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Seismometer Isolation for Noise Cancellation at 40m Interferometer
SURF2016 Final Report

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1 Introduction

The existence of Gravitatonal Waves, as predicted in 1916 by Albert Einstein, was succesfully detected for the first time on 14th September 2015[2]. Experiments to detect gravitatonal waves using resonant mass detectors began in the 1960s, whereas those with long baseline laser interferometers were proposed in the early 1970s. By the early 2000s, a set of initial detectors were commissioned which included TAMA 300 in Japan, GEO 600 in Germany, LIGO in United States and Virgo in Italy. Combinations of these detectors started to make joint observations on a variety of gravitational-wave sources while evolving into a global network[1]. In 2015, Advanced LIGO became the first of a significantly more sensitive network of advanced detectors to begin observations. It detected two gravitational wave events, one on 14th September 2015 and the other on 26th December 2015.

LIGO stands for the Laser Interferometer Gravitational-Wave Observatory which consists of two widely separated interferometer installations within the United States one at Hanford,Washington and other at Livingston,Louisiana. Figure 1 shows a simplified diagram of an Advanced LIGO detector. A gravitational wave propagating orthogonally to the detector plane and polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle, and the output photodetector at the antisymmetric part records these differential cavity length variations from which we can infer information about the gravitational wave that caused this variation [2].
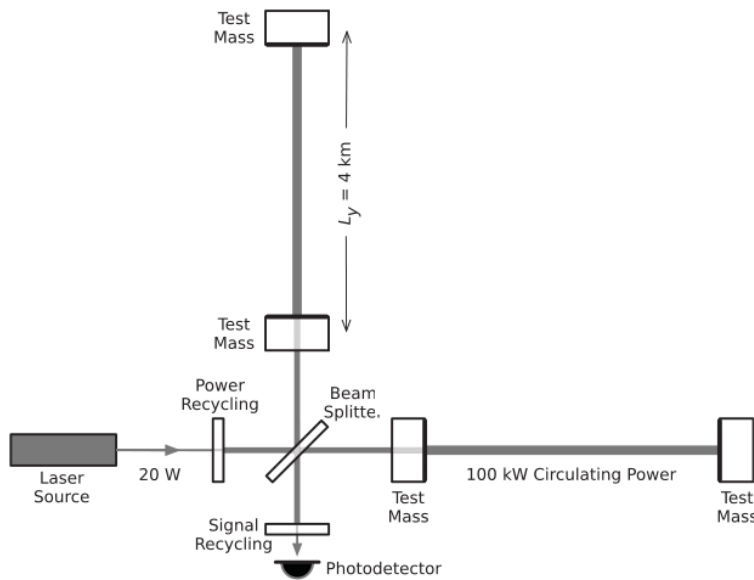

Figure 1: Simplified diagram of an Advanced LIGO detector

2   Motivation and Overview

LIGO is one of the most sensitive experiments ever built, which requires unprecedented levels of isolation from seismic noise. The seismic noise can be measured with the help of seismometers, which work on the principle of a spring mass system. For a seismometer to provide accurate readings, they must be very well isolated from the environment. Any disturbance from the environment, which comprises of thermal and electro-magnetic fluctuations among others, may lead to errors in readings and therby cause obstruction to working.
Though seismometers are made to respond to and record seismic energy, environmental factors like temperature, atmospheric pressure and electro-magnetic interference may add noise to the seismometer readings. Optimally, these sensors should be installed in an enclosure that effectively controls environmental variables such as temperature and humidity. For example, an enclosure in the form of a vault would provide better isolation to the seismometer. So, during this summer, I will develope and test an enclosure for isolating a seismometer from thermal and electromagnetic fluctuations at LIGO 40m lab. If LIGO can accurately measure and reduce its seismic noise, a greater range of phenomena will be available for study at low frequencies.

