Magnetism and Advanced LIGO

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Abstract

LIGO plans to monitor magnetic fields because they can affect the interferometer's signals. A magnetic field from a Schumann Resonance can affect both LIGO interferometers in a similar way as a gravitational wave. Magnetic field data can be used to figure out whether a signal was caused by a gravitational wave or a magnetic field. We evaluated the quality of four remote locations that can be used to measure Schumann Resonances and Ultra Low Frequency (ULF) waves. Furthermore, eleven magnetometer set-ups around the LIGO Hanford Observatory (LHO) will allow for monitoring magnetic fields specific to LHO. All eleven magnetometer set-ups were improved. Filter boxes were modified in order to obtain accurate magnetic field measurements at 10 Hz. Finally, I determined how close the Uninterruptible Power Supply (UPS), an electronic device that produces a large magnetic field, can be to the interferometer.

1 Introduction

LIGO, the Laser Interferometer Gravitational-Wave Observatory, is a physics experiment composed of two detectors called interferometers. One interferometer is in Hanford, Washington, and the other is in Livingston, Louisiana. The goal of LIGO is to directly detect a gravitational wave, which is an unconfirmed component of Albert Einstein's theory of general relativity. Also, data from a gravitational wave may reveal new information about the wave's source which could be, for example, orbiting black holes.

A LIGO interferometer consists of two, four-kilometer arms that are perpendicular to each other. At the end of each arm is a mirror called a test mass. Normally, laser light splits into both arms, reflects off of both test masses, travels back through the arms, and recombines in the same phase. In theory, a gravitational wave travelling down towards the Earth will stretch space along one arm while compressing space along the other arm. This stretching and squeezing happens periodically. At a given time, more space along one arm and less space along the other arm means that the laser light will travel different distances in both arms, causing the laser light to recombine in different phases. The resulting brightness is used to produce a current that returns the test masses back to their original positions. Over time, this current encodes the gravitational wave signal.

Each interferometer's surroundings are monitored with a Physical Environment Monitoring (PEM) system because the external environment can affect the interferometer's measurements. Both PEM systems consist of various sensors such as seismometers and microphones. Knowing how the environment affects the interferometer is crucial for the unambiguous, accurate detection of a gravitational wave.

One environmental factor that can affect the interferometer is magnetism because first, tiny magnets are used to control the position of each test mass and second, a magnetic field can induce a current in a wire that is a part of the detector. First, each test mass is hung in a suspension system containing electromagnets. The current carrying the gravitational wave signal runs through the electromagnets to produce magnetic fields which move the test mass back to its original position. Second, a magnetic field can induce a current in a wire such as the wire containing the gravitational wave signal and the wire within one of the electromagnets. An ambient magnetic field can not only displace a test mass via the tiny magnets but also induce a current in a wire. Monitoring magnetic fields around each interferometer is necessary in order to prevent a false gravitational wave detection.

Progress was made with regard to monitoring magnetic fields at LHO. The first notable conclusion is that, out of four locations, Table Mountain is the best place to collect low amplitude magnetic field data. Second, nine magnetometer filter boxes were modified to allow for measuring 10 Hz magnetic fields around the interferometer. In addition, each magnetometer set-up around LHO was improved. Finally, the magnetic field generated by the UPS, a battery reserve for the interferometer's main laser, is so strong that the device must be placed at least 33 feet away from other electronic equipment, including the interferometer.

2 Results

2.1 Global Magnetic Fields

A global magnetic field, or a magnetic field detectable on the global scale, is of interest to LIGO because gravitational waves and magnetic fields both travel at the speed of light. LIGO consists of two interferometers to provide a strong statistical confirmation of a gravitational wave detection, but this confirmation is void if the gravitational wave signal was actually caused by a magnetic field. An ambiguity in whether the signals from both interferometers were due to a gravitational wave or a magnetic field is conceivable because there are globally correlated magnetic fields. This ambiguity limits the low end of the sensitivity range of the current state of LIGO, or Advanced LIGO. The low end of the Advanced LIGO sensitivity range is expected to be 10 Hz, which means that the interferometers are predicted to confidently detect gravitational waves varying at frequencies of 10 Hz.

