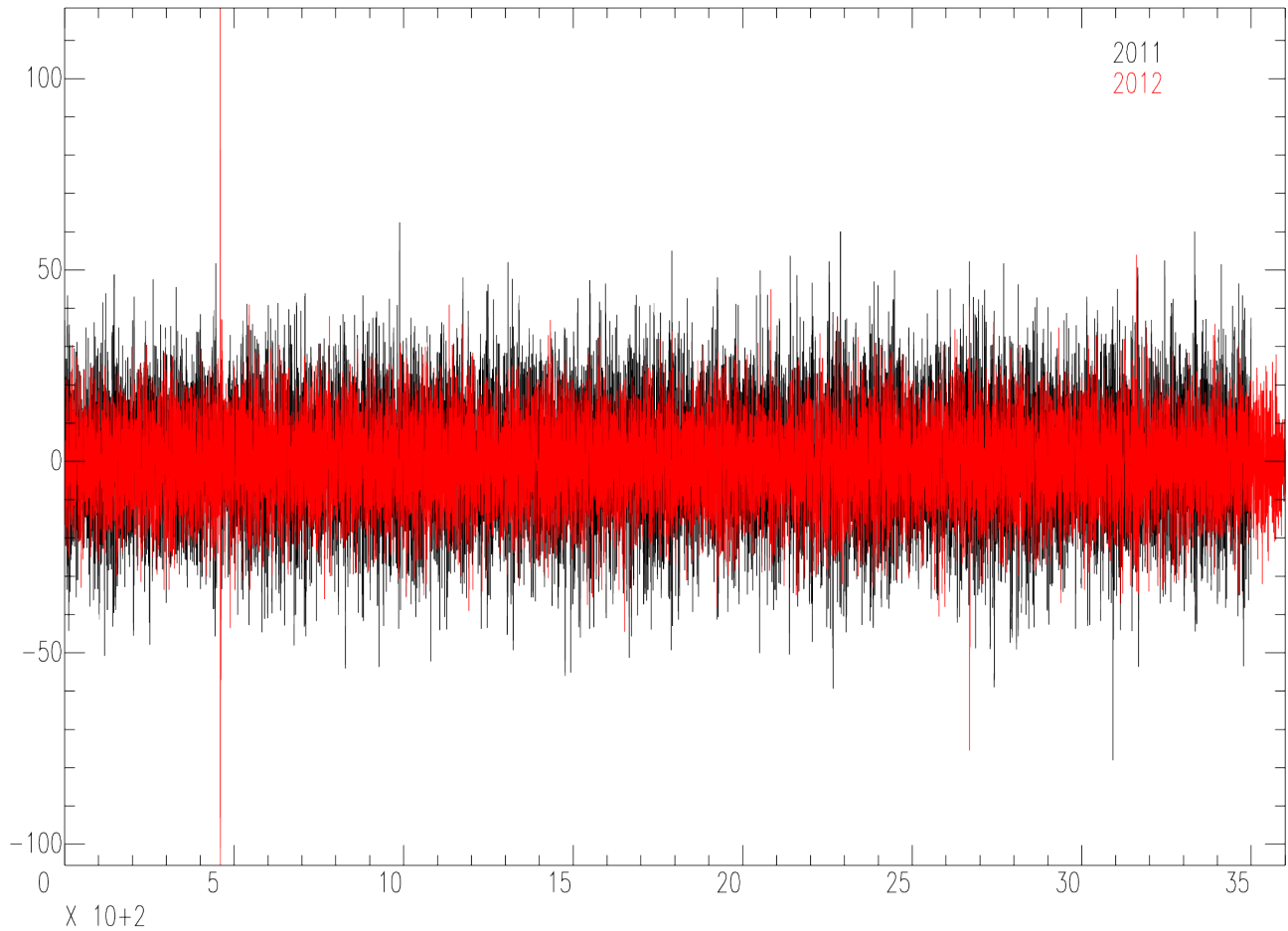

Figure 1-1. Comparison of the stacked 1 hour windows of the waveforms for before (black) and after (red) the adjustment process in time domain.
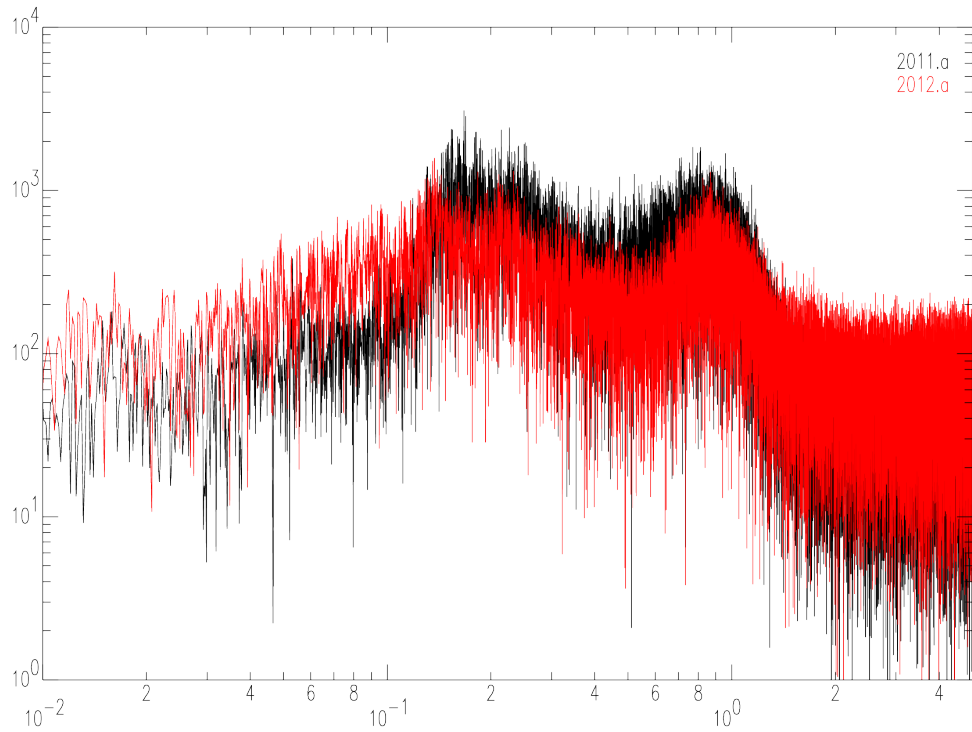
Figure 1-2. Comparison of the stacked 1 hour windows of the waveforms for before (black) and after (red) the adjustment process in frequency domain.
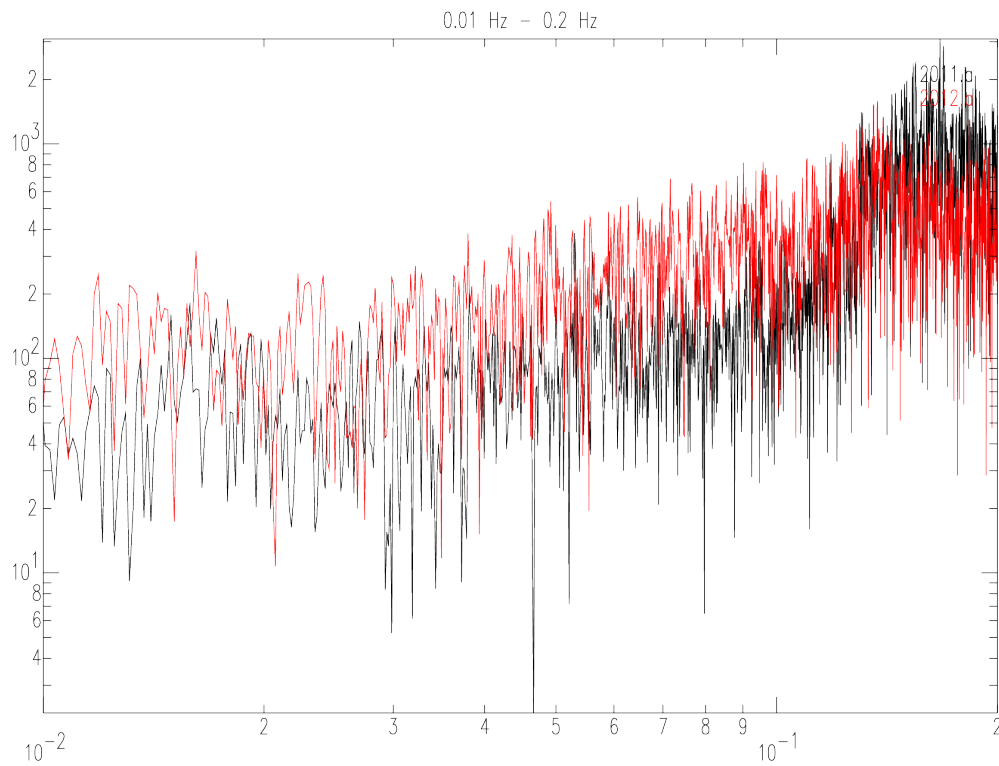

Figure 1-3. Comparison of the stacked 1 hour windows of the waveforms for before (black) and after (red) the adjustment process in frequency domain between 0.01 Hz and 1 Hz.

