Deployment of Magnetometers to Monitor Stray Magnetic Fields Near the PROSPECT Detector

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Abstract. PROSPECT is a reactor antineutrino experiment located in the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. PROSPECT's primary goals are to probe short-baseline oscillations and perform a precise measurement of the U-235 reactor antineutrino spectrum. The detector consists of 154 segmented cells filled with ^{6}Li-doped liquid scintillator. Each segment holds two PMTs, one on each end of the cell. The PMTs can be exposed to stray magnetic fields from superconducting magnets operating on the experiment hall one floor below the detector. The monitoring of the magnetic fields is an important part of our background characterization as the magnetic fields can directly influence the energy measurement. This study presents the characterization and monitoring of stray magnetic fields using triple axis magnetometers near the detector.

Introduction

The Precision Reactor Oscillation and Spectrum Experiment, PROSPECT, is designed to address some of the neutrino anomalies [1] by searching for antineutrino oscillations and precisely measuring the antineutrino spectrum. The PROSPECT detector is segmented into 154 acrylic cells of 1.176 m x 0.145 m x 0.145 m, each one containing two PMTs for a double-ended readout. In total there are 308 PMTs; 240 Hamamatsu R6594 ø127mm and 68 ET 9372B ø130mm [2]. PROSPECT is operating ~7m away from the core of the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). HFIR has a very compact core (ø40cm) making it a point-like source of neutrinos, and operates with ~93% enriched ^{235}U. HFIR operates with an approximate duty cycle of 42%, with ~24 days of reactor on and followed by ~24-40 days of reactor off maintenance period, which thereby this allows us to well characterize the background well [3].

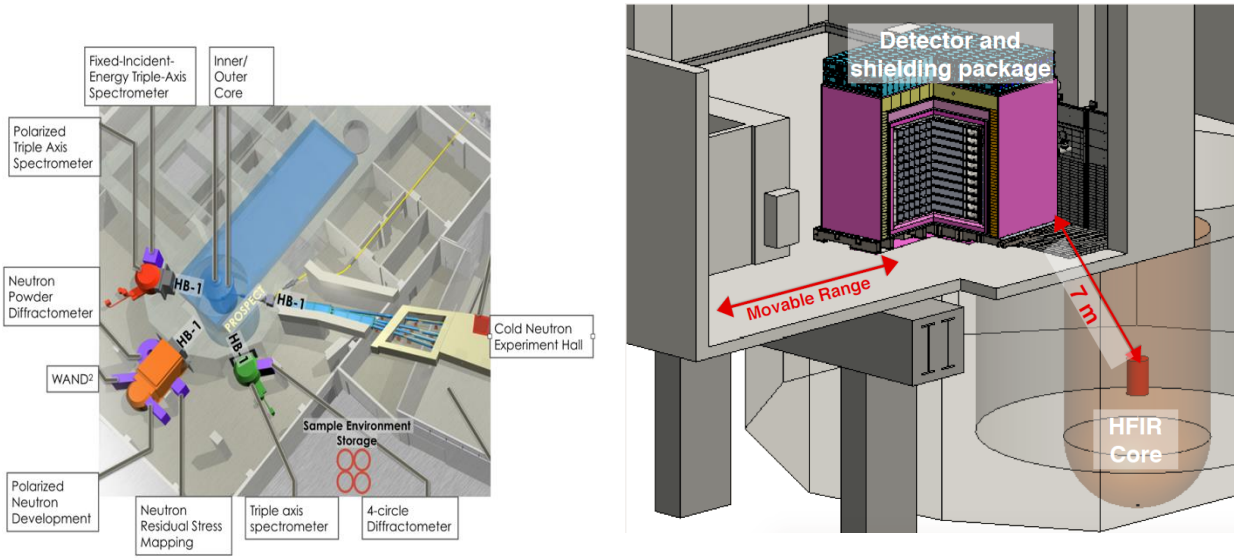
Operating on the surface level of a research reactor facility, the background environment must be carefully considered to ensure a precise measurement from the detector. Work has been done at ORNL to establish an understanding of the cosmic muon, gamma and neutron backgrounds [4]. The main purpose of HFIR is to provide a high-flux source of neutrons to the various neutron scattering instruments located one floor below PROSPECT. HFIR provides several different magnets for the neutron scattering community. Magnets ranging from field strengths of 5 to 11 Teslas can be used on various beam-lines throughout a run period. Figure 1 shows the approximate location of the PROSPECT detector one floor above the experiment hall, in yellow, as well as the location and various instruments used in the experiment hall. Beam-line 3 (HB-3) is almost directly below the detector, and is able to use magnetic field environments in the 5 to 8 Tesla range. HFIR provides 5 and 6 T vertical symmetric field magnets, 8 and 11 T vertical asymmetric field cryomagnets, and an 11 T horizontal field magnet. Improvements to the magnetic sample environments have been discussed by the neutron scattering community. It is expected that work will be done in the future to incorporate environments in the 25-30 T range and possibly a dedicated facility with magnets up to 60 T [5].

