3D-Magnetometer Arrays in Physics Experiments

A Thesis Presented for the

Master of Science

Degree

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PREFACE

” Nothing is too wonderful to be true, if it be consistent with the laws of nature.” - Michael Faraday

ABSTRACT

This study presents the design and experimental evaluation of a magnetometer array utilizing LIS3MDL chips integrated with an Arduino microcontroller. Magnetometer arrays find crucial applications in various fields, including physics research, geophysics, and navigation systems. The goal of this research is to create an affordable and versatile magnetometer array for scientific investigations and practical applications. The paper begins by outlining the hardware and software components of the array.
The LIS3MDL chips, known for their high sensitivity and low power consumption, are employed as the core sensing elements. The Arduino microcontroller is utilized for data acquisition and processing. The integration of these components is discussed in detail, along with the calibration procedure to ensure accurate magnetic field measurements. The experimental methodology is described, including the setup for testing in controlled environments and real-world scenarios. The array's performance is assessed through various experiments, such as mapping magnetic fields, detecting anomalies, and monitoring changes in magnetic fields over time. Preliminary results demonstrate the array's ability to capture magnetic field data with high precision and reliability. In conclusion, the presented magnetometer array, based on LIS3MDL chips and Arduino microcontrollers, exhibits promising capabilities for magnetic field measurements. This research offers a foundation for further exploration and utilization of the array in various scientific and practical applications.

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Chapter One

Introduction

In many physics experiments, the measurement and control of the magnitude, direction, and uniformity of the magnetic field is required. Thus, in the pursuit of precision control over magnetic fields for mirror matter experiments [10] planned and ongoing at the Oak Ridge National Laboratory (ORNL) with the participation of the University of Tennessee, Knoxville (UTK) high-energy research group, the development of a scalable and adaptable magnetometer array becomes paramount. This thesis explores the imperative need for a cost-effective solution that aligns with the rigorous standards of professional magnetometry while catering to the dynamic environment of the High Flux Isotope Reactor (HFIR) facility at ORNL. The challenge lies in designing an off-the-shelf magnetometer array capable of real-time data collection, remote access, and scalability, ensuring optimal performance amidst the intricate experimental setting. Some experiments imply some additional specific requirements, such as operation in a vacuum, in the radiation field, at elevated temperatures, etc. This thesis delves into the intricacies of designing an off-the-shelf solution that not only meets the stringent standards of professional magnetometry but also addresses the challenges posed by the ever-changing magnetic environment within the HFIR facility. The goal of the thesis is to develop a cost-effective, off-the-shelf magnetometer array that ensures real-time, precise data collection over a 16m x 1.5m in the experimental area. We need to do the following.

(i) Enable scalability to adapt to variations in the magnetic field.
(ii) Implement remote access capabilities for data collection in high-radioactive environments.
(iii) Establish a calibration procedure incorporating software development to account for manufacturing offsets.

The magnetometer array will be constructed using readily available, mass-produced components, striking a balance between cost efficiency and precision. Real-time data collection will be facilitated through a scalable design, allowing adjustments to the number of channels based on positional variations in the micro-Tesla range. Remote access capabilities will be integrated to enable data collection during reactor operation in a vacuum and in a high-radioactive environment. The calibration procedure will involve software development to account for manufacturing offsets, ensuring accurate data collection. This research holds significance in advancing mirror matter experimentation by providing a practical, cost-effective solution for magnetic field control. The

developed magnetometer array not only serves the immediate needs of the experiment but also opens avenues for broader applications in diverse magnetic field studies. This thesis aims also to contribute to the field of mirror matter experimentation by introducing a design of a cost-effective yet precise magnetometer array. The proposed solution not only meets the standards of professional magnetometry but also addresses the unique challenges posed by the HFIR facility. Through this research, we aspire to propel advancements in magnetic field control, fostering innovation in experimental methodologies and expanding the horizons of scientific exploration.

Chapter Two

Overview of Principles of Magnetometers

Flux gate Magnetometer:

The fluxgate magnetometer [11] stands as a sophisticated instrument designed for the precise measurement of both the strength and direction of magnetic fields. Operating on the principles of electromagnetic induction, this device utilizes a high-permeability core, often in a closed-loop configuration. At its core, the instrument incorporates an alternating magnetic field generated externally, inducing cyclic saturation and demagnetization within the core. The magic lies in an additional winding wrapped around the core, which detects changes in magnetic flux induced by the alternating field. To maintain equilibrium, a DC bias is applied to the core, ensuring its operation near saturation. The varying external magnetic field counteracts this bias, causing fluctuations in the core's permeability. The secondary winding, sensitive to these permeability changes, produces an output voltage reflecting alterations in the external magnetic field. The output of the signal is analyzed to infer both the intensity and direction of the magnetic field under study. Notably, fluxgate magnetometers exhibit exceptional sensitivity to weak magnetic fields, making them indispensable in many scientific fields such as geophysics, space exploration, and industrial applications. In summary, the fluxgate magnetometer, with its reliance on electromagnetic principles, offers precise measurements of magnetic fields, proving to be a versatile and indispensable tool for researchers in diverse fields, providing insights into the intricacies of our magnetic environment.

Hall Effect Magnetometer:

The Hall effect magnetometer[11] is a sophisticated instrument designed for the precise measurement of magnetic field strength and polarity, leveraging the Hall effect—a phenomenon observed when an electric current flows through a conductor in a magnetic field. Central to its design is a thin semiconductor strip, typically composed of gallium arsenide or indium antimonide, through which a current flows. When subjected to a magnetic field perpendicular to the strip, the Lorentz force acting on charge carriers leads to their accumulation on one side, generating a measurable voltage across the strip's width. This resultant voltage, referred to as the Hall voltage, is directly proportional to the strength of the magnetic field. Through meticulous measurement of this voltage, scientists can determine both the intensity and polarity of the magnetic field under examination. Hall effect magnetometers are acclaimed for their accuracy and versatility in measuring both static and dynamic magnetic fields. Their applications span diverse fields, including navigation systems, industrial control, scientific research, and space exploration. In essence, the Hall effect magnetometer exploits the fundamental physics of charged particles in a magnetic field,

providing researchers with a dependable and efficient tool to explore and comprehend the intricacies of magnetic forces in various environments.

Magnetic Resistive Magnetometer:

The magnetic resistive magnetometer[11] represents a sophisticated instrument meticulously designed for the measurement of magnetic fields by exploiting alterations in the electrical resistance of specific materials under varying magnetic influences. This device operates on the fundamental principle that the presence and intensity of a magnetic field can modify the resistance of certain materials. Central to the magnetometer's construction is a sensor comprising magneto-resistive materials semiconductors iron-nickel-cabolt alloys. Exposure of this material to a magnetic field induces changes in its atomic or molecular structure, thereby influencing the flow of electrical current. As the magnetic field undergoes variations, the material's resistance experiences fluctuations, a phenomenon detected by the magnetometer. This provides a precise indication of the strength and, in some cases, the direction of the magnetic field. The remarkable sensitivity of magnetic resistive magnetometers enables them to discern even subtle alterations in magnetic forces. Their versatility and precision find applications across various fields, including navigation systems, geophysics, and industrial applications. Their capability to operate effectively in both static and dynamic magnetic fields makes them valuable tools in scientific research and technological advancements. In summary, the magnetic resistive magnetometer stands as an exemplar of ingenuity, employing changes in material resistance to unveil the complexities of magnetic fields. Its applications span diverse industries, offering researchers and engineers a potent tool to explore and comprehend the magnetic landscapes that surround us. Fluxgate magnetometers, Hall effect magnetometers, and magnetic resistive magne-tometers are three distinct technologies employed for measuring and understanding magnetic fields, each with their unique principles and applications. A comparative analysis highlights the strengths and characteristics of these magnetometer types. [Table 2.1] shows a general overview of the magnetometers.

In this experiment, the goal is to deploy a magnetic field measurement device capable of assessing the total magnetic field in a specified area, ensuring precision, reliability, and the ability to capture low magnetic field strengths within the Earth's magnetic field. The device should enable 3D data collection, have access to user-friendly software for efficient data retrieval, support remote access, and possess storage capabilities with external backup. Additionally, the device should accommodate up to 128 channels and maintain cost-effectiveness.

