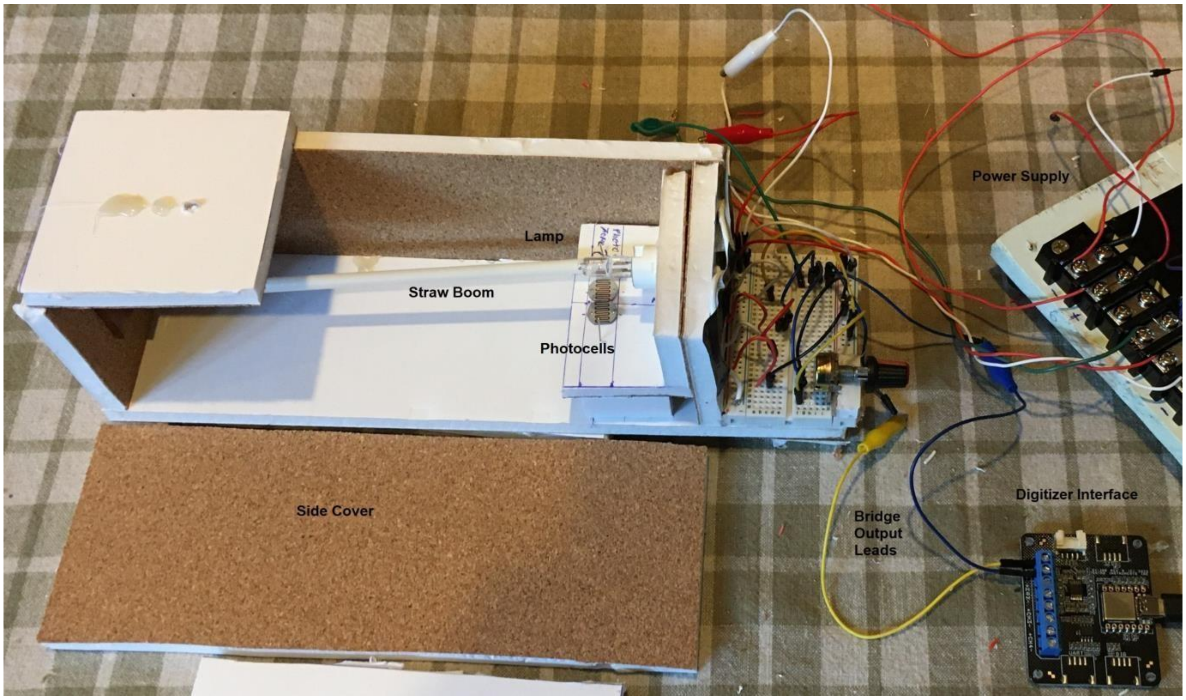
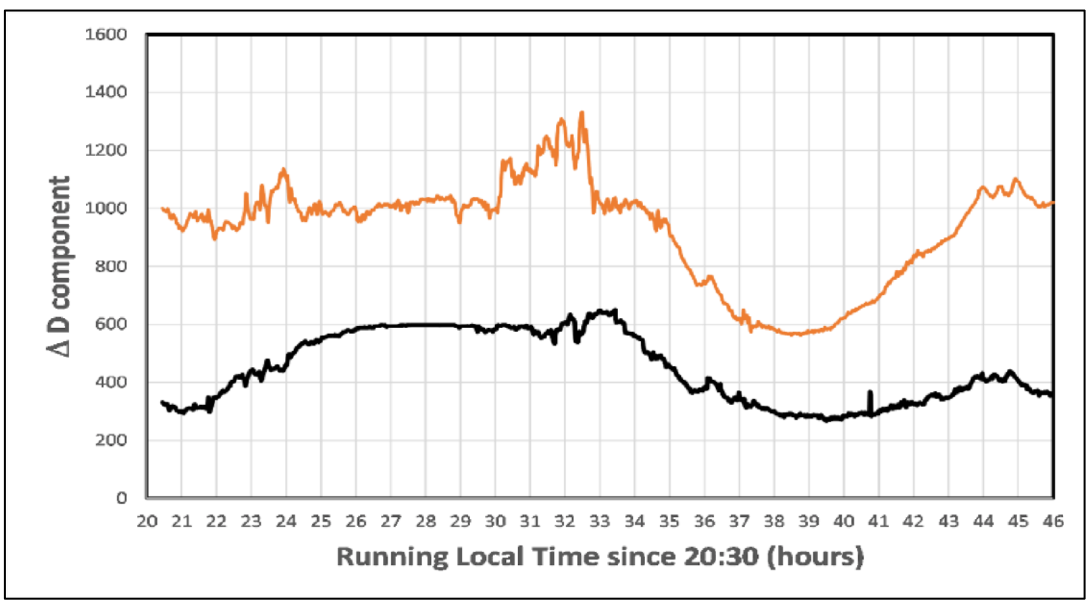
National Aeronautics and Space Administration



The Photocell Magnetometer for Space Weather Studies



The Photocell Magnetometer for Space Weather Studies

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Introduction

A magnetometer is a device that is used to detect and measure magnetic fields. It can be as simple as an ordinary compass that measures the local direction of the magnetic field polarity, or as sophisticated as the kinds of devices used by scientists which cost tens of thousands of dollars.

Magnetometers are important for studying space weather because some aspects of space weather involve sudden changes of Earth's magnetic field that occur during solar storms. These events can alter the strength of Earth's magnetic field at the ground by up to 5% and also cause changes in the orientation of Earth's magnetic field by several degrees.

This Guide provides a step-by-step construction process for you to build a sensitive magnetometer for under $50. This design is based on the soda-bottle magnetometer described in a previous Guide but uses a pair of photocells to sense the orientation of the suspended magnet.

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Cover art: (Top) Photo of the assembled magnetometer. (Bottom) Typical data from the magnetometer (black curve) compared to data from the Fredericksburg Magnetic Observatory (red).(Credit: The Author).

Table of Contents

Part I: Notes for Educators

NASA space missions often require measuring magnetism on the Sun, on Earth, and on other planets and bodies in our solar system. ***Heliophysics*** is the study of the Sun and its effects on the Earth and the solar system.

In this guide, students will learn how Earth's magnetic field interacts with the solar wind and keeps the Earth safe and how studying magnetism can help scientists learn about the unique environment that the Sun creates in the solar system.

When your students use this guide, the following information will provide an educational context for its use. The project description includes information about the Next Generation Science Standards that apply and provides guiding questions and an assessment to help teachers gauge student performance in constructing the device, acquiring data, and interpreting the data.

1. Overview

Students will measure Earth's changing magnetic field during geomagnetic storms caused by increased solar activity. The Sun goes through an 11-year cycle with periods of increased numbers of sunspots that are related to the frequency of solar flares and other 'solar storms', which can affect Earth's magnetic field. Scientists refer to the effects of these solar storms as 'space weather.' The strongest storms occur during and just after a period in the Sun's cycle called Solar Maximum. Currently our sun is in its fourth year of sunspot cycles number 25 with a maximum predicted to occur sometime in late-2023 or early-2024. Storms that are strong enough to be detected by smartphones only occur a few times each month during the time of peak solar activity. Be sure to check where the Sun is in its cycle before attempting this experiment with students. Use a service such as the one provided by the NOAA Space Weather Prediction Center (https://swpc.noaa.gov) to see if a storm is occurring, or when the next one may arrive.

2. Objective

Students will be able to observe space weather phenomena that cause variation in Earth's magnetic field.

3. Explanation

Compared to professional magnetometers used at magnetic observatories, most of the simple designs such as soda bottle magnetometers are not sensitive enough to detect weak geomagnetic storms with Kp < 7. The design described here-in is the first of its kind that has the sensitivity to record nearly all of the magnetic variations detected by professional systems, providing a continuous classroom experience of significant magnetic variability even when no solar storms are present.

4. Assessment

Use the answers to the questions during data analysis to determine if students can accurately collect and analyze data during a geomagnetic storm. These questions can include:

- ➢ What kinds of solar events can cause Earth's magnetic field to vary?
- ➢ Why are compass needles affected by solar storms?
- ➢ How does a magnetometer detect changes in Earth's magnetic field?
- ➢ What property of Earth's magnetic field is being measured by the magnetometer?
- ➢ What is the typical range of measurements that you detect during a strong storm?

5. Targeted High School NGSS Standards

Appropriate for designs involving Hall sensors, photocells, smartphones, and Arduino.

HS-ETS1-2 Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-PS3-5 Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.

6. A Glossary of Terms

Boom – a mechanical device on a spacecraft that keeps certain sensitive instruments far from the spacecraft to reduce interference.

Current – a flow of charged particles such as electrons and is measured in units called amperes

Dynamo – a device containing a rotating magnet that produces electrical currents

Electromagnetic – something that has both electrical and magnetic properties

Field – an influence, usually a force, that exists in the space surrounding an object

Force – an influence that causes nearby or distant objects to move, sometimes without physical contact

Gauss – a unit of measurement for magnetism in a system of units that also uses centimeters and grams

Interstellar – literally the space between stars, usually occupied by various gases and clouds

Magnetometer – an instrument for measuring the intensity and direction of a magnetic field

Polarity – the direction of a force or current such as magnetism (North or South-type) or (positive or negative) on a battery

Spacecraft – a platform carried into space that contains a collection of instruments for measuring distant objects and environments in space

Space weather – a collection of phenomena that describe how Earth and the other planets respond to solar activity

Sunspot – a dark spot in the solar surface where magnetic fields very intense causing the gas to be cooler and emit less light making it dark compared to the sun's bright surface

Tesla – a unit of measurement for magnetism in a system that uses meters and kilograms; one Tesla equals 10,000 Gauss. As an example, the magnetic field at Earth's surface is about 50 microTeslas (0.00005 Tesla) or 0.5 Gauss in strength.

Vector – a quantity that is defined both by its amount and its direction. The motion of a body is defined by its velocity vector, which has an amount (called speed) and direction (up, down, etc.).