To help reduce the background magnetic field effects, PROSPECT uses a Hitachi FINEMET magnetic shield that is fitted around each PMT. See figure 2. The Hitachi FINEMET shield is an amorphous metal composed of Nb, B, Fe, and Cu. Preliminary studies on the effectiveness of the magnetic shielding have been conducted and have shown that the shielding increases the PMT's resistance to magnetic flux, as shown in figure 3(b). The gain of the Hamamatsu ø130mm PMT dropped to nearly zero in the 2.5 to 3 Gauss range even with the shielding applied.

In 2016, the background magnetic fields were mapped at HFIR before the PROSPECT detector was in place. The results showed magnetic field magnitudes up to 2 Gauss during the operation of the high strength magnetic environments in the experiment hall. Figure 3(b) shows the gain variation of the PMT with respect to the magnetic flux density in Gauss. With a 2-Gauss field applied, the relative gain output of the PMT studied dropped ~80% with magnetic shielding [6]. Similar studies have been conducted in other experiments such as the STEREO neutrino experiment [7], where their entire detector was shielded from the magnetic background of high magnetic field experiments conducted nearby. PMTs were shielded in The DAMPE dark matter experiment [8] and the GRIS and PING-M space experiments [9] to protect the PMTs during operation in space. A fundamental symmetries experiment [10] requires a well-monitored and controlled magnetic environment. A study for industry shows the direct effect of a magnetic field on Hamamatsu PMTs [11].

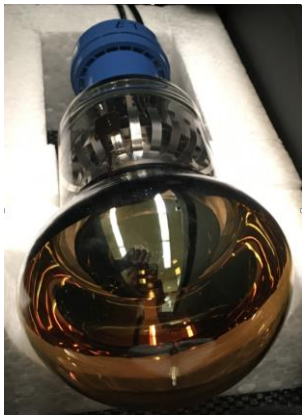
A PMT takes in an incoming photon, and through the photoelectric effect it produces an electron that is sent to a dynode configuration for amplification of 10^6. When the photoelectron travels from the photocathode to the electron dynode configuration, a slight magnetic field could distort its trajectory. With fewer electrons hitting the dynode configuration, the less of the signal is amplified, resulting in a smaller gain than what would be expected. This effect has been studied by Hamamatsu, where their reported plot of the gain versus magnetic flux density is shown in figure 3(a). Hamamatsu uses a head-on PMT about 10 times smaller than the PMTs used in PROSPECT. Hamamatsu reports the gain of their ø13mm head-on PMT dropping to nearly zero with a 20-Gauss (2 mT) field applied [12].

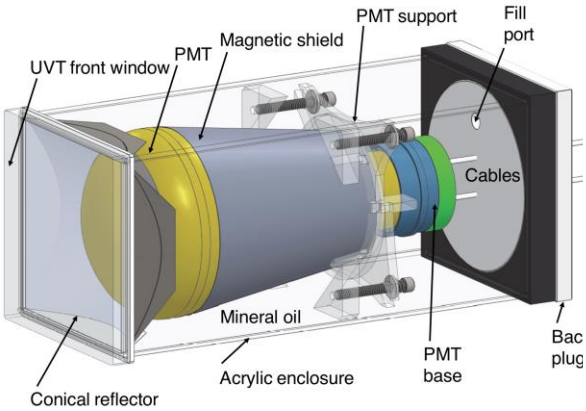
With such large magnets operating at HFIR, it is imperative to continuously monitor any stray magnetic fields that may affect PROSPECT.