If global magnetic fields are monitored, then we can reduce the ambiguity previously mentioned by identifying the source (i.e. a magnetic field or a gravitational wave). In other words, the sensitivity of Advanced LIGO can be increased by subtracting magnetic field data from gravitational wave data.[1]

Since global magnetic fields have small amplitudes, measuring global magnetic fields near LHO required using a sensitive magnetometer in a decent location. This location needed to be magnetically isolated, or minimally influenced by magnetic fields such as those generated by power lines. Magnetic field data was collected and analyzed at four possible locations: Vault, Drumheller, Rattlesnake Mountain, and Table Mountain. Table Mountain was determined as the most magnetically isolated site. In other words, Table Mountain is the best place to collect global magnetic field data while the interferometers are running.

The Table Mountain data revealed a source of a global magnetic field called a Schumann Resonance. A Schumann Resonance is caused by lightning. A lightning strike, an electrostatic discharge, can be thought of as a sudden flow of charges between two oppositely-charged surfaces. Specifically, a lightning strike consists of accelerating charges which produce electromagnetic waves. These waves propagate spherically, resonating in a spherical cavity defined by the Earth's surface and the ionosphere. The resulting resonances are called Schumann Resonances. The resonant frequencies are spaced at intervals of approximately 6.5 Hz: 7.83 Hz (fundamental), 14.3 Hz, 20.8 Hz, ... , 59.8 Hz. The fundamental is given by the light travel time around the world. Figures 1 and 2 show Schumann Resonance peaks at these frequencies.

The data acquisition system split the Table Mountain data into parts, but we combined the parts together in MATLAB. The long data set revealed a low frequency magnetic field since more time allowed for the presence of a longer wavelength which corresponds to a lower frequency. The low frequency magnetic field at approximately 0.01 Hz fell into the pc4 frequency band of ULF waves, which are electromagnetic waves. In Figures 3 and 4, the peaks at approximately 0.01 Hz represent the ULF wave. ULF waves are not of concern since their frequency range, 1 mHz to 1 Hz, falls below the 10 Hz end of the Advanced LIGO sensitivity range.[2]

2.2 Local Magnetic Fields

A local magnetic field, or a magnetic field specific to one of the two LIGO observatories, can affect an interferometer's measurements. The PEM system at LHO consists of eleven magnetometers to monitor magnetic fields around the interferometer.

2.2.1 Understanding the Data Acquisition System

To measure ambient magnetic fields in the x, y, and z directions, LIGO uses Bartington fluxgate magnetometers around each interferometer. Each magnetometer connects to a Bartington signal conditioning box, which gives the magnetometer power. During operation, the magnetometer sends an analog, or voltage, signal to the signal conditioning box. This box sends the signal to a custom filter box. The signal continues to an anti-aliasing chassis (AA chassis) and then to an Analog Digital Converter (ADC). The ADC converts the analog signal into a digital signal comprised of a certain number of counts. These counts can be displayed in a readable fashion on a computer screen with a program developed by LIGO called Diagnostic Test Tools (DTT). On DTT, one can view a power spectrum (counts vs. frequency) and a time series (counts vs. time). Inputting a calibration number—determined during the calibration process—allows DTT to display power spectra and time series in units of Tesla instead of counts.

2.2.2 Filter Boxes

In order to confidently detect a 10 Hz gravitational wave, the PEM magnetometers must provide accurate data at 10 Hz. Obtaining accurate readings at 10 Hz from a magnetometer involves modifying a filter box from the Initial LIGO configuration to the Advanced LIGO configuration. Nine magnetometer filter boxes were modified. In Section 3.2, the filter box modification process is explained.[3]

2.2.3 Installation

To understand the PEM magnetometer installation progress at LHO, one should understand the basic layout of the LIGO interferometer. The interferometer's two perpendicular arms are called the X Arm and the Y Arm. At the end of each arm, there is an End Station. Each End Station has a Vacuum Equipment Area (VEA) and an Electronics Bay (EBAY). Finally, the interferometer's arms intersect inside a room called the Large Vacuum Enclosure Area (LVEA). A third EBAY is near the LVEA.

