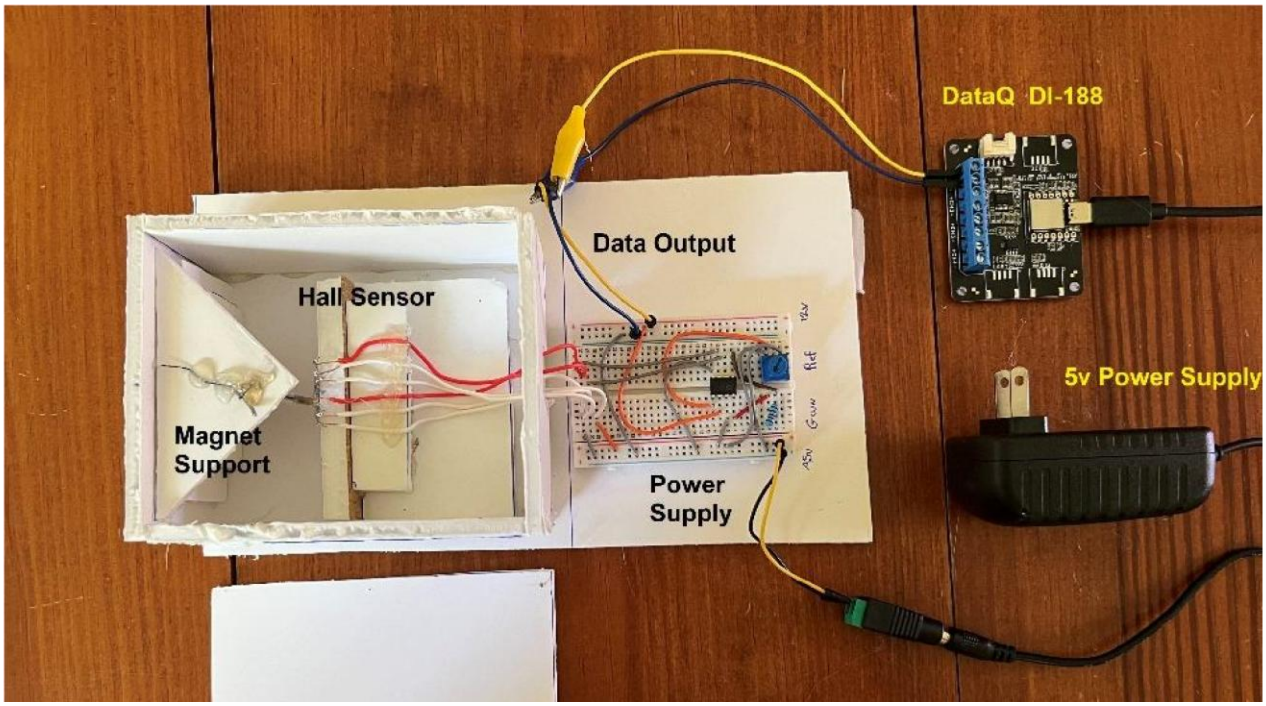
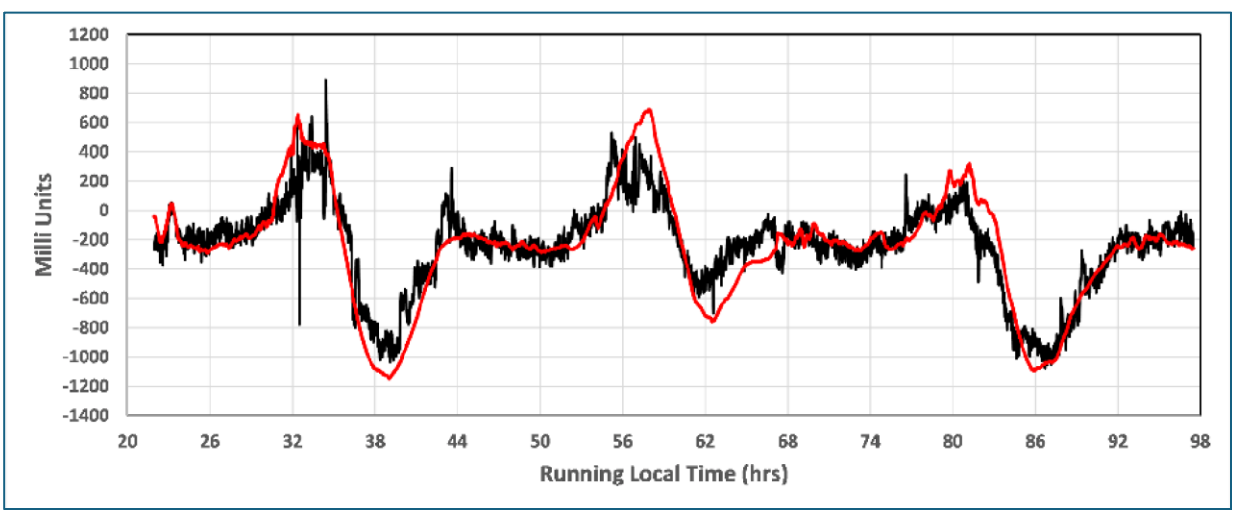
National Aeronautics and Space Administration



