

Final Report:

Building a Simple Aurora Monitor (SAM)
Magnetometer to Measure Changes in the
Earth's Magnetic Field

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Contents

1	Abstract	3
2	Introduction	4
3	Theory	6
4	Methods	8
4.1	List of Components	8
4.2	Design Rationale	9
4.3	Overview of Construction	10
4.4	Burial	12
5	Data and Discussion	13
6	Appendices	17

1 Abstract

Every day, the Earth experiences space weather, a phenomena that impacts systems and technologies both in Earth's orbit and on Earth. When a space weather storm or geomagnetic storm affects Earth's magnetosphere, large man-made conductors such as components of the power grid and pipelines on Earth can become damaged or even destroyed. Although there are no ways to prevent a geomagnetic storm, there are ways to anticipate and prepare for them, thus being able to reduce the damage they can do. One way is through monitoring the Earth's magnetic field through a magnetometer. A magnetometer measures the changes magnitude and direction of a magnetic field. The 3-Axis Simple Aurora Monitor (SAM-III) Magnetometer System utilizes three very sensitive magnetometer sensors in order to make measurements of the Earth's magnetic field. This project seeks to build a SAM-III magnetometer for the purpose of monitoring geomagnetic storms and making approximations of a mechanism called the substorm current wedge that is believed to be responsible for causing auroral displays during a geomagnetic storm. To verify its readings, a simple circuit will be made in order to produce a current which will induce a magnetic field that can be read by the magnetometer. Calculations of the expected magnetic field will be made that will verify the system is taking correct measurements. This setup is a much smaller, yet very similar, version of how the magnetometer will read the magnetic field resulting from the substorm current wedge, except in this

case the current will be unknown. Here, measurements of the magnetic field will serve as a proxy or indication of the substorm current wedge.

2 Introduction

Both the Earth and Sun have a magnetic field. Quite frequently, the sun ejects parts of its corona into space, called a coronal mass ejection (CME), and it contains plasma. The CME possesses its own magnetic field and as it propagates through space, it expands to be many times the size of Earth. Once the CME's magnetic field interacts with the Earth's, geomagnetically induced currents (GIC's) occur on the ground around man-made conductors such as high-voltage power transmissions systems. A geo-electric field induced on the ground drives the GIC's through these conductors and can damage them. There are direct and negative societal effects of extreme space weather storms as they can cause damage to both power and pipeline (another man-made conductor) equipment. Additionally, very severe storms have the potential to cause widespread electric blackouts, accelerate corrosion of steel in oil pipelines, cause signal changes in railway tracks, as well as disrupt the information traveling through communication lines [1]. During these storms a current system called the substorm current wedge is created [2]. Implications of the substorm current wedge include the creation of magnetic pulsations which contribute to auroral displays, and differ depending on the strength of the solar wind [3]. A magnetometer is a device which

measures the magnetic fields of magnetic materials [4]. They are often used to measure the Earth's magnetic field which ranges from $60\text{ }\mu\text{T}$ (at the poles) to $30\text{ }\mu\text{T}$ (around the equator) [4]. Magnetometers help to monitor geomagnetic events through measuring changes in the Earth's magnetic field. Monitoring these events can help power engineers to anticipate and prepare for incoming geomagnetic storms.

This project seeks to build a 3-Axis Simple Aurora Monitor Magnetometer System using a kit designed by Dirk Langenbach and Karsten Hansky. The system makes use of both hardware and software components. The kit provides all components necessary to assemble the magnetometer, aside from some instruments used in the construction, and comes with a step by step construction manual as well as software and a software guide which will aid in data analysis. The construction of this system will require soldering components to various printed circuit boards (PCB's). During assembly, the components of the magnetometer will be periodically tested with an AC power adapter supply, ohmmeter, and multimeter, as detailed in the construction manual.

Once built, the magnetometer will either be used in a lab setting or buried in a PVC enclosure. The burial of the magnetometer will be further explained in Section 4.4.