Table 1 General Overview of Magnetometers

Property	Fluxgate Magnetometers	Hall Effect Magnetometers	Magnetic Resistive Magnetometers
Principle	Electromagnetic induction	Hall effect	Magneto resistive effect
Core Material	High-permeability core	Semiconductor strip	Magneto resistive materials
Measurement Range	Detects weak magnetic fields	Measures both static and dynamic fields	Sensitive to subtle changes in magnetic forces
Applications	Geophysical studies, space exploration, industrial applications	Navigation systems, industrial controls, scientific research	Navigation systems, geophysics, industrial settings
Advantages	Exceptional sensitivity and precision	Compact size, low power consumption, responsiveness to changing magnetic conditions	Versatility, sensitivity in detecting subtle changes
Use Cases	Challenging environments, space exploration	Diverse environments, real-time applications	Precise measurements in static and dynamic magnetic fields

Chapter Three

Procedure

OVERVIEW:

The goal of this work is to build a magnetometer array that is cost-effective, expandable, and reliable. Each magnetometer must be able to measure magnetic fields in a range of the earth's magnetic field of 25 to 65 microteslas. The array needs to be connected to a computer, so the collected data can be accessed both locally and remotely. The magnetometer array needs to be able to operate in the environment at the GP-SANS (General Purpose Small Angle Neutron Scattering) at the HFIR (High Flux Isotope Reactor). Each magnetometer needs to be able to read the components of the magnetic field along 3 perpendicular axes, labeled X, Y, and Z. An example of this type of magnetometer is the one used in current cell phones. For an initial study at the HFIR, I purchased HMC5883L magnetometer chips. I wanted to test if they can provide reliable 3D magnetic field data. I designed a 6-channel array. I built an aluminum enclosure to allow the prototype to be moved easily down the 16-meter GP-SANS instrument at the HFIR. The enclosure needed to hold the magnetometer chips, a Arduino uno microcontroller, and the Raspberry Pi microcomputer. The GP-SANS instrument is shown [Figure 1]. The initial study was to reveal if the HFIR could be used for the search for mirror matter. Such a search requires precise control of the magnetic field in the range of 25 to 65 microteslas. I measured the local magnetic field to see if it was stable and if it could be controlled given the correct shielding. The measurements were made first when the reactor was off and second when the reactor was operational. The mapping of the field showed that the HMC5883L chip was able to measure the magnetic field over the 16 meters range. It also showed that there were local sources that caused inconsistent, non-uniform magnetic fields. We saw the changes in the field from devices around the GP-SANS instrument. However, to determine the absolute magnitude and direction of these changes, the magnetometer chips still needed to be calibrated. My initial study was a success, in that they showed that the non-uniform magnetic field at the HFIR can be controlled with shielding. Some of these non-uniform fields are produced by the local devices such as the large electromagnets and motors on the beam line. This requires position-dependent shielding. I also verified that I was able to access the magnetic field data live, locally, and remotely, using the Wi-Fi connection using the Raspberry PI. Remote access to the array is required due to the high radiation environment. The initial study at the High Flux Isotope Reactor (HFIR) involved using off-the-shelf 6-channel magnetometers, which were not calibrated. To address this, a calibration procedure for magnetic resistive magnetometer was designed and implemented. The calibration process began by taking the HMC5883L

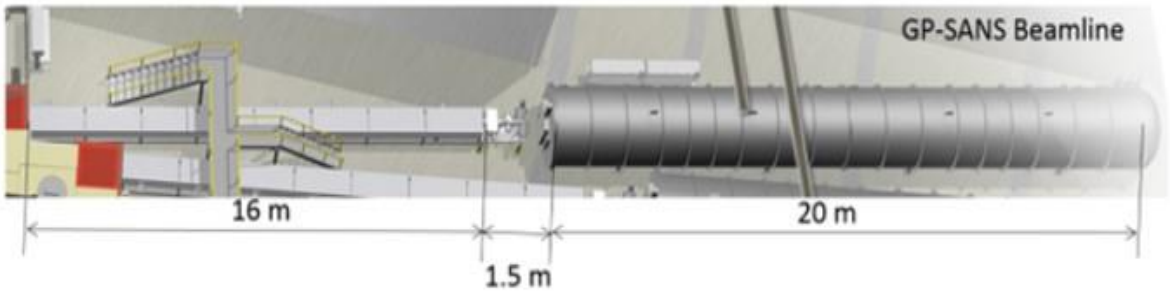


Figure 1 GP-SANS instrument at HFIR includes a 16 m long collimation vacuum tube. 1.5 m sample region and 20 m long detector tank.

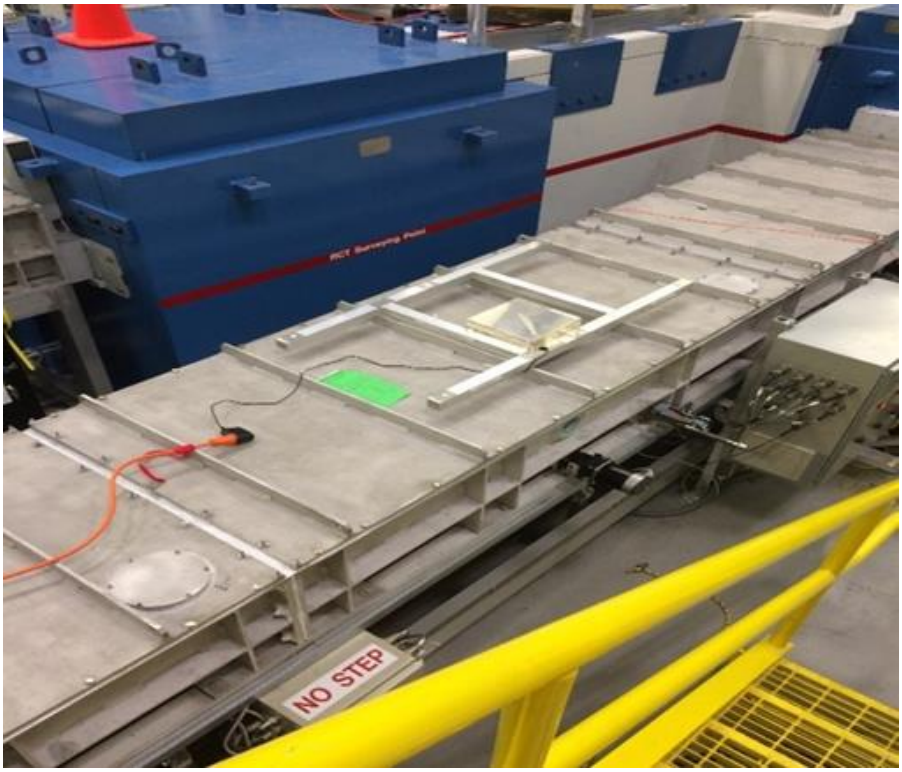


Figure 2 Magnetometer Array

chip to the Science and Engineering Research Facility (SERF) at UTK. There we calibrated the chips by comparing measurements made with the magnetic resistive magnetometers against measurements made with a Bartington Spectromag 6 fluxgate magnetometer. We needed a low-magnetic setup. An aluminum wedge to precisely position fluxgate magnetometer wands was designed and placed on a wooden table to aid in calibrating the fluxgate magnetometer wands. The setup was placed in a room where we expected the magnetic field to stay constant both in strength and direction during calibration. [Figure 3] However, while we were working on the calibration procedure, the HMC5883L chip became unavailable, necessitating the use of alternative magnetic resistive magnetometers. The LIS3MDL was selected as the replacement and utilized for the experiment. To calibrate the LIS3MDL a printed circuit board was designed to be inserted in an aluminum cube that holds the LIS3MDL chip and the microcontroller. This setup was then placed on the low magnetic field table with the wedge and the LIS3MDL measurements were compared to the fluxgate measurements. With the calibration process established, an 8-channel magnetometer array prototype was designed and set up for future experiments at HFIR. This prototype underwent testing to ensure its functionality and accuracy, paving the way for the use of 128 magnetometers in upcoming experiments. Overall, the focus was on designing and implementing a calibration procedure for magnetometers to ensure accurate measurements in the study of magnetic fields at HFIR.

DETAILS:

Initial Measurements at the HFIR

For the experiment of the magnetic field study at HFIR a magnetometer array that is cost-effective, expandable, and reliable, using off-the-shelf components, is needed. The magnetic field in a large volume of space needs to be measured. This will require several 3D magnetometers capable of measuring the components of the magnetic field vector along three perpendicular axes. I designed a 6-channel magnetometer array and used it in the cold guide hall at the HFIR. With this magnetometer array, I was able to measure the magnetic field in situ of the GP-SANS instrument. The 6 magnetometers (DAQ) hardware for data collection and the distribution of the collected data. A microcontroller Arduino Uno, a multiplexer, and a Raspberry Pi constitute the hardware used for data collection. The multiplexer allows for identical chips to communicate with the microcontroller which sends the data to the Rasberry PI for data distribution.

HFIR Study

I installed the 6-channel magnetometer on top of the GP-SANS instrument and collected the local magnetic field data along the entire 16-meter instrument. [Figure 4] shows the magnetic field measured

along the first meter of the instrument by the 6 different magnetometers. Chip 1 and Chip 2 measure about the same total field strength. We can see that during normal operating times, the field is non-uniform and varies when devices are used. This is shown in [Figure 6]. The initial setup and test were successful, they showed that we could build a multichannel array and measure the magnetic field in real-time. This also showed that the magnetic field at the HFIR is non-uniform, but that the variations can be controlled with the proper shielding. Some of the magnetic fields were caused by the local devices such as the large electromagnets and motors on the beam line. We will need to shield the area in such a way as to cover the maximum values of the field that were displayed during the active period of the operation of the reactor. The result of the experiment show that the maximum field strength was around 75 μT Figure 4. The next step is to use what we learned in the initial test and build another array so that I can test the local field without having to move the unit down the 16-meter- long instrument. I designed another 6-channel magnetometer array which I planned to use this in conjunction with the first magnetometer array. Two arrays allow for more accurate data collection because of the additional volume covered. They can measure the magnetic field in real time over 2 meters instead of 1 meter. However, during the design of the new array, the HMC5883L was discontinued. I had to find a replacement for the current magnetometer chip. The next candidate for the magnetometer was the LSM9DS0/1. This chip has more features than the HMC5883L. It has 9 degrees of freedom. The chip has an accelerometer, gyroscope, and magnetometer integrated into the board. The HMC5883L is just a magnetometer. The LSM9DS1 allows for more precise spatial calibration because of the additional degrees of freedom. During the calibration test the LSM9DS1 magnetometer went on backorder. This was due to the chip shortage. I was only able to purchase 6 of these LSM9DS0/1. Future experiment will require 128 channels allowing for the whole field to be mapped in real time. I therefore purchased the LIS3MDL magnetometer as a replacement for the HMC5883L chip. This chip is a 3D magnetometer only. It is more of a direct replacement, and it would have the same limitations for calibration as the initial chip HMC5883L. However the LIS3MDL can collect field data within the range ±4 Gauss to ±16 Gauss.

