LIGO: Power Main Disturbance Research

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Abstract

This LIGO research made use of both *S5* and *S6* data of LIGO to discuss the extent of the North American 60 Hz Power Main Disturbance.

Introduction

Gravitational Waves

In general relativity, space and time are not separate, but rather are combined and used as a single standard to measure and describe objects, as length and time may change according to different frames of reference. The new standard is called spacetime, and it accurately describes the states of objects with the mixed coordinate of space and time. Analogous to electromagnetic waves, which are caused by the change of electromagnetic fields, gravitational waves are caused by the curvature of spacetime, whereas the curvature is caused by the movement of mass. In other words, gravitational waves are produced by the change of gravitational fields, and the energy changed in the gravitational fields will radiate to space in the form of gravitational waves. Figure 1 illustrates the relationship between spacetime and gravitational waves; the waves in the figure represent the gravitational waves emitted by the stars.

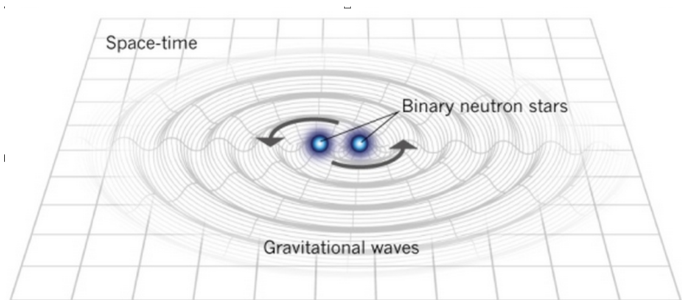

Figure 1: The relationship between spacetime and gravitational waves[3]

There are several potential sources that generate gravitational waves that have the greatest possibility of being detected. One kind of potential gravitational waves comes from the early stages of the universe. There were some events such as the Big Bang and cosmic strings, which occurred a long time ago but still maintained their influence in the form of gravitational waves. Some other kinds of potential sources of gravitational waves come from some short duration incidents, such as the bursts from supernovae or the formation of black holes.

Some continuous celestial events may also be the sources of detectable gravitational waves, such as two spinning polarized stars and the oscillating neutron stars. In 1974, Taylor and Hulse discovered a binary star system consisting of one neutron star and one pulsar, a rotating, magnetized neutron star, spinning around a common center of mass[1]. The two scientists measured and studied the arrival time of the pulses.The star system looks similar to Figure 1 shown above. This very system is the first binary pulsar system to be discovered, and its variation of the time arrival of the pulses is systematic, according to the study by those two scientists. The measurement of the time change of its rotational period precisely matched the theoretically expected change in Einstein's prediction, and it became one of the most important pieces of indirect evidence of the existence of gravitational waves.

LIGO Program and Its Detectors

In the 1990s, scientists in America started the LIGO program, which stood for *Laser Interferometer Gravitational-Wave Observatory*, intended to detect gravitational waves directly. The program was led by Caltech's and MIT's researchers and had two large observatories installed in Livingston, Louisiana, and Richland, Washington. The observatories had three detectors, two with an arm length of four kilometers and one with an arm length of two kilometers.

Both observatories are using the most advanced optical equipment to do the observation with upgrades and promotions every several years in order to acquire a higher possibility of the observation. The latest observation was named “*S6*,” which meant the sixth attempt of the observation, and had been performed from 2010 to 2011. Right now, the scientists running LIGO have upgraded the LIGO facilities, and renamed the program to “aLIGO” which stands for *advanced LIGO* with the precision improved by about 10 times, and they may have just started to perform the seventh attempt of observing gravitational waves in 2015.

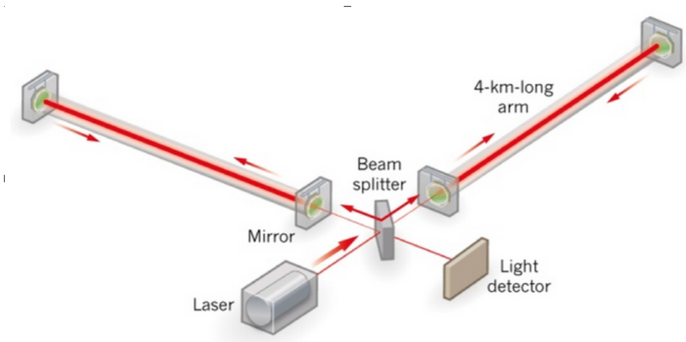

Figure 2: A brief description of the structure of the LIGO detector [3]

The mechanism of interferometers, which are the detectors designed for the LIGO, is rather straightforward to explain, but quite difficult to put in use in observatories. The positions of basic structures of an interferometer are shown in Figure 2, and it consists of a laser generator, a beam splitter, a light detector, and two long perpendicular arms with several mirrors installed within. Laser beams are represented by red lines in Figure 2, and the red lines between the mirrors are bolder as the mirrors serve as the light signal enhancers in the detectors. The direction of laser beams is shown by the red arrows in Figure 2. A single laser beam is generated by the laser generator and then is split into two by the beam splitter. With the help of those mirrors, laser beams reflect back and forth between the mirrors to reinforce the signals before they are recombined and collected at the light detector.