Once fully assembled and tested the magnetometer data will be sent through cables to be connected to a PC, and software provided by the kit will

read and display magnetometer data. The data consists of the sensor readings in Tesla, as well as a measurement of the K-index. The K-Index is used to characterize the magnitude of geomagnetic storms [5]. It is represented by an integer number that ranges from 0 to 9, where 9 indicates the most extreme geomagnetic storm [5].

3 Theory

The basis for the 3-Axis Simple Aurora Monitor magnetometer system (SAM-III) is three fluxgate magnetometer sensors. If only one sensor is used, only changes in the magnitude of the magnetic field can be determined. With three sensors, the user can detect changes in the Earth’s magnetic field as well as a direction for these changes. Having three sensors is especially useful for mid-latitude locations, such as Newport News, because the field lines of the Earth are more curved and thus have larger x and z components than they would in high or low-latitude locations.

The magnitude of the Earth’s magnetic field, assuming that it is a dipole, is given by the equation,

$$B = \frac{m}{r^3}(1 + 3 \cos^2 \theta)^{1/2}, \quad (1)$$

where m is the dipole moment at the Earth’s center, r is the radius of the Earth, and θ is the latitude of Newport News. The magnitude can be calcu-

lated by

$$B = \frac{7.9 \times 10^{15} \text{ T m}^3}{(6378 \times 10^3 \text{ m})^3} (1 + 3 \cos^2(37.1^\circ))^{1/2} \quad (2)$$

$$B = 5.19 \times 10^{-5} \text{ T}. \quad (3)$$

This is the expected value for the magnetic field of the Earth.

In the data analysis portion of this project, it is important to collect enough data to get a sense for the average or baseline value of the Earth's magnetic field. Any deviations from this baseline will be assumed to be caused by currents in the ionosphere, which are caused by moving plasma in Earth's upper atmosphere. The value for the current in the ionosphere is proportional to the change in the magnetic field and the two values are related by the expression,

$$I_{Iono} \propto \Delta B. \quad (4)$$

Measuring ΔB will give a good indication of the magnitude of the ionosphere's current. With enough data, a daily variation in the magnetic field due to the sun's enhancement of the ionosphere can be determined. Calculations of the actual current in the substorm current wedge will not be made, because there is no way to quantify some variables that go into this type of calculation, such as the conductance. Because of this, the magnetic field data will be used as a proxy to determine the substorm current wedge.

4 Methods

4.1 List of Components

The components list for this project is fairly simple since the vast majority of parts necessary for its construction are included in a kit. The following is an itemized list of components required for the completion of this project. Included on this list are the additional PVC piping parts recommended for burial of the sensor fixture, seen in Figure 1.

- Simple Aurora Magnetometer 3 Axis Magnetometer Kit
- AC Adapter Power Supply
- Enclosure
- Multimeter/Ohmmeter
- Wire Cutters
- Solder (≤ 0.8 mm)
- Soldering Iron
- PVC Device Box
- 1-1/2 in. Cap (3)
- 1-1/2 in. Cross-Tee Slip (2)
- 1-1/2 in. Pipe, 1 ft. long (5)

- 1-1/2 in. Coupling

The power supply and enclosure are two components bought from the makers of the SAM-III kit. The multimeter, ohmmeter, wire cutters, solder, and soldering iron are generic components the user can simply borrow from Christopher Newport University's Physics, Computer Science and Engineering Department.

4.2 Design Rationale

The use of a magnetometer construction kit was chosen over building a magnetometer from scratch for both convenience and increased accuracy. The SAM-III magnetometer kit is a unique kit; its creators replace broken parts for free and offer online support as well as many informative documents. The SAM-III kit contains most components needed for assembly of the magnetometer system, so the user will not have to purchase much else. The kit contains three fluxgate magnetometer sensors which are much more accurate in measuring small magnetic fields than other magnetometers such as a hall-effect magnetometer. Building a fluxgate magnetometer from scratch would require a lot more work than required for this course.

In order to construct the SAM-III, the user must know or be able to learn how to solder. There is a build option in which the creators of the SAM-III will solder all components to the PCB's and test them in their lab.