Calibration Procedure

A nontrivial step is to design a calibration procedure that can be used for each of the 128 magnetometers. For the reference device, I used the Bartington Spectromag 6. This Magnetometer has a range of 70 microteslas to 1000 microteslas. For the calibration procedure, I set up a low magnetic field table with 3D orthogonal aluminum guide for use with the reference lab coordinates. The 3D orthogonal guide was built by the UTK machine shop. It was placed on the top of the table in a secure and locked room to limit the amount of interaction. I used the lab room in the SERF (Science Engineering Research Facility) building

at UTK (University of Tennessee Knoxville). This setup was used to verify the calibration of the Spectromag 6. The calibration of the LIS3MDL is done against the reference magnetometer Bartington Spectromag 6 using the coordinate system of the lab with respect the measurement done using the Spectromag 6, and the orthogonal guide. The orthogonal coordinate system was labeled BX, BY, and BZ. The general idea of the calibration of the sensor is shown in Figure 11. Figure 8 shows the DAQ of the Bartington Spectromag which is used to configure the spectromag and to collect the data. The placement of the MAG-03 is shown in Figure 9.

Bartington Spectromag 6 MAG-03 Sensor

The Spectramag-6 is a portable Fluxgate Magnetometer. It is a 24-bit analog-to-digital converter (ADC). It is designed for the simultaneous collection and analysis of magnetic field, vibration, and acoustic data. Its six input channels provide synchronous digitization of the outputs from magnetic field sensors, accelerometers, or acoustic sensors. Combined with a PC via a USB interface, the Spectramag-6 can record data at rates up to 10kHz. The supplied software collects and displays data in the time and frequency domain, with a range of filtering capabilities and FFT options are available. Measurements of frequency domain, with a range of filtering capabilities and FFT options are available. Measurements of the magnetic fields can measure both static and alternating magnetic fields along 3 perpendicular axis X, Y, and Z which is labeled BX, BY, and BZ. The axes correspond to the cartesian coordinate system that is set up arbitrarily. The output of the sensors converts the magnetic flux density, measured along each of the three axes, into a bipolar analog voltage. This means that it can swing both positively and negatively around a reference point. The MAG-03 series sensors are versatile magnetometers designed for precise measurement of magnetic fields in three axes, offering a linear output and high performance over a broad frequency range. [Figure 9] shows a picture of 16 of the 18 rotations that are to be performed to get the offset and the gain of the magnetometer. As a reference for the Bartington measurement I also used NOAA data. Figure 7 from the NOAA website, shows the local field strength for the time the test was run. The National Centers for Environmental Information (NCEI) was used for comparison to the data collected from the Bartington Spectromag 6 Magnetometer MAG-03 70 μT and the 1000 μT sensors. For general information, the National Centers for Environmental Information (NCEI), which is part of the Oceanic and Atmosphere Administration (NOAA), collects magnetic field data using a network of ground-based observatories and satellite measurements. The average magnetic field components [Table 2] are near the NOAA 49 μT for each of the magnetometer components using the MAG-03 70 μT sensor.

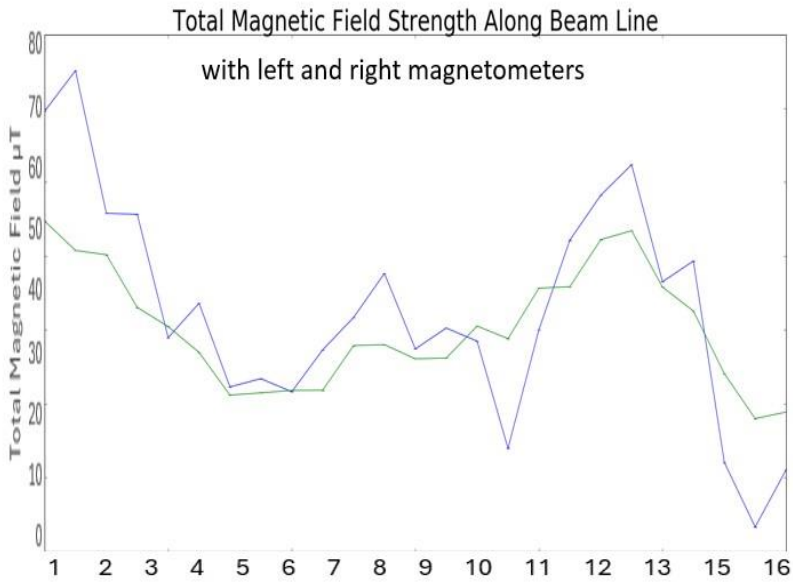


Figure 3 GP-SANS Instrument

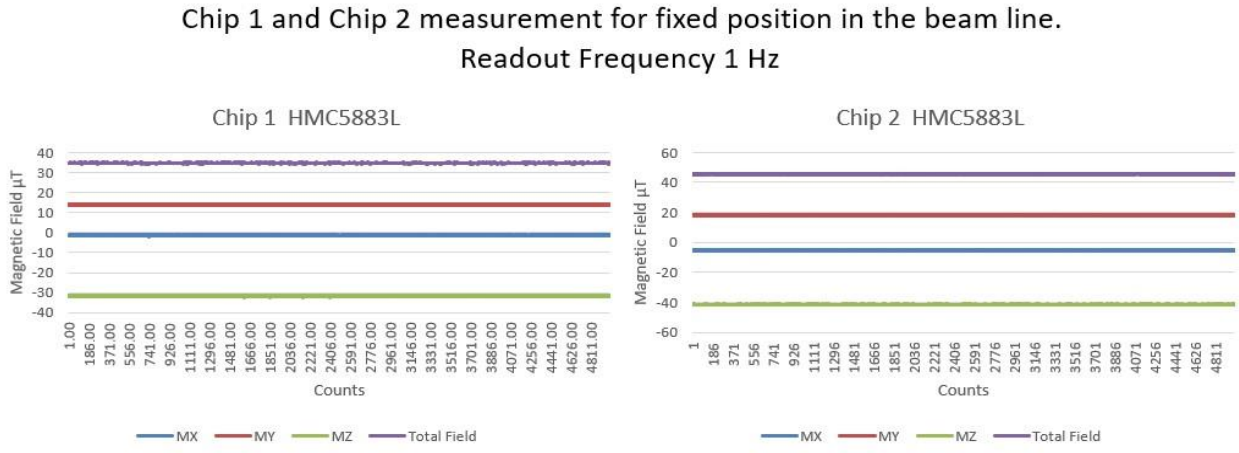


Figure 4 What we see here that all component magnetic field are stable within 5000 seconds. Put the RMS here RMS BX = 0.137 ; RMS BY = 0.136 ; RMS BZ = 0.147 ; RMS TOT = 0.144

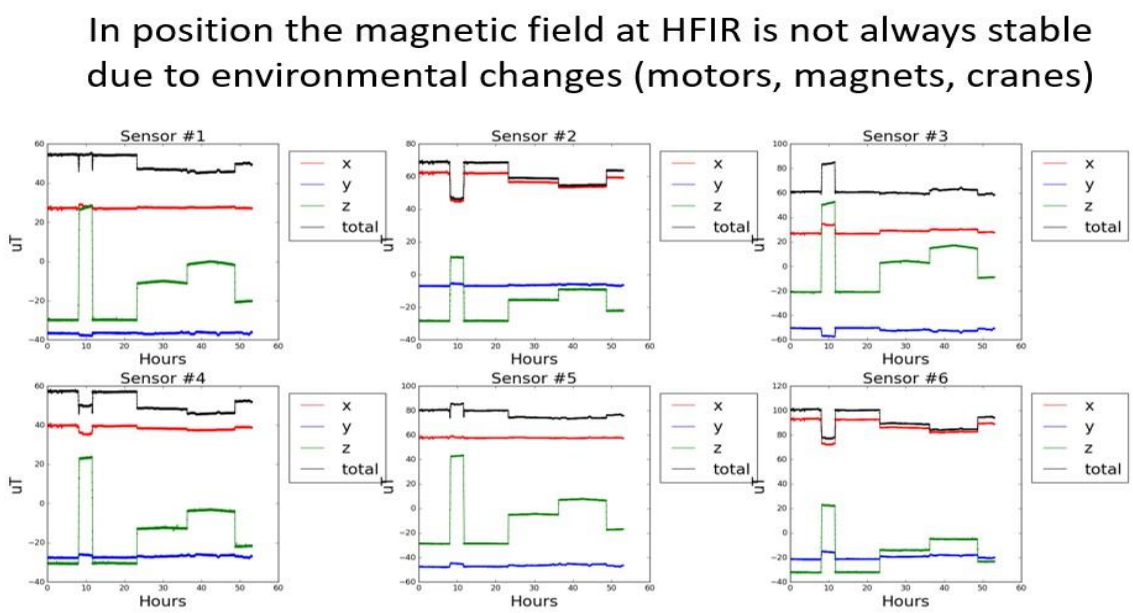


Figure 5 We learned from these data that for each measurement (usually 5000 points at 60 Hz) Measured RMS should be lower than some pre-defined limit that will guarantee the stability without perturbation. The measurement can be repeated in case of a large variance