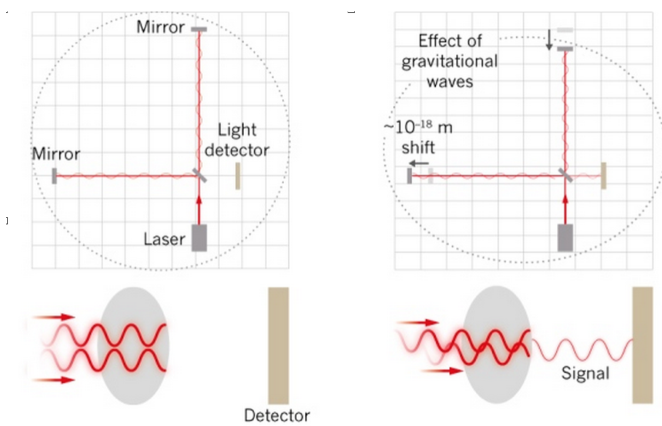

Figure 3: The two different results of combined light beams[3]

So how can an interferometer tell if there are gravitational wave signals? Normally, as those two beams travel through two paths of identical length, they should combine together "out of phase" and cancel each other when they both show up at the detector (the condition depicted on the left of Figure 3). However, when a gravitational wave passes through, the arms deform slightly and the distances traveled by the two beams will also slightly change so that they can no longer cancel each other out, thus producing a signal at the detector (this condition is shown on the right of Figure 3). If the signals coincide in both observatories, then it would be a successful capture of gravitational waves.

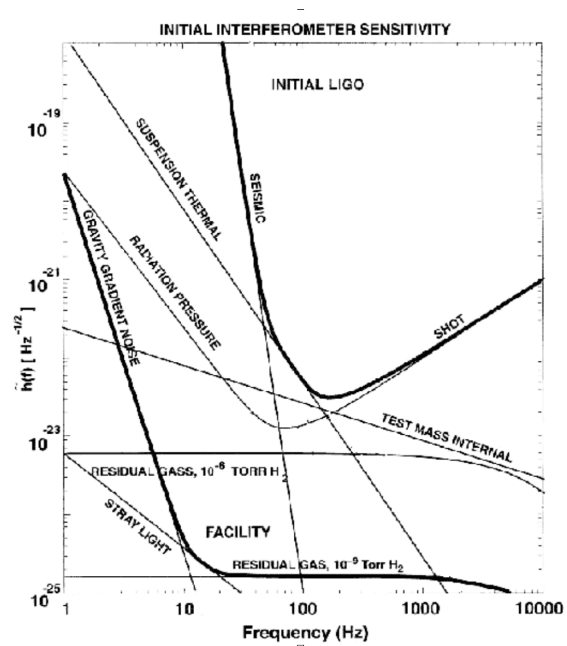

Figure 4: The different disturbances of the interferometer[5]

Many factors affect the observation. The disturbances can generally be divided into two parts, instrumental noises and environmental noises. Just like the different disturbances shown in Figure 4 above, the instrumental disturbances can be flaws or the deviation caused by the components in the detectors and detectors themselves. One famous instrumental noise is the *Violin Mode*, in which the disturbances are caused by the vibration of the suspension strings of the equipment in detectors. The environmental noises come from the seismic noise and vibration at low frequencies, the atomic vibrations at mid frequencies and the quantum nature of light limits at high frequencies. These factors can all produce disturbances that will severely affect the data gathered from the observatories. In this case, observatories only record data at the range beyond frequent environmental disturbances. Even so, the data are still susceptible to other unpredicted disturbances.

Though the observatories are able to record those signals, they are not able to compute or deal with such big and noisy raw data.

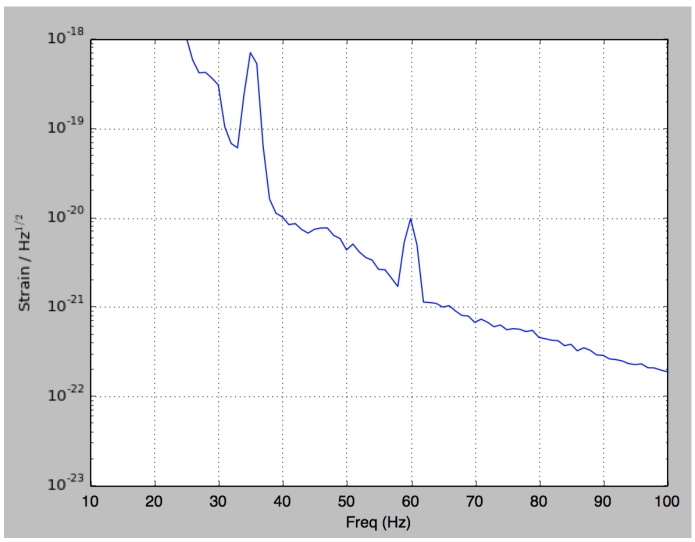

Figure 5: The ASD plot of a random LIGO file, including a distinct strain peak at 60 Hz

In the raw data, the records contain both signals and noises. In Figure 5, it is easy to observe an obvious peak at 60 Hz, and this is mainly attributed to the Power Main Disturbance. In order to restore the original signals, or to perceive possible gravitational waves, scientists use model injections. The models are all theoretical templates of gravitational waves, and there are two ways to inject these models. The first way is to inject the templates into the hardware detectors, and the second way is to inject templates into the data LIGO has collected. Both ways expect to see how well the templates match the record, but a large amount of computational effort is involved in the injection process.

Fortunately, with the help of BOINC, which stands for *Berkeley Open Infrastructure for Network Computing*, an online computing and volunteer computing program, researchers upload the LIGO data and use the platform to handle the data. Through BOINC, hundreds of thousands of volunteers join the program by donating the idle time of their computers to help process the data and send the answers and results back after the computation is done.

Research Question

One important task for researchers is to discern and analyze disturbances. In LIGO, the investigation of disturbances gets more important as the laser devices have a high requirement of precision, so they can perceive, or in other words, be affected by, even nuanced signal interference. In light of this fact, it would be very interesting and challenging to study the influence of electric power.

The electric power in North America is generated at 60 Hz. Whether the frequency of the power mains fluctuated and to what extent the frequency fluctuated were the key questions of the research. As a matter of fact, the fluctuation of electric frequency affected data collection in LIGO, and this disturbance might vary periodically every day. The disturbance of 60 Hz signals is difficult to remove from LIGO. The disturbance will always exist, as the detectors themselves are driven by 60 Hz electric power. Furthermore, whether the precision and the improvement of the LIGO equipment could affect the extent of the disturbance would be another thing to look at in this research.