Based on the amplitude of the recorded noise (which have been from relatively similar and calm days) we can clearly see in Fig. 1-3 that the working period of the Locy seismometer has been changed to higher periods as it has a bigger amplitude by an average factor of 100.

2. DATA ACQUISITION:

The data used in this study, was acquired from two seismic stations as mentioned before: the Locy Hall green seismometer and a STS-2 (a portable very-broad-band tri-axial seismometer). STS-2 is an electronic force-feedback sensor that provides an output signal proportional to ground velocity over a broad range. Similarly, the STS-2 also employs the a-static leaf–spring suspension (See Appendix A). The STS-2 uses 3 identical obliquely-oriented mechanical sensors. The tri-axial design guarantees that horizontal and vertical components are matched as closely as possible (see Fig. 2-1). Standard vertical and horizontal outputs are derived electrically rather than mechanically. The tri-axial mechanism is shown in Fig. 2-1. For discussion on the Locy seismometer (a vertical-component seismometer) see the Winter 2012 report.
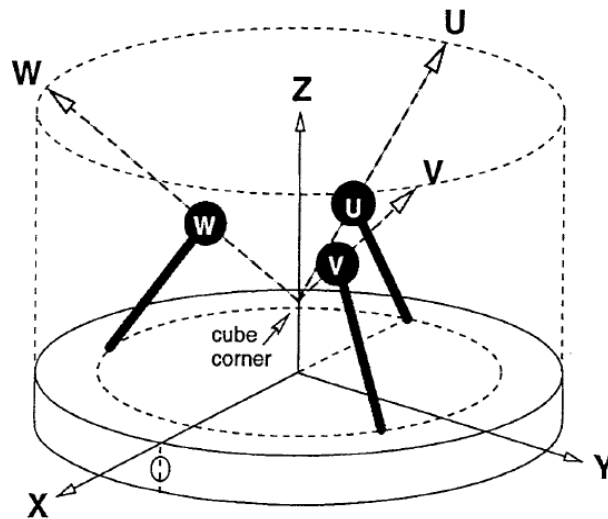
Figure 2-1. The tri-axial design of a STS-2 seismometer. Motions of the 3 masses (U, V and W)
is along the three vectors U, V and W (hollow-head arrows). These motions are then converted
to the standard Z, NS and EW (Z, Y and X) electronically (Havskov and Alguacil, 2004)

STS-2 is very sensitive to heat variations and air movements (which cause thermal imbalance) and thus, thermal insulation is very significant during its installation process. However. For the purpose of this study, such an insulation was not performed and as a result, perturbations could be seen in the recorded waveforms.

The STS-2 was installed in one of the offices at Locy Hall basement. The installation setup is presented in Fig. 2-2.
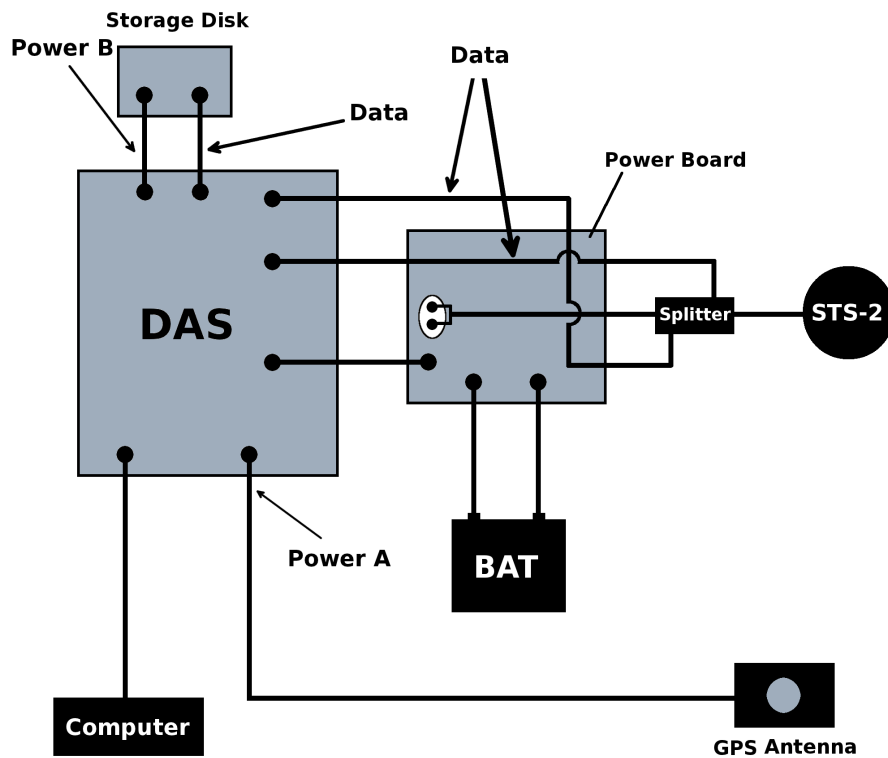
6

Figure 2-2. The installation setup of STS-2 seismometer. DAS stands for Data Acquisition System.

2.1 SETUP

The steps taken to install the STS-2 seismometer are the following:

1. Finding the East geographic direction at the location
2. Physical installation of the seismometer
3. Programming the DAS
4. Unlocking the STS-2
5. Monitoring and Maintenance

which will be discussed below.

2.1.1. FINDING THE EAST GEOGRAPHIC DIRECTION AT THE LOCATION:

The STS-2 is installed by fixing its east component (the rest of the components then get fixed). This is shown in Fig. 2-3.
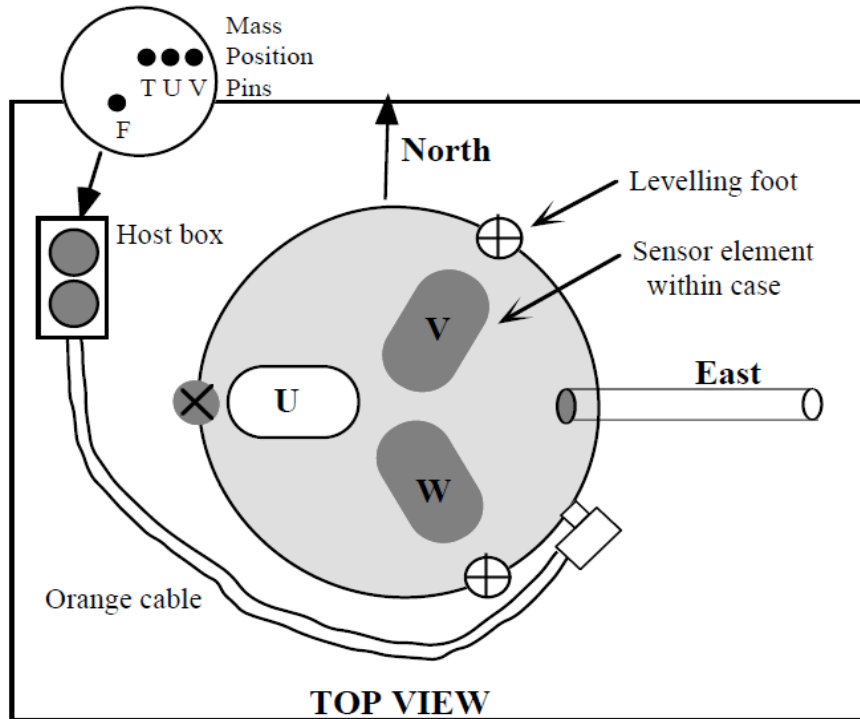

Figure 2-3. Schematic of the STS-2 from the top view.

To find the east direction, the method of minimum shadow length was used. This method is based on the fact that the shadow of any given object is minimum at noon time and moves from west. The east direction in this method is determined by connecting the two outermost measurement point which are equidistant from the noontime point.