Magnetic Field

Model Used:	WMM-2020
Latitude:	35° 57' 25" N
Longitude:	83° 56' 1" W
Elevation:	0.0 km Mean Sea Level

Date	Declination (+ E | - W)	Inclination (+ D | - U)	Horizontal Intensity	North Comp (+ N | - S)	East Comp (+ E | - W)	Vertical Comp (+ D | - U)	Total Field
2022-09-20	-5° 58' 57"	63° 45' 9"	22,044.8 nT	21,924.7 nT	-2,297.6 nT	44,707.1 nT	49,846.8 nT
Change/year	-0° 3' 22"/yr	-0° 5' 35"/yr	23.3 nT/yr	20.9 nT/yr	-23.9 nT/yr	-135.8 nT/yr	-111.5 nT/yr
Uncertainty	0° 22'	0° 13'	128 nT	131 nT	94 nT	157 nT	145 nT

Figure 6 NCEI Geomagnetic Calculators



Figure 7 Bartington Spectromag 6 DAQ Connected to PC

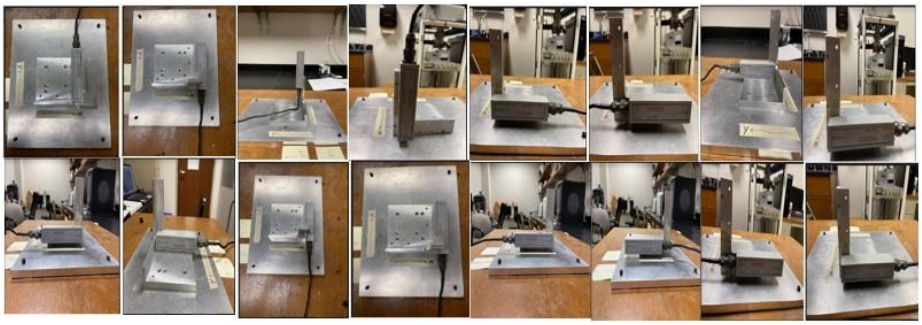


Figure 8 MAG-03 in 16 positions of the 18 in the table



Figure 9 MAG-03 Sensor, 70 µT and 1000 µT

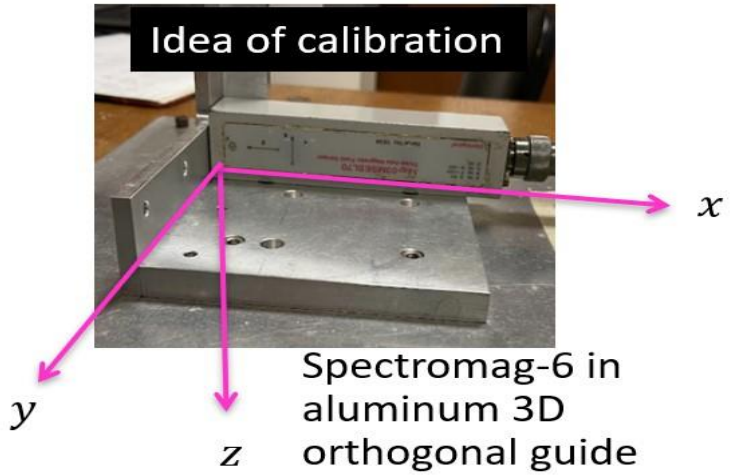


Figure 10 Calibration

Table 2 Average for each of the SX, SY, and SZ Total Field strengths. µT 9-20-2024

BX	BY	BZ
SX	SY	SZ
39.81 μT	39.86 μT	40.85 μT

HMC5883L

The chip is a popular three-axis magnetometer manufactured by Honeywell. It measures the strength of the magnetic field along three orthogonal axes, X, Y, and Z. The magnetometer is based on magneto resistive technology. The resistance of the ferromagnetic material changes with the magnitude and direction of the applied field. This change in resistance is then measured to determine the magnetic field strength. This is expressed with the following formula.

$$\Delta R = R_0 * \frac{B * \cos(\theta)}{H}$$

• ΔR is the change in resistance.

• R_0 is the initial resistance of the sensor.

• B is the magnetic field strength.

• θ is the angle between the direction of the current flow and the magnetic field.

• H is a constant

The HMC5883L was the first chip used for the magnetometer array. Let us review the setup and add some details to its design and use. I designed a case that could hold 6 of the HMC5883L magnetometers. This allows for a group of magnetometers to collect the magnetic field data in the cold guide hall at HFIR The data collected was used to see mirror matter oscillations [10]. The premise is that the mirror neutron has an additional magnetic moment. This search for neutron Transition Magnetic Moment (nTMM) will need precise magnetic field control over the GP-SANS instrument and the large volume within less than 1 Gauss. To test the viability of the HMC5883L, I left it in a single location and collected the local magnetic field data for several days. [Figure 12] Shows the array, and the magnetometers placement within the array is circled. Shown in [Figure 12] the array is designed to be as flat as possible. This is to avoid any variation in the angle while measuring the local magnetic field. The case is designed in such a way as to feed the ribbon cable to the DAQ to power each of the magnetometers and to get data from them to the microcontroller. Each of the chips is connected to a microcontroller Arduino Uno which is connected to the Raspberry PI B+ as the PC for the DAQ. The data is sent to the internet from the Raspberry PI Wi-Fi. To communicate to each of the identical serial sensors, we need to use a multiplexer (MUX) which assigns a unique address 0 through 5 to each of the sensors, in this magnetometer array. This allows each of the chips to collect data in unison. Originally the unit in the experiment was connected to the Multiplexer on a breadboard. This breadboard was connected to the Arduino which powered and collected the data passed to the multiplexer. The Arduino was powered by the Raspberry Pi B+. When moving the unit from position to position the cables could become disconnected. I designed a PCB board with the aid of the UTK physics electronic shop to hold the Multiplexer. This was built for the Arduino as a Hardware

Attached TOP (HAT). The picture of the HAT is shown in [Figure 13]. This is an attachment connected directly to the Arduino. [Figure 14] shows the Arduino with the HAT which is connected to the Raspberry PI B+. Now the unit was secured and could be moved with no loose wires or disconnects. I then proceeded to test the equipment at the HFIR. To be allowed to bring the equipment to the site I had to make sure that all of the equipment was approved by ORNL. Once the equipment was approved, I was then able to test the unit. I had to set up the Raspberry Pi B+ to connect to the local open Wi-Fi. Since I do not have direct access to the router I had to connect a monitor that has a high definition multimedia interface (HDMI) port. I also had to connect a keyboard to the Raspberry Pi B+. Once I was on site I set up the Raspberry Pi B+ using the monitor and keyboard and connected it to the Wi-Fi. Then I was able to disconnect the monitor and keyboard. From there I used the Virtual Network Controller (VNC), VNC Viewer software service. This way I had remote control over the Raspberry Pi, removing the need for a monitor and a keyboard. I then placed the 1 meter by 0.5-meter aluminum enclosure on the top of the GP-SANS instrument. I then collected data from one meter to the next physically moving the unit down the instrument. [Figure 15] shows one of the placements of the magnetometer array. It shows the location of its position on the top of the GP- SANS instrument. [Figure 15] is shown with the reactor offline. You can tell this by the lights being off in the picture. The placement of the magnetometer array is shown in [Figure 15]. The data shown in [Figure 5] give us the facility's magnetic field variations from position to position. They show us what to expect when the reactor is not on, and the activity is minimal. With the reactor off I could also use the time to resolve any issues like the wires coming loose from moving the array. With the reactor down I was able to verify that the Raspberry PI would reconnect to the Wi-Fi which then allowed access to the VPN service without having to reconnect the monitor and keyboard. This test showed that the hardware once configured did what it was supposed to do. I was able to collect data with only a brief interaction with the array while moving it from meter to meter.

LISM9DS1

The LISM9DS1 is the first chip I used as a replacement for the discontinued HMC5883L magnetometer. This is a chip that has a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer for a total of nine degrees of freedom (9DOF). This will measure the position in space and the magnetic field strength. This chip has an selection for acceleration (g) ranges from ±2, ±4, ±8, ±16. The chip can measure the magnetic field strength of ranges from ±2, ±4, ±8, ±16 Gauss. It has a gyro with a selection of ranges ±245, ±500, ±2000 degrees per second (DPS). This chip is ideal for the precise measurements of the magnetic field. It would have been a great candidate for the replacement of the HMC5883L but went on backorder because of the chip shortage.

LIS3MDL

This LIS3MDL chip is made by STMicroelectronics [12]. The chip is based on anisotropic magnetoresistance (AMR) magnetoresistance material. This unit is used to sense the external magnetic field components in 3D. Each magnetometer has 3 sensors per chip to measure the components of the magnetic field.