Why is it important to investigate the extent of the Power Main Disturbance? Because there is a potential gravitational wave source whose frequency is close to 60 Hz. The potential source body exists in the Crab Nebula, known as Crab Pulsar, the remnant of the Crab Nebula supernova[6]. It has a rotation period of 0.03339 seconds[8]. Normally, it rotates symmetrically and doesn't emit strong gravitational waves, but if some unexpected celestial events happen on the Crab Pulsar, such as the crash of debris or materials, it then becomes asymmetric and emits gravitational waves twice in one complete rotation.

According to the calculation, the potential gravitational waves of Crab Pulsar are theoretically at 59.89 Hz. The frequency is close to 60 Hz, which is a frequency that may be severely affected by the power mains. If the frequency of Crab Pulsar's potential gravitational waves is higher than 60 Hz, even if the Power Main Disturbance doesn't affect the detection work right now, it will inevitably affect the detection work later, as source bodies are losing energy and their frequencies will continue decreasing. Fortunately, the frequency is below 60 Hz, so once the research has proven that this very disturbance doesn't affect the detection, the disturbance would no longer bother North American's LIGO program anymore. From this perspective, it's very important to investigate if the power main signals really affect the gravitational wave signals.

Research Plan

In order to engage in the influence of electric power, it was necessary to examine data at different periods of the day collected by observatories. The trend of the influence of electric power might change with patterns, so it would be particularly helpful to study the strain of the peak frequencies. The data would be downloaded from the website provided by *LIGO Open Science Center*, and the data, at approximately the same time of the day, of the early, middle and late periods of *S5* and *S6* would be analyzed in order to have a general view of the improvement of the LIGO facilities, to estimate the influence of the power main, and to have an analysis contrasting the influence of the power main during the daytime and the nighttime.

One way researchers measured the extent of the 60 Hz signal disturbance was by applying Blackman Window to the data, performing Fast Fourier Transform, using the FFT to analyze Amplitude Spectral Density, which indicated the "loudness" of the noise, and observing the variation of the highest peak around 60 Hz and the magnitude of its strain of both FFT and ASD. To analyze the influence of a 60 Hz disturbance, it was important to look respectively to the Full Width

Half Max of both FFT and ASD data, as their FWHM represented spillage radius of power main signals. The whole process included the following procedures:

1. The Installation of Python and *hdf5* module
2. Downloading work of *S5* and *S6* data from LOSC
3. Production and Compilation of Python scripts for research purpose.[1]
4. Calculation of close 60 Hz signals with FFT and ASD
5. Plotting work for FFT and ASD of close 60 Hz signals
6. Calculation of standard deviation and arithmetic mean of the signals
7. Application of the scripts to all LIGO files
8. Data gathering work for the property of close 60 Hz signals of *S5* and *S6* data
9. Analysis on the variation of standard deviations and arithmetic means of Day-Time values and Night-Time values, *S5* and *S6* values

Research Procedure

The LOSC website provides the latest LIGO files and basic techniques and procedures for LIGO starters, so the research data is fairly acces-

[1] A Python script for this very use is included in Appendix A

sible and the research doesn't cost much to establish and investigate.

The installation of Python and the *hdf5* module is the preparation step of the research. The steps of installation are presented in the tutorials of the LOSC website, and they are very handy if the tutorials are followed correctly. It was important to have a first glimpse of the LIGO program and its data. One good way to do this was by viewing and modifying *lotsofplots.py*[2] provided by the LOSC website. It was not difficult to get the results exhibited on the website by simply downloading the LIGO file and the script.

For the selection of LIGO files from *S5* ad *S6* sessions, it was necessary to make sure to download files that were recorded at approximately the same time of day and ideally to download files from the early, middle and late periods of the *S5* and the *S6* session from the same observatory. The research only used the integral LIGO files which were recorded completely and had states of 100% for efficiency and accuracy. One thing that was noteworthy to mention was that the LIGO detectors seemed to work better at night, as the number of integral and perfect LIGO files recorded during the nighttime was greater than that of LIGO files recorded in the daytime, according to the experience selecting and downloading LIGO data files from the *LOSC* website. In this research, all analyses were based on the data provided by *Livingston Parish Observatory* in Louisiana. The Day-Time data were those recorded at approximately 16:00 Louisiana

[2]The scripts of *lotsofplots.py* are intended to show the sample figures and properties of LIGO data files and to provide a example of Python language script for the *hdf5* module.

local time (UTC 22:10) and the Night-Time data were those recorded at approximately 2:00 Louisiana local time (UTC 08:00).

Writing and compiling the code would be the most difficult part of the research. There were several modules that were unfamiliar, so it also took a while to study the Python language and modules. A good sketch of scripts could help a lot during compilation and the debugging process, but it still took a long time to make scripts work as intended. The code designated to analyze the influence of the Power Main Disturbance divided the data into single minutes and ran through the whole LIGO file to calculate and record the peak frequency near 60 Hz and its strain of each minute. Then, with the peak frequency and the strain provided, it was possible to calculate the FWHM respectively for FFT and ASD and the standard deviation and the arithmetic mean of all previous values. The code used the integral-minute data to do the analysis and reported the result by plotting figures and writing down several important values in file reports.[3]

By plugging in different LIGO files and letting the scripts and the computer do the calculation, all data could be collected in the file reports. The final stage of this research, the analysis stage, was divided into two parts. The first part was to analyze the plotting result of a random LIGO file, and the second part was to read, formulate and analyze the values in the file reports. Doing the arithmetic mean once again on the existing mean values and standard deviations in the file

[3]In Appendix A, the plotting feature of the code is disabled.

reports was an easy and attainable way to analyze the differences of the Power Main Disturbance between the daytime and the nighttime and the improvement of the *S6* equipment.