To find the east direction, using this method, the shadow of a wall edge outside the depot by the Locy Hall was chosen (see Fig. 2-5). Its length was measured on April 19, 2012 from ~11 a.m. to ~2 p.m.. The time interval was chosen in a way to accommodate noon time. The shadow length from its tip the wall foundation were measured, the results of which are presented in Table 2-1. The minimum shadow length would represent noon time.

Table 2-1. Shadow lengths of the chosen wall edge at different times of days in April 19, 2012.

Time of Day (hh:mm)	Shadow length (cm)
11:05	149
11:25	137
11:53	120
12:15	114
12:45	111
13:05	111
13:30	122
13:59	130

From Table 2-1 we can deduce that that noon time is between 12:45 and 13:45, since the shadow has passed its minimum length and has started to elongate (which would continue until sunset).

If we select a symmetric number of measurement points at both sides of the noontime point, then the the line connecting the two outermost points (A and B in Fig. 2-4). would point *exactly* to east (Fig. 2-4).

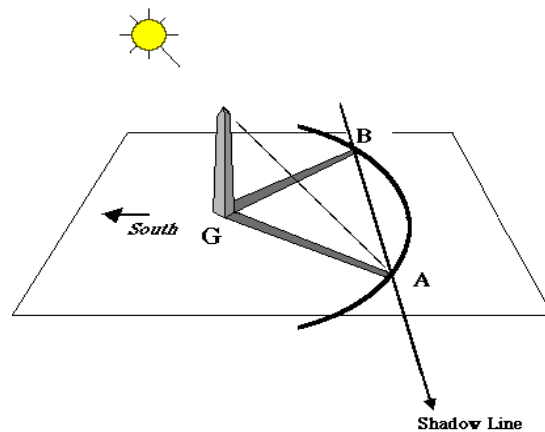*Figure 2-4. The method used to find east.[3]*

Using the method discussed above, the East direction was found. See Fig. 2-5.

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3   From astronomy online: http://www.eso.org/public/outreach/eduoff/aol/market/collaboration/luneclipse/locnoon.html
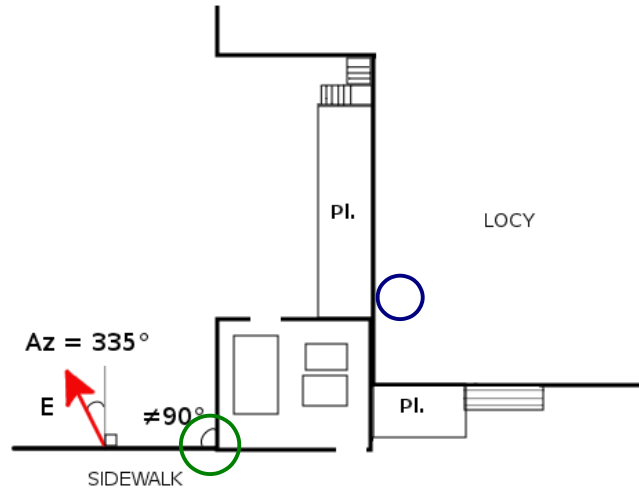
Figure 2-5. The site where the east direction was determined. The red arrow denotes the found direction and the green and blue circles represent the location of the wall edge and the STS-2 respectively.

As it is seen in Fig. 2-5, the East direction has a 335° ± 2° azimuth at the measurement point. To use it for the STS-2, the angle had to be transferred to the STS-2 point. This was done using a big protractor and trigonometric equations. From these equations, it was derived that the east direction made a ~20° ± 5° angle with wall by the blue circle in Fig. 2-5. Assuming that the walls in that point are uniform at the inside and outside faces (which is roughly true) the direction was then determined inside the building, in the basement and was drawn on the ground.

2.1.2. PHYSICAL INSTALLATION OF THE SEISMOMETER:

The installation setup is shown in figure 2-2. The most important factor in the installation and maintenance processes is power. A steady non-fluctuating power source should be provided for the system which is denoted by the battery (BAT) in Fig. 2-2. The battery is connected to a power board with diodes and a storage to make sure the input to the system has the above conditions. The battery itself (which was a charged, functional car battery in this study) was connected to an adapter which in turn was plugged into an AC socket.

The GPS antenna was placed on top of the depot wall, right outside the building (see Fig. 2-5).

2.1.3. PROGRAMMING THE DAS:

The DAS (Data Acquisition System) was programmed to work with the STS-2. This was done through a pocket-size computer. A setup file was made for this purpose, using the parameters in Table 2-2.

Table 2-2. The parameters file, used to program the DAS.

Experiment Number	3		
Experiment Name	Locy Calibration		
Comment	Amir		
Station Number	1		
Station Name	LOCYSTS2		
Comment	Northwestern Univ.		
Power State	C.P.		
Record Mode	SC		
Year	2012		
Julian Day	129		
Channels	4 = BHZ	5 = BHN	6 = BHE
Pre-amp Gain	1		
Channels Azimuths	4 -- 0°	5 -- 0°	6 -- 90°
Channels Inclinations	4 -- 90°	5 -- 0°	6 -- 0°
Sensor Model	STS2		
Comment	32-bit channel		
Data Stream	BH4	BH5	BH6
Channel Sampling Rate	40		
Data Format	CO		
Trigger Type	CON		
Record Length	3600 s		
Lat.	42.051 N		
Lon.	87.673 W		

The rest of the procedure is straight-forward. We format the disk, send the parameters we just declared to the DAS. In this process, the DAS and the computer should be at ODD polarities in order for the communication to happen. The timer on the computer (which is for the DAS status) will activate when the GPS could make a connection with the satellites (Loop Lock).

2.1.4. UNLOCKING THE STS-2:

After we level and unlock the seismometer, we should check for the mass balance at the splitter (after unlocking the STS-2, it should not be touched or changed). This is done, by measuring the voltages between (T,U,V) and F in Fig. 2-3. The measured voltages here, should be *reasonably* within −1.5 and +1.5 volts. If they are not, it means that the masses are not *centered* well and should be centered. This is done by pushing the button on the splitter. A tick sound will be heard from the STS-2 which means masses have been released. The balance will take some time to be reached.

Everything being OK, we can start acquisition by commanding the DAS through the computer. But before that we can monitor the channels. This is possible by commanding the DAS using the computer.[4] Monitoring showed that the channel 5 data are not good and in fact it is not responsive to jumps and stomps.[5]

The malfunction in channel 5 (NS) is probably due to a problem in the DAS or the cable[6]. The seismometer itself was probably OK, since the Z component observed in the monitor was fine (see the theory section).

2.1.5. MONITORING AND MAINTENANCE:

Monitoring and maintenance of a seismic station should be performed on a regular basis. For a STS-2 station, some routine checks should be done in every visit, the most important and influential of which is power. Power is the most important factor in the function of a seismic station (especially a STS-2. The first thing to be checked in a servicing visit to a seismic station must be power and in troubleshootings, it should be the first factor to check.

The next thing to check is the mass positions in the seismometer which was described before. Table 2-3 shows some examples of such measurements in some visits. The highlighted cells belong to the installation, and show the corrected new values which were obtained as a result of centering the masses.

After that, the status of the DAS should be checked. In case of problems, the storage disk should be checked (whether or not it is spinning).

The quality of the thermal insulation for the seismometer and the station should also be checked.

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4   Monitoring the channels is only possible by stopping data acquisition. In fact, at every station service visit, the procedure described here should be done.
5   The operator could jump, stump or bend his/her knees (the latter produces longer periods) to see if they could be observed on the computer.
6   It could not be really checked which one was the case, since the whole acquisition system was very old (no more support service) and we did not have the equipments.

Table 2-2. Voltage values from the mass position checks. The highlighted cells belong to the installation.

T – F Voltage	U – F Voltage	V – F Voltage[7]
12.8	-13.4	6.7
- 0.3	- 6.5	0.7
- 0.5	2.4	0.8
- 0.5	- 0.8	0.7
7.3	-3.4	-7.8
0.52	0.17	3.92
0.45	0.12	- 1.54
0.48	- 0.37	- 2.1
0.57	- 0.57	1.85
- 1.15	- 1.90	0.58

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7   For the naming, see Fig. 2-3.

3. THEORY

In this section, the concept of component conversion and the theoretical framework for the data processing done in the next section are explained.