3   Objective

The objective of this summer project is the development of enclosures for the seismometer at the LIGO 40m lab so as to protect it from environmental fluctations. Insulative enclosures will be developed to isolate the instruments from external thermal and electromagnetic fluctuations. If it works well, this technology will be applied to the aLIGO detectors to improve low frequency sensitivity to astrophysical events, and progress made on seismic cancellation will be used to adaptively reduce other noise sources

4   Work Done

4.1   Temperature Measurement

Temperature measurement can be done either by thermocouples or resistance temperature detectors. Thermocouples consist of two wires of different metals connected at two points. A voltage is developed between the two junctions in proportion to the temperature difference between them. On the other hand, resistance temperature detectors(RTD) are simply resistors whose resistance is significantly affected by temperature. It is better to use a resistance temperature detector based integrated circuit for temperature measurments since they are simple in operation as well as robust in design and give accurate readings without any complex setup unlike a thermocouple which may require a cold junction arrangement for accurate readings. While selecting a resistance temperature detector type transduce IC, it is better to select one which provides an output current ptoportional to absolute temperature. Initially, I selected a RTD which needs a constant current source for giving a voltage output proportional to temperature. So for constant current source, after a few iterations, I

made the electronic circuit design which is shown in figure 2. It is complicated to design a
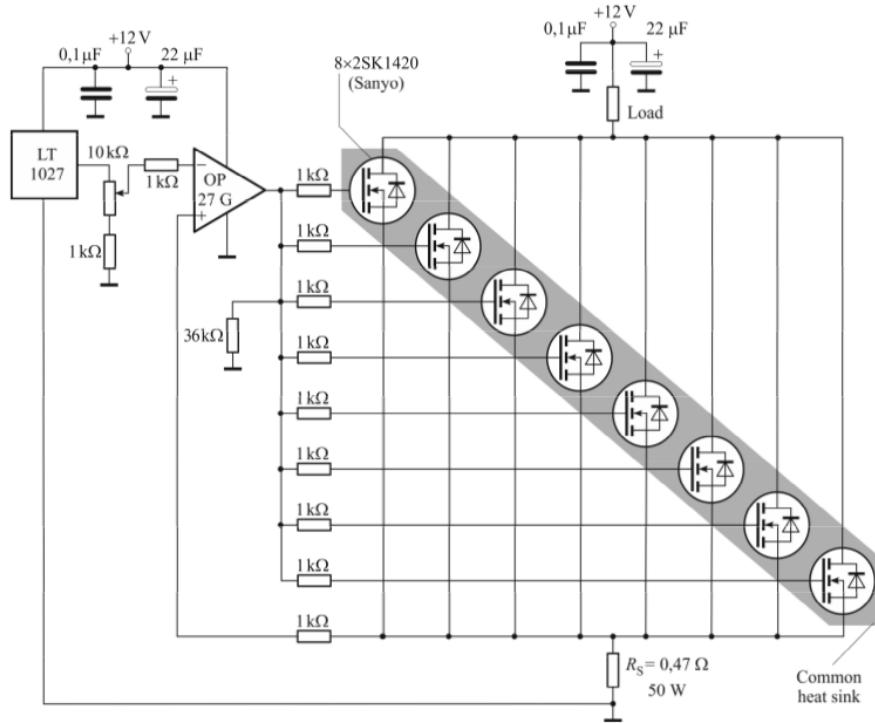

Figure 2: Electronic Circuit for a Constant Current Source

constant current source, and hence it was decided that it is better to select a temperature transducer IC which works on a specific voltage range. I selected AD592 which is a high precision temperature transducer IC which provides an output current proportional to absolute temperature. Its features include high accuracy, minimal self heating and excellent linearity. This temperature transducer IC can measure temperature upto 0.5 K accuracy at 298 K which enables to measure the change in temperature by as small as 0.5 K [5].

To measure the temperature fluctuations inside as well as outside the enclosure, two AD592 temperature transducers are placed on outside and inside of the seismometer enclosure. Since AD592 is a current output ic, a transimpedence electronic circuit shown in figure 3 is used to obtain temperature in terms of potential difference which then can be read by volatge measurement boards. Also, a differential temperature measurement circuit is made as shown in figure 4 for measuring differntial temperature across the enclosure. This differential temperature measurement circuit uses OP27G operational amplifier which is a precision operational amplifier combining the low offset and drift with both high speed and low noise upto e_n=3.5nV/$Hz^{-1/2}$ at 10 Hz. Offsets down to 25 μV and maximum drift of 0.6 μV/C make the OP27G ideal for precision instrumentation applications and hence it is best suited ofr our application. These differntial temperature measurements would be useful for developing temperature control for the enclosure.