A Hall Effect Magnetometer for Space Weather Studies



A Hall Effect Magnetometer for Space Weather Studies

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Version 3.0: June 2024

NASA-Heliophysics Education Activation Team

NP-2023-5-070-GSFC

Introduction

Magnetometers are devices used to detect and measure magnetic fields. They range in simplicity from ordinary compasses that measure the local direction of the magnetic field polarity to sophisticated devices costing tens of thousands of dollars which are used by scientists.

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 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 your own magnetometer capable of detecting these 'magnetic storms' during severe space weather events. The design in this Guide is based on the Hall Effect sensor and can be assembled using simple low-cost components and provide greater geomagnetic storm sensitivity than 'soda bottle' designs.

This Guide is a product of the NASA Heliophysics Education Activation Team, supported by NASA under cooperative agreement number NNH15ZDA004C.

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Cover art: (Top) Assembled magnetometer showing typical arrangement. (Bottom) Typical daily data from the magnetometer (black) and the Fredericksburg Magnetic Observatory (red) showing detailed similarities and sensitivity. (Credit: The Author).

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Part I: Notes for Educators

Many NASA space missions involve measuring magnetism on the Sun, on Earth, and on other planets and bodies in our solar system. Following each experiment, an example of how NASA scientists work with magnetism, where possible, bridged the content of the experiment to the specific scientific or engineering application of the mission. ***Heliophysics*** is the study of the Sun and its effects on the Earth and the solar system. Students will learn how the 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 the Sun creates in the solar system.

When this Guide is used with students, the following information will provide an educational context for its use.

1. Overview

Students will use their assembled magnetometer to measure the 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 sunspots that affect the Earth's magnetic field. Scientists refer to the effects of these solar storms as 'space weather.' The strongest storms occur during a period in the Sun's cycle called Solar Maximum. Make sure to check where the Sun is in its cycle before attempting this experiment with students by using a service such as the NOAA Space Weather Prediction Center (https://www.swpc.noaa.gov/).

2. Objective

Students will be able to observe factors that causes variation in the Earth's magnetic field.

3. Explanation

Compared to professional magnetometers used at magnetic observatories, most of the designs we will explore (especially those involving suspended magnets) are not the ideal instruments to use to detect geomagnetic storms. But they can be used to detect some of the stronger storms at modest statistical confidence. This process requires careful analysis of the data. Generally, for severe storms with $Kp>7$, these events should be detectable in most locations across North America. These storm events are very rare, however, and occur about once every month during times when the Sun is active (called sunspot maximum). They are also unpredictable, so you need to carefully monitor such space weather websites to see if a storm is likely in the next 24-48 hours.

5. 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 the 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?

6. 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.

7. A Glossary of Terms

<u>Boom</u> – a mechanical device on a spacecraft that keeps certain sensitive instruments far from the spacecraft to reduce interference

<u>Coordinate</u> – a set of numbers that defines the location of a point in space represented by sets such as (1.5, -2.2, -3.5) for three-dimensions and (1.5, -2.2) for two-dimensions

<u>Current</u> – 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

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 a direction (up, down, etc.).