Technical Specifications

- 3D magneto resistive sensors, each with
- Range ± 4 G (also, ± 8 G, ± 12 G, ± 16 G)
- Conversion 16-bit, nonlinearity $\pm 0.12\%$ FS
- Conversion 6842 counts per 1G ($\pm$4G range)

- Conversion 6842 counts per 1G ($\pm$4G range)
- Possible offset ± 1 G ($\pm$4G range) depending on chip.
- Sampling Rate 0.625Hz-80 Hz

The LIS3MDL [1] has pre-programmed code to allow for instant prototyping within the same day of delivery of the chip. The code is compatible with the Arduino library. It also has preprogrammed code that is compatible with Python. The new Adafruit magnetometer sensor can be used with or without headers; these are pins to connect to a breadboard or the printed circuit board (PCB) or the quick-connect adapter (Qwiic). This allows for a simple plug and play using a compatible microcontroller and the serial cable connected to the sensors. The company that designed this is SparkFun. I tested the LIS3MDL from Adafruit on several types of microcontrollers. The following microcontrollers were used: Portenta H7, Nano Every, RP2040 Feather, Raspberry Nano, and Raspberry Pi Zero with Wi-Fi. To look for differences in performance. In my experiment I used the LIS3MDL connected to the Arduino Nano Every and the Arduino H7 for ease of compatibility and pre-programmed code availability. Arduino also provide the components for using the microcontroller, software and have a small footprint, especially the Arduino Nano Every. I attached the LIS3MDL to the PCB that was created specifically to test the magnetometer. The cube is shown in [Figure 15]. I designed and built an aluminum cube for calibration of the LIS3MDL which would be compatible with the 3D orthogonal angle that was used to calibrate the Spectromag 6. Placing the aluminum cube on the orthogonal cube I could rotate it with respect to the coordinate system of the lab reference frame. This needed to be rotated as it was done with the Spectromag 6 This LIS3MDL has an operating temperature minimum of -40° Celsius and a maximum of 80° Celsius and was tested in a climate-controlled environment.

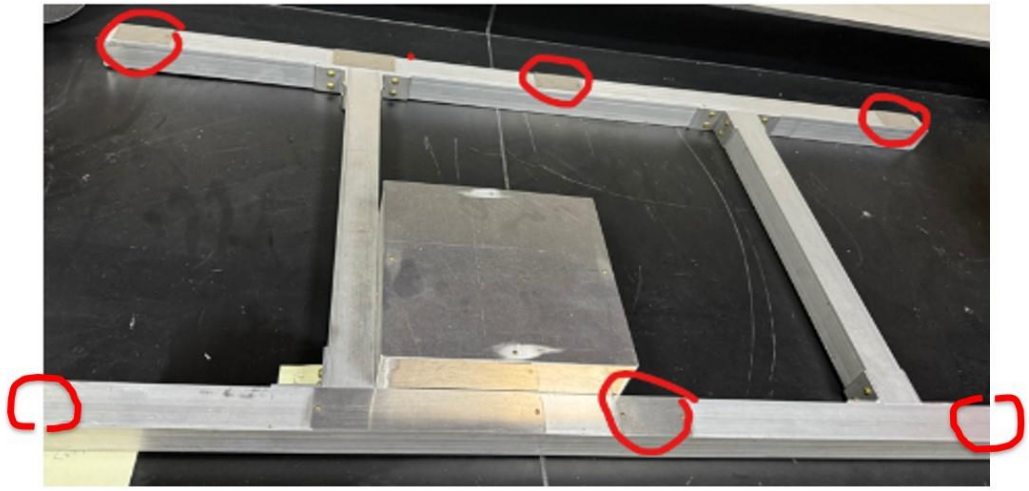


Figure 11 Magnetic Field Array for the HMC5883L TMM



Figure 12 The PCB HAT

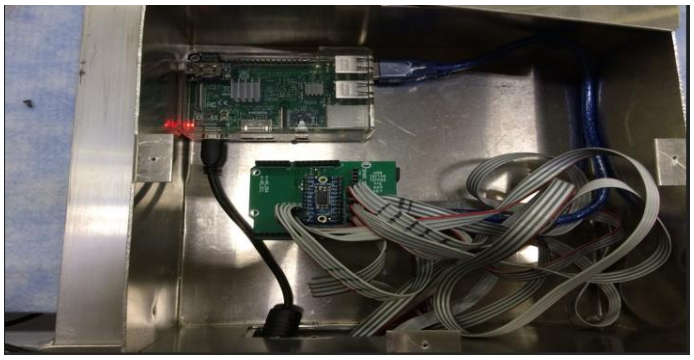


Figure 13 Arduino Uno with HAT



Figure 14 Placement of the Array on GP-SANS

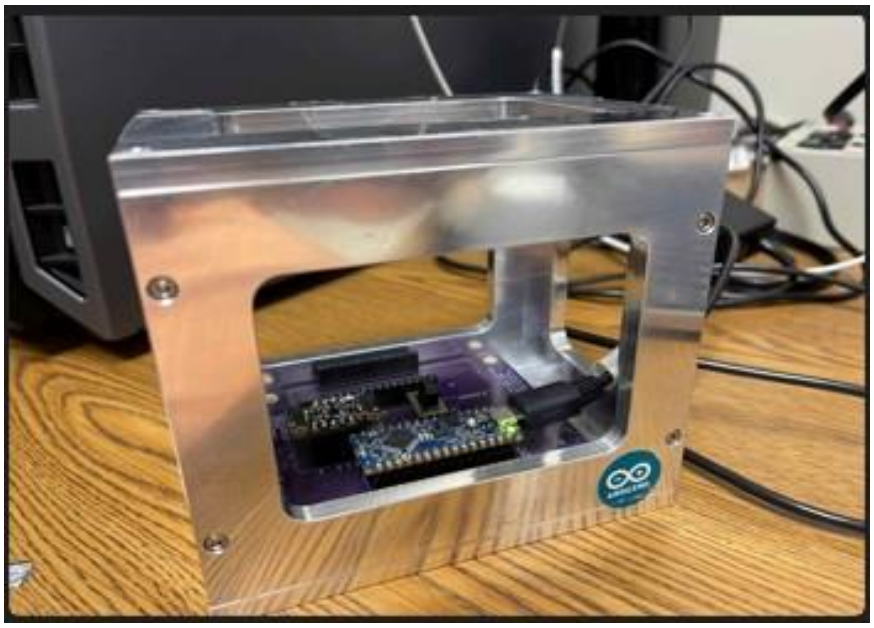


Figure 15 Aluminum Cube For Calibration

Table 3 Average for each of the MX, MY, and MZ. in µT

MX	MY	MZ
21.58 μT	11.81 μT	28.39 μT

LIS3MDL Data Collection

The LIS3MDL collects the data from the registers which is explained in the STM Datasheet pg. 18/32 and pg. 19/32. The data are collected through a serial interface I2C. You can see the data through the Arduino IDE using the screen feature within the IDE. The way to save the data to a file you need to access the serial device through the terminal software. The details of the magnetic characteristics are on STM Datasheet pg. 4/32. For the calibration and test I used the ±4 Gauss range which has the least significant bit (LSB) is 6842 per Gauss at that range. To calculate the LSB for the LIS3MDL sensor, you need to consider the sensor's resolution and its measurement range. This is determined when programming the microcontroller and setting up the sensor. The LIS3MDL can measure B-field in the ranges of ±4, ±8, ±12, and±16. Following the data sheet and adjusting the code that is provided by the company you can choose the settings to match the LIS3MDL specifications. This will enable the sensor to perform the correct readings based on the full-scale range of the chip. You then must decide whether to send the data to a text file or to the screen. The data shown in [Table 3] shows the raw data converted to μT. These data are from the calibrated data set. The LSB/Gauss is used each time to read the value stored in the register based on the settings of the range that you set up with the code and then installed in the microcontroller. Let's take an example to better understand on how to use the LSB/Gauss, LSB/Gauss following the datasheet equation page 4/32 if we get a raw reading of 1073 from the register, we can covert this to gauss by using the value collected/bits per Gauss using the $\pm$ 4 Gauss. Then this will give us a value in Gauss that then can be converted to micro-tesla value her using the formula $\frac{1073}{6842} = 0.1568$ Gauss. Then take the value $0.1568 * 100 = 15.68\ \mu T$. This provides the desired result from the signal that is collected from the AMR Magnetometer. This displays the result of the ± μT. I can take the difference of the plus and minus values to get the measured magnetic field strength. This is done before converting to μT using the raw data you take the average of each of the components measured. Each sensor will get a value of plus or minus based on the 180 flipping of the sensor with respect to the coordinate system of the lab. Use the difference of the two (MX - (MX2))/2 here MX stands for sensor x in the direction of the x coordinate system then flipped 180 to read the negative value of the x field. This can be converted to micro teslas by dividing the amount above by the 6842 per gauss at the range of $\pm$ 4 Gauss times 100 which gives you the field in μT. This was shown in the example. You are required to use the 6842 number when converting the bits to a gauss value. The offset is not needed when you are able to flip the chip. When flipping is not able to be done then you must use the offset of the chip and the gain of the chip. You will need to do this for each sensor using the cube, the 3d orthogonal wedge with respect to the coordinate system x, y, and z. This will give you the total field being measured by the magnetometer labeling the MX, MY and MZ for the measured values. Again, this will only be valid for flipping.