Analysis

There are two parts in *Analysis* section. The first part is *Data Analysis*. In this section, research data will be shown and analyzed in detail. The second part is *Error Analysis*; possible factors of the errors appeared in the previous section will be discussed in this section.

Data Analysis

In section *Data Analysis*, a random LIGO file would be analyzed first in order to find some details within its plots, and then the statistics of all sets of LIGO files would be presented and investigated to see if there were any patterns of the Power Main Disturbance, and to answer the research questions.

Single File Analysis

Primarily, the code[4] would plot the strain, peak frequency and FWHM of a perfect LIGO file respectively like graphs shown in Figure 6, 7 and 8.

[4]The code for this research purpose is provided in Appendix A.

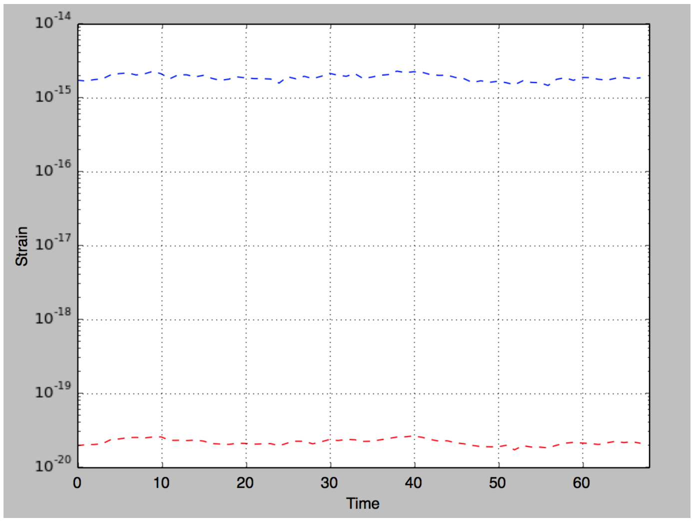

Figure 6: The sample figure of strain. The red dashes represent ASD and the blue dashes represent FFT

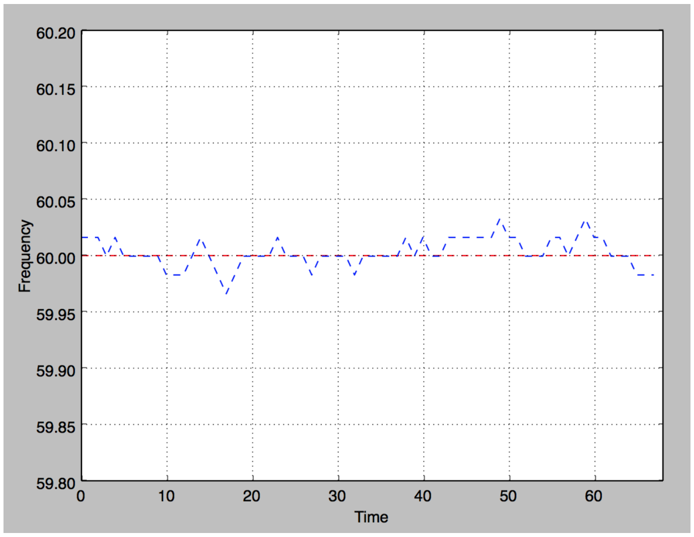

Figure 7: The sample figure of peak frequency. The red dashes represent ASD and the blue dashes represent FFT

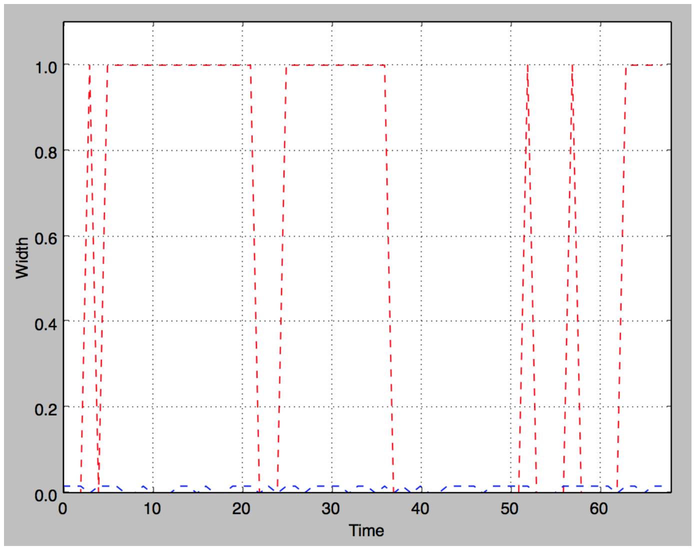

Figure 8: The sample figure of FWHM. The red dashes represent ASD and the blue dashes represent FFT

The Figure 6, 7 and 8 showed the three main characters of FFT and ASD. The origin LIGO file of the figures was a random *S6* file, but the file did show some significance here. Figure 6 shows the strains of both ASD and FFT. Even though the magnitudes of the strains were different, the strains varied in the same pattern. In the code compilation, the same pattern of variation suggested the validity of the construction of ASD's peak frequency and strain.

According to Figure 7, the peak frequency of FFT was continuously varying from beginning to end, but that of ASD was reasonably stable at 60 Hz. Figure 7 provides an answer to the research question about the extent of the Power Main Disturbance. The figure suggests that the frequency of the Power Main Disturbance didn't vary much from time to time, and the extent of the disturbance was primarily very close to 60 Hz.

According to Figure 8, the FWHM of FFT kept varying at a very low width, almost below 0.1 cm, but the FWHM of ASD was sometimes at 1.0 cm, so the Half Width Half Max of ASD was sometimes 0.5 cm. The FWHM of ASD was sometimes at 1.0 cm and sometimes at 0 cm, and this was a quite anomalous phenomenon.