Part II. A simple Hall Sensor magnetometer

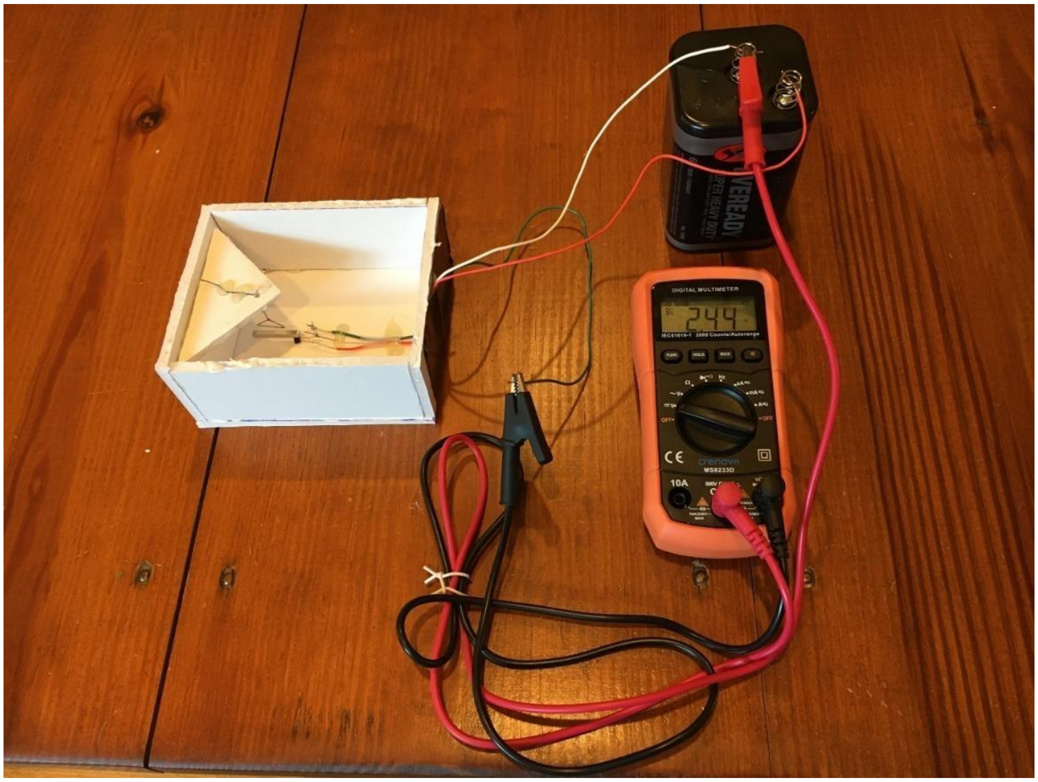

Figure 1. Completed magnetometer

1. Background

The previous magnetometer design did not use a light beam to determine the deviation angle of the magnet but instead used a smartphone magnetometer app to measure the magnetic field change of the bar magnet. It then converted this into an angular deflection.

In this design, the smartphone is eliminated and a Hall Effect sensor is used instead to sense the position of the magnet. The voltage change in the Hall Effect sensor is related to the strength of the bar magnet magnetic field and this changes as the bar magnet moves across the sensor.

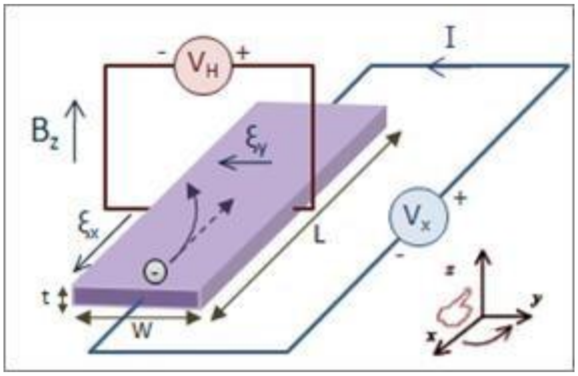

Figure 2. The basic details of the Hall Effect.

A Hall Effect sensor 'chip' creates an output voltage that is proportional to the strength of the magnetic field applied to its sensing face. It is a 1-dimensional detector. Figure 2 shows the geometry of the Hall Effect. The sensor has dimensions W x L. An operating voltage Vh is applied across the Y-axis of the sensor. When a magnetic field (Bz) is applied across the face of the sensor along the Z-axis, it generates a voltage Vx across the X-axis of the sensor. The voltage Vx is linear and scales with the applied magnetic field along the Z-axis.

2. Materials

- Bestol A1302 Ratiometric Linear Hall Effect Sensor.
- Foam board.
- Bar magnet (3 mm x 3 mm x 25 mm, NdFeB).
- Glue gun.
- 30 cm thread.
- Four sewing pins.
- Digital multi-meter that reads to millivolts.
- 3) 30 cm lengths of copper wire; 28-gauge insulated.
- Soldering iron and solder.
- 6-volt lantern battery.