Part II. A differential photocell comparator with magnetic damping

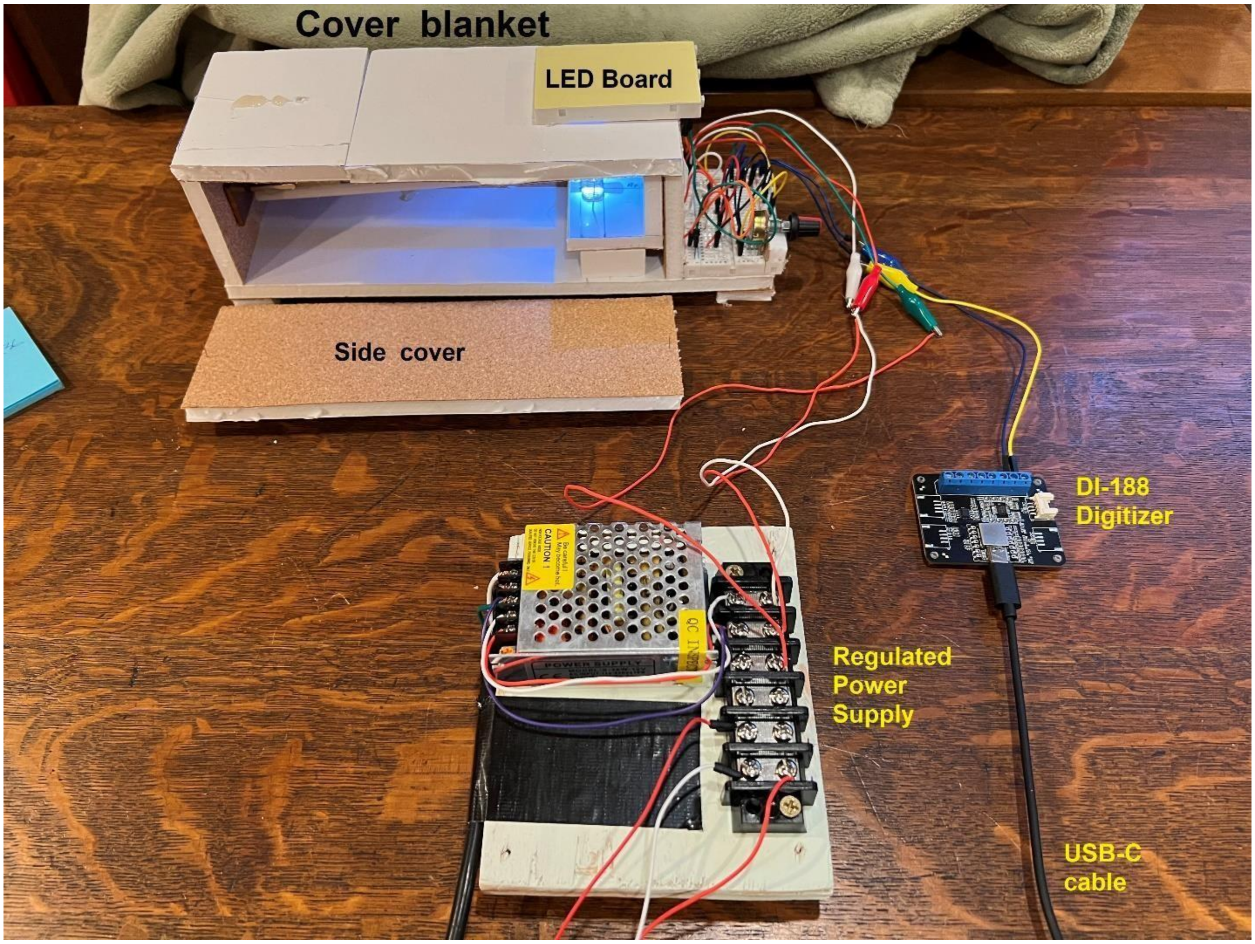

Figure 1. Example of completed magnetometer.

1. Background

This design uses an LED light source monitored by photocells, which then produces an output current correlated to the magnet motion as it eclipses and dims the light from the LED.

The design for this device is based on the work by Alexander McWilliams from the University of Minnesota in 1979 and reported in the Journal of the American Association of Variable Star Observers[1] (AAVSO) by Casper Hossfield. The suspended magnet with an attached shade passes across two photocells that are connected to a balanced circuit.

Any movement of the magnet causes the amount of shading of the two photocells to change. This produces a voltage change that can be amplified and used to run a strip chart recorder. A similar design was offered in 1998 by Jim Mandaville[2] (also an AAVSO member) but with some changes that allowed it to detect car traffic 200-meters from the device! A design based upon similar operating principles is also available from the Science and Engineering Projects[3] website and uses PVC pipe to enclose the system.

The following step-by-step guide will show how to construct and operate this devise with some alterations to allow for more modern resources. For example, cadmium selenide photocell used in the original designs is no longer available. The halogen lamp was hot enough that it produced convection currents in the sensor housing, which constantly perturbed the sensor. It was replaced by a clear, low-voltage LED. The following design is more compact, uses magnetic braking to damp the swinging magnet, and uses a digital output to interface with a laptop rather than an antique 'strip chart' recorder. The completed system is shown in Figure 1.

2. Materials

- 2 - Photoresistors GL12528, 12 mm dia; Vmax=250 VDC; (Juried Engineering; pack of 5) https://tinyurl.com/3adzkez2
- Potentiometer, 1000 Ohm.
- Clear bright LED.
- Regulated power supply - 12v ; 3A (36 watts) https://tinyurl.com/3w9jyphh
- Data logger - DataQ Instruments; DI-188 Data acquisition computer interface; +/-10 v input; 12-bit ADC, 100 sec/sample to 8000 samples/sec, USB-port connection; includes WinDaq software. https://tinyurl.com/65xczvau
- 1x 330 ohm and 1x 220-ohm resistors.
- Bar magnet (3 mm x 3mm x 25 mm, NdFeB, 6584 Gauss).
- Foam board.
- Soldering iron.
- Hot glue gun.

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[1] The McWilliams Magnetometer, Journal of the American Association of Variable Star Observers, vol. 8, no. 1, p. 16. https://www.aavso.org/sites/default/files/solar_bulletin/AAVSO_SB_1998_09.pdf

[2] A Simple Homemade Magnetometer for Geomagnetic and Solar Studies, John Blackwell, U. New Hampshire, https://eos.unh.edu/sites/default/files/media/2020/11/a_simple_homemade_magnetometer_for_geomagnetic.pdf

[3] DIY Geomagnetic Storm Monitoring, http://avtanski.net/projects/magnetometer/

- ➢ 1 m sewing thread.
- ➢ Extension cord – 2 m, 2-conductor.
- ➢ Small screwdriver with Phillips blade.
- ➢ 2 pieces of 28-gauge copper ‘bell’ wire about 30 cm long.
- ➢ Optional - Multimeter with a DC Volts scale

3. Construction

Constructing the sensor box

The box can be fabricated from foam board, or, if you are skilled in wood working, you can construct a box with a more professional look. The following details will describe a foam board box, but they can be adapted to wood. Ultimately, the box needs to be closed and to be able to seal in light during its operation.

Step 1) Cut one piece 8.25 cm x 30 cm to form the bottom.

Step 2) Cut two pieces 8.25 cm x 25 cm to form the sides of the box.

Step 3) Cut one piece 7.6 x 8.25 cm” to form the back end of the box.

Step 4) Use the hot glue gun to fasten one of the sides and the back end to the base. Hot glue the PC board to the rear of the base. Fit the pieces together without gluing to make sure they are cut properly. The result should look like Figure 2.

Figure 2. Example of assembled box at this stage.

Constructing the magnetic sensor

Step 5) Cut an opaque straw to a length of 19 cm.

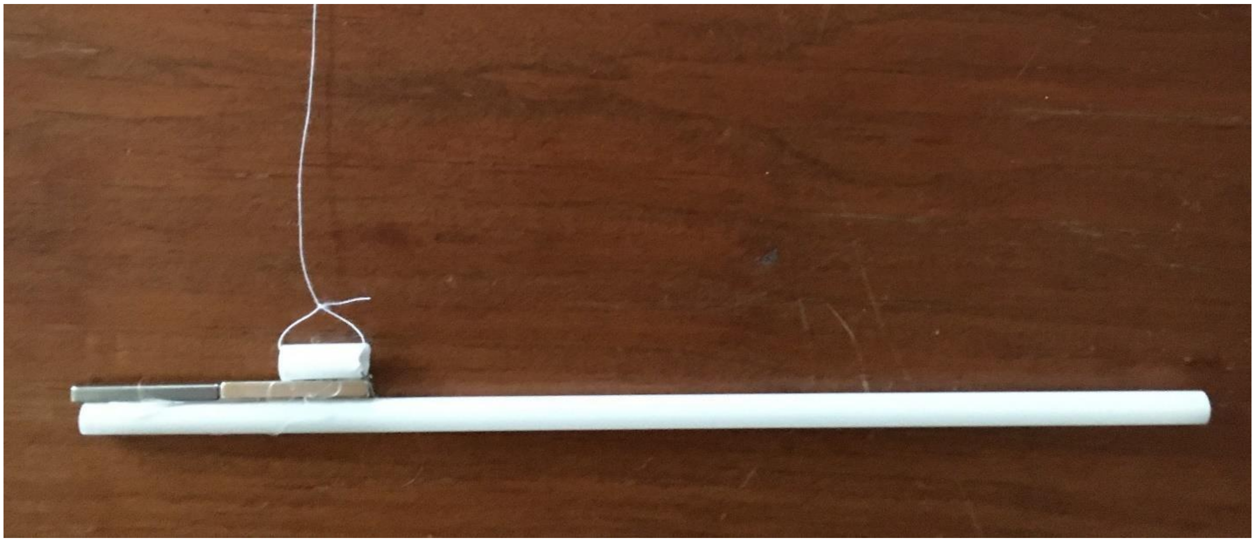

Figure 3. The magnet sensor assembly.

Step 6) Hot glue two bar magnets end to end to the rear of the straw.

Step 7) With the scrap straw, cut a piece 2 cm long.

Step 8) Hot glue the short straw to the end of the magnet farthest from the end of the straw.

Step 9) Insert sewing thread through the short straw and loop to form an equilateral triangle about 2 cm tall. Cut off excess thread so that only one long thread remains. The result should resemble Figure 3.

Installing the metrology unit

Note: The project requires a large-size photocell with a diameter of at least 10 mm. Most photoresistors that are available are only 5 mm or less in diameter and cannot be used. When placed side-by-side, the two photocells have to span the swing range of the magnet sensor shade in order for the illumination across the light detector to span the range of the magnet displacement.

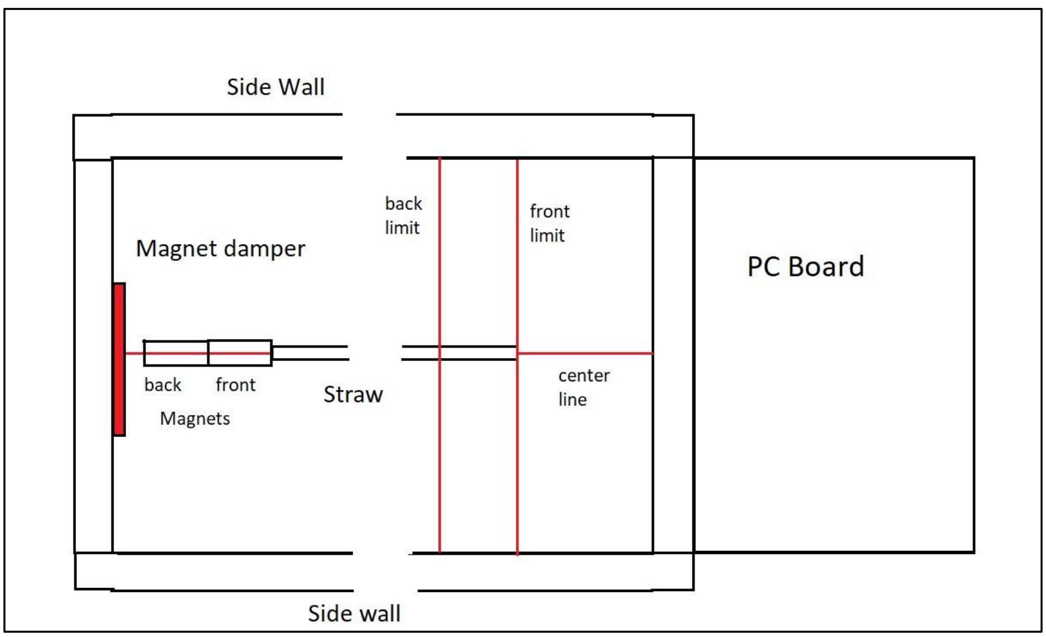

Figure 4. Setup of sensor and center line Null axis.