Taking into account the fact that the ASD Peak frequency of the Power Main Disturbance was always 60 Hz, and the Crab Pulsar's gravitational wave frequency was 59.89 Hz, the ASD of the Power Main Disturbance suggested that it was actually getting in the way of the detection of the potential gravitational waves. The interesting thing was, however, that the FWHM of FFT was lower than 0.1 Hz, so according to FFT, the gravitational waves' detection wouldn't be affected by the North American Power Main Disturbance. The very conflict here suggested more study and investigation was still required in this field, or maybe this conflict was the reason that some gravitational waves were hard to detect.

Statistic Analysis

Aside from the single LIGO file, the arithmetic means and standard deviations of the whole series of LIGO data were more meaningful to analyze. The standard deviation values were the results of arithmetic means of the standard deviations of every single LIGO file. In this case, the presented standard deviation values were not the actual standard deviation of every minute's data, but they had higher reference value as the previous discussion established that the range might vary from day to night and from period of year to period of year, so the average of standard deviations of segments reflected better on the variation of the noises in short periods.

Mean Value(Average)

	Day Time	Night Time	S5	S6
FFT Strain	2.084E-15	1.755E-15	2.284E-16	1.646E-16
ASD Strain	2.436E-20	2.051E-20	2.664E-20	1.928E-20
FFT Peak Freq	60.000	60.003	59.999	60.004
ASD Peak Freq	60.000	60.000	60.000	60.000
ASD FWHM	0.5294	0.4412	0.5466	0.4393
FFT FWHM	0.0119	0.0117	0.0116	0.0119

Figure 9: The chart of arithmetic means

According to the values in Figure 9[5], it is fairly clear that the Night-Time values were generally smaller than Day-Time values. The possible explanation for this phenomenon was that local people generally used electric devices less at night, so the LIGO received fewer 60 Hz signals. The considerable differences between Day-Time values and Night-Time values, primarily as large as 12%(using the data of FFT Strain and ASD Strain), suggested that the power main did have a great influence on gravitational wave detection work. The mean val-

[5] For more detailed information, please see Appendix C.

ues of ASD's FWHM, which were all higher than 0.4 cm, suggested that the power main disturbance did have the potential to affect the detection of gravitational waves, in accord with the results of Figure 8. Fortunately, according to the comparison between *S5* and *S6* data, there was an improvement on the protection of environmental noise. According to the data, the noises had been reduced by about 28%. Even though there still was a great deal of noise interference, it was a significant improvement and advancement.

Standard Deviation Chart(Average)

	Day Time	Night Time	S5	S6
FFT Strain	1.653E-16	1.315E-16	1.387E-16	1.567E-16
ASD Strain	1.647E-21	1.265E-21	1.264E-21	1.600E-21
FFT Peak Freq	0.0127	0.0154	0.0128	0.0149
ASD Peak Freq	2.132E-14	2.132E-14	2.132E-14	2.132E-14
ASD FWHM	0.4051	0.4449	0.3966	0.4463
FFT FWHM	0.0075	0.0076	0.0076	0.0074

Figure 10: The chart of standard deviation. The values were the results of the arithmetic mean of standard deviations of every single data file.

The standard deviation, according to Figure 10, was generally higher during the daytime, which indicated that the use of electric devices was more active during the daytime. As for the comparison of standard deviation of *S5* and *S6*, the higher value of the standard deviation of *S6* indicated that the detectors of *S6* observatories were more sensitive to variations and signals.

When combining the data in Figure 9 and 10, however, there was an inconsistency. Figure 7, 8 and 9, suggested all ASD's peak frequencies near 60 Hz should be exactly at 60 Hz; however in Figure 10, it suggested that the standard deviation of ASD's peak frequency was 2.132×10^{-14}, which should be 0. This was a very obvious and critical error in the result.

Error Analysis

One uncertainty that occurred in this research was the length of the width of FWHM of ASD. According to Professor Myers, the Power Main Disturbance shouldn't have any effects on the detection of gravitational waves, as scientists had proven before. One element that could lead to the error was the bug made in the script written for the research; however, no existing error was spotted in the code.

Another possible factor that could lead to this error was the wrong interval picked for ASD. As a matter of fact, the longer interval meant the higher resolution on data, but also a more blurred embodiment of the Power Main Disturbance, as the frequency of such a disturbance kept changing. When the interval of data was changed, the mean value of ASD's FWHM and its standard deviation were also changed. As a result, a wrong interval could also lead to such error.

Several trails of selecting different intervals showed that the condition of the abrupt variation between 1.0 cm and 0.0 cm still occurred, and only the frequency of the variation changed. The trails suggested that even though choosing a right interval was a subtle and critical task in the whole research, it wasn't the main reason for this phenomenon. Both of the two possible factors had been discussed, but it seemed that neither of them was the element leading to this uncertainty. It indicated that either the phenomenon of FWHM was a correct one, and only the interval should be chosen properly, or the real reason was still remained undiscovered.

Nevertheless, this conflict itself had great significance: it either indicated that more work should be done on the investigation of LIGO or pointed to the problem which has caused the difficulty of detection of gravitational waves. Still, the inconsistency occurred in the ASD's peak frequency, which suggested that the research has a potential for improvement. With continued effort and analysis, the research could provide a more satisfying result.

As for the inconsistency on the peak frequency of ASD, it was quite puzzling. When the scripts ran through the whole LIGO data, the very standard deviation was always 2.132×10^{-14}; however when they ran through only segments of the single LIGO file, the result was correct and gave an outcome of 0. With such a strange phenomenon, it was believed that the problem was with the precision of Python's floating point calculation, and it was difficult to get rid of.