The A1302 Hall-effect sensor provides a voltage output proportional to an applied magnetic field. This device has a quiescent output voltage that is 50% of the supply voltage which is between 4.5 and 6-volts DC. The output sensitivity is 1.3 millivolts/ Gauss (mV/G). A multimeter that can reliably measure to 0.001 Volts DC will allow magnetic changes of about 1 Gauss (100 μTesla) to be detected as the bar magnet swings. A typical bar magnet field is shown in Figure 3.

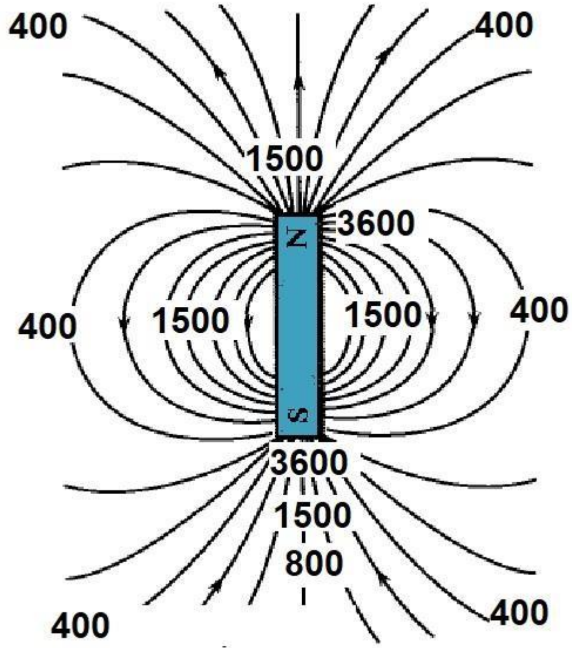

Figure 3. Magnetic field of the bar magnet in the Materials list.

3. Procedure

<u>Sensor Construction</u>

Step 1) Cut a short piece of drinking straw and hot glue to one edge of the magnet. Use the sewing thread to create a suspension system as shown in Figure 4.

Figure 4. The bar magnet sensor. Make sure that excess thread is trimmed off.

Box Construction

Step 2) Cut two pieces of foam board measuring 12 cm x 8 cm. Cut pieces for the four walls: 2 pieces 4 cm x 8 cm and two interior pieces 4 cm x 12 cm". The two long side will be mounted ON TOP of the base, and the two shorter pieces will be mounted ON TOP of the base in-between the two long sides. This way, the top piece will fit flush with the sides. Use the hot glue gun to carefully assemble the sides on the bottom piece. Do not attach the top piece.

Step 3) Bar magnet suspension: Now we need to suspend the magnet inside the box independently of whether the lid is on or off so it cannot be merely suspended through a hole in the lid. To do that, we must create a suspension framework attached to the bottom of the box. Figure 1 shows one design for such a framework using foamboard elements. A rectangular piece of foamboard, Wall-A, was cut and hot glued to the interior wall of the box.

Step 4) Cut a triangular piece, Piece-B, with sides of 6.4 cm and a hypotenuse of 8.9 cm and place it atop the Wall-A. Locate the magnet's midpoint on this triangular piece and use an awl or a nail to punch a hole at this location. The magnet will be suspended from its midpoint by a string and the string will be fed through this hole. When suspended, the North Pole of the magnet will be directly over the Hall effect sensor location.

Step 5) Hot glue the hypotenuse of Piece-B to the top edge of Wall-A, and hot glue a small piece of foamboard to the underside of this joint to reinforce it. The sensor has a mass of only 7 grams or less depending on the type of mini magnet used so it will not place much strain on the foamboard support joint unless the box is severely shaken.

Step 6) Thread the Sensor string through the hole in Piece-B. Place the Hall sensor directly under the spot where the magnet's North Pole will cross. Adjust the height of the suspended magnet so that it will hang freely just above the Hall sensor. Make sure that the Hall Sensor chip does not touch the magnet but is about 8 mm from the bar magnet's North Pole end. Hot glue the thread in place securely so that it does not slip and change the height of the magnet.

Preparing the Hall Sensor

The A1302 Hall sensor is about 3 mm x 2 mm x 1 mm in size and has three leads. Figure 5 shows the designations for the leads.