All eleven PEM magnetometers are in their respective locations, and each magnetometer has a signal conditioning box. There are two magnetometers in each Electronics Bay to monitor magnetic fields emanating from surrounding electronic devices. One magnetometer is in each End Station VEA, and three magnetometers are located in the LVEA.

Progress was made with regard to mounting. All EBAY magnetometers are securely in place. Also, the HAM2 setup is now reoriented such that the magnetometer is vertical. This new orientation prevents the supporting, ferromagnetic metal from disrupting the sensor's magnetic field measurements.

LIGO records magnetic field data in the x, y, and z directions defined by the right-hand coordinate system outlined by the interferometer's X and Y arms. The axes on all six EBAY magnetometers were labeled to be aligned with the LIGO coordinate system, and the signal conditioning boxes, which have coordinates, were correctly relabeled.

2.2.4 Custom Mounts

At LHO, the PEM system requires both End Stations and the LVEA to each have a magnetometer mounted on a tripod. A custom mount allows for securing a magnetometer to a rigid tripod. 5 mounts were sent to LHO and 4 mounts were sent to the LIGO Livingston Observatory (LLO). The mounts are the same for both sites (with the exception of a spacer at LLO) to allow for hardware compatibility and simplicity.

2.2.5 Calibration

Calibrating a magnetometer involves imposing a known, magnetic field through one axis of the magnetometer. The calibrating device at LIGO consists of a solenoid wrapped around a hollow tube. The tube secures the magnetometer inside the solenoid. Running a current through a solenoid generates a one-dimensional magnetic field through the center of the solenoid. To obtain a current, one can use a function generator which produces a voltage of a certain frequency and amplitude. The current is allowed to flow to a circuit containing a 1 kΩ resistor. After flowing through the circuit, the current runs through the solenoid. Measuring the voltage difference across the resistor with an oscilloscope and using Ohm's Law

$$I = \frac{V}{R} \tag{1}$$

where R is 1 kΩ and V is the voltage difference, one can find the value of the current flowing into the solenoid, I. Finally, the magnetic field through a solenoid, derived from Ampere's law, is

$$B = M_0 \frac{NI}{L} \tag{2}$$

In this equation, M_0 is the permeability of free space, L is the length of the solenoid, and N is the number of turns in the solenoid. If, on DTT, the magnetic field read by the magnetometer at a certain frequency differs from the calculated magnetic field at that frequency, one must change the calibration factor on DTT until the two magnetic field values match.

When starting to calibrate one of the magnetometers in the LVEA, DTT's time series plot was saturated. The maximum number of counts provided by the ADC was consistently exceeded. In other words, all the data was not fitting on the DTT time series plot, so calibrating in this state would produce an incorrect calibration factor. The power spectrum showed a tall peak at 60 Hz. The surrounding, fluctuating magnetic fields from the 60 Hz wires which power the entire LVEA, especially the clean rooms, were so strong that magnetometer's sensitive measurements could not be accurately viewed on DTT. To calibrate the magnetometers, one must wait until the clean rooms are gone.

2.3 Magnetic Field from an Electronic Device

In the event of a power loss while the interferometer is taking data, the APC Smart-UPS (Model: 1500, Max Configurable Power: 980 Watts/1440 VA) will continue powering the Pre-Stabilized Laser (PSL) to prevent laser damage. The UPS draws for its transformer a large amount of current, so measuring the device's magnetic field at various distances allowed for determining the minimum distance—how close the UPS can be to other equipment, including the interferometer.

Robert Schofield and I defined the maximum allowable magnetic field at 60 Hz from any electronic device to be 0.4 nT, which is one tenth of the root mean square 60 Hz magnetic field during Initial LIGO science runs.

For magnetic field measurements, we used two 500 Watt lights (to simulate the PSL load), a Bartington magnetometer (mounted on a tripod), and the UPS (placed horizontally and face-up on a plastic bin).