3.1 MASS POSITIONS IN STS-2:

The masses in the STS-2 seismometer (shown in Fig. 2-3) move in the directions of the arrows shown in Fig. 2-3. So their motion directions should be converted to 'real' geographic component to make the seismometer useful. This conversion is done electronically and follows equations (1) to (6) (see Appendix A):

$$U = (2/3)^{1/2} X + \qquad\qquad + (1/3)^{1/2} Z \qquad\qquad\qquad (1)$$
$$V = (1/6)^{1/2} X + (1/2)^{1/2} Y + (1/3)^{1/2} Z \qquad\qquad (2)$$
$$W = (1/6)^{1/2} X - (1/2)^{1/2} Y + (1/3)^{1/2} Z \qquad\qquad (3)$$

$$X = -(2/3)^{1/2} U + (1/6)^{1/2} V + (1/6)^{1/2} W \qquad\qquad (4)$$
$$Y = \qquad\qquad\quad + (1/2)^{1/2} V - (1/2)^{1/2} W \qquad\qquad (5)$$
$$Z = (1/3)^{1/2} U + (1/3)^{1/2} V + (1/3)^{1/2} W \qquad\qquad (6)$$

where U, V and W are the mass system Cartesian coordinates and X, Y and Z are Cartesian coordinates of the geographic system (see Fig 2-1). Equations (1) to (6) are a simple coordinate system rotation. We can see that Z component depends on all the masses.

3.2. Relative Response:

Spectral amplitudes of different seismometers are different in the amplitude and the corresponding frequencies. For example in Fig. 3-1 spectral amplitudes for the same event have been compared.

Dividing the waveforms of the earthquakes in the frequency domain, means:

$$W_i = A_i(\omega)\exp[i\varphi_i(\omega)] \qquad\qquad\qquad (7)$$

$$W_1/W_2 = (A_1(\omega)/A_2(\omega))\, \exp[i(\varphi_1(\omega) - \varphi_2(\omega))] \qquad (8)$$

where W_i is the generic waveform of an earthquake in the frequency domain. $A_i(\omega)$ is the amplitude and $\varphi_i(\omega)$ is the phase, all functions of frequency. Now, if one of the waveforms is totally known, the ration obtained in this way will be very helpful.
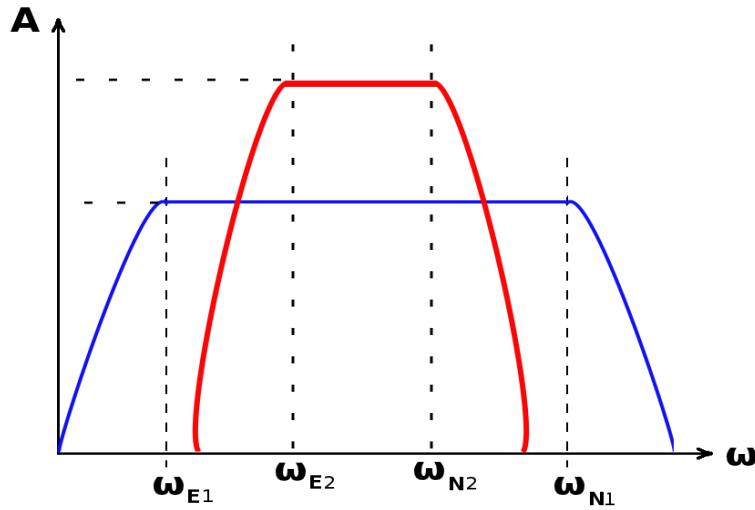
Figure 3-1. Spectral amplitudes for two waveforms. ω_{E1} and ω_{N1} are the eigen-frequency and Nyquist frequency for the first (blue) waveform and ω_{E2} and ω_{N2} are the eigen-frequency and Nyquist frequency for the second (red) waveform.

If the instruments are located at almost the same place finding their ratio in this way (dropping the effect of the earthquakes, which would be the same for both of them and the site effects which are also the same), would lead to finding the instrument response, which is inherent to each seismometer. If one of the responses is known, the ration would be the response from the second one.

Therefore in this study we first converted the waveforms into the frequency domain and then divided the amplitude files and subtracted the phase files (see Eq. (8) above) using SAC.

4. DATA PROCESSING

4.1 DATA AND PREPROCESSES

The Texas earthquake (M_w = 4.8) occurred at the East-Northeast corner of Timpson (31.908°N, 94.385°W), Texas on May 17, 2012 (Fig. 4-1).
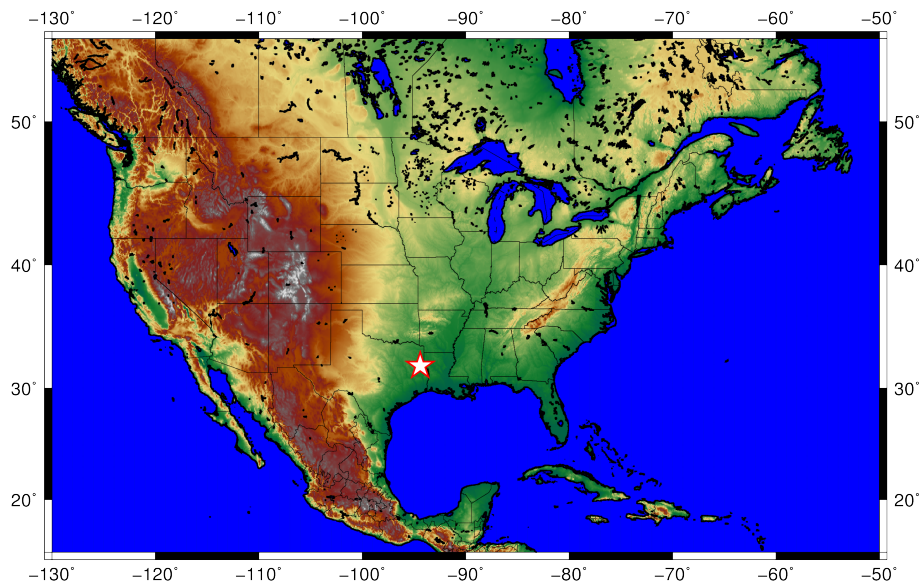

Figure 4-1. Map of the May 17 Texas earthquake. The epicenter is represented by a star.

The Texas earthquake waveforms was extracted from the STS-2 data set acquired at Locy Hall (May 11 – June 1, 2012) and the Locy Hall green seismometer. The Texas earthquake had occurred on May 17, 2012 and so it was in the 138th set[8] which is a folder called *R138.01*.

4.1.1 STS-2 DATA SET FORMAT:

The STS-2 data is (finally[9]) saved in a Julian day format in separate folders with the following format:

RJJJ.NN

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8   2012 is a leap year.

9   The saving mechanism of the STS-2 depends on the way the DAS is programmed. The DAS regularly saves the data stored on its RAM on the storage disk. This process produces the so-called *events* on the storage disk.. The length of events could be manipulated by the small commanding pocket-size computer. The recorded data is in mini-seed format. But finally the data would be stored in the Julian day format.

where JJJ stands for the Julian day number and NN represents the folder number in that specific day. The latter is usually '01' which means there is only one folder for each day.

The data itself is recorded in mini-seed (.m) format and since the recording length (event) is usually set to 1 hour, there usually would be 72 files in each folder (3 files for every hour since STS-2 has 3 components). The file naming follows the convention:

YY.JJJ.HH.MM.SS.????.C.m

where YY is the year and JJJ is the Julian day number. HH, MM and SS represent hours, minutes and seconds respectively. C denotes the channel number[10] and *m* is the suffix to the mini-seed file.[11] MM and SS are not constant through the data set, but gradually change from 00 to 59.

4.1.2 CHANGING FROM MINI-SEED TO SAC:

This is done using the PASSCAL package[12] which is a set of programs to convert and manipulate seismic waveforms. To accomplish our goal, we used the *ms2sac* program. For instance:

```
ms2sac –f b 12.138.08.05.03.1005.4.m 12.138.08.05.03.1005.4.sac
```

The "-f b" flag dictates that the output should be a binary sac file.

A simple shell script was written to do the job for all the files in each folder (day). The three files containing the Texas earthquake were selected after this process (one for each component). Since the NS component was corrupted (see Fig. 4-2), only two files were selected (channels 4 and 6).

4.1.3. TRIMMING THE WAVEFORMS:

To obtain the relative instrument response or investigate the relative behavior of seismic stations, we can divide their pertaining waveforms by each other. This could be easily done using SAC software. However, there are some points which should be taken into account in order to do that:

1. The waveforms must be from the same event (earthquake, noise, etc). [obvious, but see 2].
2. The waveforms must start at the same moment of time and end at the same moment of time.

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10 It could be 1, 2 and 3 or 4, 5 and 6 depending on which port on the DAS you are using. In our case we used the second port, so the channels were 4, 5 and 6. These numbers refer to the seismometer components and denote Z, NS and EW respectively (See appendix B). For a more detailed discussion on the STS-2 seismometer, see Appendix A (manual).