A short period measurement of temperature across the enclosure shows that the average temperature inside the enclosure is about 0.180 K less than the avrage outside temperature and this result uncertain since the accuracy of the AD592 temperature transducer is +/-0.5K,
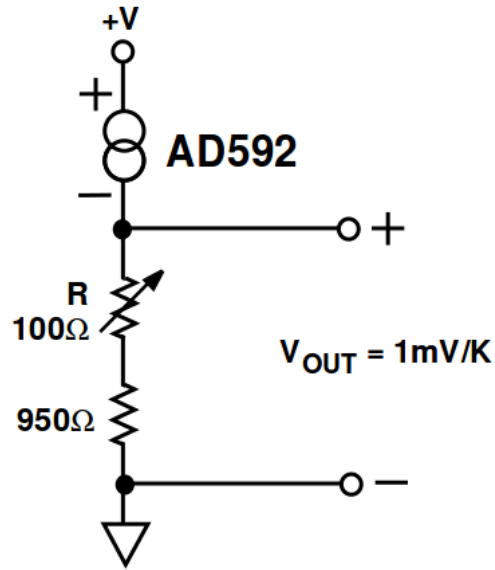
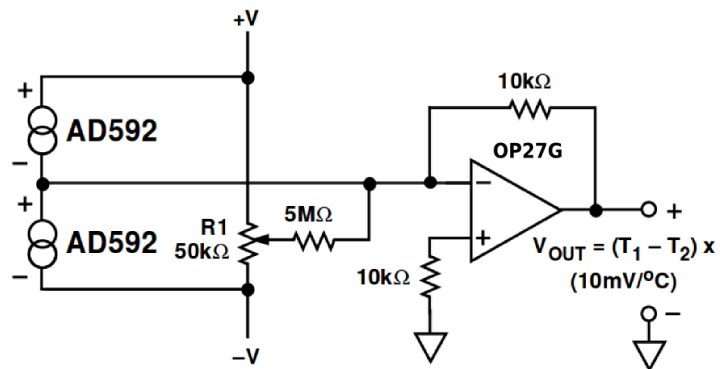Figure 3: IC AD592 Temperature Tranducer Connection Diagram

Figure 4: Differentail Temperature Measurement Circuit
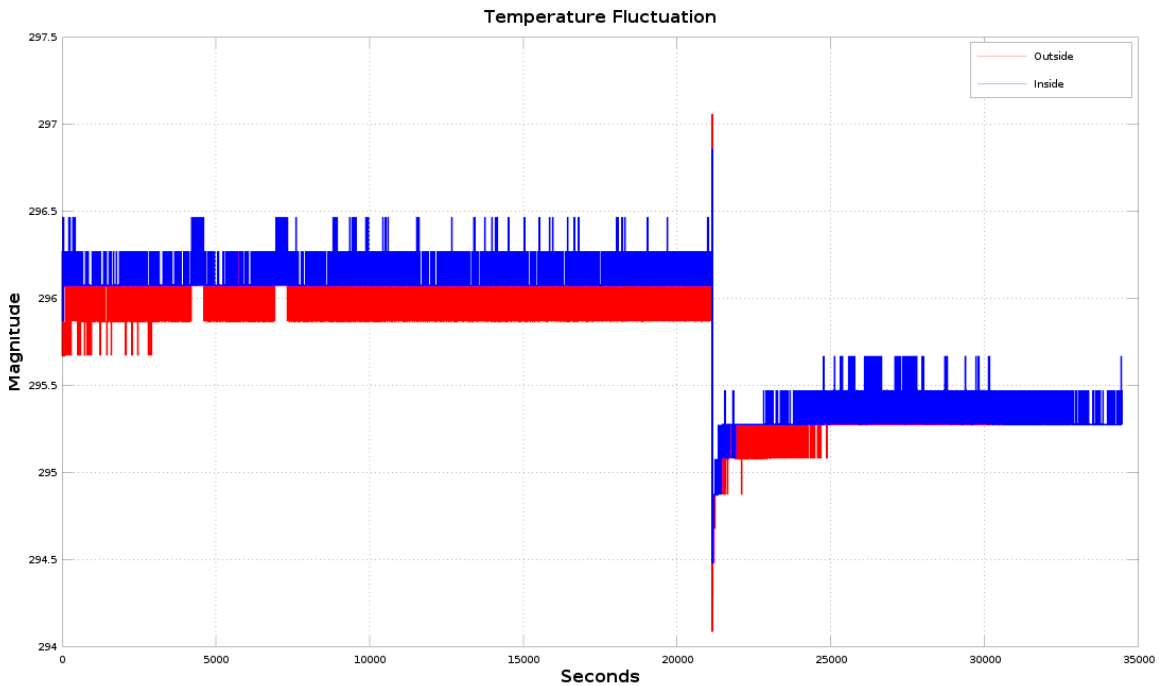
which can be seen from figure 5

Figure 5: Plot of Temperature Data

Morever, it can be seen from figure 6 that the measured data is nothing but the ADC noise. Hence we could not make any conclusion about the validity of collected temperature data.

