LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Note **LIGO-T2000292–v1** 2020/06/5

Temperature control system and Seismic heat map

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) was designed to open the field of gravitational-wave astrophysics through the direct detection of gravitational waves predicted by Einstein's General Theory of Relativity. LIGO's multi-kilometer-scale gravitational wave detectors use laser interferometry to measure the minute ripples in space-time caused by passing gravitational waves from cataclysmic cosmic events such as colliding neutron stars or black holes, or by supernovae.

LIGO consists of two widely-separated interferometers within the United States—one in Hanford, Washington and the other in Livingston, Louisiana—operated in unison to detect gravitational waves. LIGO's mission is to open the field of gravitational-wave astrophysics through the direct detection of gravitational waves. LIGO detectors use laser interferometry to measure the distortions in space-time occurring between stationary, hanging masses (mirrors) caused by passing gravitational waves. LIGO is a national facility for gravitational-wave research, providing opportunities for the broader scientific community to participate in detector development, observations and data analysis.

These gravitational waves which we wish to detect have a very small amplitude and create an infinitesimal strain in the space-time. The measurement of such waves calls for having unmatched precision in experimentation and maximum possible noise reduction for accurate results. Seismic noise is one amongst such noises and will be the main focus of this project. Often seismic events usher in a lot of unwanted noise in measuring these wave signals which is a major concern given the accuracy we need in our results

2 Objective

Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface. This can be fairly troublesome for the LIGO setup and thus the main aim of this project is to better seismic noise detection by improving the seismometers used and to locate seismic sources more efficiently by mapping this seismic noise as accurately as possible in order to make the mitigation of this noise easier. The objectives of this project can be categorised as follows :

- Building a PWM heater circuit to control the temperature of the seismometer enclosures
- Simulate and design the feedback using PID
- Develop a ML based nonlinear feedback controller that outperforms the linear PID system
- Making a seismometer sensitivity map using aperture synthesis

My contribution to the project would be primarily related to the creation of the seismometer sensitivity map using the improved seismometer data.

3 Project details and implementation:

3.1 Phase 1 : PWM heater circuit and PID feedback control

Seismometers need extremely stable temperature environments to function in. In our seismometer assembly, any kind of heat losses will result in temperature fluctuations leading to erroneous results. To counter for these heat losses, we introduce a Pulse width modulated Heater circuit which compensates for the heat loss thereby providing a stable temperature environment. A non-linear PID feedback loop will then be implemented to further reduce the error and the setting time.

3.2 Phase 2 : Neural Network non-linear feedback control

Neural Network: Studies[2] have shown that neural network controllers provide better transient response and performance when compared to PID controllers, especially in non-linear systems.A TensorFlow flow model of a simple feedforward network will be made, for which the following will be decided :
1. The inputs that will be require to generate the output parameters
2. The number of output parameters and their corresponding effect on the system
3. Number of hidden layers
4. Type of learning that will be implemented.

The above information can be used to convert the simple feedforward network into more complex models

3.3 Phase 3 : Seismic Heatmap

Seismology has been a dynamically improving field for the past few decades. Multi-sensor detection techniques are improving day by day resulting in well co-ordinated seismic phased array networks. Many approaches are used to localize seismic sources and will be listed as given below

3.3.1 Epicenter Detection

'Epicenter detection' or 'Source detection' is an important aspect of this field for disaster risk management and over the years, many methods have been devised for the same. Even though we won't always be looking for a seismic source as massive in magnitude as an earthquake, the method which is used to locate earthquakes can definitely be used to our benefit.

To understand how epicenters are detected, understanding how a shock wave propagates through the ground is essential.The waves are classified into two primary types :

- Body waves
- Surface waves

Body waves have a high velocity as well as a high frequency in comparison to the Surface waves. They can propagate through Earth's inner layers as opposed to the Surface waves which only travel along the surface like the ripples in a liquid. Seismometers generally use body waves to locate earthquakes using the 'Primary Body waves' (P-wave) and the 'Secondary Body Waves'(S-waves).

The P-waves are the fastest kind of seismic waves and are thus naturally detected first by the seismometer after any seismic event. The P wave can move through solid rock and fluids, like water or the liquid layers of the earth. It pushes and pulls the rock it moves through just like sound waves push and pull the air and are thus also known as compressional waves. The S-waves travel only through rock and are thus being slower than the P-waves arrive late at the seismometer. S waves move rock particles up and down, or side-to-side,perpendicular to the direction that the wave is traveling in.