This option is much more expensive, adding \$300 to the budget and was not employed. In any case, soldering everything together gives the user a better sense for how each PCB works and how the three PCB's work together to read sensor input.

Ideally, the magnetometer will be buried in order to minimize the amount of disturbances that could interfere with the magnetometer sensors. In the worst case scenario, the system will be able to work in a lab setting. However due to the magnetic disturbances, it will be hard to tell if the user is looking at a geomagnetic event or interference. A comparison of two identical SAM-III magnetometer systems, one in a lab setting and one in a geomagnetically quiet area, is detailed in one of the documents provided by the makers of the kit and can help the user make decisions on whether or not they should bury the system [6]. If the magnetometer system is chosen to be buried, it will be encased in PVC piping. This choice was recommended by the construction manual, but the piping is not included in the kit. Encasing the system in PVC seems to be the best option to permanently secure the sensors in place in the ground, as well as protect it from water damage.

4.3 Overview of Construction

The user must follow the construction guide, which is both publicly available at

<http://www.reeve.com/Documents/SAM/SAM3ConstructionManual.pdf>

and contained on the software disc provided by the kit, in order to save himself from making grave mistakes. Another page that contains many helpful links is the 3-Axis Simple Aurora Monitor (SAM-III) Description and Specifications page, and is located at

<http://www.reeve.com/SAMDescription.htm>.

The manual also has detailed “Troubleshooting” sections, and provides contact information for any issues not explicitly described in these documents. The user will first start out installing all components to the keyboard PCB, as seen in Figure 2. The user will then install the power supply components to the controller PCB, shown in Figure 3, making sure to test them afterwards. Figure 4 shows the specified voltages each component should be reading at this point. Once voltage testing is completed, the user will solder the rest of the components onto the controller PCB, and in Figure 5, the user can see how the completed controller PCB should look. The next step is to install the display component, which consists of installing one 34-pin PCB header to the display PCB. Once all components are installed on all three PCB’s, they are to be connected with ribbon cables. An illustration of the PCB’s is shown in Figure 6.

Testing and adjusting is the next step, and the construction manual details how to test each PCB using firmware installed on the circuit’s micro-processor. Software is then installed and used to verify that all components

are connected and working properly. The manual details a step-by-step process for this testing, and provides helpful screenshots of what the user should be seeing. Once all testing and software/firmware installation is complete, the three PCB system is to be installed in the enclosure seen in Figure 7.

The SAM-III magnetometer sensors are then connected to the system and subsequently tested. A picture of two of the three sensors can be seen in Figure 8. If the sensors were chosen to be buried, then they are to be placed in a fixture after all testing is completed, detailed in Section 4.4.

4.4 Burial

Burial of the magnetometer system is the optional last step. This should be performed after all parts have been verified that they are properly working. The system is recommended to be buried 20 meters away from any geomagnetic disturbances and 1 meter down [6]. These disturbances include, but are not limited to, passing vehicles and railways [6]. In the event that the user cannot secure a burial location with these specifications, it is recommended that the system be placed in an area as geomagnetically quiet as possible [6].

In the ground, the system should be set up with respect to true north, and the vertical axis sensor should be exactly vertical [7]. It is worth mentioning that the software used in data display and analysis which is provided

by the kit is compatible with only Windows XP, 7, 8 and 10, so the user must have access to a PC running one of these operating systems. The user must return to the burial site in order to collect data, which consists of connecting the system's cables to a PC. This requires the system to be buried in such a way that allows the cables to be easily accessed.

As stated in Section 4.2, the construction manual details a way to both permanently orient the sensors and safely extend cables so that they can be used in data collection. This option utilizes PVC piping and details a parts list complete with the types of PVC, and their quantity and size. Unfortunately, this is an optional choice and the parts are not included in the kit. Figure 1 shows the finished magnetometer, encased in a PCV piping structure with a similar design to the one recommended by the manual.