Step 10) Place the magnet sensor along the central axis of the floor of the box. Offset the sensor 6 mm from the back wall. Mark on the floor the spot where the tip of the sensor reaches. Draw a perpendicular ling through this point. This ‘front limit’ represents the distance of the maximum reach of the straw and the upper edge of the two photocells. Mark a second parallel line 12 mm from this front limit line to define the back limit. The zone in between the two limit lines is where the photocells will detect the shadow of the swinging straw. See the sketch in Figure 4.

Step 11) With the back wall abutting the PC board temporarily installed, measure the inside distance from the back wall to a point 12 mm in front of the photocell zone. This should be about 4 cm. Cut a piece of foam board 4 cm wide and 8.3 cm long to serve as the shelf for the two photocells.

Step 12) Cut two foam board spacers 4 cm long and 18 mm tall. These will serve as support for the shelf when they are attached to the side wall and the back walls.

Step 13) Mark the midline of this shelf along the axis of the straw 4.1 cm from either edge of the shelf.

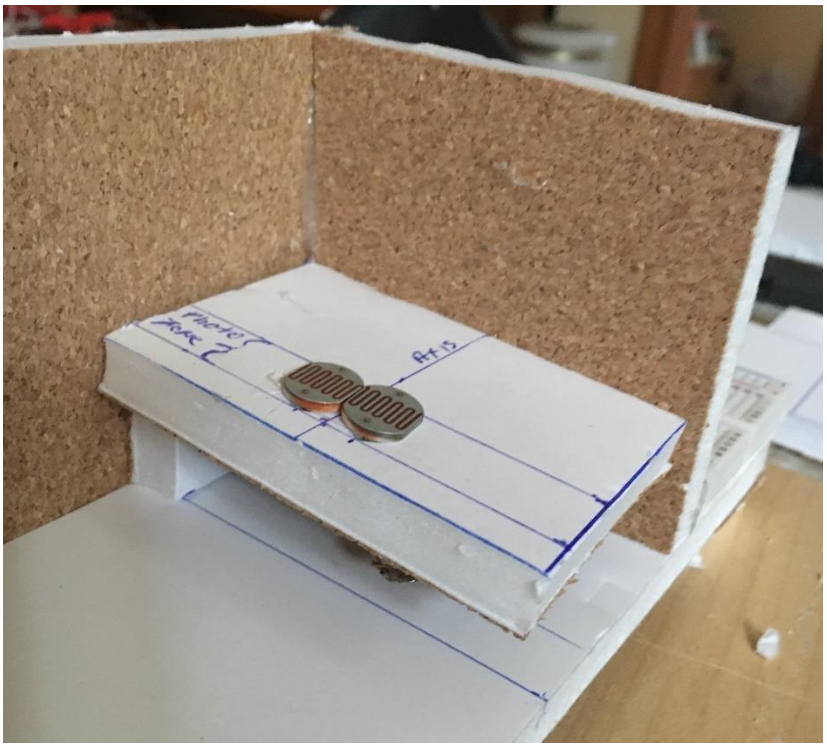

Figure 5. Example of installed photocells and shelf.

Step 14) Place the photocells on opposite sides of the midline on the shelf so that the long axes of the metal zig-zag sensors are parallel to each other. Note the locations where holes need to be punched for the photocell leads. Use a small screwdriver to punch these holes and verify that the photocells can be mounted side-by-side touching each other and flat with the top surface of the shelf as shown in Figure 5. It is important that the zig-zag sensors be oriented exactly as shown.

Step 15) Carefully solder 15 cm copper wire extensions to each of the four photocell leads and insert the photocells into the shelf. Punch four holes into the back wall and thread the four photocell wires through these holes so that they can be connected to the PC board.

Step 16) Push the photocells off the shelf and add a dab of hot glue, pushing down on the photocells to firmly attach them to the shelf and oriented as shown in Figure 5.

Step 17) Hot glue the shelf to the inside wall so that the shelf is parallel to the plane of the magnet sensor and the centerline matches up with the Null position of the suspended magnet and the reference axis for the straw. The inside of the box should resemble Figure 5.

Setting up the regulated power supply

Because the intensity of the sensor lamp must remain constant over long periods of time, we need to use a regulated power supply to maintain a fixed voltage and lamp intensity.

The power supply is the one specifically used in the Materials List as the GALYGG, 12V, 3A converter. The backside looks like Figure 6. The input and output connector is a 5pin black terminal block. The designations for the terminals are stamped into the metal frame as L, N, G, -V, +V. In a 3-wire extension cord, the third wire is for the ground line 'G' and is usually green. The 'G' terminal is the third from the left and is shown as the standard electrical symbol for Ground. This ground terminal will also be used in the photocell circuit to be discussed later on.

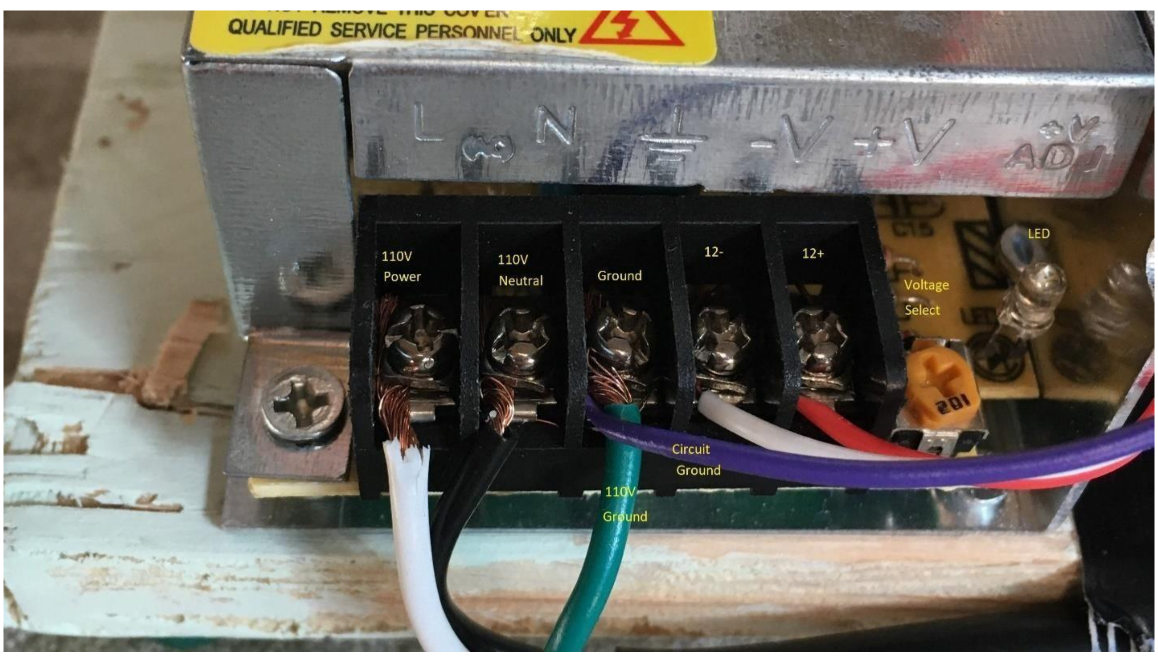

Figure 6 – Example of power supply connection block with lines inserted for a 3-conductor cable. The power supply adjustment screw is located between the LED lamp and the V+ connector.

Step 22) Take the extension cord and cut off the female end receptacle leaving only the male plug end attached.

Step 23) Separate about 8 cm of cord into three wires. Strip off about 12 mm of insulation from each wire and twist each bundle of copper wire into a single strand.

Step 24) Use the screwdriver to open each of the five screws about halfway.

Step 25) Insert one of the cord wires into the 'L' slot and tighten the screw so that the cord wire is firmly seated. Insert the other cord wire into the 'N' neutral slot and tighten its screw. Attach the third line for the ground line to the 'G' slot.

Step 26) Remove 12 mm of insulation from each end of the two 28-gauge copper 'bell' wires and insert them into the -V and +V terminals, securing them tightly. Note: Larger gauge wire (i.e. 24 or 20-gauge) are too thick to fit into the wire pin holes.

Step 27) Power up the multimeter and select the 'DC Volts' scale with a > 12 VDC range.

Step 28) Plug-in the cord for the power supply into a local 110-V AC receptacle to start the converter. The LED light will turn on to indicate the unit is working. Touching the metal case may indicate a slight warmth if the unit has been operating for a long time. Also, a faint humming sound will be heard from the 60-cycle input AC as it vibrates the converter's transformer.

Step 29) Use the multimeter-voltmeter to measure the output voltage on the two copper wires to confirm that the unit is operating and producing 12-volts of DC output. With a screwdriver, adjust the Voltage Select screw shown in Figure 6 until the meter reads 12.00 V. This power supply is regulated, and it will remain at this exact level for many hours and return to this voltage when it is turned off and turned on again.

Installing the magnet sensor and damper

Step 30) Suspend the magnet sensor inside the box so that it lines up with the central axis. Insert a 2 cm x 2 cm piece of copper on the back wall of the box so that the sensor is no more than 3 mm from its surface but extends to cover the photocells. Hot glue the copper piece to the wall.

Step 31) Cut a 6 cm x 6 cm square of foam board that fits over the top of the box where the magnet is suspended.

Step 32) Draw a line that follows the centerline of the magnetometer box used for the photocells. Carefully measure the location of the vertical thread above the suspension point of the magnet and punch a small hole at this location on the magnetometer axis.

Step 33) Insert the thread through the hole so that you can suspend the magnet inside the box by holding the thread at its other end through the short roof of the box.