This velocity difference between the two body waves manifests itself in the seismograph plot. As shown in the diagram in Fig.1, P-waves and S-waves can be clearly distinguished.

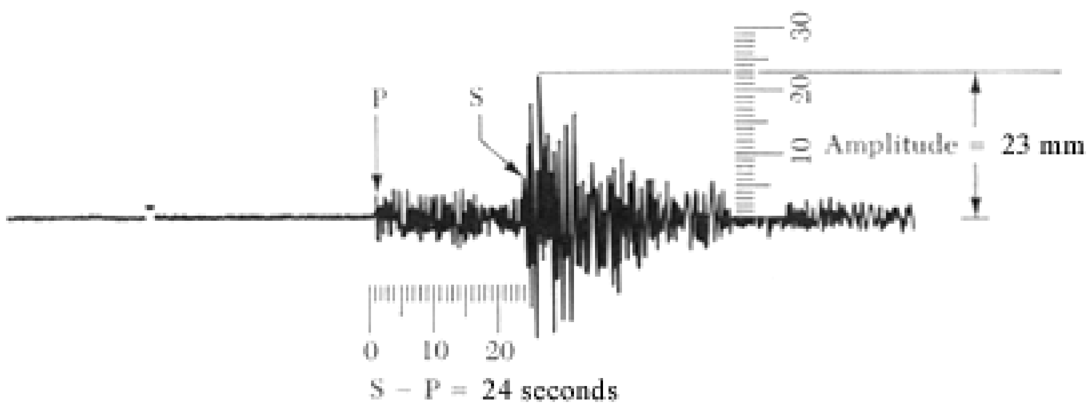

Figure 1: Seismograph reading

As these waves travel farther and farther from their origin, the difference in their times of arrival increases. By analysing this difference, the distance of the seismometer from the origin of the seismic noise source can be estimated as follows :

$$d = \frac{t_s - t_p}{\frac{1}{v_s} - \frac{1}{v_p}}$$

where,
t_s = Time of arrival for the S-wave
t_p = Time of arrival for the P-wave
v_s = Velocity of the S-wave
v_p = Velocity of the P-wave

This procedure will just give us the distance but not the direction. A circle is then drawn around the seismometer with the distance acquired before as radius. A minimum of three seismometers would then be needed to construct three such circles to find a single intersection of them as shown in Fig.2. This center will be the epicenter of the seismic event. This process is also known as Triangulation of seismic data.

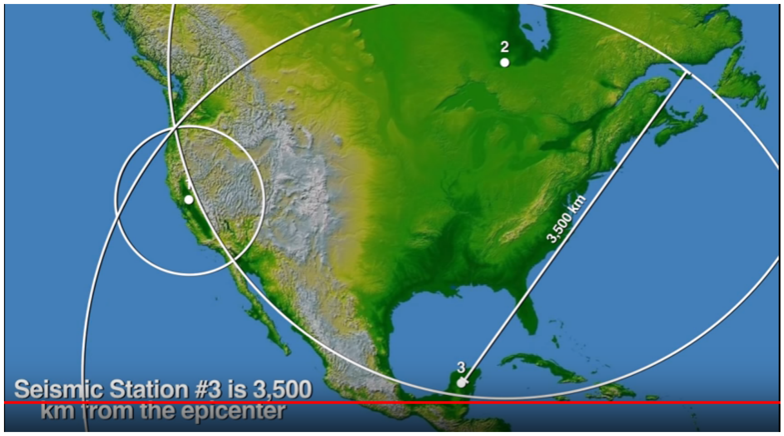

Figure 2: Seismic data triangulation

The triangulation will go on improving with the increase in the number of seismometers. The 40m prototype at Caltech has three seismometers which will be used for the experimentation in this project. The seismometer used will be the Guralp CMG 40-T seismograph which will provide an output which is the velocity of the ground i.e ground movement in micrometers per second. The seismometer provides vibrational data for all the three axes separately. After acquiring this data, cross correlation will be performed amongst the datasets of 2 different seismometers to reduce error. The data output will then be converted into intensity of the seismic source by using :

$$Ml = log(A \times 2080) + logD + 0.00301 \times D + 0.7$$

where,
ML= Richter magnitude
A = Measured ground motion in μm
D = Distance of event in km
The magnitude data will be then manipulated by analysing the intersection of the radii of the three circles drawn and the map will be plotted of this accordingly using python libraries like Folium.