(a) (b)

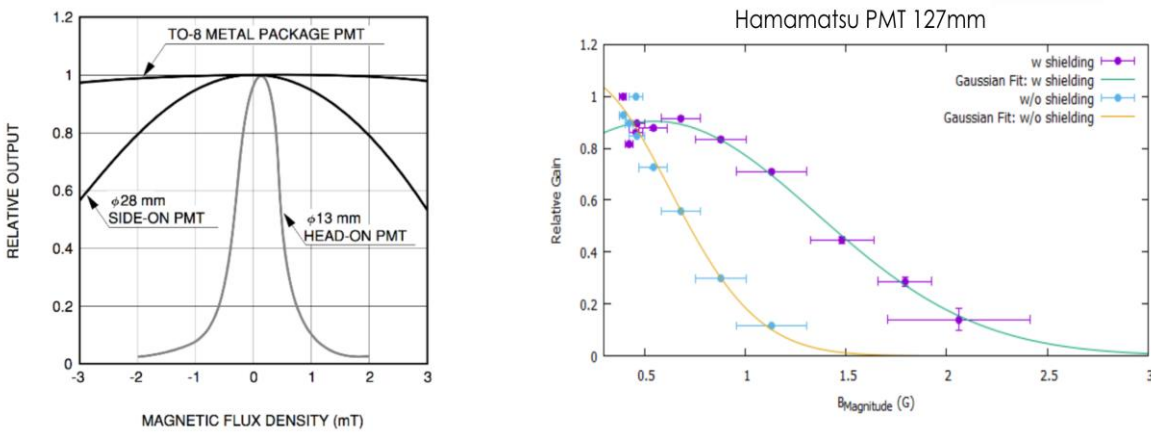
Figure 1: Map of experiment hall inside HFIR with PROSPECT's approximate location one floor above in yellow.





(a) (b)

Figure 2: (a) ET 9372B PMT **(b)** PMT cell setup inside The PROSPECT Detector



(a) (b)

FIGURE 3: (a) Relative output of Hamamatsu ø13mm head-on PMT without magnetic shielding [12]. **(b)** Relative gain of Hamamatsu ø127 mm head-on PMT with and without magnetic shielding surrounding the photocathode. The magnetic flux density was varied to demonstrate gain drop with increasing magnetic flux [6].

Magnetic Field Monitoring Setup

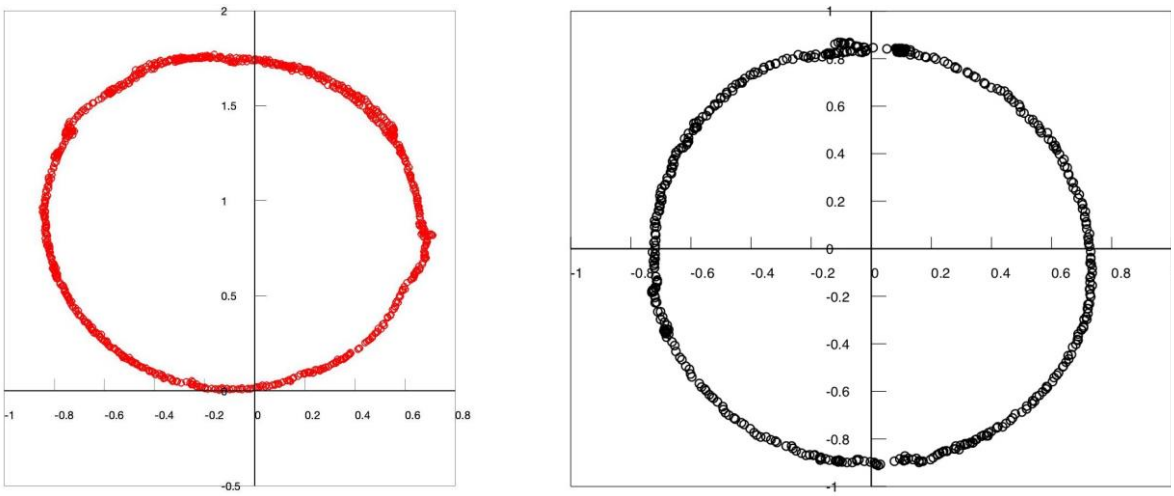
A simple to use and cost effective monitoring system has been developed using 0.9 cm x 0.8 cm Adafruit LSM303DLHC Triple Axis Magnetometers, an Adafruit TCA9548A I2C Multiplexer, Sparkfun I2C Bus Extender s (PCA9615), RJ45 cables and a Raspberry Pi 3 Model B V. 1.2 (RPi). The Adafruit LSM303DLHC Triple Axis Magnetometer uses the Hall Effect to measure small fields within ± 8.1 Gauss. It has an I2C serial interface making it easy to connect to an RPi. The I2C bus extenders allow the I2C signal to travel to distances up to 100 ft via RJ45 cable. The magnetometers are all wired to a RPi and mounted inside 3D printed boxes with brass screws, shown in figure 5(a), to keep the sensors in place and aligned during operation and calibration. The output voltage of the Adafruit Hall sensors is read by the RPi as Least Significant Bits (LSB) and that is converted to Gauss by a constant given in the LSM303 data sheet. The sensors can be set to read various ranges from ± 3.1 to ± 8.1 Gauss by changing the LSB/Gauss conversion factor. For this monitoring setup, we are concerned with magnetic fields in the 1 to 3 Gauss range, so the sensors are programmed to read within ± 4 Gauss. The magnetic resolution of the LSM303 is reported as 2 mGauss.