5 Data and Discussion

While the magnetometer was in the lab setting, we verified that it was taking the correct measurements. This involved creating a simple circuit consisting of a solenoid, a battery, and a resistor. The goal of this circuit was to run a current through the solenoid which induced a magnetic field that the magnetometer would then read. We isolated the sensors so that measurements could be made for each sensor individually, and then together. Calculations were made for the direction and magnitude of the magnetic field

and compared to the magnetometer's readings. The magnetic field, B , inside a solenoid is given by

$$B_{\text{in}} = \mu_0 \cdot \frac{N \cdot I}{l} \quad (5)$$

where μ_0 is a constant, N is the number of coils of the solenoid, I is the current, and l is the length of the solenoid. Here, we assumed we were using an infinite solenoid. The number of coils, length of the solenoid and the current were measured. We varied the resistance of the resistor, 560 Ω and 50 Ω , in the current to test the sensors with different currents.

We started by putting each sensor in the solenoid and reading the magnetic field from that sensor. For each sensor reading the 560 Ω circuit, we got a magnetic field of about 30,000 nT, which is about double what we would expect. For each sensor reading the 50 Ω circuit, we got a magnetic field of about 60,000 nT, which is about half of what we would expect. Although these readings were wrong, they were consistently wrong, meaning that each sensor read the same wrong value. With more experimentation and observation, we can correct for this systematic error. We also have to consider the resistance lost to the wires in the leads used in the circuit. It is also worth noting that the system does detect the correct, or at least consistent, polarity (positive or negative). This was confirmed by placing each sensor in one end of the solenoid, observing the direction and then placing it in the other end of the solenoid and observing that direction.

In these experiments, we were mainly verifying that the system is both

reading the magnetic field correctly and detecting the correct orientation. We determined that the sensors are working correctly and we can go on with more measurements with confidence. Measuring a magnetic field gives a good indication of the current it is being induced by, and this resembles how the system will determine characteristics of the current substorm wedge by measuring the Earth's magnetic field.

After initial tests were completed, we began looking at the system's measurements of the Earth's magnetic field. This is slightly more difficult while in a lab setting, but not impossible. In order to analyze data, the user must sample a number of days and pick the quietest day to serve as a baseline average for the Earth's magnetic field. Any deviations from this baseline will be assumed to be caused by geomagnetic activity. There is no way to precisely calibrate the magnetometer's data, but data is available online from other SAM magnetometers and the user can compare data to that of others in the same latitude to verify the magnetometer's readings. In the event that the readings consistently do not match with observatories in a similar location, a correction value and/or offset value can be found through trial and error and used in the analysis software's filtering options.

Figures 9, 10 and 11 display samples of data taken by the system in the lab setting. The x-axis represents the time in UTC and the y-axis represents the change in the magnetic field in nanoTesla. A pattern is clearly shown to repeat on a daily basis and is believed to be caused by the lab environment.

With additional data sampling, this pattern can be filtered out. Unfortunately, there have been no geomagnetic storms during the time the sensors have been set up in their structure, thus we have not been able to make measurements of any storms or the substorm current wedge. In the future, the magnetometer system can be buried to minimize noise. If not, testing will need to be made to filter the data taken in the lab.