Offsets for Calibration

To calculate the offsets for LIS3MDL or other AMR magnetometers you must perform the procedure of rotating it 180 degrees orthogonal to the reference coordinate system setup for the lab reference frame. This is needed to calculate the average of the data. Using the following formula (positive average measured data + negative measured data)/2 will give you the offset of the magnetometer. For better statistics you should take at least 5000 measurements for each magnetometer sensor in the orthogonal coordinate system of the lab reference frame following the values here. Sensor (MX) for lab frame (X, Y, and Z). MY for X, Y, and Z then for MZ for X, Y, and Z. The procedure needs to be performed for each of the chips that are going to be used. Taking this data will give you the chips offset with its error. Per the manufacturer, you can get the hard and soft iron offset using a code that was created but this will only work in an isolated and well-defined field. This can only be created using the Helmholtz coils and then shielding them so there is no interaction with the outside field. for our test, the best solution is to use the Bartington which is a well-calibrated system used to define the field. With that system we can compare it to the collected data measured with the LIS3MDL. The same rotations for the calibration of the LIS3MDL were performed. The MX, MY, and MZ in respect to the lab frame X, Y, and Z. This was to find the standard deviation of the chip and try and find the offset from the zero. The details for the analysis are as follows,

- Measure the magnitude of the magnetic field $M_i = \frac{B_{i1} - B_{i2}}{2}$ with 3 reference fields B_i the linearity of the device can be checked. If flipping the sensor is possible in measurement, offset measurement is not needed.
- Offset value for the sensor $S_i = \frac{B_{i1} + B_{i2}}{2}$ with its error. If flipping is not possible then the offset should be stable.
- Analyze the data which includes a comparison of the chip with the Spectromag-6, a reproducibility check for the multiple measurements, with the same chip, and a comparison of different chips between themselves.
- All measurements are to be analyzed with a Python code developed that can be used for both the chip and the Bartington data.

The following shows the Stability of Offset measurement for 3 values of reference field Bi for the Chip and Spectromag-6 (Bartington) reference magnetometer. The offset comparison from the offset and the between the Spectromag-6 with the magnetometer LIS3MDL.

Spectromag-6: The average for 3 sensors offset for 3 fields Bi: $-0.12\mu T \pm 0.86\mu T$

LIS3MDL Chip 1: Average for the 3 sensors offset for 3 field Bi: −16.4μT ± 0.55μT
Offset of ±100μT is allowable in the LIS3MDL specification.
The results of this calibration and study show the stability and reproducibility of the chips demonstrated that individually calibrated 3D- magnetometers LIS3MDL in an array can be used with measurement accuracy ≤ 1μT Multiple samples of ≈ 5000 3D field measurements can be quickly measured in place with the frequency of 10 to 80 Hz in a few minutes. In the case of a large perturbation in measurement seen as a large RMS, another measurment can quickly be taken to maintain accuracy. Each of the magnetometer chips must be calibrated providing the parameters of the sensor's gain (with accuracy ≈ 1% and offset with an accuracy ≈ 0.5%. [Figure 17] shows the gain factor relative to the Spectromag-6 and its relation to time. The [Figure 18] Shows the linearity and gives the constant of calibration. Finally, [Figure 19] Shows the offset stability versus time.

Prototype of an 8 Channel Array

I designed a prototype board that is made up of 8 LIS3MDL magnetometers. I can also install the original array of 6 LIS3MDL within the original aluminum case that I designed for the HMC5883L magnetometer array. The original array is limited as it can only use 6 magnetometers while the new array is up to 8. For the procedure for installing multiple magnetometers, I came up with a labeling scheme. Do the following, use a permanent marker, and label them with a number 1 through 128 on the bottom of the LIS3MDL. This can be improved if you design a PCB board by labeling each one with the number when the PCB is printed. However, labeling the unit is important since you must know which one of the identical boards you are using when calibrating the magnetometers. This will ensure that you do not repeat the calibration on the same board when you need to do it to all of them. Creating a logbook is an essential part of the whole calibration and testing of the LIS3MDL. This logbook may be digital or in traditional form. It must be updated when anything is done. This ensures that you have a record of the procedure for later use. After following the calibration steps of magnetometers and using the fluxgate calibration as the baseline we can then install the magnetometers in the array. To get the data from each of the serial magnetometers is to a multiplexer from SparkFun [2]. The device uses the TCA9548A chip which has the qwiic. This allows for more rapid prototyping. Before this connection was created, I had to use the TCA9548A from Adafruit [14] which required a PCB or a breadboard for connecting each of the devices using pins. The connection is a vast improvement for quick prototyping. Rather than having to solder the PCB board I need only connect them through the serial wires with the compatible 4-pin JST connection. The Multiplexer enables the data collection from identical devices. This device works is like a router for a computer network. It will assign a unique address to each of the identical IDs of the serial sensors. The multiplexer (MUX) can use up to 8 sensors per board. The data is collected from each of the sensors and

then sent to a file on the main computer. I picked this board because it has the option to change the address of the MUX to connect up to 8 multiplexers with each one holding 8 sensors. The MUX can be daisy changed to connect 8 of the TCA9548A. This allows for up to 64 channels per setup. This means that one microcontroller and one Raspberry PI per 64 Channels. I would then need to connect the boards to another microcontroller for the last set of 64 channels. This would give me the possible setup of 128 LIS3MDL magnetometers. This is crucial for the experiment looking for neutron oscillation. Which requires precise control of the magnetic field over the entire GP-SANS instrument. The [Figure 20] shows the multiplexer that was used for the array with the new Qwiic connections, and 8 sensors connected to it. I used Python to interact with the microcontroller serial port to sort the data that was read from each sensor. This code creates a separate text file for each sensor and labels the file with the sensor that is being read from. Each of the sensors are calibrated per the calibration procedure. The data in [Figure 21] show the collection of the data from 8 of the LIS3MDL magnetometers. I collected this data for several hours and the graph shows the stability over the period for each of the chips. I set the printout with a delay of a second per readout. I left this running overnight and connected to the laptop on-site at UTK to see if the data would have any noticeable changes and if there were any noticeable errors. I collected the magnetic field data every second for several hours. The start of the collection was Tuesday, March 26th to Wednesday the 27th. The data shows 59292 data points. The mean for the total field is 40.07μT. The test was run with 8 of the LIS3MDL magnetometers. The data was collected through a Python script. I ran the serial interface collecting the data from each of the chips, and then separated the data from each of the chips. This is sent to a file that can be analyzed at a later time. I labeled each of the text files based on the chip being used. This is a crucial test to see if the LIS3MDL can be set up and used as an array for measurements. Using what was done for the HMC5883L and applying this to the new hardware I proved that the unit could measure using 8 magnetometers.