The RPi reads the output of the magnetometers through a Python script that is then averaged over 1 minute intervals and logged locally on the RPi. The data is plotted and monitored in the PROSPECT slow control system that is accessible by everyone in the collaboration. Alerts will be sent if a magnetometer breaches a defined range.

Each one of the sensors was calibrated with a Lakeshore Single Axis Hall Probe (Model #: HMMT-6J18-VF) in their monitoring location on the detector. The Lakeshore Hall Probe is used as the accepted value after it is zeroed inside a Lakeshore Zero Gauss Chamber (Model #: 4060) as shown in figure 4(b). Each direction is measured on both the Lakeshore and Adafruit sensors and the difference between the two is set in the Adafruit readout code as an offset on each axes value to match the Lakeshore values. Another offset from origin (0,0) is applied. Each magnetometer is rotated as much as possible to record a maximum positive and negative value for each measurement axis. If the maximum and minimum values are not equally distributed around the origin, figure 5(a), the program records the shift needed to center the axis measurements, figure 5(b) .

(a) (b)

Figure 4: (a) Photo of the lid with the magnetometer attached. (b) Lakeshore probe on left being inserted into Lakeshore Zero Gauss Chamber for calibration



(a) (b)

Figure 5: Plots showing the *x*- and *y*-axis magnetic field as a sensor is rotated about the *z* axis (a) **Before calibration** (b) **After calibration.**

The placement of the magnetometer around the detector was based on the position of the first layer of PMTs located approximately 16 cm above the chassis. Each detector was centered at 14 cm, near the bottom edge of the first layer of PMTs. The steel chassis of the detector produces its own magnetic background. A rough scan was conducted using the Lakeshore probe to find a local magnetic 'hotspot' on the chassis, figure 6 shows the height dependence of the magnetic field from the 'hotspot' of 1.170 Gauss at 0.0 cm to 0.490 Gauss (Earth's magnetic field background at ORNL) at 10 cm above the chassis. At the height of the magnetometer, as shown in figure 7, the magnetic field magnitude is usually less than 0.6 Gauss.