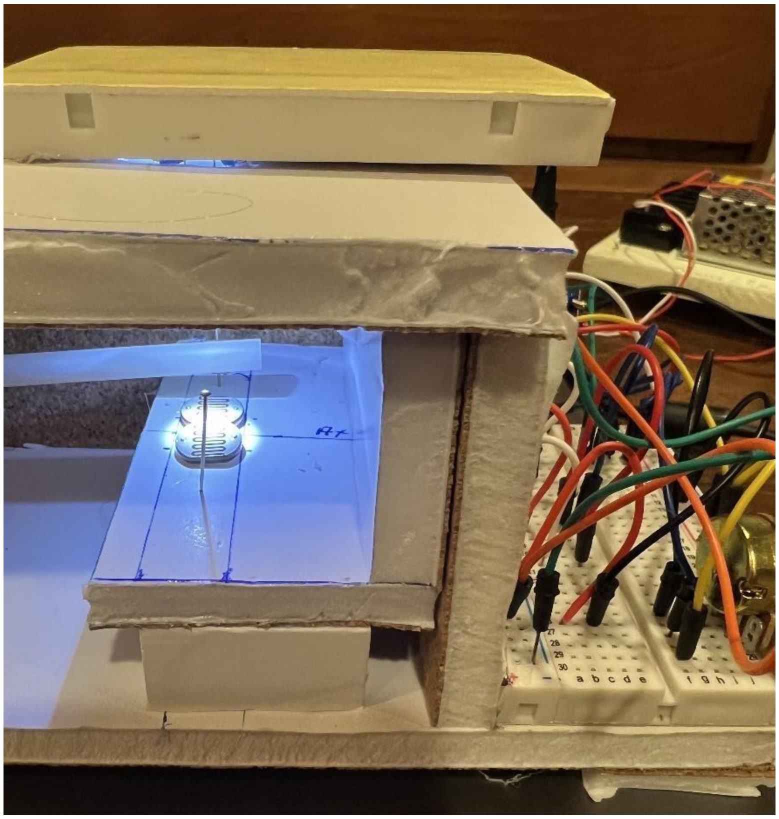

Figure 7. Final alignment of magnetic sensors. Note that straw is very close to the surfaces of the photocells with about a 3 mm gap.

Step 34) Carefully adjust the height of the magnet sensor and straw so that it is just above the surfaces of the photocells and centered on the copper plate. You may have to rotate the entire box so that the freely suspended straw is aligned with the axis of the box. When the height and alignment are correct, hot glue the roof onto the two corner walls and hot glue the thread onto the roof so that it does not shift. See Figure 7 for an example of this final alignment.

Step 35) Cut a 25 cm x 10 cm piece of foamboard to serve as a wall so that the sensor area is enclosed. Cut a 15.2 cm x 8.3 cm piece of foamboard to complete the roof of the enclosure. Hot glue the top roof piece to the box to complete the roof. The side wall can be temporarily attached to the sensor box using bobby pins so that access can be gained to the sensor at a later time.

Step 36) Create limit stops for the straw by moving the straw off each photocell about 1/8" and inserting a sewing pin. The straw will only be able to move through this limited range as you move the box.

Connecting the magnetometer electronics

The electrical schematic is shown in Figure 8. There is one variable resistor (potentiometer) to control the zero-level of the output voltage. The regulated power supply will have three connections for V+, V- and G where G is the neutral zero-volt line. This design produces no amplification and the difference signal between the two photocells can be measured by connecting Points A and B to a common voltmeter that registers millivolts.

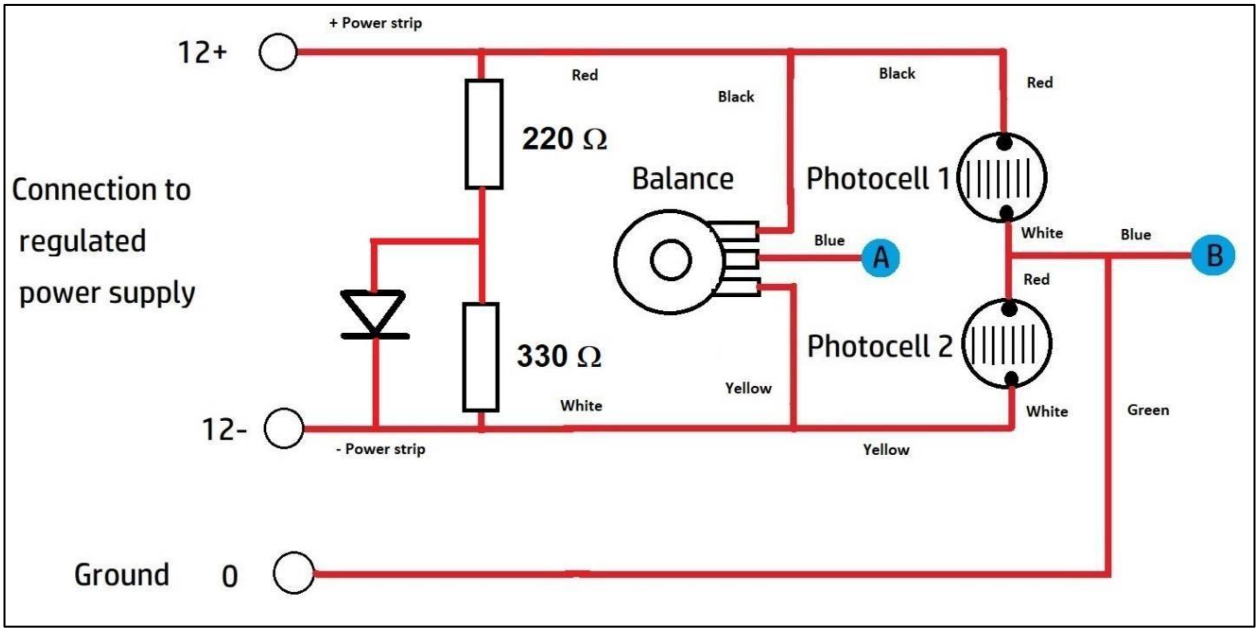

Figure 8 – Connections to components in the metrology assembly and detector.

Step 36) An example of how the components are connected on the PC board is shown in Figure 9. The Output A and B wires labeled in the figure will be used by a multimeter or a computer interface to measure the differential voltage between the photocells, which correlates with the magnet displacement angle. Depending on how you set up your power supply, you may want to use alligator clips to connect the 12+, 12- and ground to the power supply terminals. Note the Ground connection will be to the third 'ground' line in a standard 3-prong, 110 VAC plug. This is the purple wire shown in Figure 6. Also, the potentiometer plugs into three of the pin holes on the PC board but must be supported by a small piece of foam board and hot glued into place securely. Make sure the potentiometer makes proper connection with the board by using ohmmeter to verify continuity.

With the PC board in this orientation, with the letters running in rows from top to bottom and the columns decreasing in number index from left to right, all of the pins in the columns from A to E are electrically tied together. The pins in columns from F to J are also electrically tied together, BUT the pins in these two row blocks A-E and F-J are not tied together. Also, there are two power strips denoted by the (-) and (+) signs. All of the pins in the + row are tied together as are all of the pins in the – row. There are two power strips like this along the top and bottom rows of the PC board as shown in Figure 9. This means that each of the blocks A-E and F-J can be independently powered and have their own independent circuitry. If you want to tie a component in column 10 in Block A-E to a component in column 10 of Block F-J together, you have to put a jumper wire across the gap in column 10 between row E and row F.

When inserting wires and components, make sure that each pin connection is secure and that you are placing jumpers in the correct rows. In a crowded board such as the one in Figure 9, it is easy to place a jumper in an adjacent pin (column/row) instead of in the electrically-correct one.

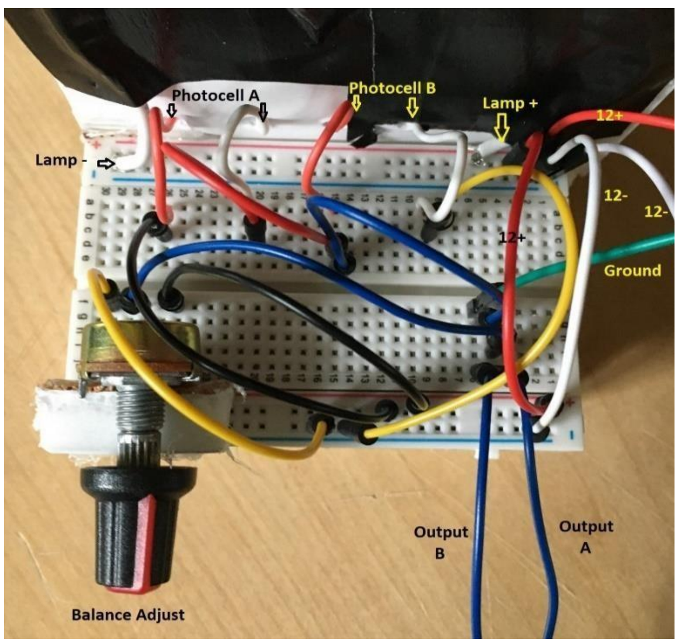

Figure 9. Hook ups on PC board. Jumper and wire colors correspond to those in Figure 8.

Step 37) The LED circuit is assembled on a separate PC board as shown in Figure 10, which will be fastened to the top of the sensor box so that the LED is positioned directly over the center point between the two photocells as shown in the previous Figure 7.

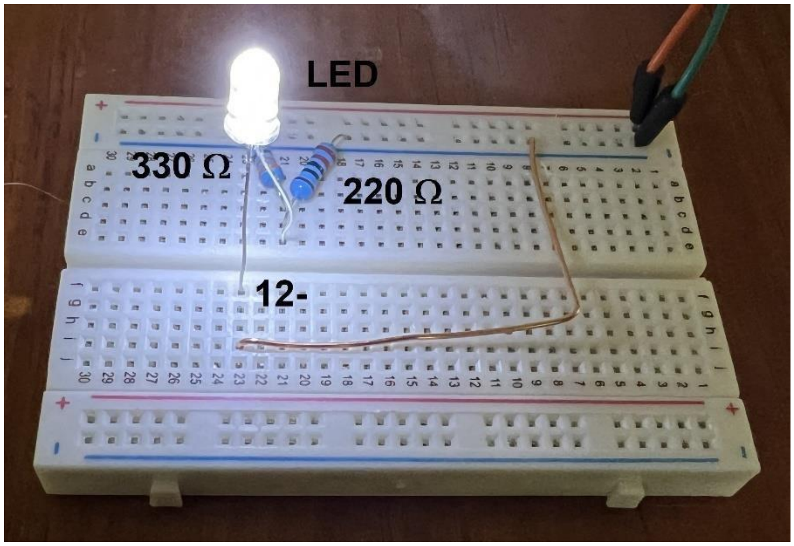

Figure 10. Circuit board for LED lamp.

4. The Computer Interface

Although a multimeter display is a simple way to monitor the movement of the magnetometer magnet, a better way is to interface the output terminals A and B with a computer, which can not only display a real-time graph of the data but save it for future analysis. The DataQ Instruments DI-188 Data acquisition computer interface is one such inexpensive option. It is a module that plugs into the USB port of your laptop and has up to four channels of analog input. By connecting one of these inputs to the output of the magnetometer sensor at points A and B, the downloaded software will process the analog data and convert it into a variety of displays based on user-selected sampling times. You can sample and plot the input data with a delay up to 1 second, or as short as a millisecond, depending on your needs. The data can be saved as a comma separated .csv file that can be used with Excel to further analyze and store the data.