During preliminary tests, we found that the system's plugged-in while on and plugged-in while off configurations produced similar magnetic field magnitudes. Therefore, the UPS must be placed at its minimum distance whenever the device is plugged-in (and either on or off).

Next, at 1 meter, we measured the magnetic field at three different angles relative to the physical center of the device. Of these measurements, the lowest value was 55 percent of the highest value. The magnetic field at 60 Hz was strongest when the magnetometer was aligned with the device's front (face with buttons) left edge, and the remaining measurements were taken at this angle.

The final step in determining the minimum distance was measuring the attenuation of the device's magnetic field with distance. I took data from 3 to 39 feet, with a constant interval of 3 feet. At each distance, I used DTT to record the power spectra of the magnetic field when the UPS was unplugged and off and when the UPS was plugged-in and on. I took two data sets—both were numerically similar.

I used a program called Grace to perform a linear regression on, at 60 Hz, the natural log of the magnetic field vs. the natural log of the distance. Solving for y revealed the fitted curve, shown below.

$$y = 171x^{-1.74} \tag{3}$$

In conclusion, when y is 0.4 nT (maximum allowable field, see above), x is about 33 ft, which is the minimum distance. Figure 5 shows the UPS magnetic field attenuation.

2.4 Future Work

In the future, one could investigate magnetic coupling to the gravitational wave channel and other PEM sensors such as a seismometer. Quantifying magnetic coupling to the gravitational wave channel would involve figuring out how many Tesla is required to move a test mass one meter. In addition, remaining tasks regarding LHO PEM magnetometer installation such as calibration are documented.

3 Methods

3.1 Global Magnetic Field Data Collection

On June 17th, 2014, Robert Schofield, Margarita Vidrio, and I travelled to Drumheller. At this location, we measured global magnetic fields with a sensitive magnetometer called the LEMI-120, an induction coil, and a KMS-820 data acquisition system.

In order to gather data in the entire two-dimensional plane, we took two sets of data—one to measure the magnetic field along the North-South (NS) axis of the Earth and one to measure the magnetic field along the East-West (EW) axis of the Earth. For Rattlesnake Mountain, Vault, Drumheller, and Table Mountain, the same procedure for taking data was used.

When taking global magnetic field data, we did not want to measure magnetic fields from power lines and other devices. In the United States, currents in wires oscillate at 60 Hz so the magnetic field generated around a wire is 60 Hz. One way to choose a location sufficiently isolated from magnetic fields was by finding, from each site's data, the smallest peak at approximately 60 Hz. The smallest peak indicated the least amount of noise, which in our case was surrounding magnetic fields. The Table Mountain NS and EW data sets had the smallest peaks at 60 Hz, at approximately 101 $T/\sqrt{Hz}$ in magnitude, so Table Mountain was the best place to collect global magnetic field data.

I used MATLAB's 'pwelch' function to perform a Fast Fourier Transform (FFT) on each data set. I used the following terms. Note that 1 and 2 are not standard FFT terms while 3, 4, and 5 are.

1. Timepoints: total number of points in a data set
2. Stride or FFT length: For a FFT, the data points are divided into multiple sections. The number of data points in each section is the stride.
3. Overlap: number of data points to be overlapped between two strides, given in terms of stride (e.g. stride/4 represents a 25 percent overlap)
4. Bandwidth = (sampling frequency)/(stride)
5. Number of Averages = (timepoints – overlap)/(stride – overlap)

Here is an excerpt of code showing how the pwelch function was used (quad4 is the array of data and Fs is the sampling frequency):

```
[Px1, f] = pwelch(quad4, stride, overlap, fftlength, Fs);
```

A small number of averages corresponds to a high resolution. Figures 3 and 4 have high resolutions to allow for detail in the low frequency range. On the other hand, the more averages used in a FFT, the smoother the resulting graph. Smooth curves are useful for seeing a general trend such as multiple peaks, such as in Figures 1 and 2.

In Figures 1-4, the LEMI-120 including the KMS-820 Data Acquisition System noise floor is plotted. Data points above the noise floor are legitimate measurements not influenced by the system itself, as claimed by the KMS Manufacturer.