6 Appendices

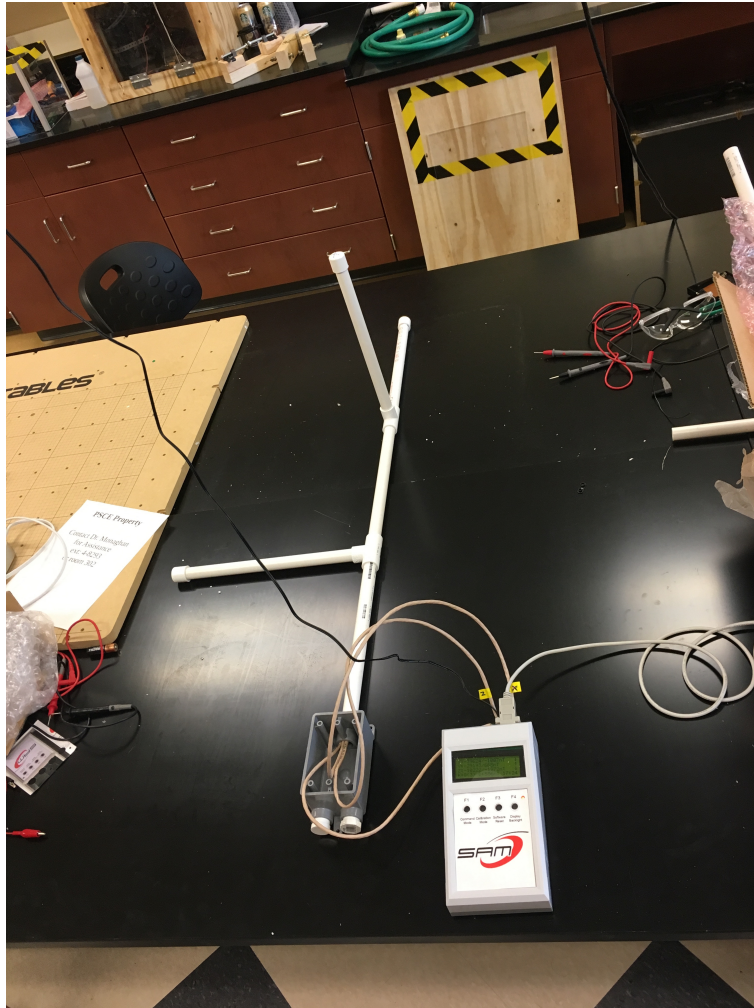


Figure 1: Magnetometer in PVC Structure

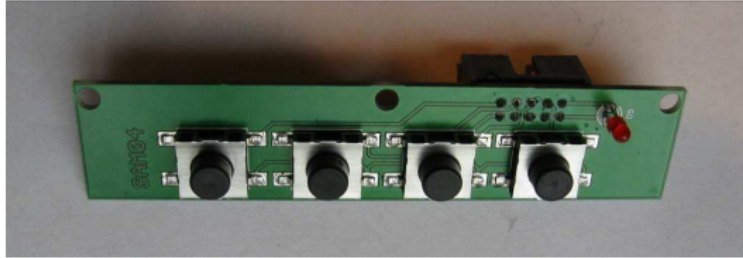


Figure 2: Completed Keyboard PCB [8]

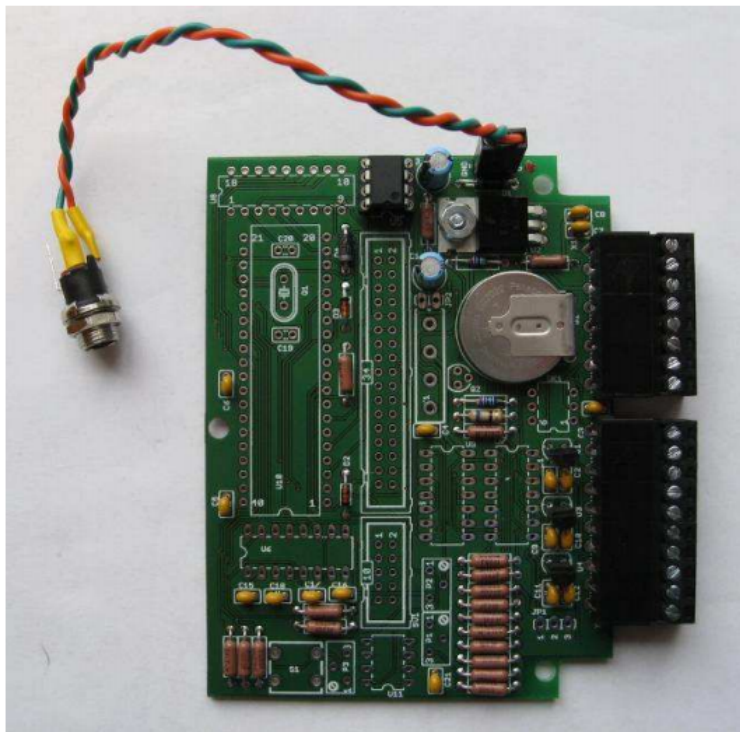


Figure 3: Controller PCB with Only Power Components and Connected Power Cable Used for Testing [8]