Research Conclusion

From the result, it was clear that the frequency of the Power Main Disturbance didn't vary much from 60 Hz, but it still had the potential to affect the detection of gravitational waves. Through the comparison of the mean values of the peak frequencies' strain of FFT and ASD between the daytime and the nighttime, the great interference of the Power Main Disturbance was observed, and through the comparison between the statistics of *S5* and *S6*, it was easy to detect a significant improvement of environmental noise processing on LIGO detectors. An error and a conflict were identified in the statistics, and they suggested that more delicate and elaborate research and investigation might still be required in this field.

Acknowledgements

Research cannot continue without the LIGO Open Science Center. The website of LOSC provided about four years of observation data of the LIGO program and granted the research with easy accessibility to those data.

This research was mainly done under the guidance of Professor Eric Myers[6]. Professor Myers provided much technical support for the Python language and its modules. He has given a great deal of incisive advice for the research and has helped improve the algorithm

[6]Eric Myers, a physics Professor of State University of New York at New Paltz

for the peak frequency and the FWHM.[7]

In addition, the Pioneer Program provided the platform for this research. The Pioneer Program set up the platform for Professor Eric Myers to guide and facilitate this research. The Writing Center, a department of the Pioneer Program, also provided help in improving the quality of this research report.

Last, thank you to all institutions and people that helped and supported this LIGO research on the Power Main Disturbance.

[7] The Peak Frequency and FWHM are two critical parts in the script. See *Research Procedure* for more information.