4.2 Acquiring and Storing Data

The experimental data acquision process should be digital so that data can be easily retrived and analysed as well as to integrate with the existing digital control system at the LIGO 40m lab. I have been working to use Acromag BusWorks data logger card for recording data from my experiment. Acromag BusWorks is an ethernet I/O card with 8 analog channels and 4 digital channels. Figure 7 shows the setup I am using currently which consists of the Acromag BusWorks card, Raspberry Pi Model B and a power supply.

First I configured the acromag busworks card using the usb configuration setup mentioned on model XT 1541-000's manual. For inital setup, a windows machine needs to be used. Initial setup consists of assigning a static ip address to this card as well as testing the channels. Since this card requires modbus TCP/IP for operation, I used a raspberry pi model B to setup and use this card over ethernet. I also installed EPICS(Experimental Physics and Industrial Control System) on raspberry pi which is a set of open source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments such as a particle accelerators, telescopes and other large scientific experiments.Figure 7 shows the schematic of physical connections to the Acromag card. The 40m E-Log as well as the ATF wiki has a detailed explaination of installing and connecting Acromag Bus works card, refer [7].
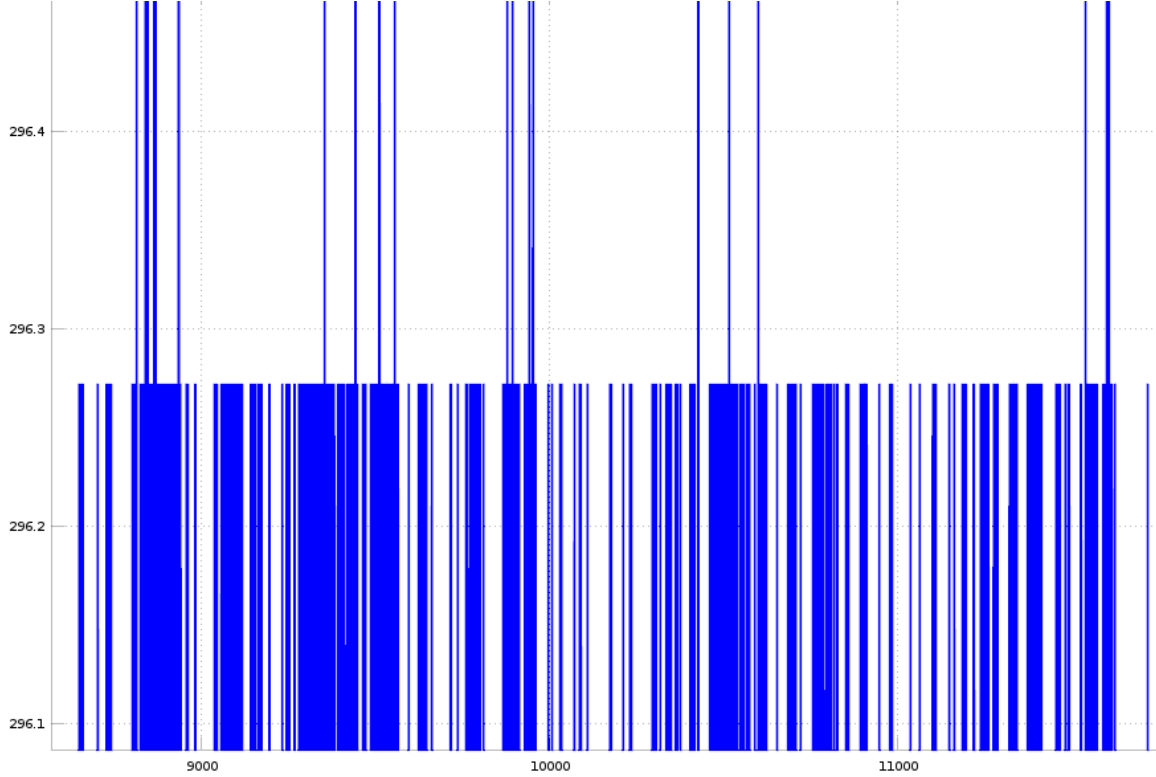
Figure 6: Plot of Temperature Data which is ADC Noise