11 I have no idea what ???? stands for!! In our case it was 1005.

12 The latest version of the package could be downloaded from:
          http://www.passcal.nmt.edu/ftp/software/passoft/linux/
    It is easiest to download and install the .rpm files. Instructions to set the environmental parameters are included in the README.txt file.

3. The waveforms must be of the EXACT same length. This means that they should have the same number of points.
4. The waveforms must be sampled in the same way, that is their sampling rates must be the same.
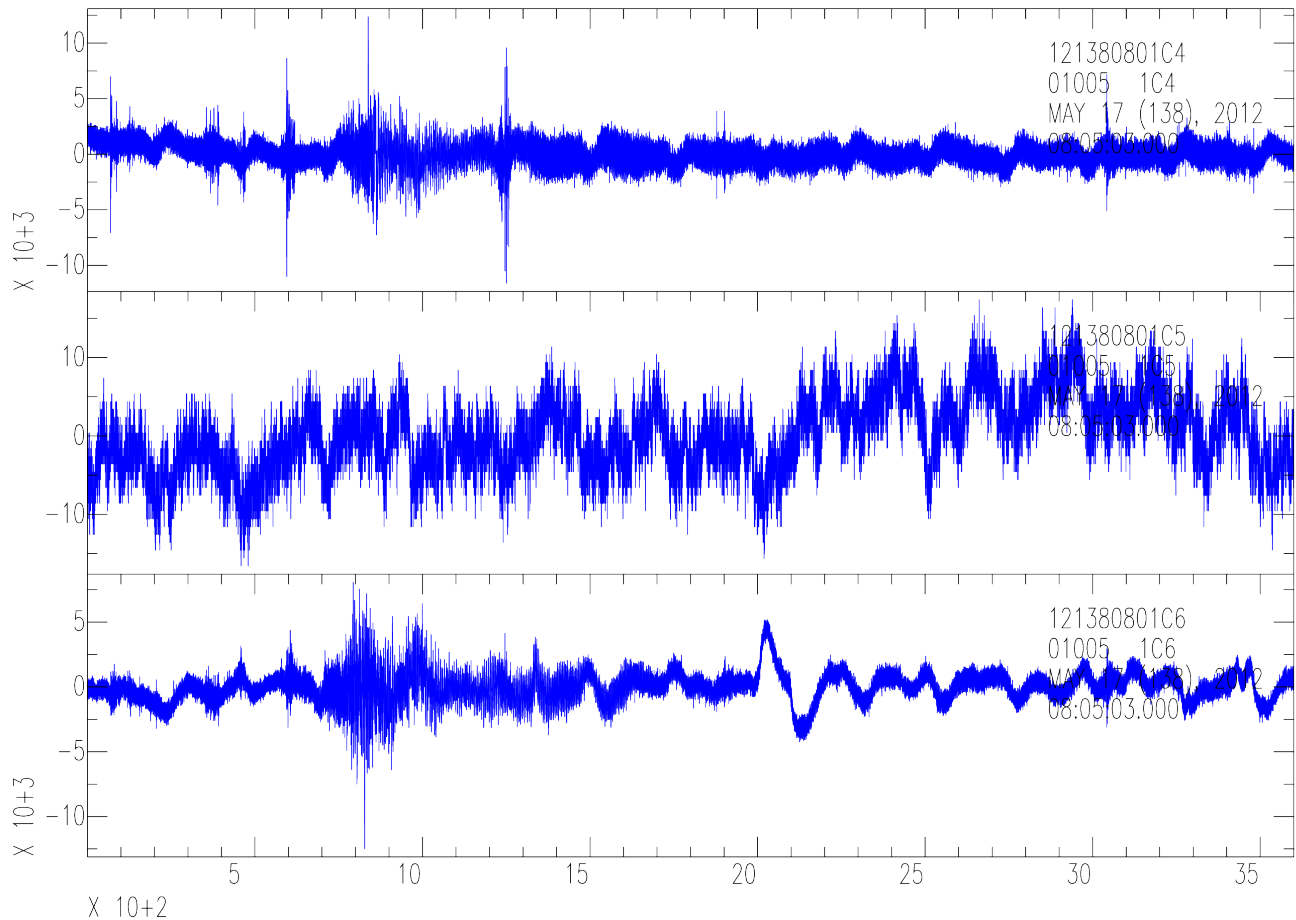
Figure 4-2. The three components of the Texas earthquake recorded on the STS-2. Obviously channel 5 is not working correctly and thus its data was not used in the study.

The above points are necessary since, the division (or any other algebraic operation) process for the waveforms (or any other time series) is based on point-by-point division (or any other algebraic operation) and therefore the program should be able to operate on the next two points from the two waveforms by passing the same distance (this makes the chosen new points, the ones corresponding to the same moment of time). Following this process also lets us avoid putting zeros in the denominator and having meaningless values in the results. Fig. 4-3 shows our data and we can see that there are offsets at both ends of the waveforms.
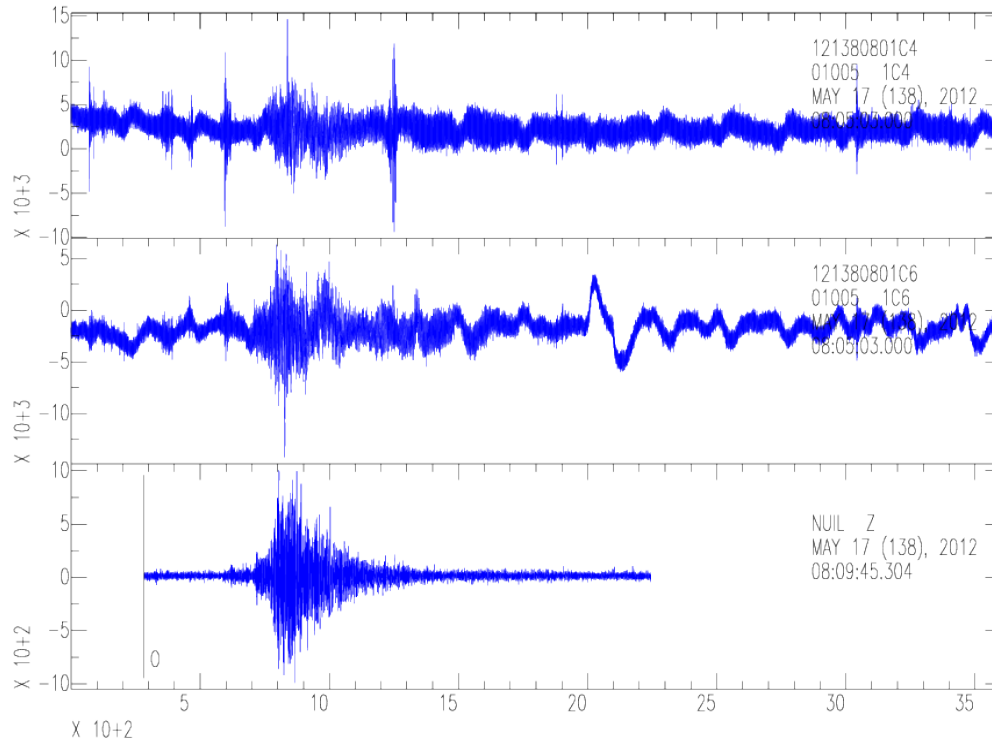
Figure 4-3. The Data used in this study. From top to bottom: Channels 4 and 6 of the STS-2, and the Locy (Z) record.

In order to do this, you can follow the procedure below. Enter SAC and:

1. Trim the longer waveform (Fig. 4-4). You should convert the difference in the beginning point of the waveforms (which are given in the hh:mm:ss format) to seconds.