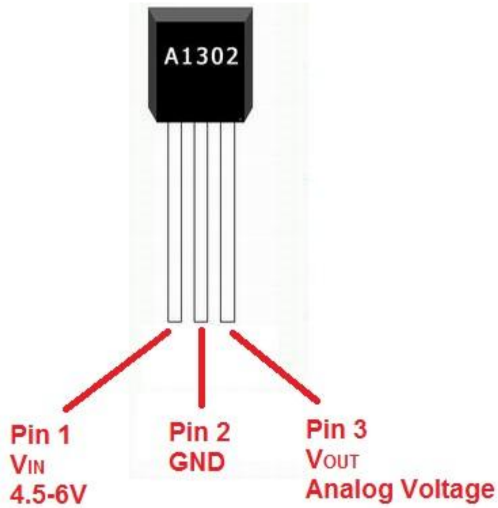

Figure 5. Diagram of the A1302 Hall sensor. Pin 1 receives positive DC voltage for the sensor to work. This, again, is voltage between 4.5-6V. Pin 2 is the ground, so it receives the ground or negative terminal of the DC power supply. Pin 3 is the output of the IC, outputting an analog voltage in proportion to the magnetic field it is exposed to.

The Hall sensor is so small that there is no writing on its faces to identify the orientation for which the pin assignments in Figure 5 apply. The only clue is in the physical shape of the device. Note that it is not a perfect rectangle but has one flat side and one tapered side. Place the sensor with its flat side down and the smaller tapered face up. In this orientation, the input Vin voltage (+) is the pin on the left. The center pin is for the battery ground (- terminal) and the pin on the right is the output voltage.

Step 7) Adjust the orientation of the entire box so that the rest position of the bar magnet is aligned with the long axis of the box.

Step 8) Strip about 12 mm of insulation from each end of the three pieces of copper wire. Bend the pins from the sensor carefully so that they can be easily soldered and provide access for the wires. Solder one end of each wire onto the three pins of the Hall sensor as shown in Figure 6A. Do not overheat the wires as you solder them because this could damage the sensor. Bundle the wires together with a piece of tape.

Step 9) Cut a small hole in the box and thread each of the wires through this hole. Label each wire with a tag that indicates V (for voltage input), G (for Ground) and O (for Output).

Step 10) Feed the wires through the hole from the inside of the box and position the Hall sensor under the pole of the suspended magnet. Glue the bundle of wires to the bottom of the box and make sure the Hall sensor remains flat under the magnet and about 3 mm of an inch below the magnet as it freely swings. Also, use a piece of tape to tape down the wires outside of the box so that they do not put direct pressure on the tie-down on the inside of the box. This prevents movement of the external wires from being communicated to the Hall sensor placement. The result should resemble what is shown in Figure 6A.