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Appendix A: PMD.py

```
# PMD stands for Power Main Disturbance
# The script is intended to analyze the disturbance of North American power main
# Author @ William Li @ BHSFIC
#*********************************
import numpy as np
import readligo
import matplotlib.mlab as mlab
import cmath as math
import matplotlib.pyplot as plt


## Open the "frame" file (.hdf5 not .gwf) and read the strain
## and the time arrays

fileName = '946515968'

print "Reading file ",fileName,"..."
strain, time, channel_dict = readligo.loaddata('L-L1_LOSC_4_V1-'+fileName+'-4096.hd

ts = time[1] - time[0]      #-- Time between samples
fs = int(1.0 / ts)          #-- Sampling frequency  (should be 4096)

## Get the list of segments in this file

segList = readligo.dq_channel_to_seglist(channel_dict['DEFAULT'], fs)
print "There are ",len(segList)," segments in this file."

## Loop over all the segments.
## Each time through the loop segSlice is set to a Python slice object
## which can be used to get a subset of the strain data for just that segment.
## (Also, remember that Python uses  indending for grouping.)

ii=0
for segSlice in segList:
    ii = ii + 1
    print " "
    print ii,") Segment list: ", segSlice
```

```
strain_seg = strain[segSlice]
time_seg = time[segSlice]
Nseg = len(strain_seg)
print "    Number  of samples: ", Nseg, "(for ", Nseg/fs," seconds ) "

## copy from best_strain.py, set range for the whole slice

start, stop, inc = segSlice.indices(len(strain))

## help determine the number of 60-sec intervals
min=(stop-start)/4096/60

print start
print stop
print min
minarr=[]

## create list for: MAX_VAL MAX_FREQ FWHM

mFfreq=[]
mFval= []
mAfreq=[]
mAval= []
mFFWHM=[]
mAFWHM=[]

for m in range(0,min,1):

    ## 60*fs(4096)=245760
    st=start+m*245760
    ed=st+245760
    #st, ed, inc = segSlice.indices(len(strain))

    if(ed>stop):break
    minarr.append(m)

    ##copy from lotsofplots.py
    ##modified strain_seq and time_seq variable.
    strain_seg = strain[segList[ii-1]][(st):(ed)]
    time_seg = time[segList[ii-1]][(st):(ed)]
```

```
    window = np.blackman(strain_seg.size)
    windowed_strain = strain_seg*window

    ## modified freq variable
    freq = np.arange(0, 4096, 1.0/60)
    freq_domain = np.fft.fft(windowed_strain)

    Fmax_freq=0
    Fmax_val= 0
    Amax_freq=0
    Amax_val= 0
    Frbound=  0
    Flbound=  0
    Arbound=  0
    Albound=  0
    FFWHM=    0
    AFWHM=    0


    for j in range(0,len(freq)):                          #range(0,len(freq))
        t=freq_domain[j]
        f=freq[j]
        if(f<57 or f>63):continue
        mag_t=abs(t)
        #print mag_t
        if(mag_t>Fmax_val):
         Fmax_val = mag_t
         Fmax_freq = f

    mFfreq.append(Fmax_freq)
    mFval.append( Fmax_val)

## calculate FFWHM

    for j in range(0,len(freq)):
        t=freq_domain[j]
        f=freq[j]
        if(f<53 or f>Fmax_freq):continue
```

```
    mag_t=abs(t)
    if(mag_t-Fmax_val/2>=0):
        Flbound=f
        break

for j in range(0,len(freq)):
    t=freq_domain[j]
    f=freq[j]
    if(f<Fmax_freq or f>67):continue
    mag_t=abs(t)
    if(mag_t-Fmax_val/2>=0):
        Frbound=f
        break


FFWHM=Frbound-Flbound
mFFWHM.append(FFWHM)

Pxx, freq = mlab.psd(strain_seg, Fs = fs, NFFT=fs)
Axx = np.sqrt(Pxx)
for j in range(0,len(freq)):
    f=freq[j]
    if(f<57 or f>63):continue
    if(Axx[j]>Amax_val):
      Amax_val = Axx[j]
      Amax_freq = f
mAfreq.append(Amax_freq)
mAval.append( Amax_val)


for j in range(0,len(freq)):
    f=freq[j]
    if(f<53 or f>Amax_freq):continue
    if(Axx[j]-Amax_val/2>0):
        Albound=f
        break
```

```
    for j in range(0,len(freq)):
        f=freq[j]
        if(f<Amax_freq or f>67):continue
        if(Axx[j]-Amax_val/2>0):
            Arbound=f
            break
    AFWHM=Arbound-Albound
    mAFWHM.append(AFWHM)

 #Show all results of calculation
 #print mAFWHM
 #print "FFT peak Frequency"
 #print mFfreq
 #print "FFT peak strain"
 #print mFval
 #print "ASD peak Frequency"
 #print mAfreq
 #print "ASD peak strain"
 #print mAval
 #print mFFWHM

# Graphics
 #print "Plotting Strains..."
 #plt.semilogy(minarr, mAval,'r--',minarr, mFval,'b--',)
 #plt.axis([0, len(minarr), 1e-20, 1e-14])
 #plt.grid('on')
 #plt.ylabel('Strain')
 #plt.xlabel('Time')
 #plt.show()

 #print "Plotting Frequency Peaks..."
 #plt.plot(minarr, mAfreq,'r--',minarr, mFfreq,'b--',)
 #plt.axis([0, len(minarr), 59.8,60.2])
 #plt.grid('on')
 #plt.ylabel('Frequency')
 #plt.xlabel('Time')
 #plt.show()

 #print "Plotting Full Width Half Max..."
 #plt.plot(minarr, mAFWHM,'r--',minarr, mFFWHM,'b--',)
```

```
#plt.axis([0, len(minarr), 0,1.1])
#plt.grid('on')
#plt.ylabel('Width')
#plt.xlabel('Time')
#plt.show()

##Calculate for Mean Values and Standard Deviation
Fvals=0.0
Avals=0.0
Afrqs=0.0
Ffrqs=0.0
A_FWHM=0.0
F_FWHM=0.0

SDFvals=0.0
SDAvals=0.0
SDAfrqs=0.0
SDFfrqs=0.0
SDAFWHM=0.0
SDFFWHM=0.0

for i in mFval:
    Fvals+=i/len(mFval)
for i in mAval:
    Avals+=i/len(mAval)
for i in mFfreq:
    Ffrqs+=i/len(mFfreq)
for i in mAfreq:
    Afrqs+=i/len(mAfreq)
for i in mAFWHM:
    A_FWHM+=i/len(mAFWHM)
    #print "A_FWHM: "+str(A_FWHM)
for i in mFFWHM:
    F_FWHM+=i/len(mFFWHM)

for i in mFval:
    SDFvals+=(i-Fvals)**2
for i in mAval:
    SDAvals+=(i-Avals)**2
for i in mFfreq:
```

```
    SDFfrqs+=(i-Ffrqs)**2
for i in mAfreq:
    SDAfrqs+=(i-Afrqs)**2
for i in mFFWHM:
    SDFFWHM+=(i-F_FWHM)**2
for i in mAFWHM:
    SDAFWHM+=(i-A_FWHM)**2
    #print "SDAFWHM: "+str(SDAFWHM)

SDFvals=SDFvals/len(mFval)
SDAvals=SDAvals/len(mAval)
SDAfrqs=SDAfrqs/len(mAfreq)
SDFfrqs=SDFfrqs/len(mFfreq)
SDFFWHM=SDFFWHM/len(mFFWHM)
SDAFWHM=SDAFWHM/len(mAFWHM)

SDFvals=np.sqrt(SDFvals)
SDAvals=np.sqrt(SDAvals)
SDAfrqs=np.sqrt(SDAfrqs)
SDFfrqs=np.sqrt(SDFfrqs)
SDFFWHM=np.sqrt(SDFFWHM)
SDAFWHM=np.sqrt(SDAFWHM)
#print SDFvals
#print SDAvals
#print SDAfrqs
#print SDFfrqs

func=open(fileName+' result','w')
args="File Name: "+fileName+"\n"
func.write(args)
#args="Fval: " +str(mFval)+"\n"
#func.write(args)
#args="Aval: " +str(mAval)+"\n"
#func.write(args)
#args="Ffreq: " +str(mFfreq)+"\n"
#func.write(args)
#args="Afreq: " +str(mAfreq)+"\n"
#func.write(args)
args="SDFvals: " +str(SDFvals)+"\n"
func.write(args)
```

```
args="SDAvals: " +str(SDAvals)+"\n"
func.write(args)
args="SDFfrqs: " +str(SDFfrqs)+"\n"
func.write(args)
args="SDAfrqs: " +str(SDAfrqs)+"\n"
func.write(args)
args="SDAFWHM: " +str(SDAFWHM)+"\n"
func.write(args)
args="SDFFWHM: " +str(SDFFWHM)+"\n"
func.write(args)
args="Fvals: " +str(Fvals)+"\n"
func.write(args)
args="Avals: " +str(Avals)+"\n"
func.write(args)
args="Ffrqs: " +str(Ffrqs)+"\n"
func.write(args)
args="Afrqs: " +str(Afrqs)+"\n"
func.write(args)
args="A_FWHM: " +str(A_FWHM)+"\n"
func.write(args)
args="F_FWHM: " +str(F_FWHM)+"\n"
func.write(args)
func.close
```

Appendix B: LIGO File Selection

The LIGO Files selected and used in this research are listed below.

The Random LIGO File:

`L-L1_LOSC_4_V1-946515968-4096.hdf5`

Day Time (At approximate UTC 22:10:00):

S5 File:

```
L-L1_LOSC_4_V1-821313536-4096.hdf5,
L-L1_LOSC_4_V1-862179328-4096.hdf5,
L-L1_LOSC_4_V1-872460288-4096.hdf5
```

S6 File:

```
L-L1_LOSC_4_V1-938123264-4096.hdf5,
```

```
L-L1_LOSC_4_V1-946679808-4096.hdf5,
L-L1_LOSC_4_V1-957046784-4096.hdf5,
L-L1_LOSC_4_V1-965169152-4096.hdf5
```

Night Time (At approximate UTC 11:00:00):
S5 File:

```
L-L1_LOSC_4_V1-820310016-4096.hdf5,
L-L1_LOSC_4_V1-862044160-4096.hdf5,
L-L1_LOSC_4_V1-872321024-4096.hdf5
```

S6 File:

```
L-L1_LOSC_4_V1-938422272-4096.hdf5,
L-L1_LOSC_4_V1-946679808-4096.hdf5,
L-L1_LOSC_4_V1-957083648-4096.hdf5,
L-L1_LOSC_4_V1-964853760-4096.hdf5
```

Appendix C

The raw values are listed in the following chart.