To check the legitimacy of the resultant plot, it would be compared with a similar plot created with the USGS seismic data which was taken during the same time frame. A software named QGIS which is an open source software also can be used for the same.
The end goal of this project is to make the most accurate seismometer ever and to test it. The seismic heat map in the end should look something like what is depicted in Fig.3

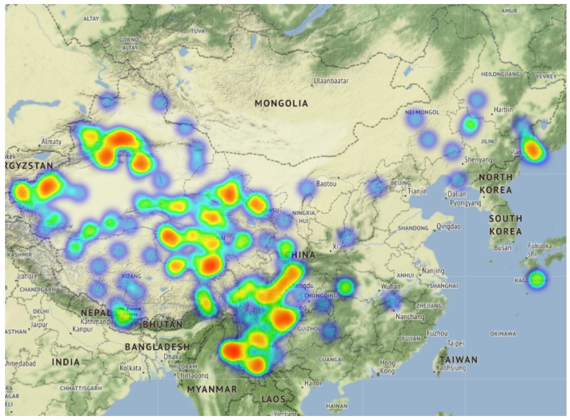

Figure 3: Seismic Heatmap of USGS data

3.3.2 Frequency-Wave Number analysis

According to sources[3], methods like Beam forming, Vespa (Velocity Spectral Analysis), Phase Weighted Stack (PWS) method, Double Beam method (DBM), and Frequency-Wave Number analysis are commonly used to integrate the data of a seismic array. For our purpose, we would want to calculate the velocity and the direction of the incoming wave and most of the above methods are just for calculating either. One amongst these methods namely Frequency-Wave Number analysis is popularly used because it can simultaneously calculate both i.e the velocity vector and the direction of the incoming wave.

The fk analysis calculates the power distributed among different velocities and directions of approach. The time delays required to bring the signals from different seismometers into phase provide a direct estimate of the velocity and the direction of the signal. This computation is performed in the spectral domain to save computation time.

In seismology, instead of using velocity, a quantity called as 'slowness' which is the inverse of velocity is used. This simplifies the equations which are used for calculating or inducing time delays in signals according to the seismometer location vectors.
Consider $s(t)$ to be the source signal. The nth seismometer with the location vector r_n, relative to the array reference point records the signal $x_n(t)$:

$$x_n(t) = s(t - u \cdot r_n)$$

where u is the slowness vector.
The maximum amplitude of the sum of all array seismometers is reached if the signals of all stations are in phase, that is, if the time shifts $u \cdot r_n$ disappear. The output of the array can be computed by :

$$y(t) = \frac{1}{N} \sum_{n=1}^{N} x_n(t + u \cdot r_n)$$

for an array of N elements. The total energy arriving at the array would be then written as :

$$E(k) = \int_{-\infty}^{\infty} y^2(t)dt$$

where k is the wave number vector and is given by $\omega \cdot u$. This equation can then be converted according to Parseval's theorem to :

$$E(k) = \frac{1}{2\pi} \int_{-\infty}^{\infty} |S(\omega)|^2 | \frac{1}{N} \sum_{n=1}^{N} e^{2\pi i \cdot k \cdot r_n} |^2$$

where $S(\omega)$ is the fourier transform of the signal $s(t)$.
Thus, by following the aforementioned method, we can calculate the energy distributed in each frequency and also find out the location of the source with a particular frequency.

Using an appropriate combination of the methods described above and the methods which are used for general phased array signal processing, the location of the signal will be determined.

4 Timeline

- Week 1-3 : Cleaning of the downloaded seismic data, data conversion and verification
- Week 4-6 : Cross correlation of the seismic data
- Week 7-10 : Data triangulation and interpolation
- Week 11 : Integration of all the modules and plotting of the heatmap contours

References

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[3] Rost, Sebastian Thomas, Christine. (2002). *Array Seismology: methods and Applications* Reviews of Geophysics. 40. 1008. 10.1029/2000RG000100.

[4] http://www.geo.mtu.edu/UPSeis/locating.html

[5] http://www.geo.mtu.edu/UPSeis/locating.html