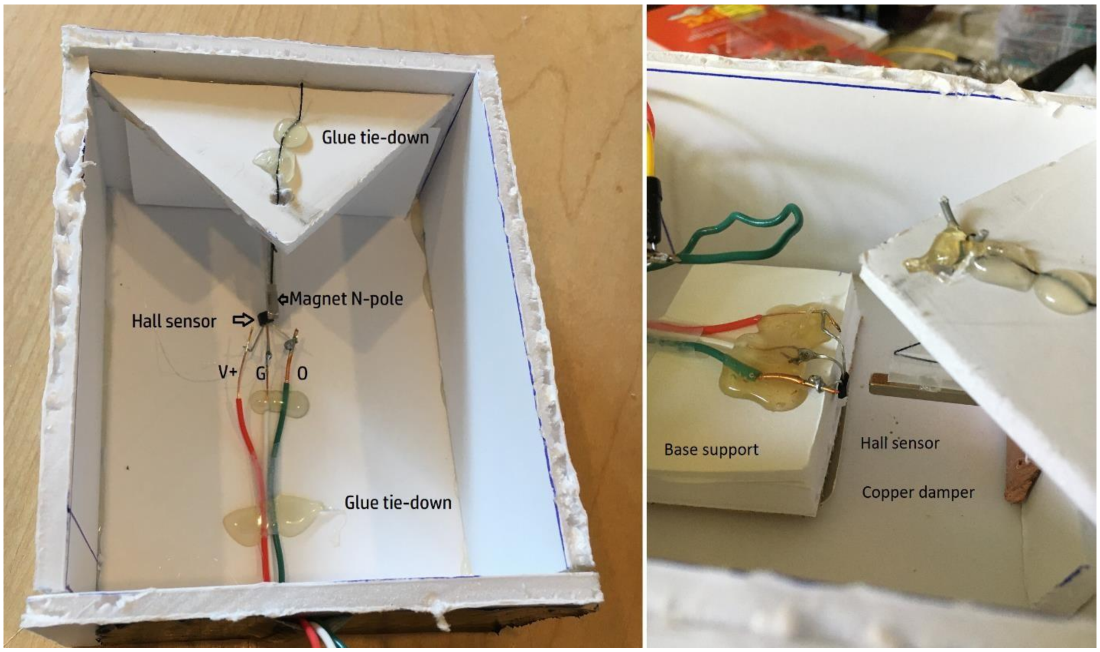

Figure 6. A) Hall sensor system with lid of box removed to show placements. B) An alternative configuration for the sensor.

An alternative way to mount the Hall sensor is so that the active surface of the sensor is directly opposite the pole of the magnet as shown in Figure 6B. This will require attaching the sensor to the front of a block of foam board so that its height is equal to the height of the magnet. A liberal amount of glue should cover the sensor leads so that they do not shift. The advantage of a front-mounted sensor in Figure 6B is that the perpendicular flux of field lines through the sensor will be higher and yield a higher output voltage. <u>The disadvantage is that it is unresponsive to small angle deflections below about 5^o and so it is not useful for geomagnetic storm detection.</u>

Step 11) Attach the top of the magnetometer box by using several sewing needles as 'nails' so secure the lid.

<u>Connecting the Hall Sensor</u>

Step 12) Attach the V-wire to the positive terminal of the 6 V battery. Attach the G-wire to the negative terminal of the battery.

Step 13) Attach the multimeter leads between the negative battery terminal and the O-wire. Turn the multimeter on and select the 'DC-volts' scale.

Step 14) Move the bar magnet slightly and observe how the voltage measured by the meter changes. The Hall sensor will read +2.5 V when no magnetic field is applied. Its maximum range is up to +5.0 V when the North pole of a magnet is brought near, or 0 V when the South Pole is closest. You may need to select a range that shows this change easily over the 0 to 5.0 V of the sensor's output range. Figure 7 shows a typical set up.

When the magnet swing is +/- 6 mm, the voltage changes up to +/- 0.2-volts but when the swinging is barely discernable to the eye over small angles, the changes are about +/- 0.02-volts.