LIGO Calculation Result

Fvals	Day	Night	Day	Night	Day	Night	Day	Night	Mean Value
S5	2.32435033177E-15	1.97537437244E-15	2.68511127419E-15	1.89153211894E-15	2.84131450776E-15	1.98468187369E-15			2.28372741313E-15
S6	1.6546263622E-15	1.58036037497E-15	1.8444411869E-15	1.58607585206E-15	1.86361539421E-15	1.80237678013E-15	1.37238484415E-15	1.46506566541E-15	1.64611830750375E-15
Mean Value	2.08369198588286E-15	1.75506671966E-15							
Avals	Day	Night	Day	Night	Day	Night	Day	Night	
S5	2.7156666548E-20	2.30506906495E-20	3.1253959472E-20	2.21533059151E-20	3.30754505181E-20	2.31290322007E-20			2.66365175505667E-20
S6	1.94892571777E-20	1.84478746817E-20	2.16140731966E-20	1.86332770453E-20	2.19486836443E-20	2.11257955078E-20	1.59675619201E-20	1.70264683137E-20	1.92816239359E-20
Mean Value	2.43579503538286E-20	2.05094920448E-20							
Ffrqs	Day	Night	Day	Night	Day	Night	Day	Night	
S5	59.9946078431	59.9882352941	60.0085784314	60.0029411765	59.9916666667	60.0075980392			59.9989379085
S6	60.0022058824	60.0051470588	59.993872549	60.0107843137	60.0019607843	60.0058823529	60.0095588235	60.0041666667	60.0041973039125
Mean Value	60.0003501400572	60.0035364145571							
Afrqs	Day	Night	Day	Night	Day	Night	Day	Night	
S5	60.0	60.0	60.0	60.0	60.0	60.0			60.0
S6	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Mean Value	60.0	60.0							
A_FWHM	Day	Night	Day	Night	Day	Night	Day	Night	
S5	0.779411764706	0.897058823529	0.147058823529	0.455882352941	0.794117647059	0.205882352941			0.546568627450833
S6	0.558823529412	0.455882352941	0.882352941176	0.235294117647	0.397058823529	0.397058823529	0.147058823529	0.441176470588	0.439338235293875
Mean Value	0.529411764705714	0.441176470588							
F_FWHM	Day	Night	Day	Night	Day	Night	Day	Night	
S5	0.0120098039216	0.0115196078431	0.0110294117647	0.0122549019608	0.0120098039216	0.0107843137255			0.01160130718955
S6	0.0115196078431	0.0112745098039	0.0137254901961	0.0122549019608	0.0107843137255	0.0117647058824	0.0122549019608	0.0120098039216	0.011948529411775
Mean Value	0.0119047619047714	0.0116946778711571							
SDFvals	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Mean Value
S5	1.70463455469E-16	1.01810958889E-16	1.5444860466E-16	1.02486345517E-16	1.85165304639E-16	1.18019655917E-16			1.38732387515167E-16
S6	1.07851813315E-16	7.77720984434E-17	2.0553453477E-16	2.39170172344E-16	1.42869608213E-16	1.44323991869E-16	1.91154787349E-16	1.370260272E-16	1.55712879187925E-16
	1.65355444059286E-16	1.31515607168486E-1							
SDAvals	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	
S5	1.72998790683E-21	8.99939894794E-22	1.39496683598E-21	6.83054717455E-22	1.65192175473E-21	1.22562568759E-21			1.26424946623E-21
S6	1.11415891507E-21	5.63734098442E-22	2.24655458162E-21	2.68304546573E-21	1.34292798712E-21	1.36654429249E-21	2.05003250894E-21	1.43332392046E-21	1.60004022123E-21
	1.64722149861E-21	1.26503829671E-21							
SDFfrqs	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	
S5	0.0126029020904	0.0118054848812	0.0101026783556	0.0193736008288	0.0122940551019	0.0104763285653			0.0127758416372
S6	0.0124277032687	0.0208592687469	0.0120945390112	0.0142241354201	0.0167959232343	0.0173310485585	0.0122328232485	0.0138192699598	0.014973088931
	0.0126500891872286	0.0154127338515143							
SDAfrqs	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	
S5	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14			2.13162820728E-14
S6	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14	2.13162820728E-14
	2.13162820728E-14	2.13162820728E-14							
SDAFWHM	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	
S5	0.414643299408	0.303882034114	0.354164546435	0.498049830055	0.404344914261	0.404344914261			0.396571589755667
S6	0.496527735769	0.498049830055	0.322189739709	0.424182502996	0.489288375283	0.489288375283	0.354164546435	0.496527735769	0.446277355162375
	0.405046165328571	0.444903603219							
SDFFWHM	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	Day Time	Night Time	
S5	0.00747850308941	0.00770013631	0.00788515095203	0.00735294117647	0.00747850308941	0.00796474353396			0.00764332969188
S6	0.00770013631	0.00779704594146	0.00635366735138	0.00735294117647	0.00796474353396	0.00759408499256	0.00735294117647	0.00747850308941	0.00744925794646375
	0.00745909221466571	0.0076057708886185							
	S5: 3 day files 3 night files S6: 4 day files 4 night files								

Figure 11: The raw calculation result of LIGO data.