Once you have purchased the module, you need to download[4] and install the WinDAQ Dashboard from the DataQ website[5]. Once the application is installed on your laptop, you click the icon to open the dashboard. After you have plugged-in the module on your USB port and have connected the input wire to Channel 1, the application window will show that it has found your active COM port in its list of available input devices as shown in the screenshot in Figure 11. The module will appear as 'DL-188'. On the menu bar below, click on the 'Start WinDaq Software' button. When you check the box, the laptop screen will be replaced by a dynamic graph of the live data at the default rate of 20

[4] https://run.dataq.com/

[5] https://www.dataq.com/blog/data-acquisition/new-windaq-dashboard/

samples per second, which will generate over 72,000 data samples every hour and is not commensurate with the very slow changes of minute-duration that typically occur during geomagnetic storms.

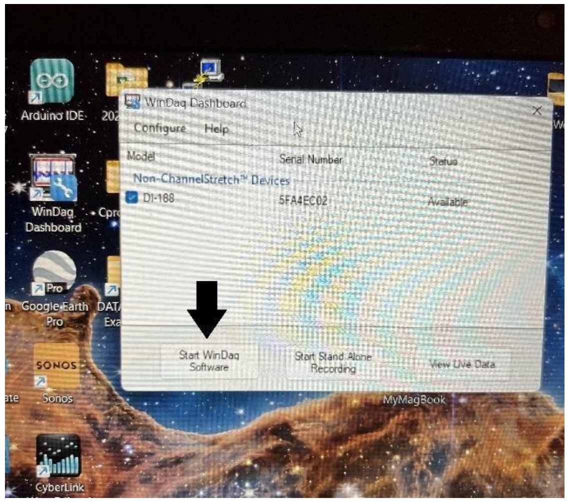

Figure 11. Start-up screen.

With the data scrolling on your screen, to select a different sampling time, click on the 'View' button on the top menu bar. A new window will open shown in Figure 12.

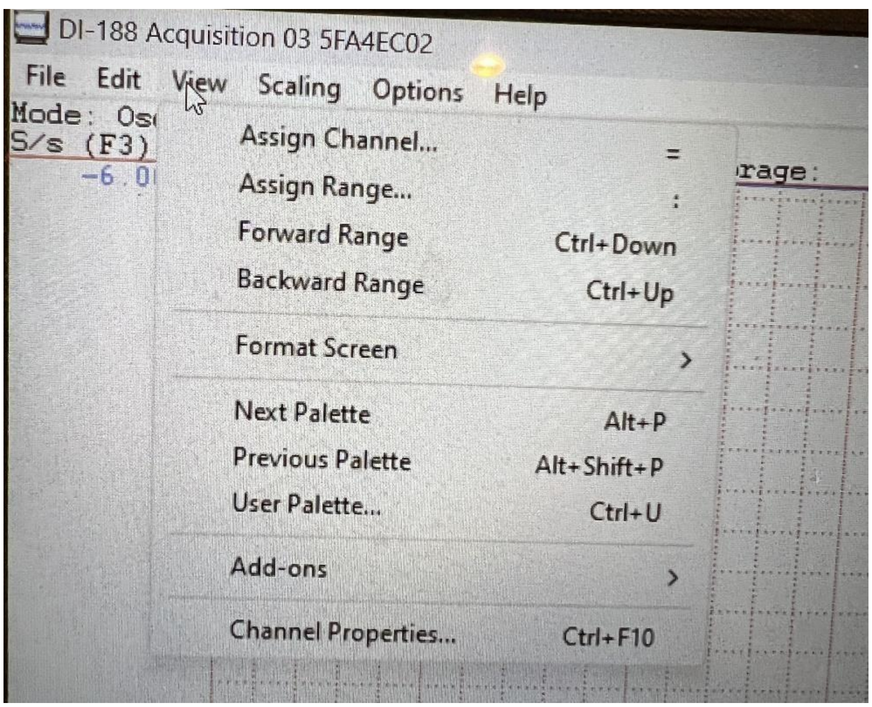

Figure 12. The View pop-up menu.

There are a number of features in this menu, but the one we are interested in is the 'Add-ons' feature. Click on it and a new menu opens up as shown in Figure 13. Click on the 'ToolBox' feature and a new menu bar will open as shown in Figure 14. On the top row of icons, click on the 'Rate' icon. It will open an input form shown in Figure 15 that lets you select the number of samples per second for the plotted and saved data. In this example, I have selected '1' as one sample per second.

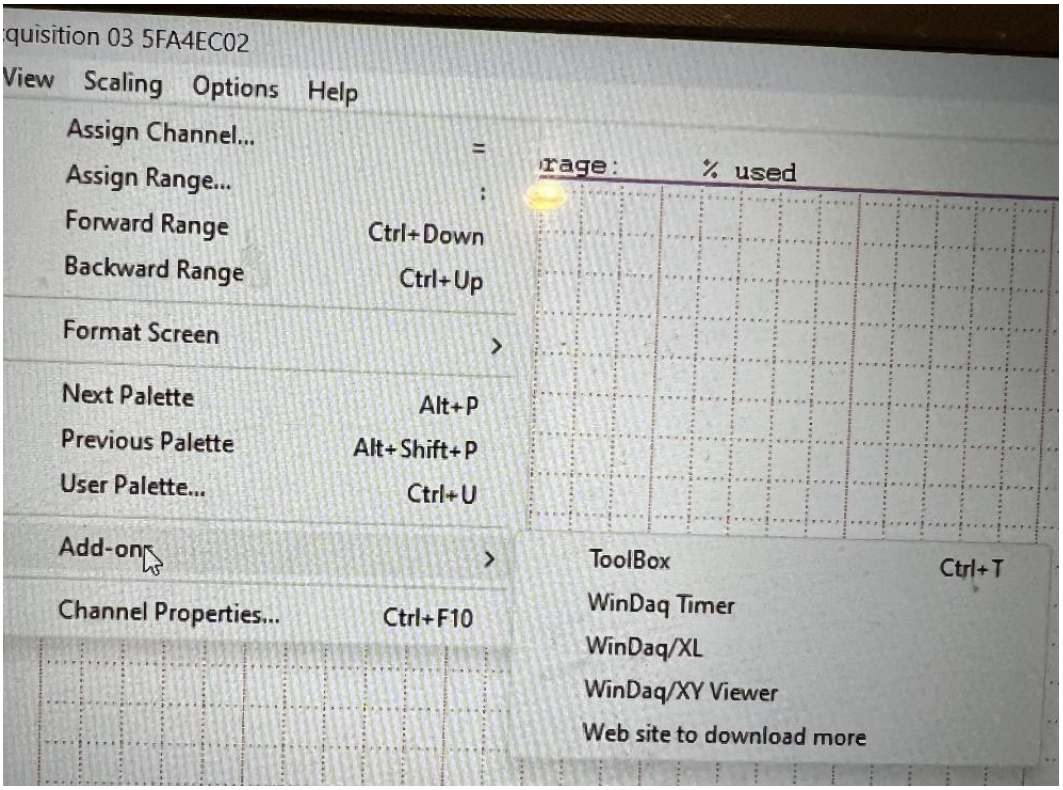

Figure 13. Opening the Add-ons menu to select the ToolBox.

Figure 14. The ToolBox menu.

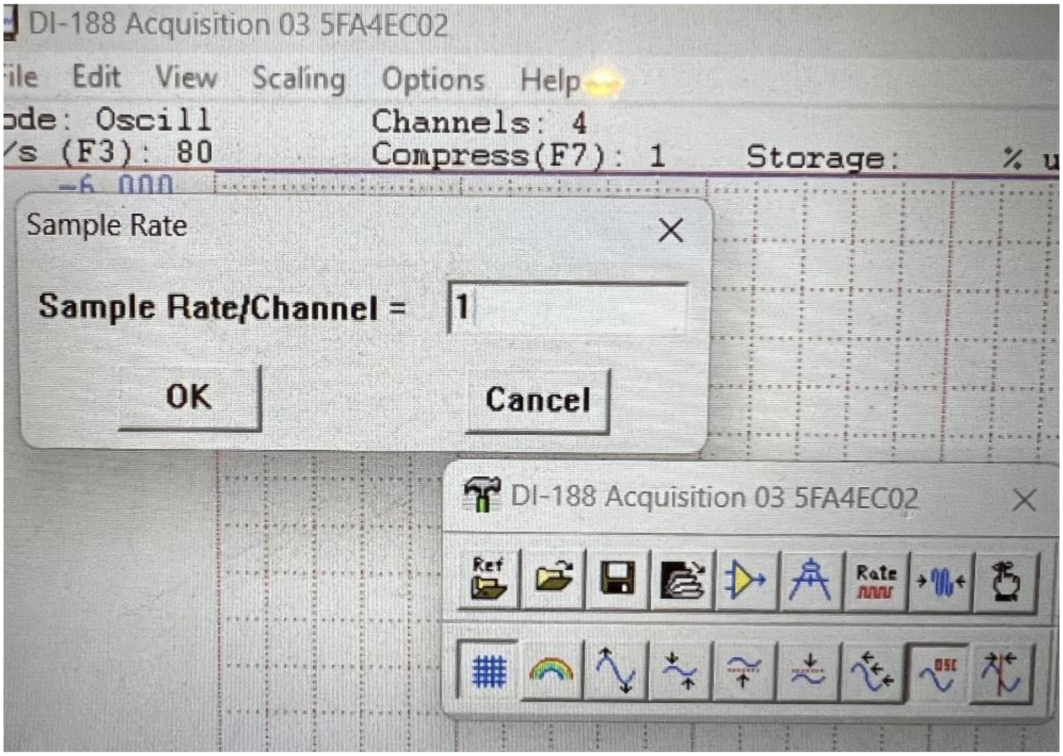

Figure 15. Example of selecting a 1 Sample per second rate.

You can adjust the Y-axis (Voltage) plotting range by clicking on the top left vertical axis value (in this case 10.000) shown by the black arrow in Figure 16. This will allow you to click on and activate the 'Scaling' option in the top menu. The pop-up Scaling menu is shown in Figure 17. Select the voltage range that gives a comfortably detailed plot of the data, in this case -6.0 to -7.0 volts. Click on the 'OK' button to update the graph display.

Once you have established that the data is displaying properly, click the 'File' option on the top menu bar. A pop-up window will appear with 'Record' as an option as shown in Figure 53. Click 'Record' to start data recording into a file. When you have finished with the data session, click on the File option and then on 'Stop' to cease recording. The real-time display, however, will continue to show the data coming in but not being recorded.