4.3   Seismometer and Enclosure

The existing enclosure for seismometer at LIGO 40m lab is simply a cylindrical stainless stell can placed upside down over the seismometer. It is shown in figure 8. It has a large amount of empty space between the seismometer and the internal surface of enclosure. This large empty space may lead to development of free air currents which would increase the kinetic energy of air inside the enclosure and therby cause flutuations in temperature. Hence more empty space inside the enclosure is not desirable [8]. Stainless steel has a thermal conductivity in the range of 16.3 to 16.7 $Wm^{-1}K^{-1}$ and magnetic permeability 1.260 x 10^{-6} Hm^{-1} [3] [4].

The rate of heat transfer by a cylinder through conduction is given by :

$$Q = \frac{2\pi kl(T_1 - T_2)}{ln(r_2/r_1)}$$

where k is the thermal conductivity of material, L is the length of cylinder, r_1 and r_2 are inner and outer radius of cylinder respectively and T_1 and T_2 are temperature on inner side and outer side of the enclosure respectively.

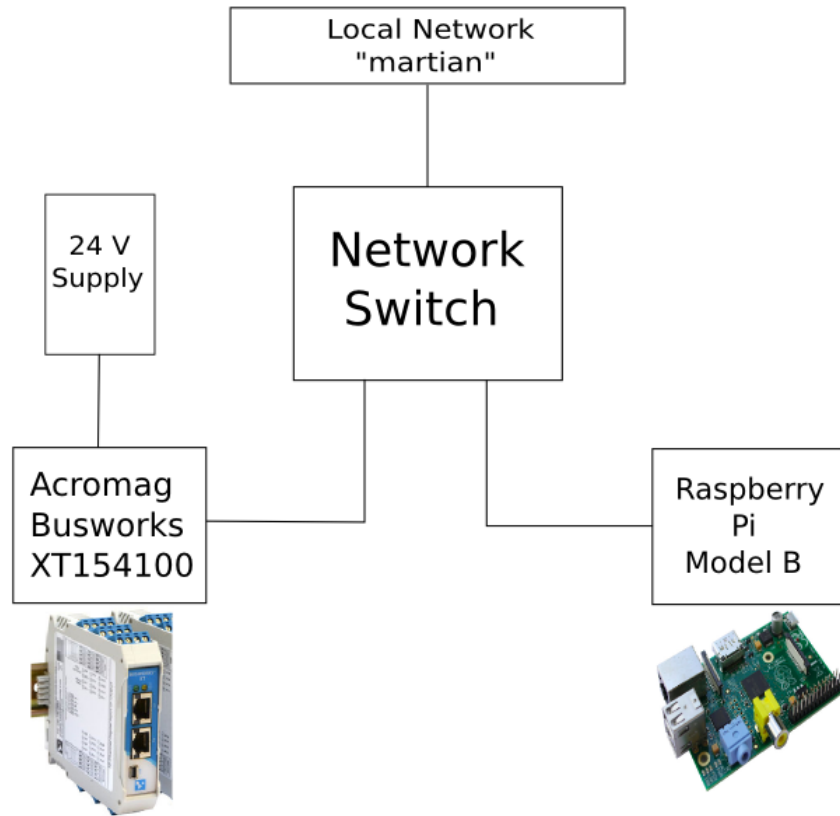The attenuation coefficient of a cylinder is given as :

Figure 7: Acromag Connection Schematic

Figure 8: Photograph of Existing Enclosure for seismometer

$$\eta = \frac{9\mu}{(2\mu + 1)(\mu + 2) - (\frac{a}{b})^3(\mu - 1)^2}$$

where μ is the magnetic permeability of the material and a and b are inner and outer radius of cylinder respectively.

The average temperature outside the enclosure as 297.27 K, and the average temperature inside the enclosure as 297.09K, as well as substituting all the values for dimesions and material properties of existing enclosure,

k=16.4 W/mK

μ=1.260e-6 H/m

L=2ft=0.6096m

b=r_2=0.5ft=0.1524m

thickness=5mm

a=r_1=0.1474m

Thus we obtain the value of attenuation coefficient=5.953584e-05 and the value of rate of heat transfer= 2.1329W.