3.2 Filter Box Modification

The filter box has a circuit for each of the x, y, and z directions. Each circuit is a sigmoid filter. When testing each sigmoid filter, the function generated by a signal analyzer must look like a sigmoid function. The shape of the sigmoid function is important because the flat portion after the sharp increase ensures a consistent and therefore accurate magnetometer calibration factor. The filter box should be modified such that this flat portion starts around 1 Hz, a frequency sufficiently below the desired sensitivity of 10 Hz. The crossover frequency f, one of the frequencies at which the sharp increase occurs, should be between .1 and 1 Hz. This crossover frequency is defined by using

$$f = \frac{1}{wRC} \tag{4}$$

Keeping the angular frequency w and capacitance C the same, we obtain a crossover frequency of .6 Hz when changing the resistance R from 1 kΩ to 5 kΩ. However, the gain, or signal amplification in the circuit, must remain the same. We use

$$Gain = \frac{R_2}{R_1} \tag{5}$$

Since the $Gain$ in the circuit is 100 and R_1 is 5 kΩ, we deduce that R_2 must be 500 kΩ. Therefore, modifying the filter boxes involves replacing a 1 kΩ resistor with a 5 kΩ resistor and a 100 kΩ resistor with a 500 kΩ resistor.

4 Figures

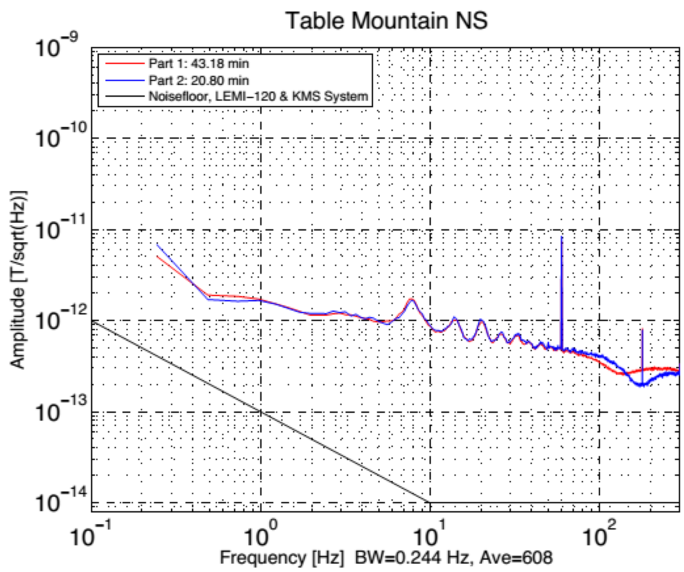

Figure 1: Magnetic Fields in NS Direction at Table Mountain.

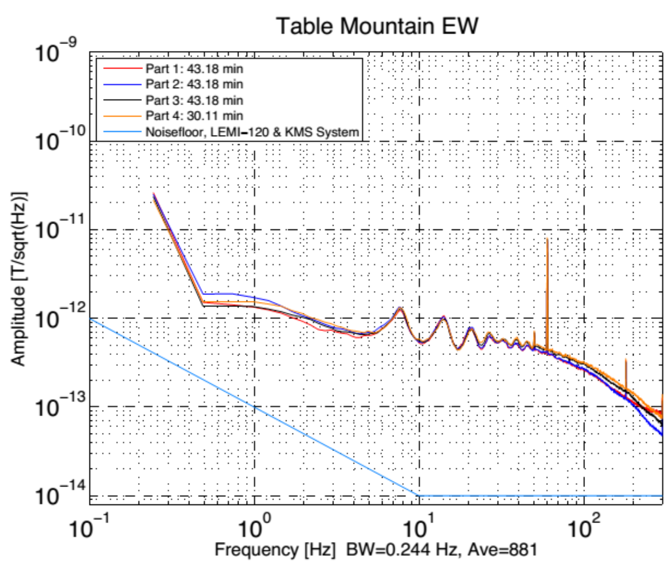

Figure 2: Magnetic Fields in EW Direction at Table Mountain.