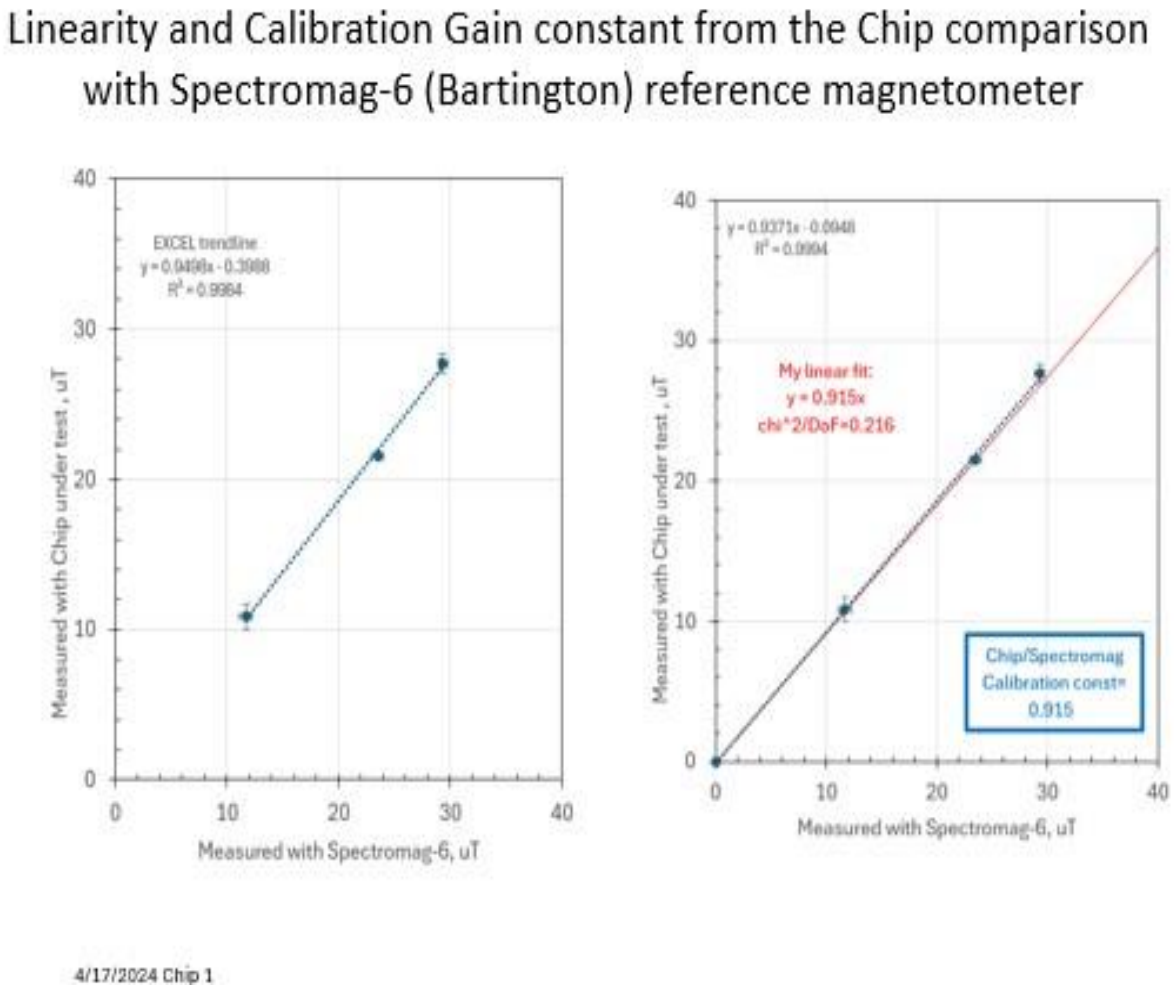


Figure 16 Linearity and Calibration Gain

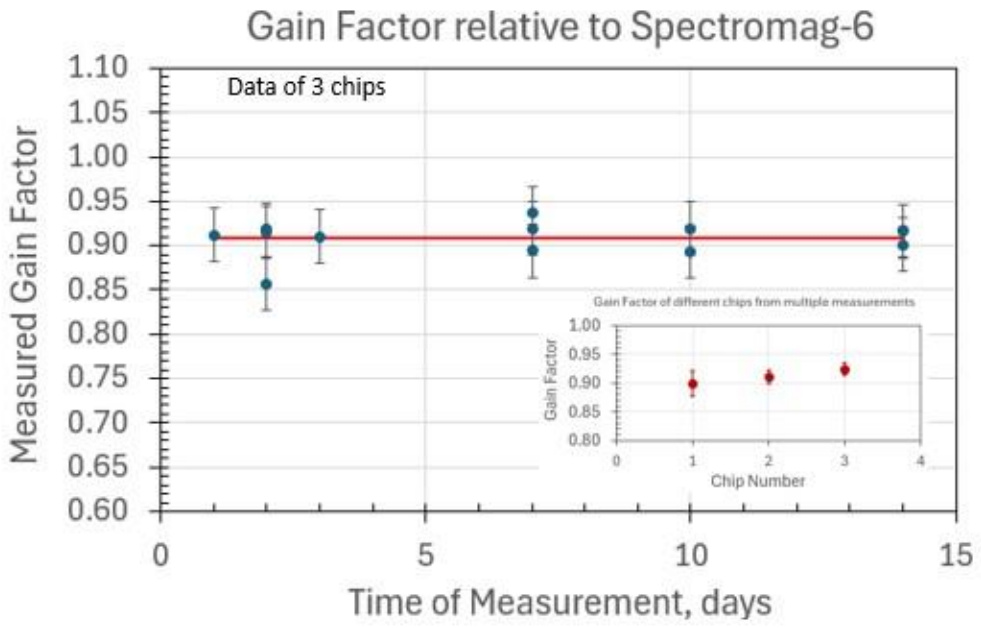


Figure 17 Gain Factor Relative to Spectromag-6

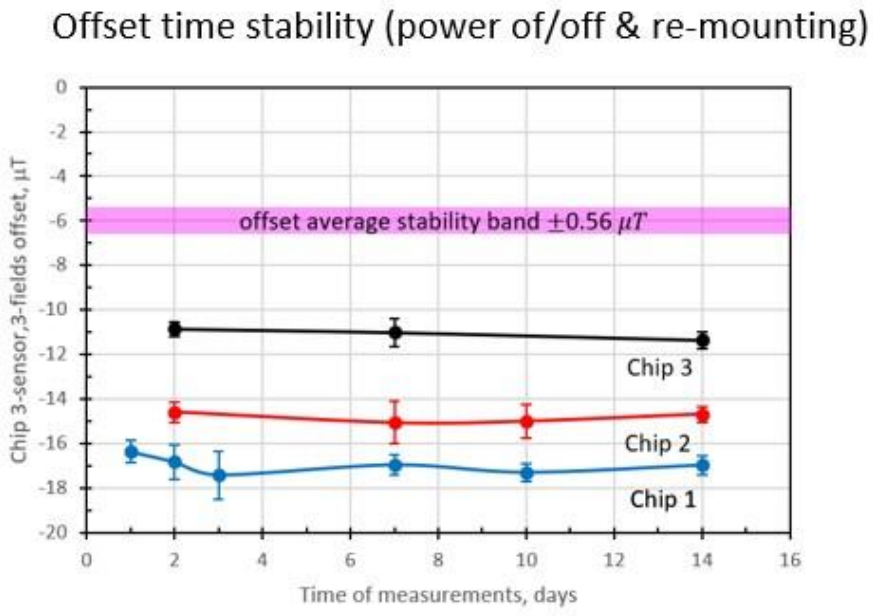


Figure 18 Offset time stability

Chapter Four

Results and Conclusion

Results:

The result of the prototype is a proof of concept for the new LIS3MDL magnetometer. This sets the baseline for the magnetometer array replacement and upgrade from the 6 channels to the 128 channels. The most important part of the design of the magnetometer array was to come up with a valid calibration technique and this was accomplished. The second goal of the design was to use more than 6 magnetometers. Before the test, the only confirmed use was the 6- HMC5883L that were used to find the local field strength at HFIR. One objective was to find a replacement for the HMC5883L chip and to expand to more than 6 channels using calibrated magnetometers. [Figure 21] shows how the readout of each of the magnetometers is collected and labeled with the multiplexer. This means that every second the 1-8 LIS3MDL magnetic field data is printed. In order to separate this data, you need a script that will scrape the data and separate each of the chips. The current process prepares the data and then uses a Python script to extract the data. [Figure 4.5] the multiplexer from SparkFun [2] connecting each of the LIS3MDL Adafruit [1] PCB using the qwiic serial cables of 100 mm length. For this setup, I used the full range of the Magnetometer ± 16 Gauss. I collected the data for a total count of 59293 data points. Each point was collected every second for the duration. In [Figure 4.6] the microcontroller H7 was used because it has the integrated connection for the qwicc serial connection. This microcontroller powers the 8-magnetometers and the MUX through the USB C to USB cable which is connected to the USB port on the laptop.

Conclusion:

For the main objective of finding a replacement for the HMC5883L magnetometer, I was successful. The LIS3MDL [1987, STMicroelectronics] is a good replacement candidate for the HMC5883L [1906, Honeywell] chip. This chip has additional sensitivity since it is a 16-bit versus the original 12-bit. For the future experiment looking for neutron oscillation with the magnetic field range of 1 to 2 Gauss, the magnetometer will be able to provide an accurate readout of the local 3D magnetic field. This LIS3MDL [1987, STMicroelectronics] magnetometer will be used at the instrument of the GP-SANS with the full 128-channel setup over the total volume of the GP-SANS instrument. This off-the-shelf hardware is considerably less expensive than the industrial magnetometer. Even with the increase in the cost per chip, this is a substantial savings.

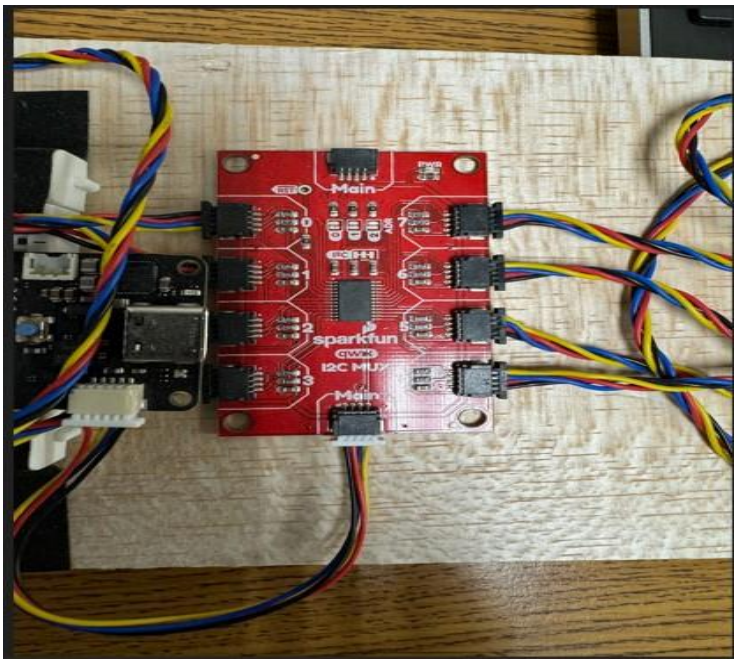


Figure 19 MUX For LIS3MDL

```
Magnetometer 0 - X: 21.73 Y: -3.09 Z: -24.71
Magnetometer 1 - X: 22.29 Y: -13.55 Z: -30.28
Magnetometer 2 - X: 22.75 Y: -15.75 Z: -32.73
Magnetometer 3 - X: 21.31 Y: -9.60 Z: -30.88
Magnetometer 4 - X: 28.20 Y: -12.92 Z: -28.39
Magnetometer 5 - X: 21.71 Y: -13.84 Z: -28.56
Magnetometer 6 - X: 21.80 Y: -11.67 Z: -28.89
Magnetometer 7 - X: 24.67 Y: -11.05 Z: -31.05
Magnetometer Data:
```