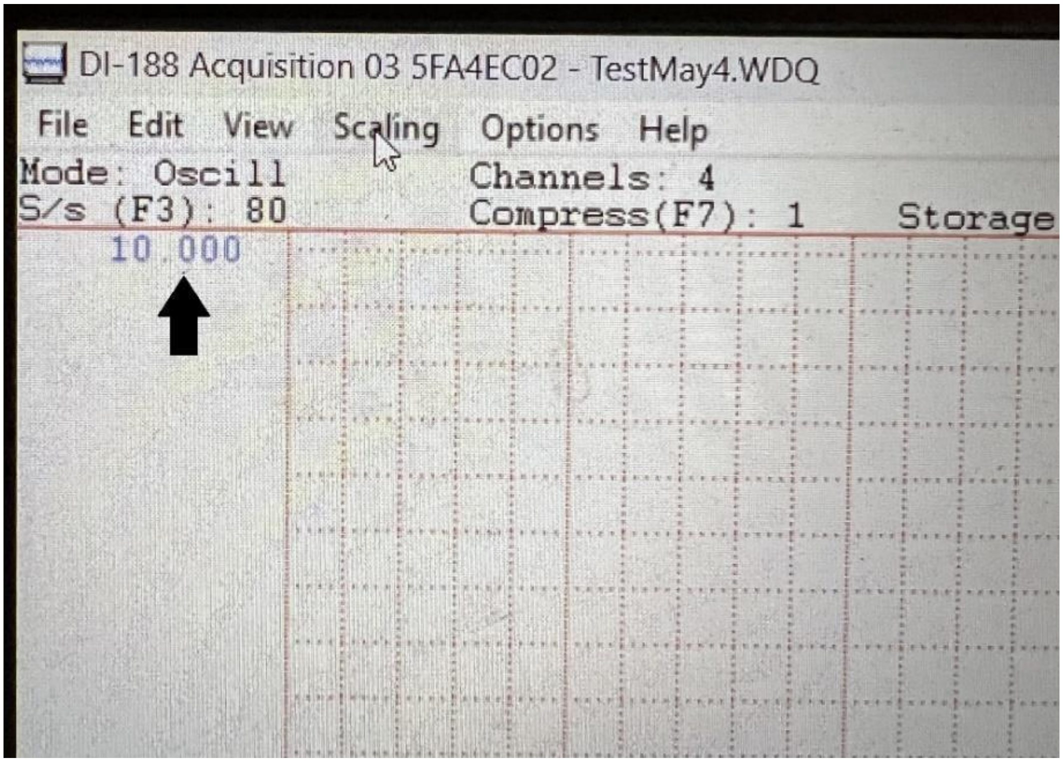

Figure 16. Accessing the Scaling window.

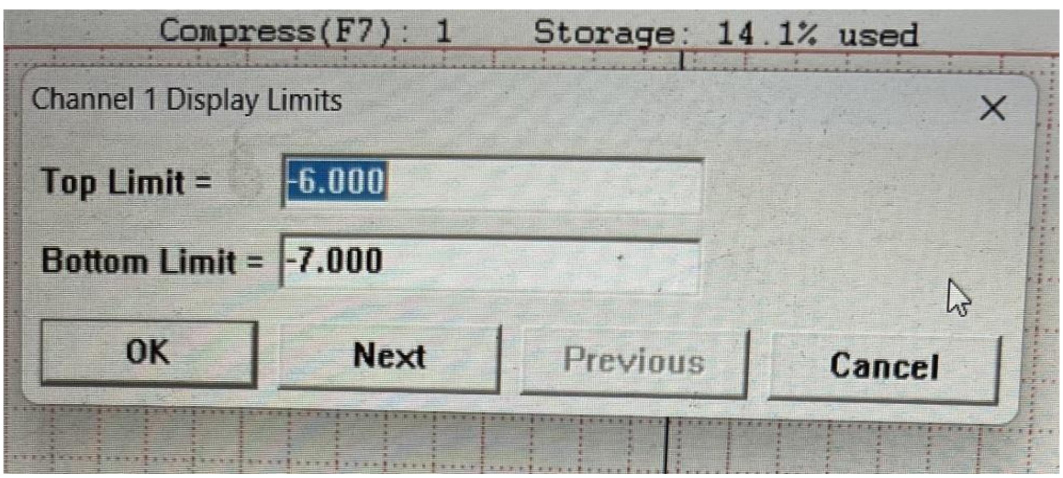

Figure 17. Selecting the Y-axis scaling limits

Open the File menu again. This time click on the ‘Browse’ function shown in Figure 18. This will open a popup menu shown in Figure 19.

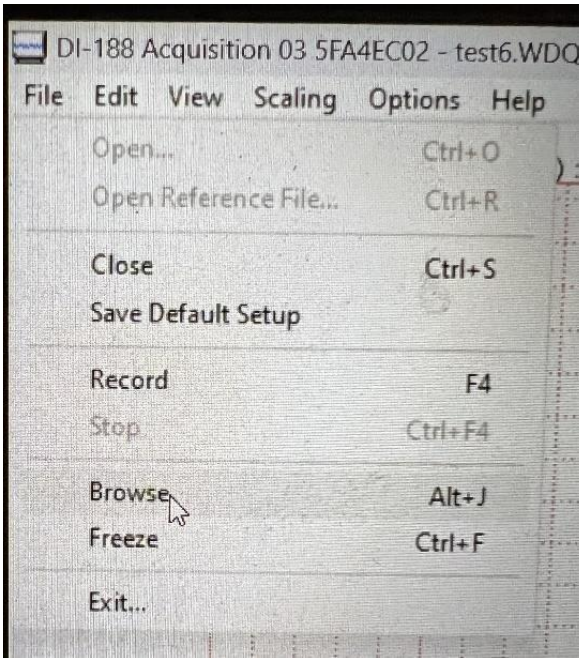

Figure 18. Enabling the Browse feature indicated by the cursor arrow.

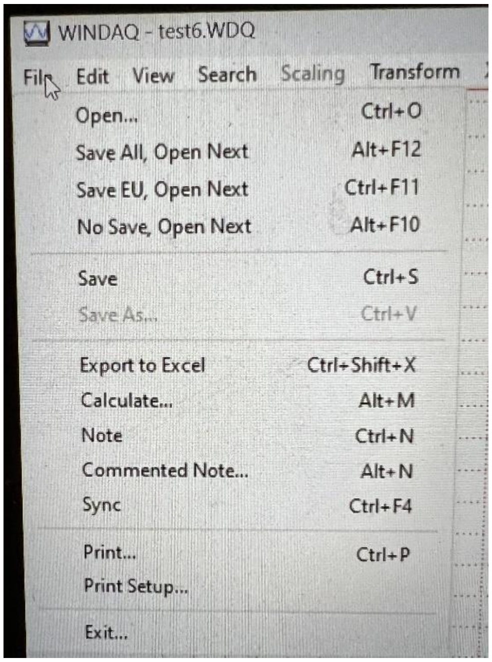

Figure 19. Options within the Browse menu.

Select the option ‘Export to Excel’. A new window will open shown in Figure 20. Select ‘Entire File’ and then click on the arrow button on the lower right corner.

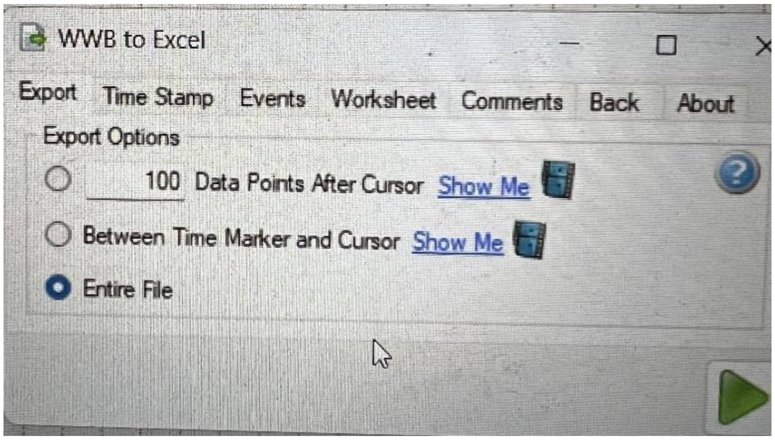

Figure 20. Copy to Excel file menu.

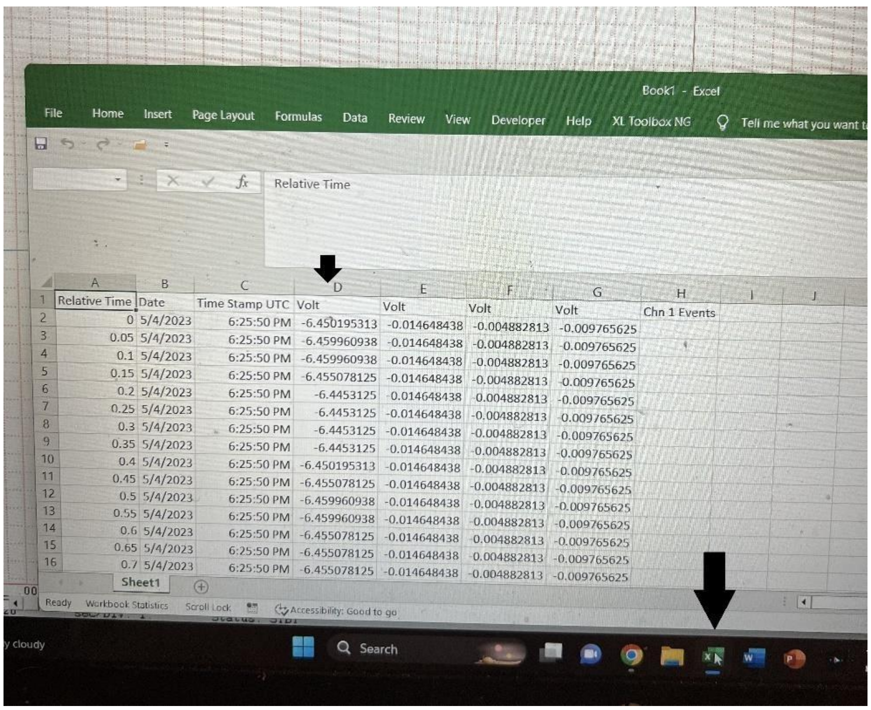

Figure 21. Example of Excel output.

The program will usually open a standard Excel file, but it may be hidden by the graphical display. Click on the Excel icon (Arrow) in your desktop tray to bring it to the front as shown in Figure 21. The data from your active channel will be displayed in Column D if Channel 1 is used as the analog input. The data will be tagged in each row by the current Universal Time (Col. C) as well as the running time (Col. A). In this example, I used a 20 Hz sample rate so the time interval between samples is 0.05 seconds as shown in Column A. You can then use standard Excel menu commands to plot the data and save the spreadsheet into a folder of your choice remembering to change the file name.

5. Testing

Once all connections have been double-checked, connect the power supply and the multimeter. The lamp should turn on and the multimeter should show changing voltage numbers on its screen as the magnet assembly swings. When its pendular and oscillatory motions cease, carefully rotate the magnetometer so that the shadow vane is exactly centered on the two photocells (called the Null configuration). The slightest movement of the magnet sensor should cause the millivolt readings to change.