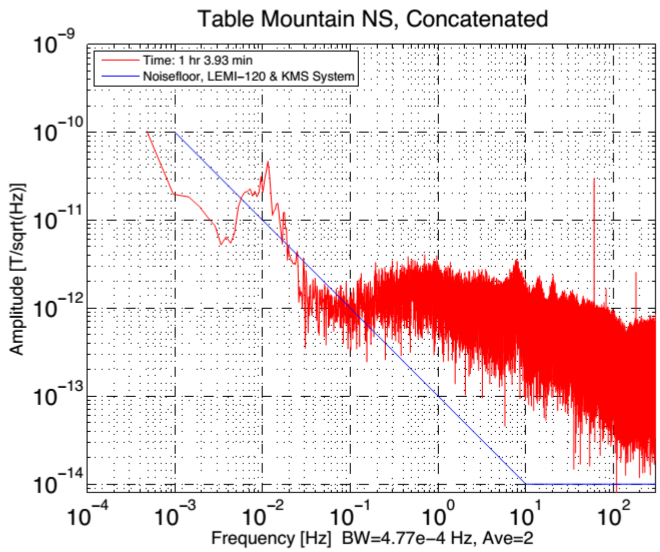

Figure 3: Low Frequency Magnetic Field in NS Direction at Table Mountain

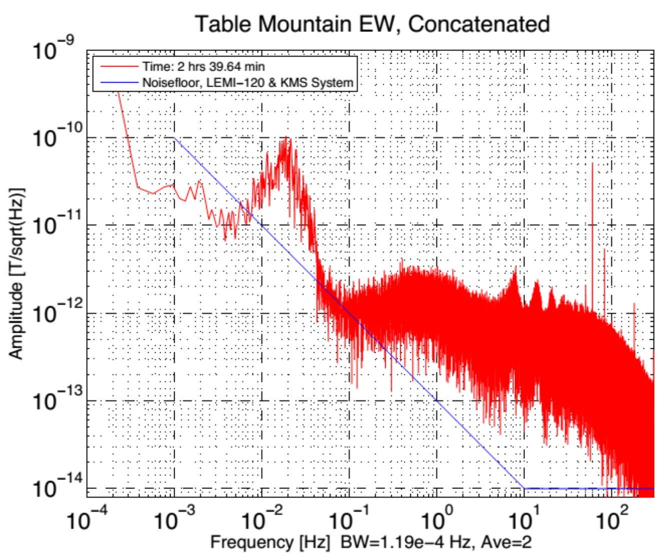

Figure 4: Low Frequency Magnetic Field in EW Direction at Table Mountain

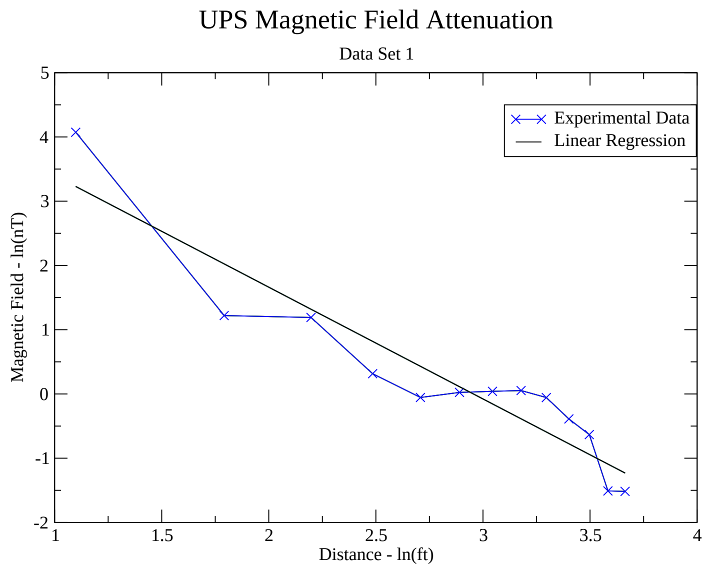

Figure 5: UPS Magnetic Field Attenuation

References

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[3] Myers, Joshua *Magnetometer Whitening Filter* LIGO DCC Number: D070443.

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