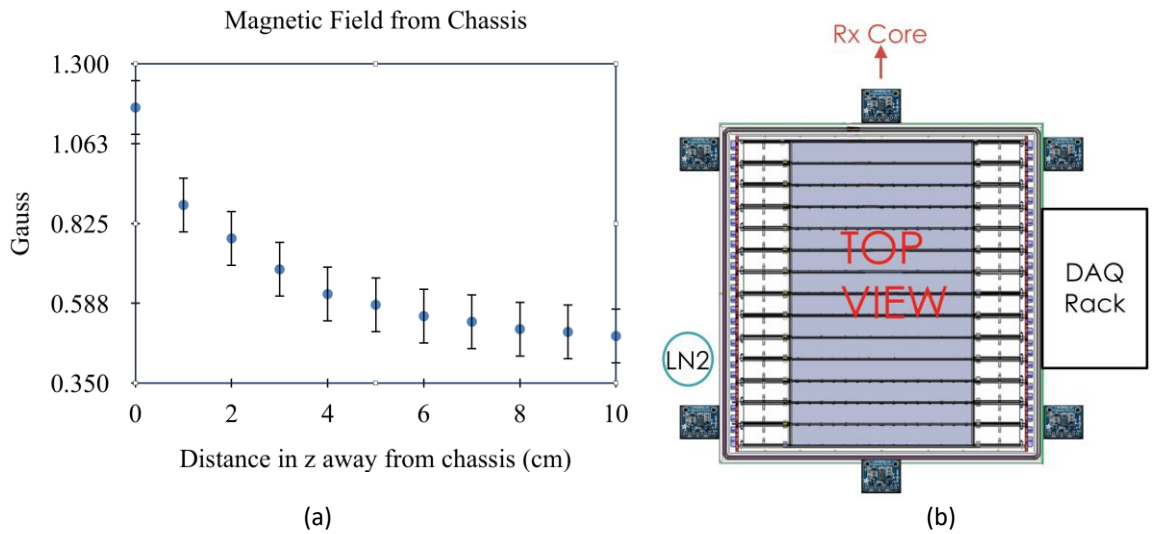


FIGURE 6: (a) Z scan of the magnetic field from magnetized chassis using the Lakeshore Single Axis Hall Probe **(b)** Position of sensors attached to the detector

Results

The Adafruit sensors have shown good stability over time and sensitivity to background events. A bench test calibration was made where each sensors was compared to the known value from the Lakeshore Hall probe. The sensors were grouped together and calibrated in the same background field to demonstrate how the sensors compare when reading the same value. The initial spread in readouts of the Adafruit sensors is about 0.5 Gauss before calibration, after they are calibrated, the sensors matched with a less than a 0.15 Gauss spread; this is presented in figure 8(a). The stability of the sensors during an overnight measurement are shown in figure 8(b), the jump at the very end corresponds to a computer being placed near the small cluster of sensors. Some of the sensors read higher jump and some read a lower jump in magnetic field, due to the *x* and *y* measurement axes being inverted between two groups of three sensors.

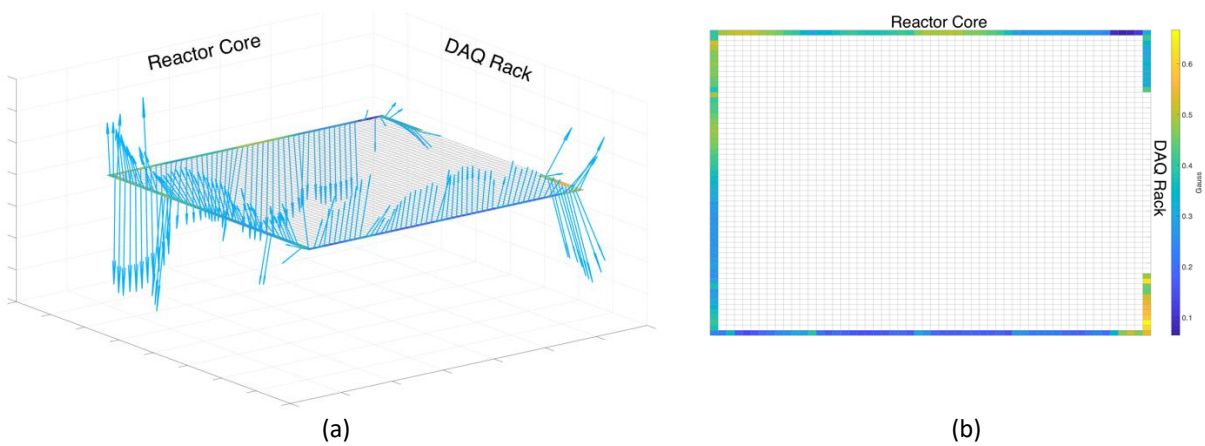
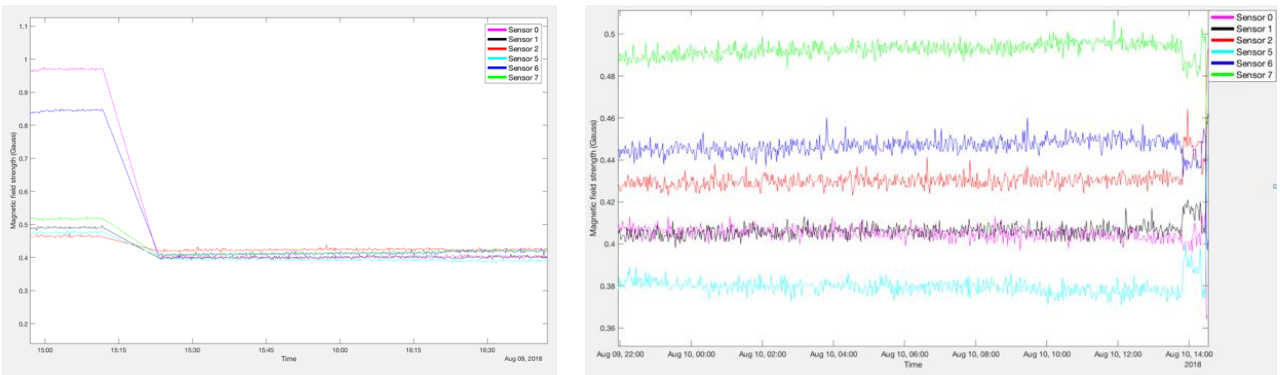