With the magnetometer oriented in the Null configuration towards local North so that the shadow vane is directly over the center line between the two photocells, turn the potentiometer until the multimeter voltage reaches zero-volts. The magnetometer is now configured to detect changes in the direction of Magnetic North during geomagnetic storms relative to the Null direction in which the magnet sensor is pointing. An example of the output looks like Figure 22.

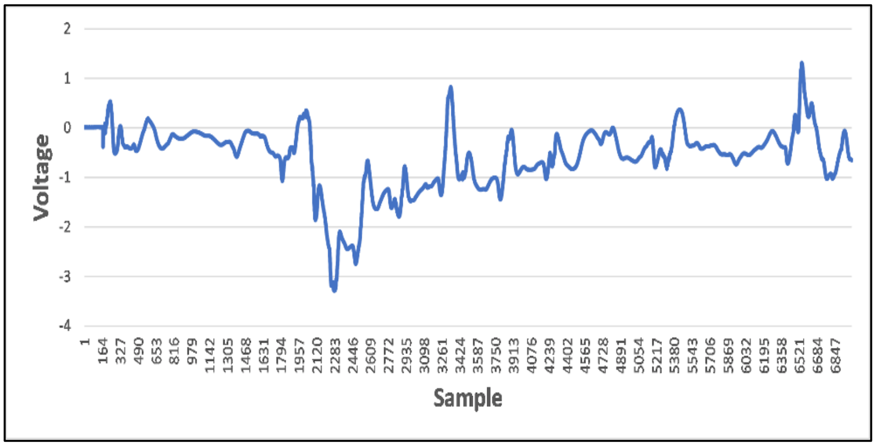

Figure 22. Baseline Null voltage with box open to dim outside light.

6. Sensitivity

Between the suspension point and the tip of the straw over the photocells, the distance is 15cm and the width of the full swing over the photocells is 24mm. The sweep angle is θ= atan(24/150) or $\theta = 9^o$. This means that the angular deviation to either side of the North direction is $\pm 4.5^o$.

The raw output from the digitizer looks like Figure 23 when the straw occulter is scanned across the photocells. When the left-hand (Western) photocell is fully covered, the output voltage reaches a positive peak. When it is between the two cells and covering one half of each, it is near-Zero. When it covers the right-hand (Eastern) cell it registers its peak negative voltage. The peaks will be equal and opposite in value when the Zero adjust is used to Null the output to 0-V when the shadow vane is exactly centered between the photocells.

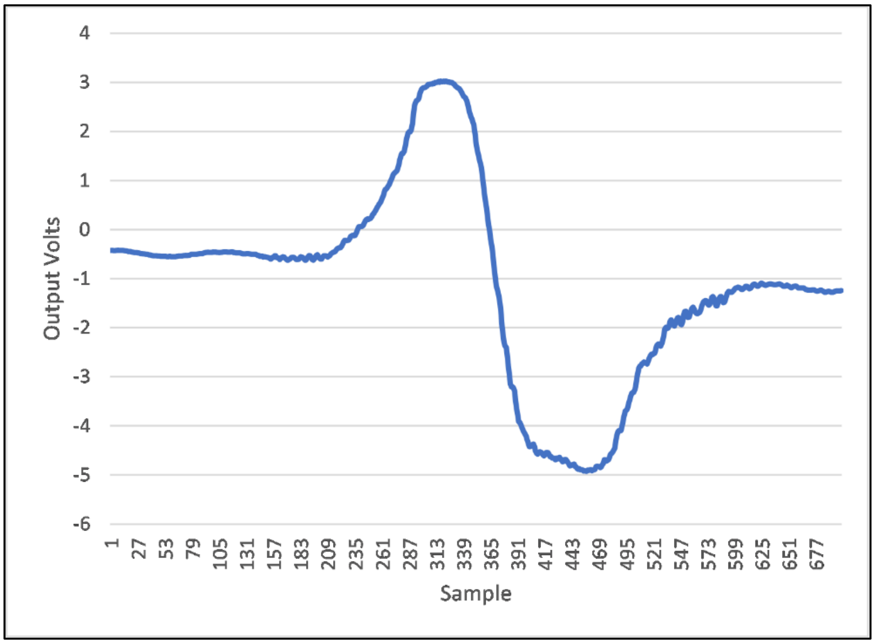

Figure 23. Example of a scan through the photocells.

In order for this system to be reliable we have to confirm that the output values represent actual magnetic changes and not artifacts from the environment. The first of these is the stability of the LED light source. If it changes, this change may mimic actual magnetic changes in the resulting plot. To check this, the system was run in two configurations. First the system was active, and the LED was turned on, but the shadow vane was moved off the photocells. This situation is shown in the data in Figure 24. This represents 44500 samples or an equivalent duration of 37 minutes. After about 30 minutes, the system reaches a relatively stable level.

Figure 25 shows 45 minutes of data taken at 20Hz of the photocell output under external dark conditions using a halogen lamp rather than the LED. The average voltage level is -6.67 V with σ = 96 mV. This is far above the σ = ± 5 mV for both photocells illuminated with no shadow vane obstruction, suggesting that the shadow vane is in constant motion due to weak air currents caused by the heating of the halogen lamp.

Under the LED illumination, figure 26 shows that the average output voltage is -8.347 and the noise is just σ = ±6.4 mV. We can also clearly see the digital 'steps' due to the 5 mV per bit resolution of the DataQ interface. The introduction of the LED lamp has improved the system noise by nearly a factor of 16-times over the halogen lamp illumination.

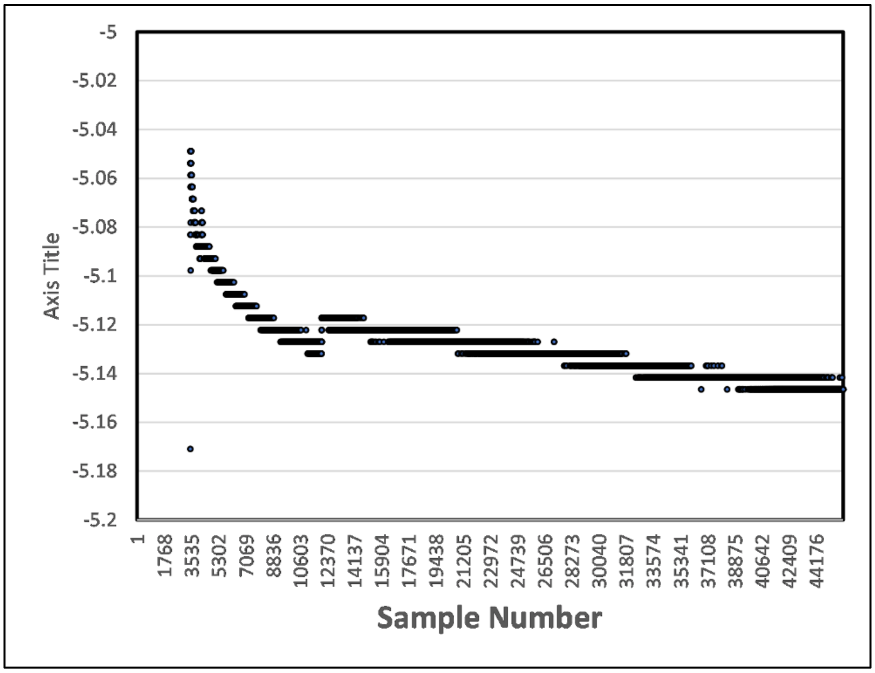

Figure 24. Illumination of photocells by unobstructed LED.

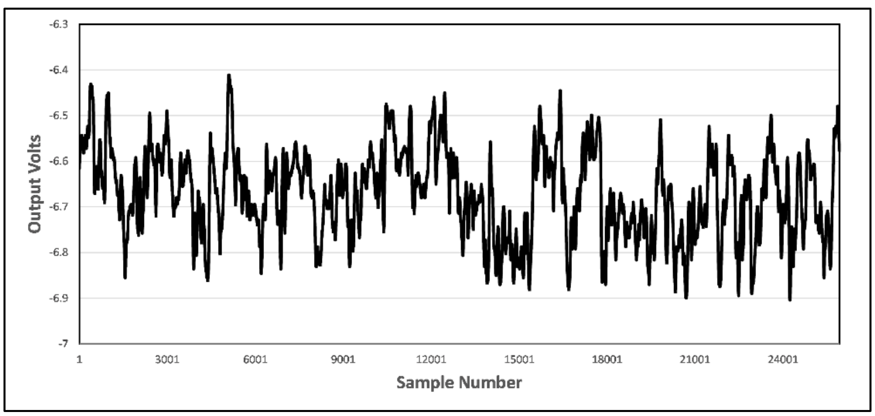

Figure 25. Photocell output with halogen lamp.

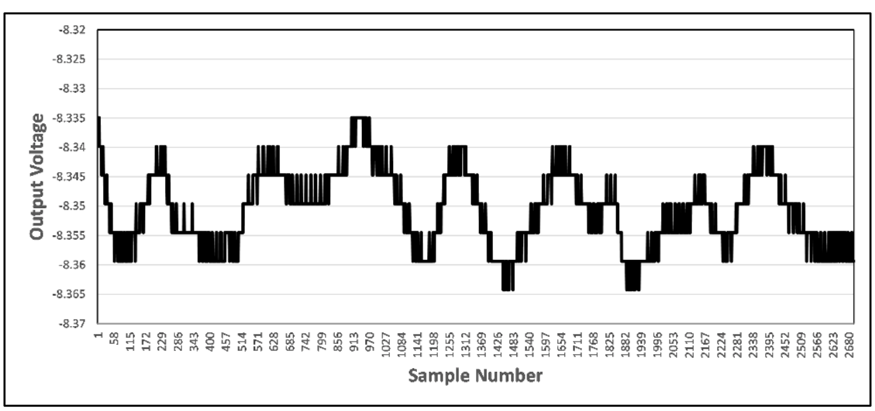

Figure 26. Unobstructed photocell output with LED.

7. Observations

Detecting geomagnetic storm events

The instrument ran continuously without interruption from 9:30 AM on May 7, 2023, to 9:30 PM that evening. This corresponded to 13:30 UT on May 7 to 1:30 UT on May 8. A geomagnetic storm was predicted for a level exceeding Kp=5 due to the arrival of a CME. Data was sampled and saved at a 1-second cadence. The actual progression of this storm is shown in Figure 27. The bracket shows the time period covered by the instrument. The actual D-component data from the nearby Frederiksberg Magnetic Observatory (FRD) shown in Figure 28 along with the instrument's data binned in one-minute intervals to match the observatory data.