For studying the variation of rate of heat transfer and attenuation with the thickness of enclosure material, I have plotted the following graphs in Figure 9 and Figure 10 for different materials which include hardened stainless steel, aluminium, pure iron and nanoperm-muMetal [6].
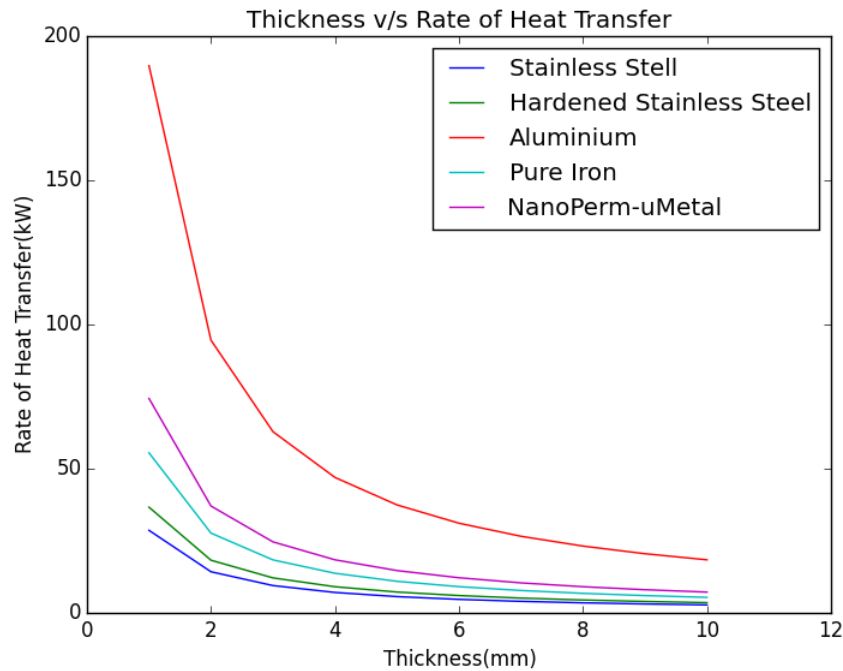

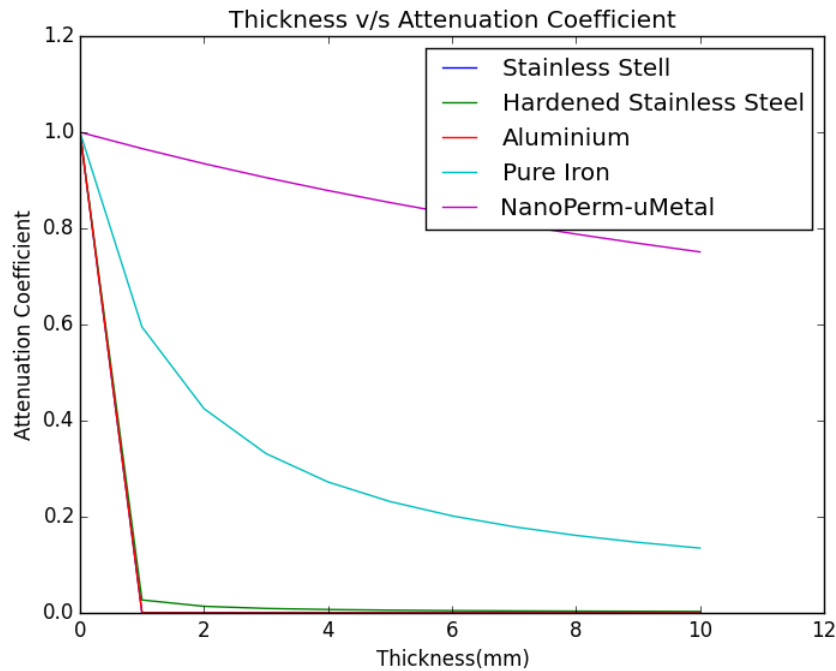Figure 9: Plot of Thickness v/s Rate of Heat Transfer

Figure 10: Plot of Thickness v/s Attenuation Coefficient

A thermal insulation is applied to both the sides of existing enclosure. As shown in figure 11, the insulation is a 5mm thick compound sheet of aluminum foil, polyethylene backing and closed-cell polyethylene foam commercially available as Prodex-Total. The total heat exchange accross the insualtion could not be calculated due to uncertainity in temperature measurements. The figure 12 shows a schematic representation of the existing enclosure with insualtion on either or both sides.