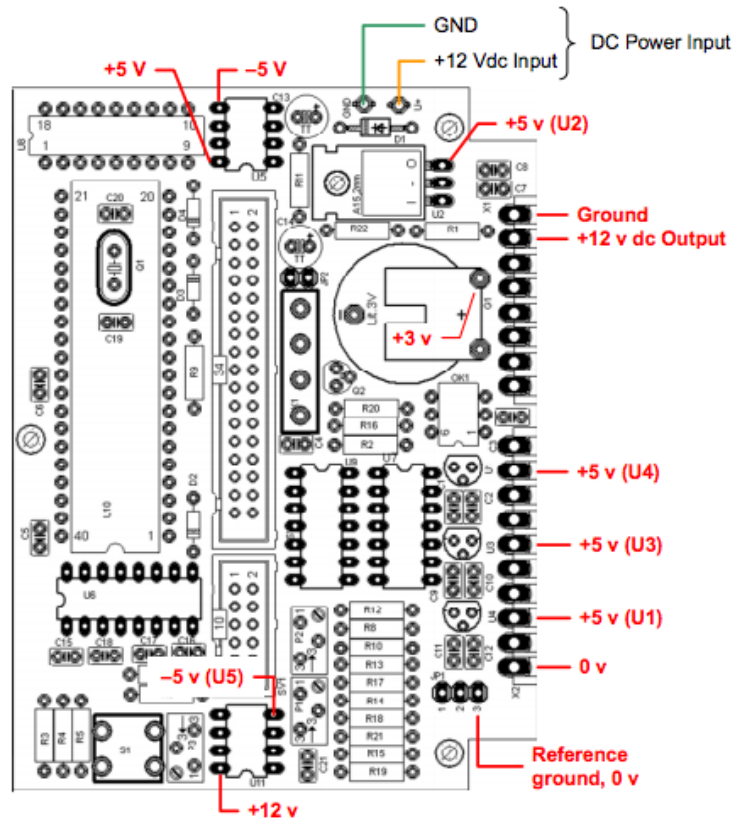


Figure 4: Specified Voltages for Controller PCB [8]

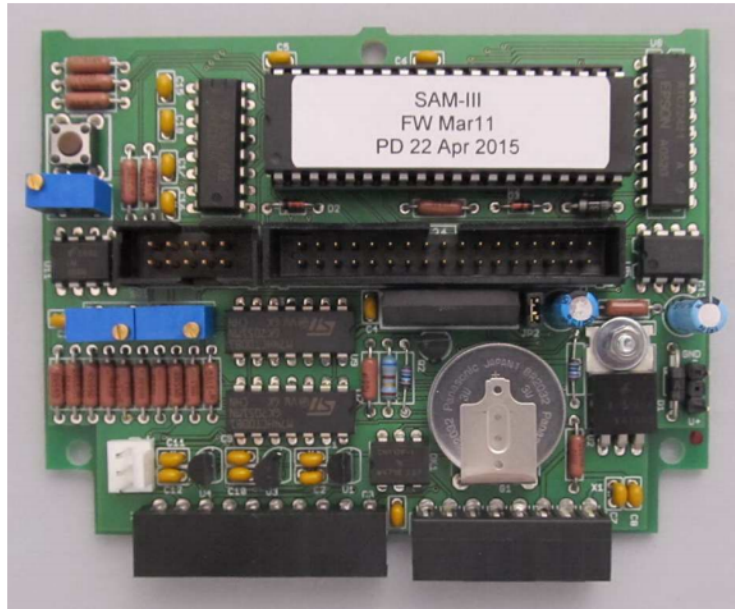


Figure 5: Completed Controller PCB [8]