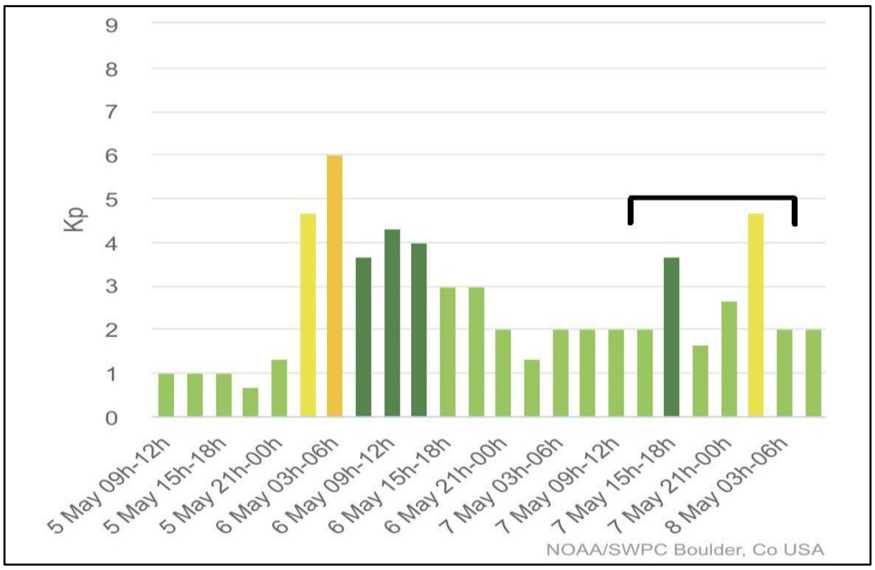

Figure 27. Kp indices from NOAA showing the current storm in brackets.

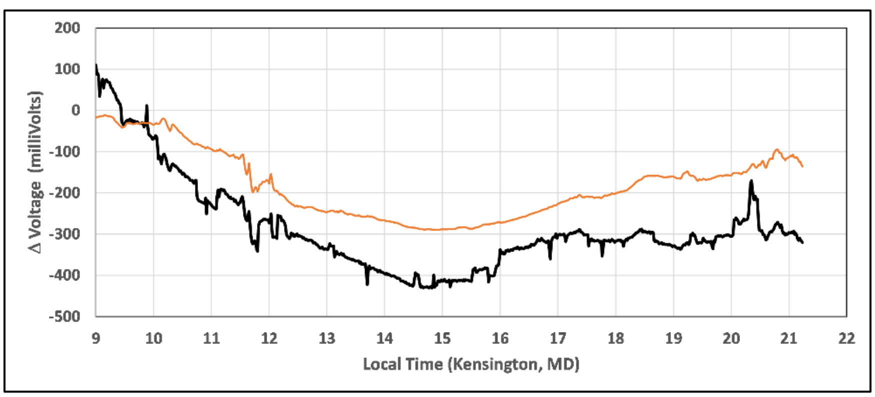

Figure 28. Data from 9:00 AM to 9:00 PM EST in Kensington, MD. Dark line is device data with average value at start of session subtracted and converted into millivolts. The red line is D-component data from FRD with arbitrary rescaling in the deflection angle to fit on the same graph.

In Figure 28, sunrise occurred at 6:02 AM and sunset was at 20:08 EST. The trace for the FRD D-component angular deflection shows a minimum near 15:00 EST (3:00 PM) and a recovery to pre-sunrise levels with an amplitude of 0.95 arcminutes. The instrument data in the black curve follows this decline and minimum near 15:00 very accurately, including a feature at about 11:45 AM, and other features between 17:30 and 19:30. Based on the depth of the minimum detected by both systems, the 0.95 arcminute change in the D-component angle corresponds to a 200-mV change in the output voltage so that C = 0.95 amin/200 mV. Since the output voltage is digitized at 5 mV/bit, this means that the resolution of this instrument is 0.024 arcmin/bit or about 1.5 arcseconds/bit.

Figure 27 shows that the geomagnetic storm achieved a maximum Kp of 4.5 during the three-hour period between 0:00 and 03:00 UT on May 8, corresponding to 20:00 and 23:00 EST local time. We see from the plots in Figure 63 that there is some activity in the FRD and especially in the device data during this time. Also, the earlier event seen in Figure 27 with a Kp of 3.5 between 15:00 and 18:00 UT or 11:00 to 14:00 EST local time is matched by the feature at 12:00 EST local time in Figure 28. This suggests that this device is capable of detecting geomagnetic activity at the latitude of Kensington (+39^{o}N) with a significant amplitude of 100 mV or twenty times the digitization threshold of the device.

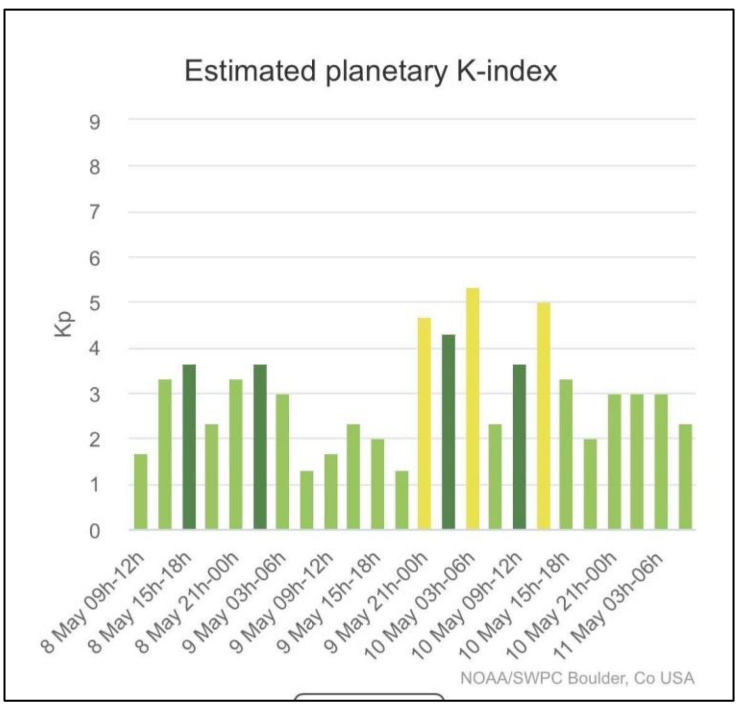

Figure 29. Geomagnetic storm on May 10, 2023, between 00:00 UT and 18:00 UT.

A second significant storm shown in Figure 29 occurred on May 10 and reached a Kp=5 around 9:30 am local time (00:30 UT). The raw data is shown in Figure 30 and the processed data with the level shifts and glitches removed and averaged into 1-minute samples is shown in Figure 31 along with the D-component data from the FRD observatory.

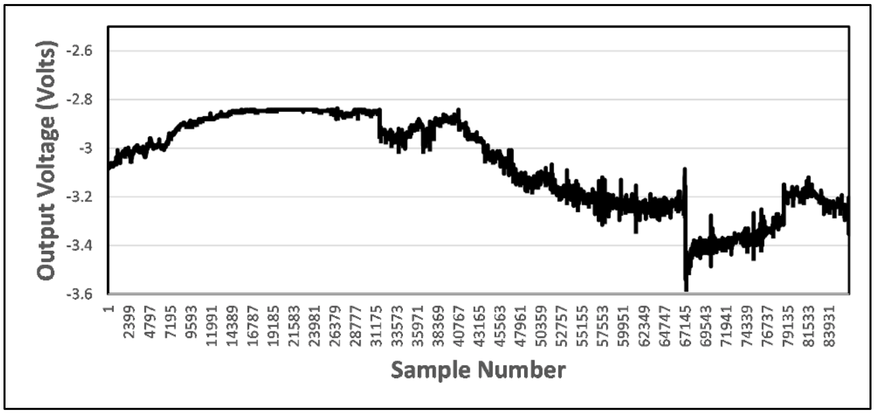

Figure 30. Raw data for May 10 storm including level shifts and glitches.

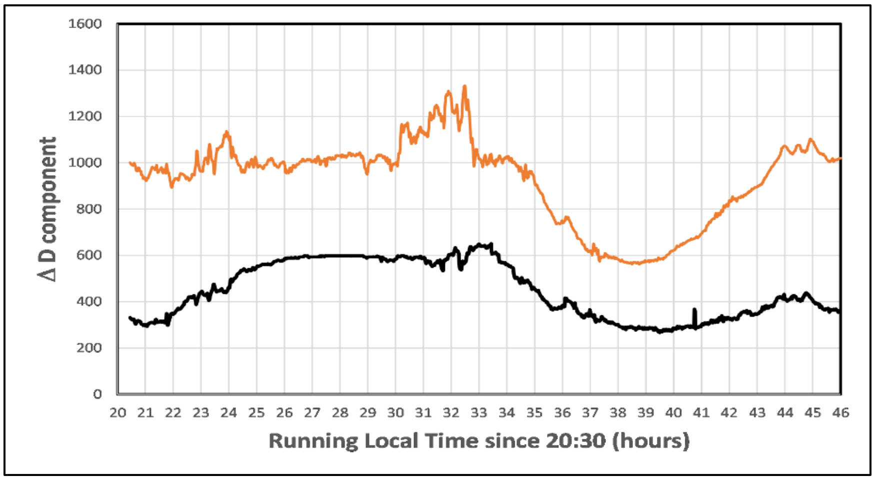

Figure 31. Cleaned data and FRD data with arbitrary shift to place both on same plot beginning at 20:30 EST (8:30 pm) on May 9 (00:30 UT on May 10)

Once again as for the previous storm shown in Figure 28, there are many features in common between the professional observatory data and the current device data in Figure 31. The Kp maximum occurred near a running time of 33.5.

The Diurnal Sq current

Of particular interest is the large dip in values between 10:00 am and 8:00 pm EST local time in Figure 31 and Running Times 30.0 to 44.0 corresponding to 6:00 am and 8:00 pm EST local time. These dips are caused by the Sq current which follows the sun as it rises and sets across the sky. The sun creates a current of charged particles in the ionosphere which form in a circular flow. As viewed from the ground, this flow looks like a donut across the sky with the sun at its center. It is most intense near the sun, and follows the sun across the sky. The current produces its own magnetic field that alters slightly the magnetic field of Earth at ground level. It is called the Sq current because it is a 'solar-quiet' feature that follows the sun across the sky during times even when the sun is not producing any storm events.

The Sq current is a diurnal feature, which means this device can detect changes in Earth's magnetic field that are present every day and not just during major solar storm events. This detection allows the home hobbyist to explore many different aspects of our changing magnetic field much as one might do with a home weather station for temperature and pressure. The strength (depth) of this daily depression is correlated with the seasons. When the sun is at maximum Noon elevation during the summer solstice, the strength of the Sq current will be at a maximum. During the winter solstice it will be near minimum strength due to the low noontime sun angle. There are also many minor events that can be detected even at nighttime such as the ones near Running Times 23-24 on Figure 31 that have to do with minor rearrangements of Earth's magnetic field especially around the time of a strong solar storm.

As the current sunspot cycle progresses toward maximum in ca 2024, I will post data from this instrument at the Astronomy Café (http:/www.astronomycafe.net) as more and stronger storms occur. Please visit this site periodically to see the most recent detection attempts. The results will be posted on my Blog under the general Blog title 'DIY Magnetometer Observations'.

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