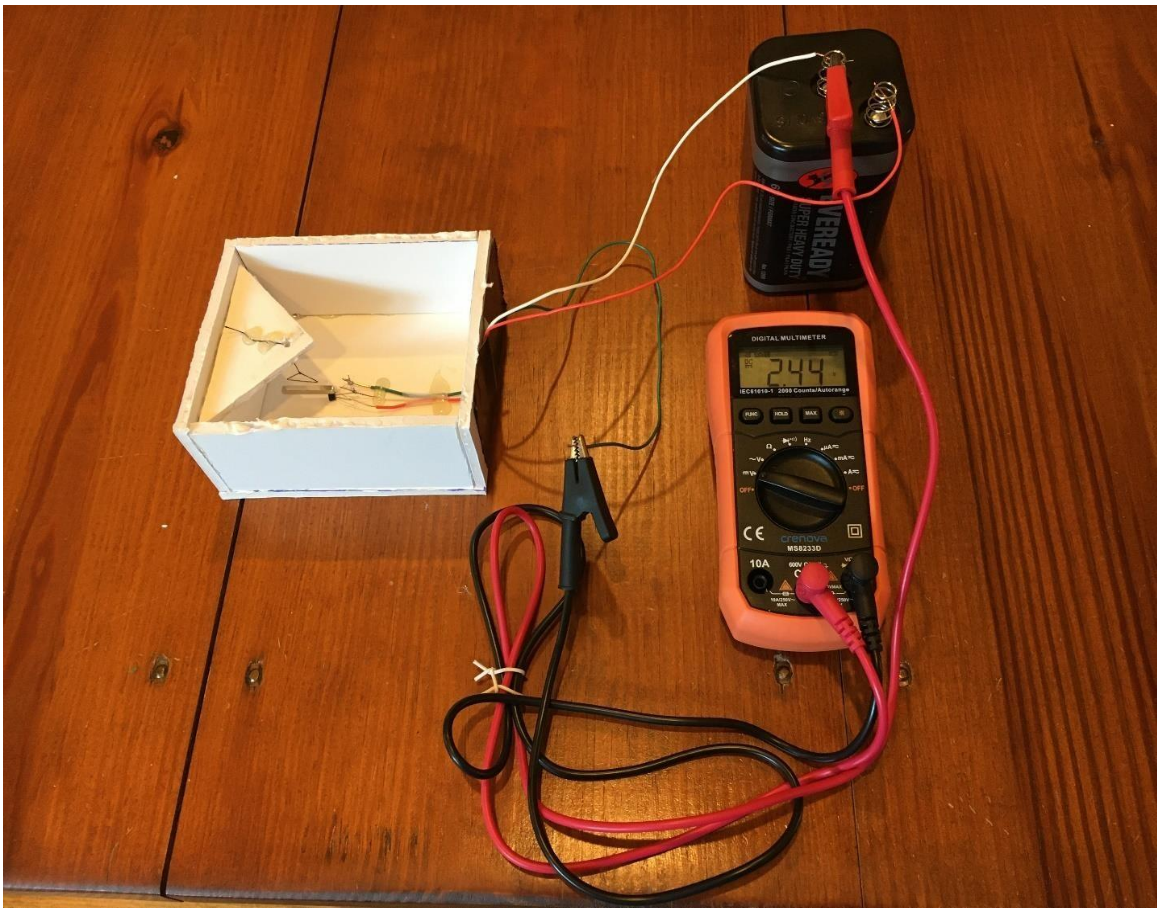

Figure 7. Measuring set up for the Hall sensor magnetometer. White wire is the ground Battery – and the red meter lead. Red wire is V+, and Battery+. The Green wire is clipped to the black meter lead.

Most inexpensive multimeters can read to 0.01 V which according to the Hall sensor scaling of 1.3 mV/Gauss, makes the measurement sensitive to about 13 Gauss changes in the placement of the suspended magnet, which according to

Figure 3 has a strength of about 2000 Gauss. So, this metering system can detect a ΔB = 100*(13/2000) = 0.7% change in the suspended field orientation. More expensive multimeters can display values to 0.001 V or 1 mV so that changes as small as 0.07% in the field strength can be detected.

4. Troubleshooting

If no change is observed in the Hall sensor output, try these steps:

- The typical sensitivity of a Hall sensor is about 0.0013 V/Gauss, so the strongest magnetic field it can measure is 2.5/0.0013 = 1,923 Gauss. If your bar magnet at its distance from the sensor is stronger than this, the Hall sensor output will show a constant +5.0 V. You need to either increase the distance between the magnet and the sensor, or use a different, weaker magnet type. Generally, neodymium alloy magnets are too strong for this. The magnet used in this design has a magnetic field shown in Figure 3. So long as the Hall sensor is no closer than about 6 mm from the magnet (greenish color) the intensity of the field will be below 2000 Gauss. Re-adjust the height of the magnet using the suspension tread until the output voltage no longer ‘saturates’ the multimeter range.
- Check that your wires are correctly matched to the output pins of the Hall sensor.
- Instead of using a 6 V battery, use 3, 1.5 V A or AA-type batteries connected in series to provide 4.5 V at the lower input voltage Vin of the Hall sensor. This will provide fewer volts of output for the same applied magnetic field intensity.
- Check that the Hall sensor was not damaged during soldering. You may need to replace the installed sensor with a new one and be more careful with soldering. The sensors cost about $1.50 each so this trial-and-error approach can be costly.

5. Calibrating the deflection with the output voltage.

When the power supply is turned on, the Hall sensor voltage should vary as the magnet moves across it. We can use the laptop digital interface to capture this data. The representative data from the bottom-mounted configuration (Figure 6A) is shown in Figure 8. The sensor was undisturbed between times 25-30 and times 50-65. The activity between Times 33 and 45 show the disturbed magnet moving in an oscillation in the horizontal plane with no magnetic damper being used. The maximum amplitude of the oscillation is about 10^{o}, so the voltage scale implies 10^{o}/500mV or 0.02^{o}/mV.