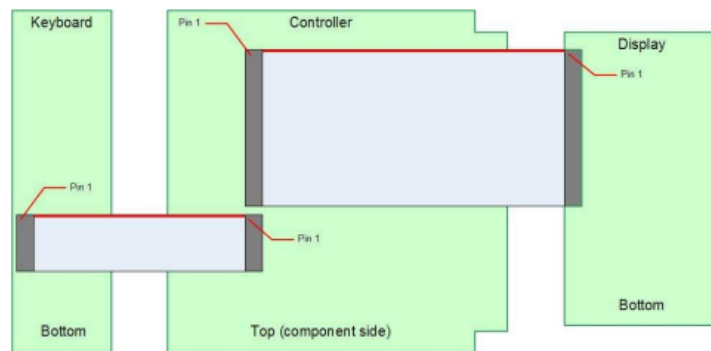


Figure 6: The Three PCB's Connected with Ribbon Cable [8]



Figure 7: Enclosure Containing Keyboard, Controller, and Display PCB's
[8]



Figure 8: Two (of Three) Fluxgate Magnetometer Sensors [8]

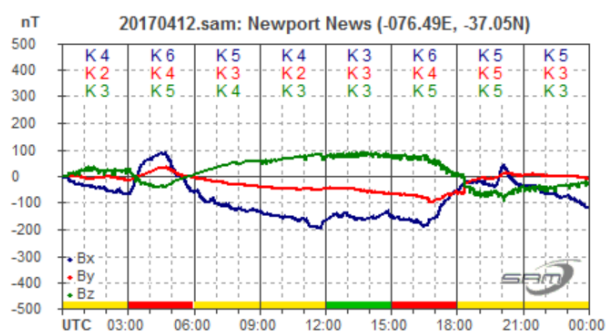


Figure 9: Sample of Data, April 12, 2017

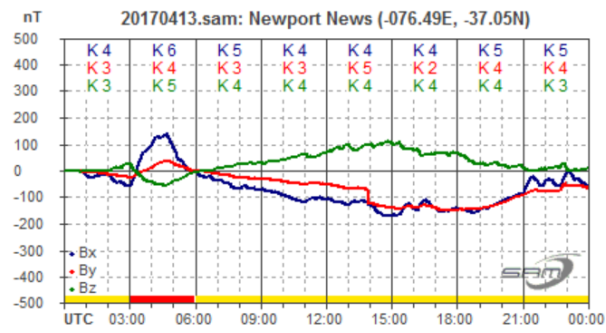


Figure 10: Sample of Data, April 13, 2017

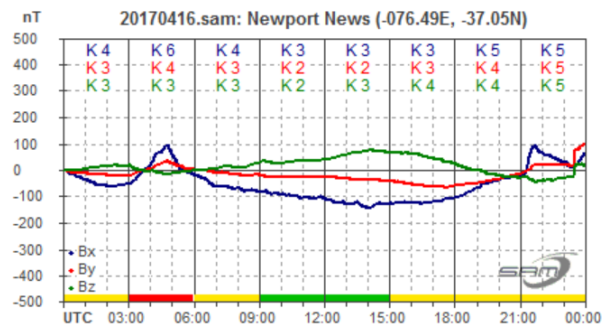


Figure 11: Sample of Data, April 16, 2017

References

- [1] F. Tapson, “Overview: Geomagnetically induced currents (gic).” Web, July 2015.
- [2] “Substorm current wedge (swc).” Web, January 1999.
- [3] “Pi 2 pulsations.” Web, January 1999.
- [4] P. Jain, “Magnetometers.” Web, 2012.
- [5] “Planetary k-index.” Web, 2015.
- [6] W. D. Reeve, “Siting of sam-iii magnetometer sensors case study.” Web, 2016.
- [7] W. D. Reeve, “Geomagnetism tutorial.” Web, 2015.
- [8] W. D. Reeve, “Simple aurora monitor sam-iii 3-axis geomagnetometer construction manual.” Web, 2016.