Temperature data was collected across the enclsoure with or without insulation by appyling it on both sides or either sides. The figure 13 shows the sesimometer, exisitng enclosure and enclosure with insulation applied.

I have also measured the transfer function of temperature fluctuations inside the enclosure to that of the temperature fluctuations outside. The transfer function has been estimated by using 'tfestimate' which is library function in Matlab and which estimates the transfer function based on Welch's method. Figure 14 shows the transfer function of the temperature inside the enclosure to that of outside temperature.

In order to determine a relation between temperature inside the enclosure to that of the outside temperature, I have calculated the mean squared coherence. Coherence is the statistical measure of the relation between two signals, which are temperatures across the enclosure. It is either used to measure the linearity between the two signals or to estimate the cause and effect between the input and output. The magnitude-squared coherence between two signals x(t) and y(t) is a real-valued function that is defined as:
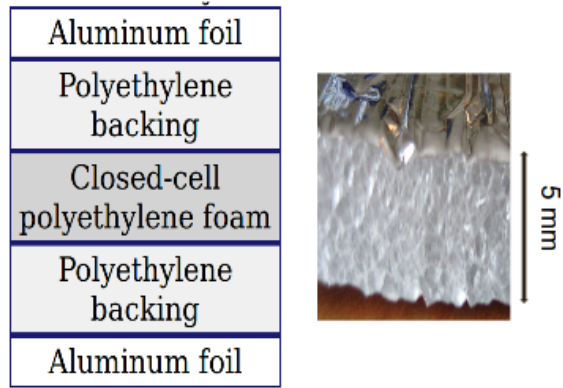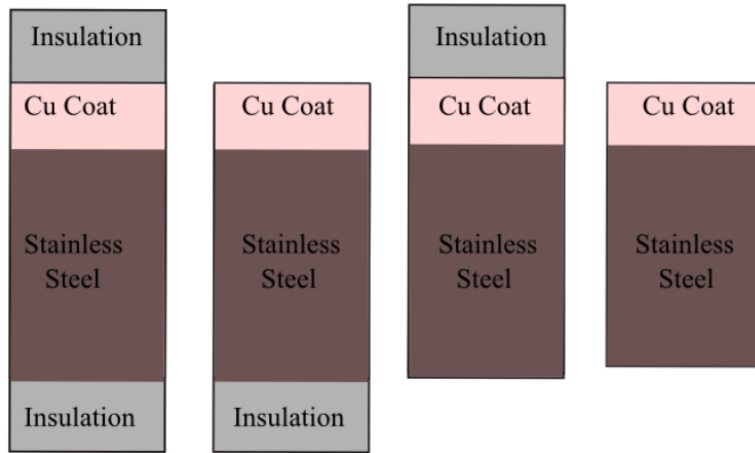
Figure 11: Insulation Prodex-Total

Figure 12: Representation of enclosure with or without insulation

Figure 13: The seismometer, existing enclosure and enclosure with insulation
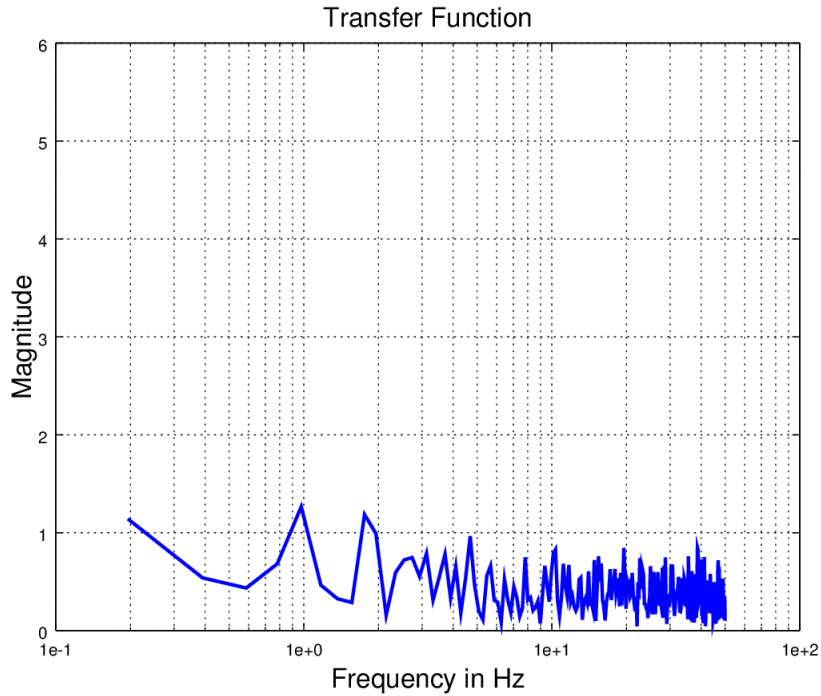
Figure 14: The transfer fucntion of temperature inside the enclosure to that of outside