Figure 20 Data from the python Monitor in µT

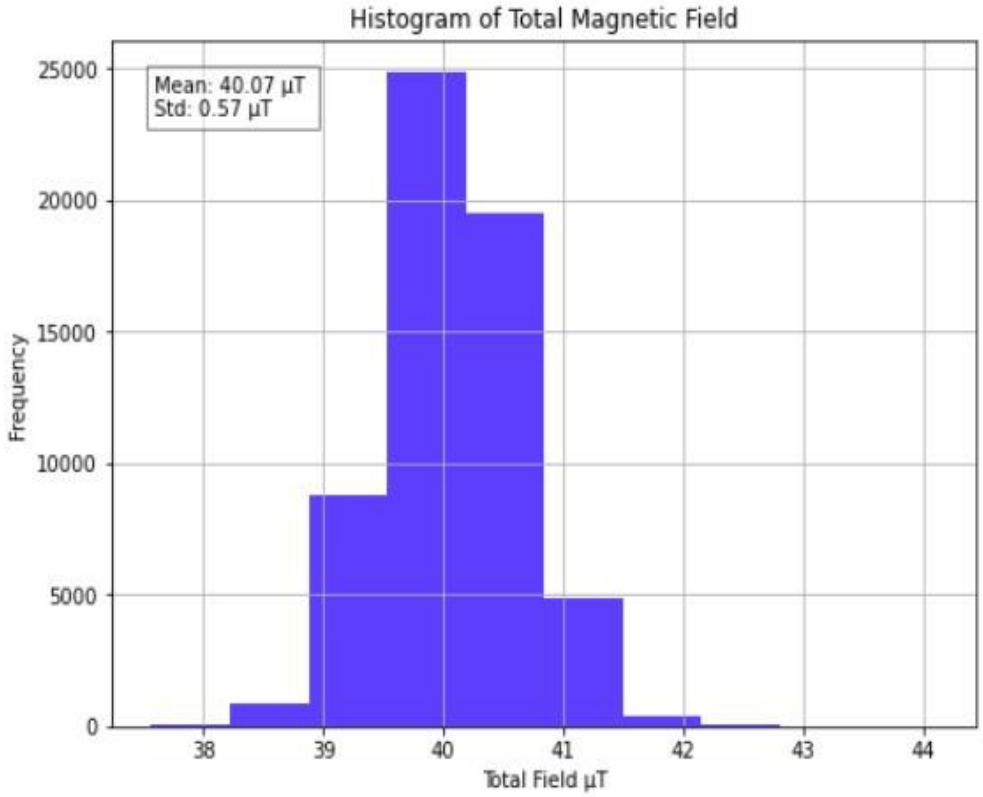


Figure 21 Data Collected over Several Hours

Table 4 of data collected over several hours From Magnetometer sensor 1

MX	MY	MZ
22.67	-12.97	-29.79
22.62	-12.25	-30.39
22.33	-12.5	-31.08
22.46	-12.66	-30.15
22.64	-12.34	-31.15
22.08	-12.66	-30.7
22.86	-12.14	-31.17

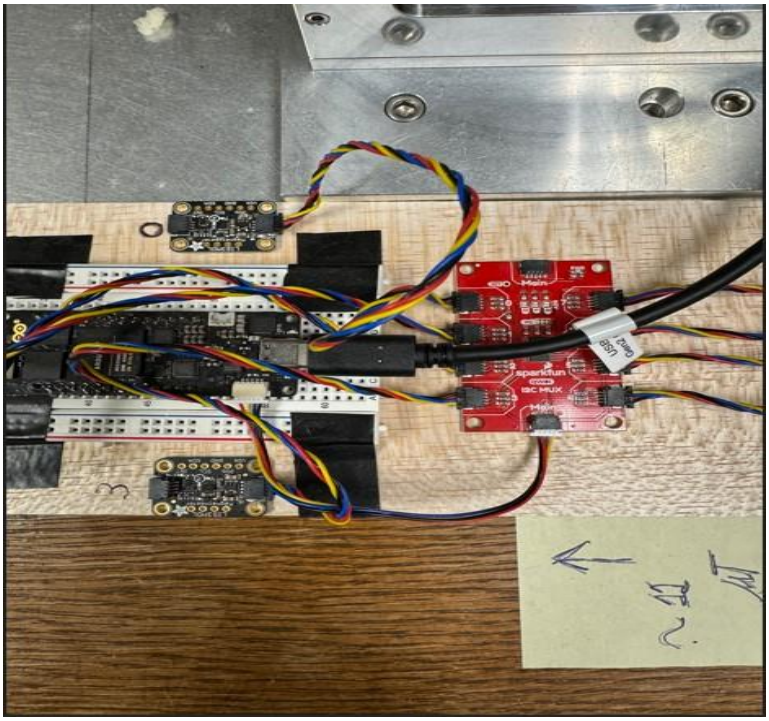


Figure 22 the multiplexer from SparkFun connecting each of the LIS3MDL

Limitation:

The calibration procedure for each of the magnetometer is time consuming. To overcome the length of time, I will need to have several wooden calibration tables and several aluminum cubes built to run the calibration on more than just one chip at a time.

Another limitation is the length of the serial cable. This is limited to 200 mm and will need to extend to the full volume of 16-meters of the GP-SANS instrument in the cold guide hall. To remove the limitation of the length you have to purchase and install the PCA9615 differential bus extender. This removes the limitation by installing one in-between each of the MUX and connecting them to each other using an RJ45 cable. The Cat5 cable set the new length limitation to 30 meters.

The Magnetometer needs to be tested in situ in the experimental hall to get an accurate behavior before being installed onsite. Data collection is performed with code and scripts. These scripts are run through the command line and then the data is tested after they are collected. Ideally the process needs to be put together and set up like the Bartington Spectromag 6 [9] DAQ software. The software DAQ needs to have a friendly interface that will run the scripts and code in a more efficient manner. A full test of the total 128 magnetometers also has not been performed. The principle using the current setup can be extended to the full 128 channel magnetometer array using the LIS3MDL sensors.

The Future of the Magnetometer Array

The experiment that the magnetometer will be used with is the nTMM. This will be installed inside the GP-SANS instrument. Unlike the original design of the array to sit on top of the instrument this will be installed into the vacuum chamber. The future of the magnetometer array is to create rings that will hold 4 magnetometers each ring for the total volume of the instrument. It will have a diameter of 20 cm with a circumference of 62.83 cm. Each of the chips will be connected using the wires that are designed with the Qwiic connection. It needs to have a well-designed DAQ system to collect the data with an interface that would make it possible for easy collection of the data and possible integration into the local DAQ. The integration of some type of GPS system is needed for an accurate position of the magnetometers. The GPS will ensure which part of the volume is being measured. In addition to the accurate measured field in real time over the volume using the lis3mdl for collecting the data is to extend it use the microcontroller with an integrated Bluetooth adapter. Bluetooth is several advantages Arduino H7 has as an integrated feature. It can then send the data to the phone or computer without the need to have access to the local

network. Using a single version of this unit as a general purpose magnetometer for local experiments that need the magnetic field measured with accuracy and a low cost solution.

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Appendix

1. **Arduino LIS3MDL Triple-axis Magnetometer**

    - Website Source: Adafruit Industries
    - URL: https://learn.adafruit.com/lis3mdl-triple-axis-magnetometer
    - Date Accessed: April 4, 2024
    - Description: Setup of the LIS3MDL with example code that can be used to get the magnetometer up and working.

2. **Qwiic**

    - Website Source: SparkFun
    - URL: https://www.sparkfun.com/qwiic
    - Date Accessed: April 4, 2024
    - Description: This tutorial explains how the qwiic is designed and how it can connect the sensors to the microcontroller boards and each other.

3. **Qwiic Mux TCA9548A**

    - Website Source: SparkFun
    - URL: https://www.sparkfun.com/products/16784

Date Accessed: [April 4, 2024]

- Description: This explains how to connect the Mux Breakout board to the sensors and the microcontroller.

4. **Arduino Nano Every**

- Website Source: Arduino
- URL: https://docs.arduino.cc/hardware/nano-every/
- Date Accessed: [April 4, 2024]
- Description: This explains in detail the Nano Every. Gives access to the datasheet as well.

5. **Arduino Nano Every**

- Website Source: Arduino
- URL: https://docs.arduino.cc/hardware/nano-every/
- Date Accessed: [April 4, 2024]
- Description: This explains in detail the Nano Every. Gives access to the datasheet as well.

6. **Portenta H7**

- Website Source: Arduino
- URL: https://docs.arduino.cc/hardware/portenta-h7/
- Date Accessed: [April 4, 2024]
- Description: This explains in detail the Portenta H7. Gives access to the datasheet as well. This will be crucial for the setup of the unit for the sensors.

7. **Arduino IDE**

Website Source: Arduino

- URL: https://www.arduino.cc/en/software
- Date Accessed: [April 4, 2024]
- Description: This is the website to gain access to the IDE for the software to interact with the Arduino microcontrollers.

8. **Raspberry Pi**

- Website Source: Raspberry Pi 3 Model B+
- URL: https://www.raspberrypi.com/products/raspberry-pi-3-model-b-plus
- Date Accessed: [April 4, 2024]
- Description: This is the data on the generation used for the magnetometer array using the HMC5883L sensors. Please note that this has since 2024 been replaced with version 5.

9. **ANACONDA**

- Website Source: Raspberry Pi 3 Model B+
- URL: https://www.anaconda.com/
- Date Accessed: [April 4, 2024]
- Description: This is a collection of tools for programming and scientific analysis. This is ideal and should be installed on the main server or computer that will be used to analyze the data. Make sure to sign in each time.

10. **ChatGPT**

- Website Source: ChatGPT
- URL: https://chat.openai.com/gpts

- Date Accessed: [April 4, 2024]
  Description: Used for help on coding. A good way to get a general idea of the topics.

Vita

Shaun Vavra is a physicist specializing in research conducted at the High Flux Isotope Reactor (HFIR) and the Spallation Neutron Source (SNS). In addition to his research, he serves as a Graduate Teaching Assistant (GTA), where he is dedicated to educating and mentoring students. Shaun also leads a team of GTAs, ensuring that students receive an accurate and reliable experience in the lab. He received the Student Faculty Research Award and utilized it to create a magnetometer array, which will be used in future experiments at HFIR's Neutron Transition Magnetic Moment (NTMM) experiment. His work bridges advanced scientific research and practical teaching, contributing to both the academic growth of students and the advancement of physics research.