    NOTE:
    Not all the waveforms start at 0.0000! To see when the trace starts and how long it is, see the file header. You can use :

    ```
    SAC> lh b e
    ```

    For instance, for our 3 files (1 for Locy seismometer and 2 for the STS-2) this would return:

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```
     FILE: ./12.138.08.05.03.1005.4.sac - 1
     --------------------------------

        b = 9.500000e-02
        e = 3.600195e+03

     FILE: ./12.138.08.05.03.1005.6.sac - 2
     --------------------------------

        b = 9.500000e-02
        e = 3.600195e+03

     FILE: ./20120517_texas-lousiana_5.0.sac - 3
     ----------------------------------------

        b = 0.000000e+00
        e = 1.962551e+03
```

which means that the STS-2 data start NOT at 0.000 (The third file is from the Locy seismometer).
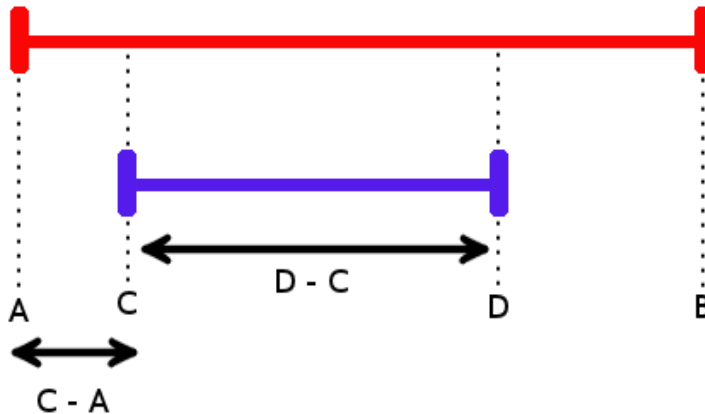
Figure 4-4. The waveforms should start and end at the same times.

Then we use the *cut* command was used in the following order (and not the other way around):

```
SAC> cut 282.209 2244.76
SAC> r ./12.138.08.05.03.1005.* ./20120517_texas-lousiana_5.0.sac
SAC> rmean
SAC> w sts2_4.sac sts2_6.sac locy_z.sac
SAC> cut off
```

NOTE:

The arguments for the *cut* command were chosen according to the starting points of the records (see Fig. 4-3 and Fig. 4-4). STS-2 data started at 08:05:03.00 while the Locy data started at 08:09:45.304, but the starting point for the STS-2 data (according to the headers) was 0.095 s and thus this gave rise to 282.209 s (C – A in Fig. 4-4). The Locy record has a length of 1662.551 according to its header info (D – C in Fig. 4-4) and so the final point for the STS-2 records had to be 2244.76 s (D in Fig. 4-4).

The results of this operation is shown in Fig. 4-5.
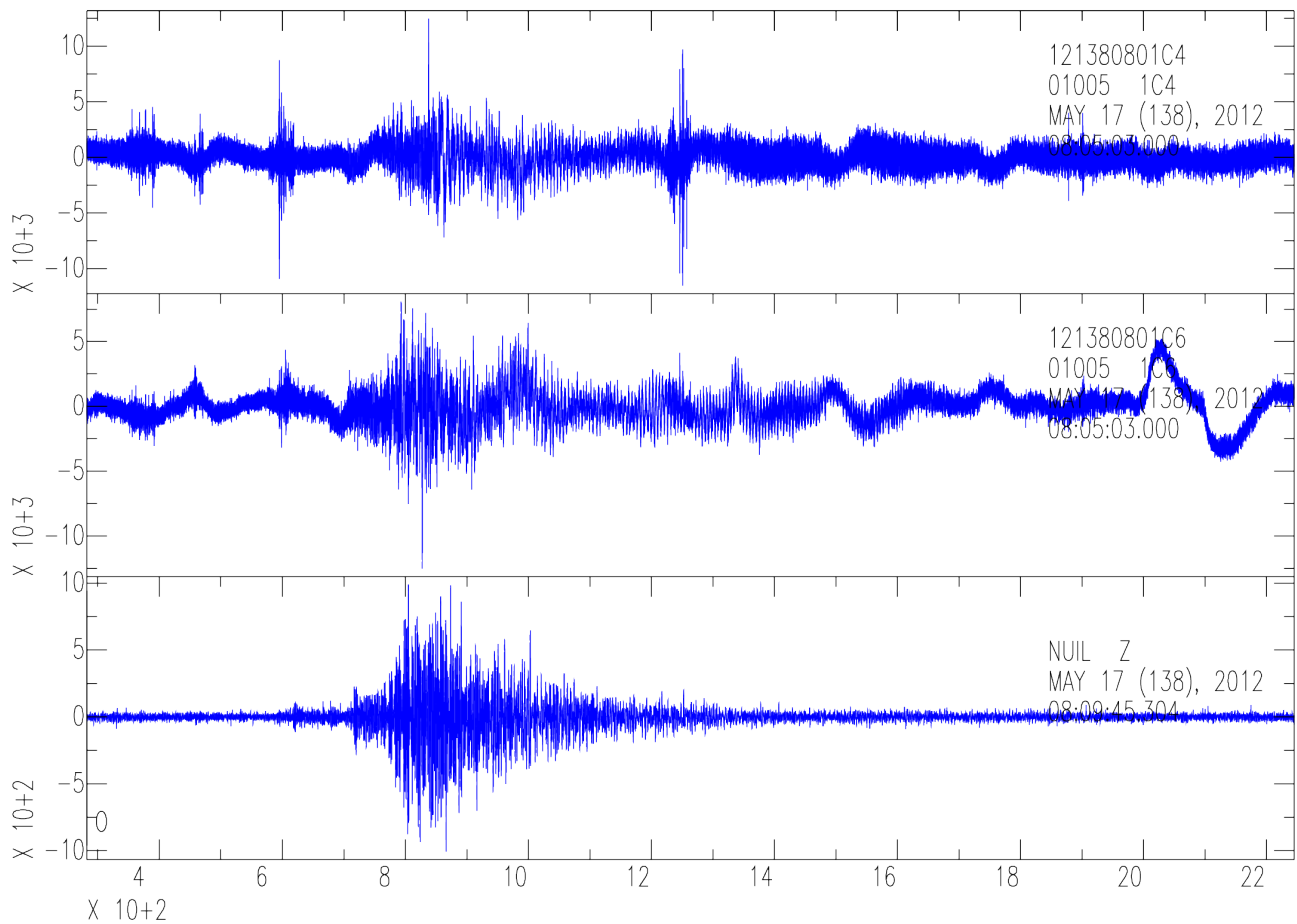
Figure. 4-5. The trimmed waveforms. The order is the same as that of Fig. 4-3.

***) Now, it was time to check for the number of points! It's very important that the records should have the same number of points.

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2. You can change the number of points in the record or the sampling interval. The STS-2 data were sampled at 40 Hz (0.025 s) and the Locy data were sampled at ~10 Hz (1.003093 s). Therefore the Locy data was resampled at 40 Hz.