$$C_{xy}(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)}$$

where $G_{xy}(\mathrm{f})$ is the Cross-spectral density between x and y, and $G_{xx}(\mathrm{f})$ and $G_{yy}(\mathrm{f})$ the autospectral density of x and y respectively. and the cross spectral density is the fourier transform of measure of similarity of two series as a function of the lag of one relative to the other.

I have used Matlab's 'mscohere' library function which uses Welch's method to calculate the coherence. Figure 15 shows the coherence between the temperature across the enclosure.
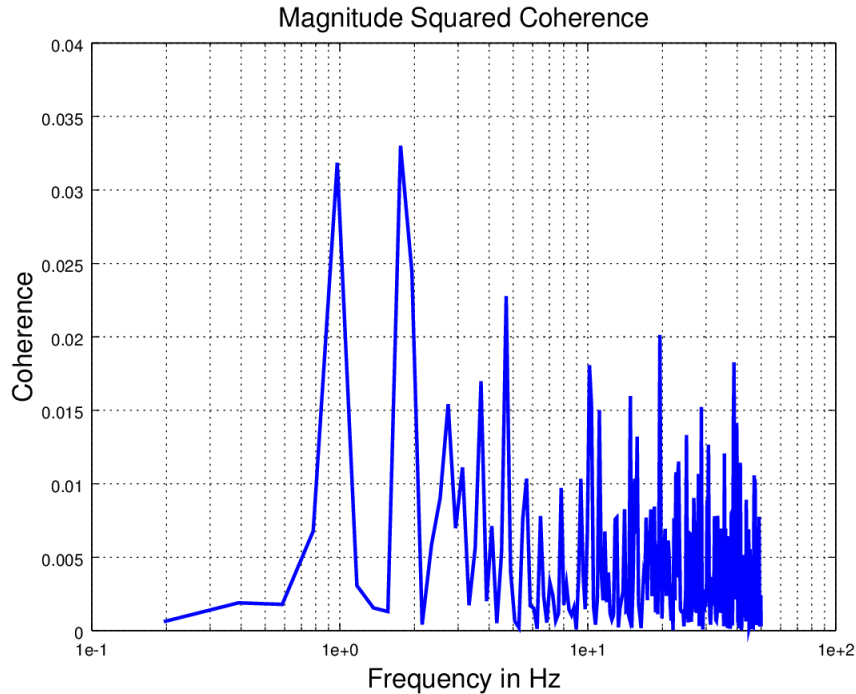
Figure 15: The coherence of temperature inside the enclosure to that of outside

5   Future Work

1.DAQ
The Acromag Busworks card could not be succesffuly configured for acquiring data. The initial configuration details as well as setup could be found on ATF Wiki page and the 40m e-log.

2.Enclosure Design
About new design of enclosure, I was planning to make it smaller, just enough to accomodate the internal insulation and the seismometer because it is better to leave less empty space inside the enclosure as more empty space may lead to development of free air currents. Sharp corners may lead to higher turbulent kinetic energy inside enclosure's free space [8] and hence new design should ensure that the sharp corners are avoided. I am also planning to adopt the enclosure design strategy as adopted for measurements in the antarctic research on sesimic activity [9].

References

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[4] *http://www.bssa.org.uk/cms/File/SSAS2.81-Magnetic20Properties.pdf*

[5] *http://www.analog.com/media/en/technical-documentation/data-sheets/AD592.pdf*

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