Figure 7: (a) Angled view of PROSPECT detector with magnetic field vectors plotted around the edge. **(b)** Top view of the detector with magnetic field magnitude plotted as a heat map along the edges

A triple axis hall magnetometer from Metrolab (THM1176-LF) has been used to map the field around the detector in 5-cm increments. In figure 7, the magnitude of the background measurements is plotted with both vector and magnitude. The 3D plot, figure 7(a), shows a 10x amplified magnetic background magnitude to make the direction of

the vectors more clear. Figure 7(b) shows a heat map of the magnitude of the background field. The highest background magnetic field is measured next to the data acquisition rack caused by the electronics.

Shortly after placing the sensors around the PROSPECT Detector, a test was conducted with Mag-E, the 8-T vertical field cryomagnet. This test took place over an hour and the magnet was ramped-up and down manually before beam-line operation. There is no recorded data of the exact field that was produced by this magnet during this test, however it was confirmed that the spike shown in Figure 9 on November 5 correlates to the time in which the test was conducted. The spike that was seen by this system of magnetometers exceeds 1-Gauss for one of the sensors.



(a) (b)

Figure 8: (a) Sensor output before and after calibration. **(b)** Sensor measurement of magnetic background on a bench test to show **stability.**

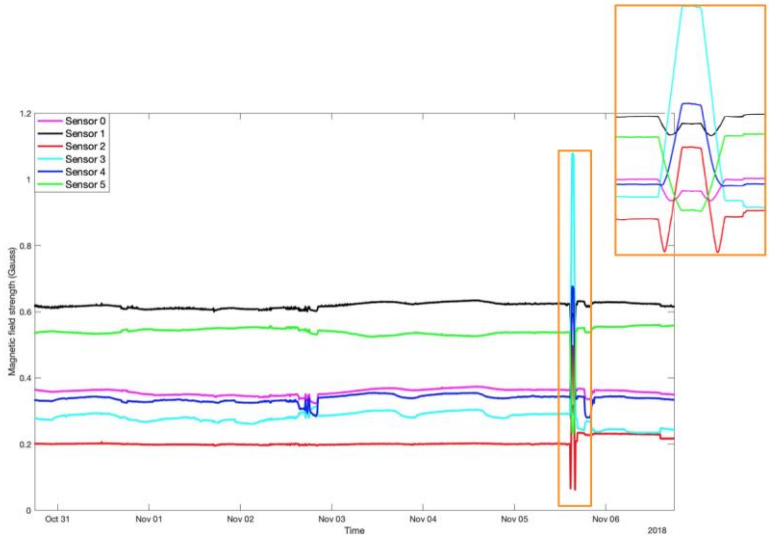


Figure 9: Sensor output over 1 week of being deployed around the detector

Conclusion

The PROSPECT detector is located at the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. This research reactor can potentially have high magnetic field backgrounds that may affect the PMTs of the detector. We are developing a compact, low-cost magnetic monitoring system using Adafruit triple axis magnetometers. As a first step, we have designed a remotely-operated monitoring system of six sensors surrounding the detector. The sensors have been calibrated and have shown stability and accuracy with less than a 0.15-Gauss spread. The location

of the sensors have been selected at the edge of the bottom of the first layer of PMTs. These locations have been surveyed with a triple-axis hall magnetometer from Metrolab, having a magnetic fields less than 0.7 Gauss.

This simple and inexpensive array allows us to monitor magnetic field conditions that could affect PROSPECT by integrating the environment's magnetic background data into the slow control system. An array like this can be easily adapted to other experimental setups that require spatial and temporal monitoring of magnetic fields. Future work will include simulation of magnetic fields inside the detector using COMSOL Multiphysics.

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