```
SAC> r sts2_4.sac sts2_6.sac locy_z.sac
SAC> interpolate delta 0.025
```

NOTE:
When interpolating to lower frequencies, you will face the aliasing risk. Therefore you would have received a warning if you wanted to resample the STS-2 data to ~10 Hz.

NOTE:
Number of points (npts) and the sampling interval (delta) in a record depend on each other. By reducing delta, you will decrease the number of points and vice versa.

NOTE:
In this study, although the records were cut to have the exact same length, they were of by two data points:

STS2:   npts = 78503
LOCY: npts = 78505

This was probably caused by the different sampling rates which means even though the data are cut at the same moment of time, the data point right after that time could be located at any distance till the next sampling interval. Therefore, the Locy data was re-cut to drop 2 of its points.[13]

Having performed all these pre-processes, it was time to find the relative response according to what was discussed in the theory section.

4.2 FINDING THE DIFFERENCS BETWEEN THE WAVEFORMS:

A brief look at Fig. 4-5 suggests that the amplitudes of the STS-2 data is bigger than those of the Locy Hall green seismometer and thus the STS-2 gain is higher than the Locy seismometer. Therefore it is better to divide the STS-2 data by that of Locy green seismometer. The spectral amplitude and phase diagrams for the data are shown in Fig. 4-6. The results of the dividing operation is shown in Fig. 4-7 and Fig. 4-8 in time and frequency domains respectively.

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13 The length to be cut was calculated according to the sampling rate. The sampling rate is 40 Hz which means that for 2 samples we would need 0.05 s. Thus the Locy record was trimmed by 0.05 seconds (($1^s * 2^{(samples)}/40^{(samples)}$).

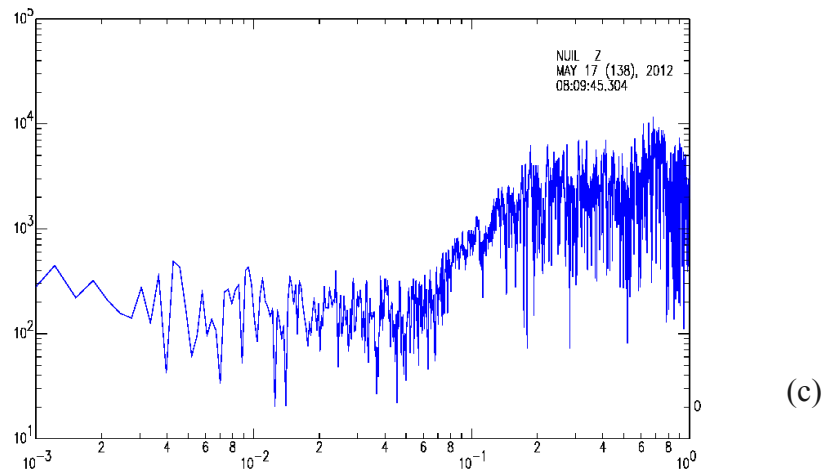***) Here the work has been done on both of the STS-2 components for not being sure as to which one is Z.
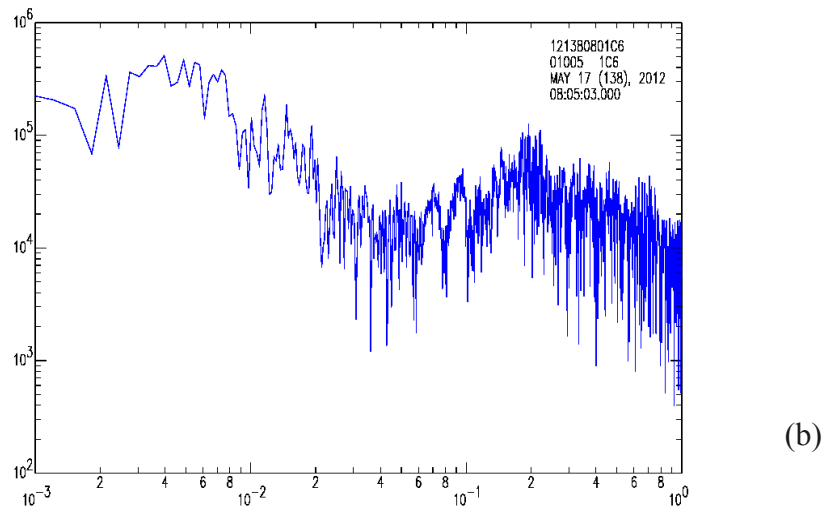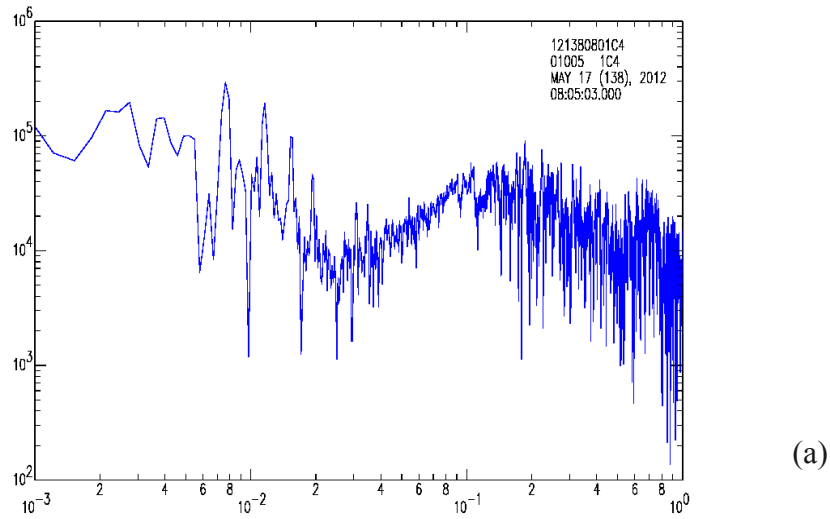

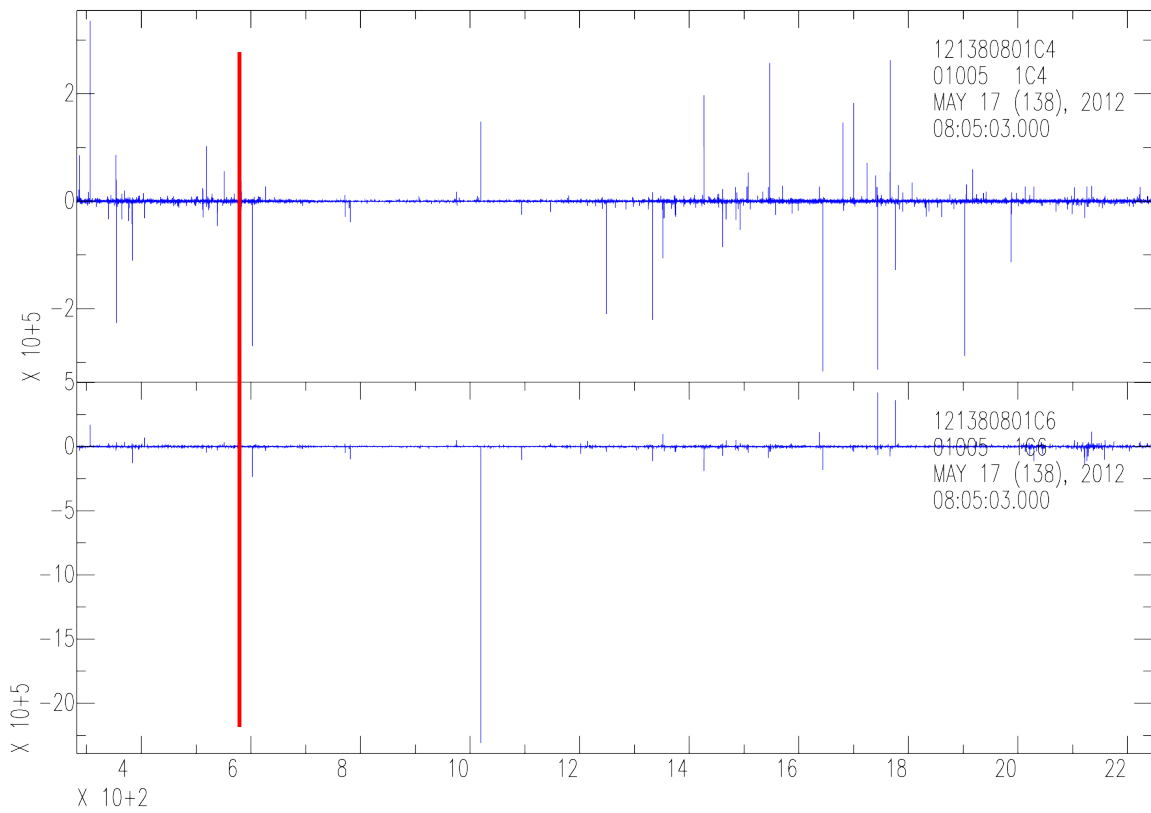Figure. 4-6. Spectral amplitudes for (a) STS-2 c-4, (b) STS-2 c-6, (c) Locy waveforms.

Figure. 4-7. Results of dividing STS-2 channels 4 (top) and 6 (bottom) data by the Locy Hall seismometer data in time domain. The red line shows the approximate arrival time for P-waves.
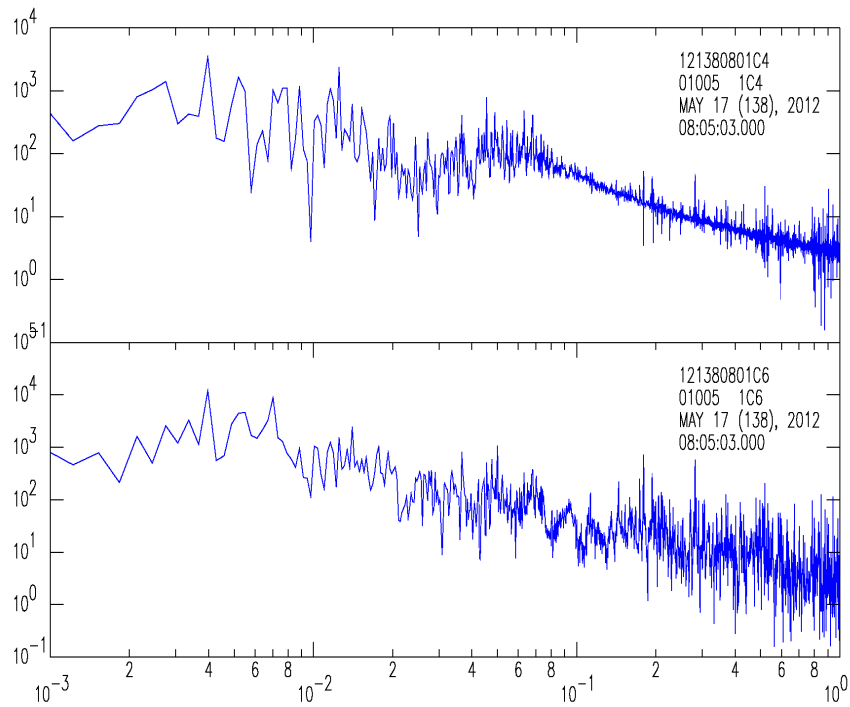

Figure. 4-8. Results of dividing spectral amplitudes of STS-2 channels 4 (top) and 6 (bottom) data by that of Locy Hall seismometer data in frequency domain.

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The results of multiplying the ratio of amplitudes by that of powered phased (i.e. subtraction of spectral phases in SAC) are shown in Fig. 4-9 and Fig. 4-10 with linear and logarithmic axes respectively.
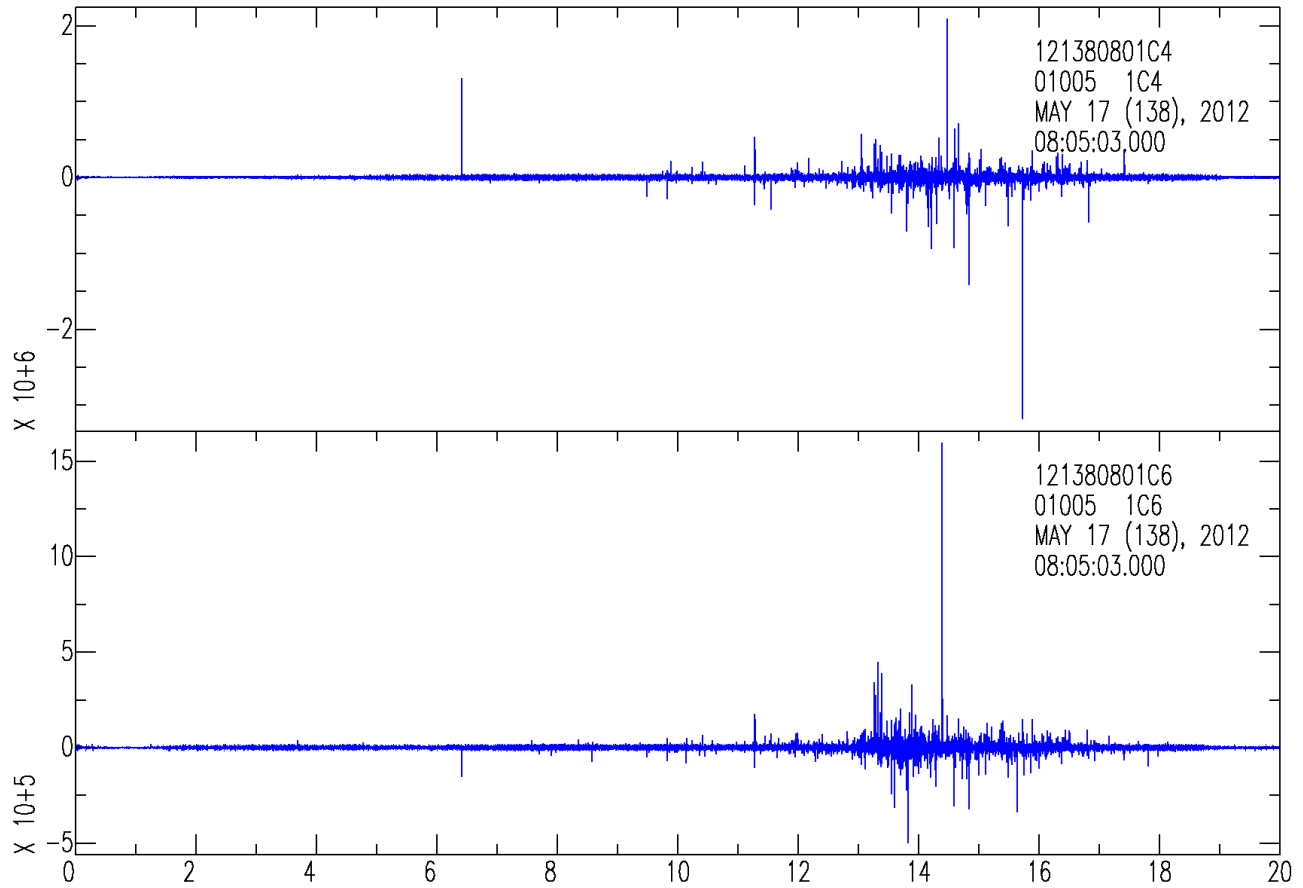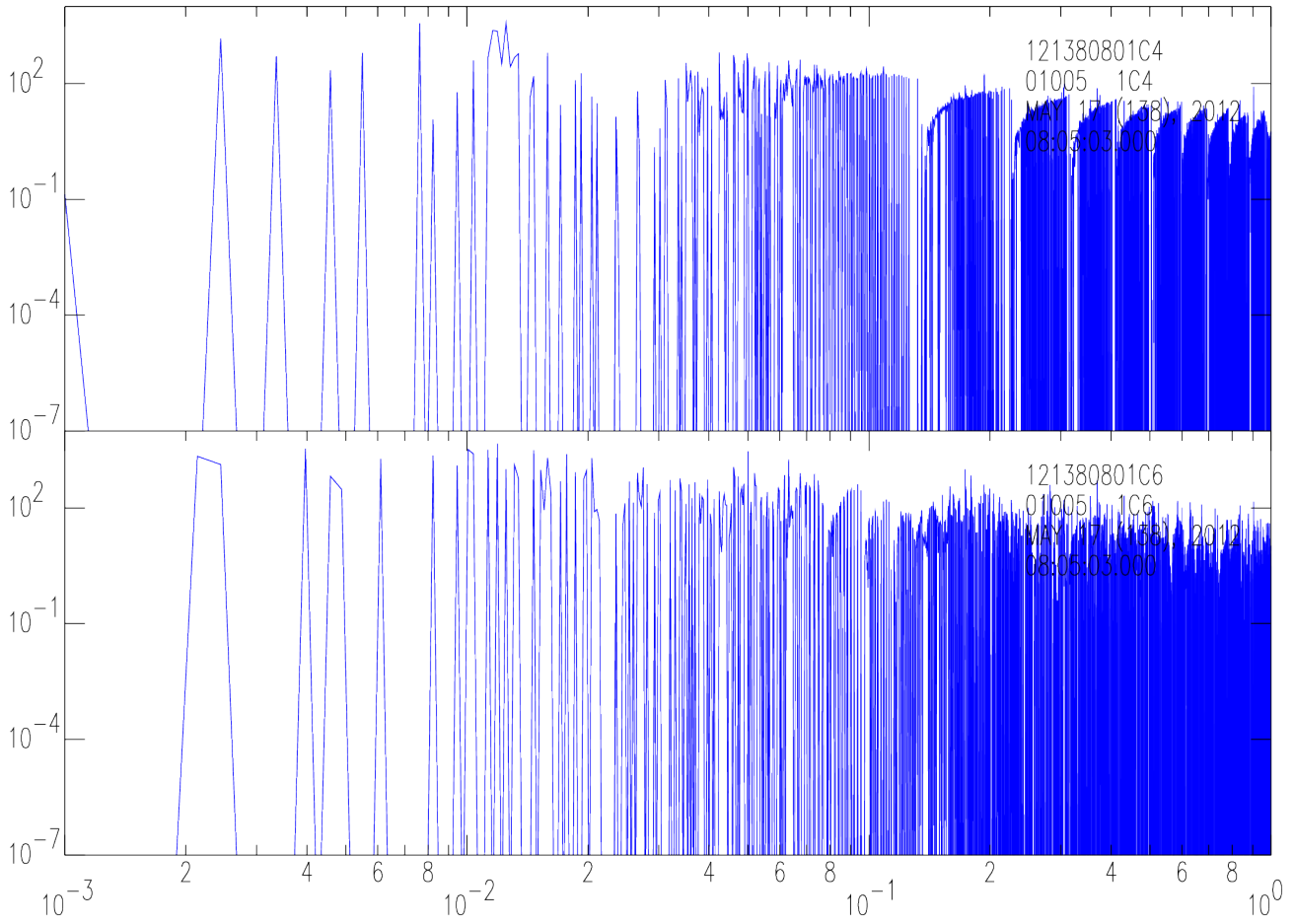

Figure. 4-9. The final results of dividing the STS-2 data by Locy Hall seismometer data in frequency domain in a linear representation.

Figure. 4-9. The final results of dividing the STS-2 data by Locy Hall seismometer data in frequency domain in a logarithmic representation.