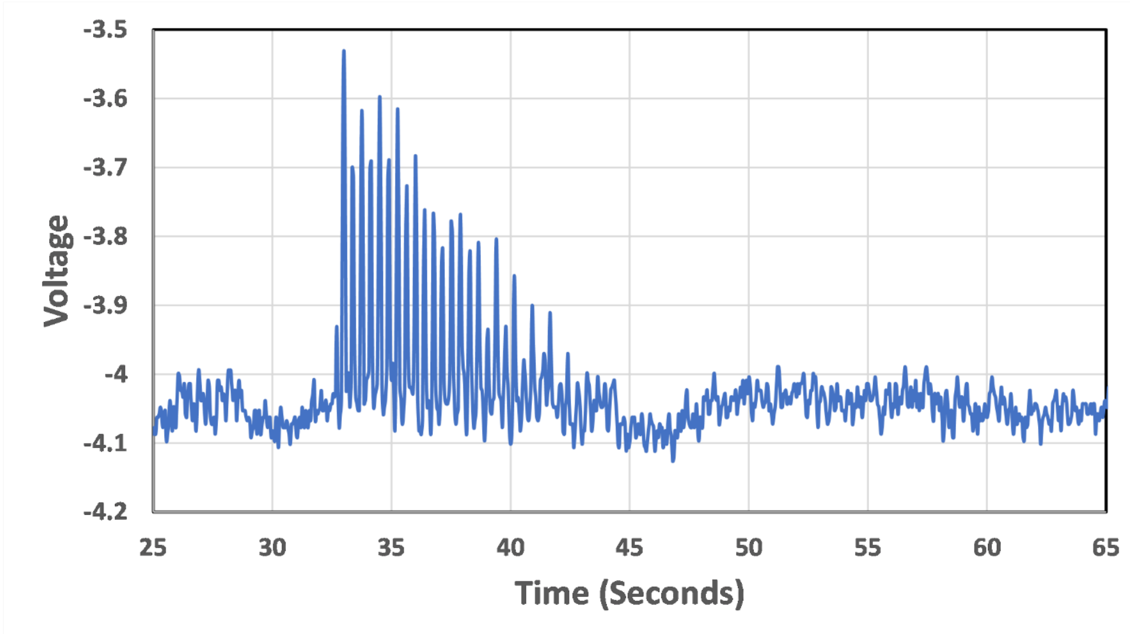

Figure 8. Representative output from sensor. The multimeter records a voltage of about 1.6 V, but the digitizer applies a -5V offset to the data.

From the .csv file, the jitter 'noise' in the quiet sections of Figure 8 based on the section between Time 50 and 55 (120 samples @ 24 samples/sec) gives <V> = -4.0353 with a standard deviation of σ = ±19.3 mV. This s.d. converted into degrees corresponds to an uncertainty (1-σ) of 0.02x19.3mv =± 0.39^{o}. Can this be reduced by making more measurements?

For N=120 samples spanning 5 seconds we get a measurement 'noise' of σ = ±0.39^{o}. The magnetometer was left undisturbed for 10 minutes to accumulate 14,400 samples. The data is shown in Figure 9 with the lid on.

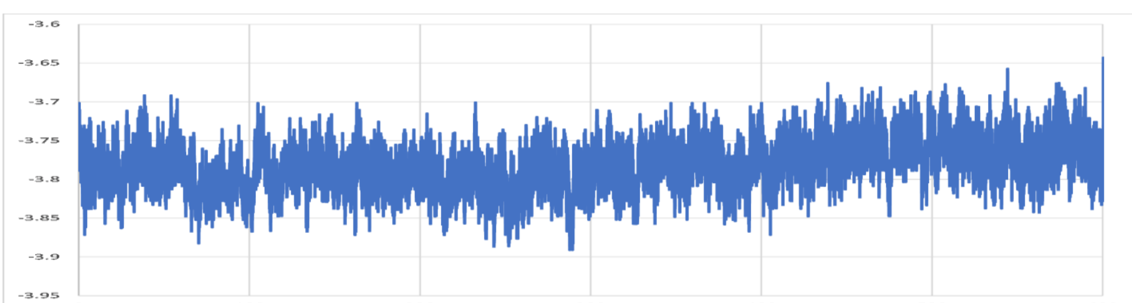

Figure 9. Example of long-term monitoring of magnet position with cover on to minimize air currents.

From the N=300 samples between 100 and 400 in Figure 9 with the cover on, the s.d. of this quiet data is σ = ±23 mV so the regulated power supply is only slightly less noisy than the battery, but both are essentially comparable. It is also more reliable in producing a fixed output voltage rather than sagging over time as the battery discharges.

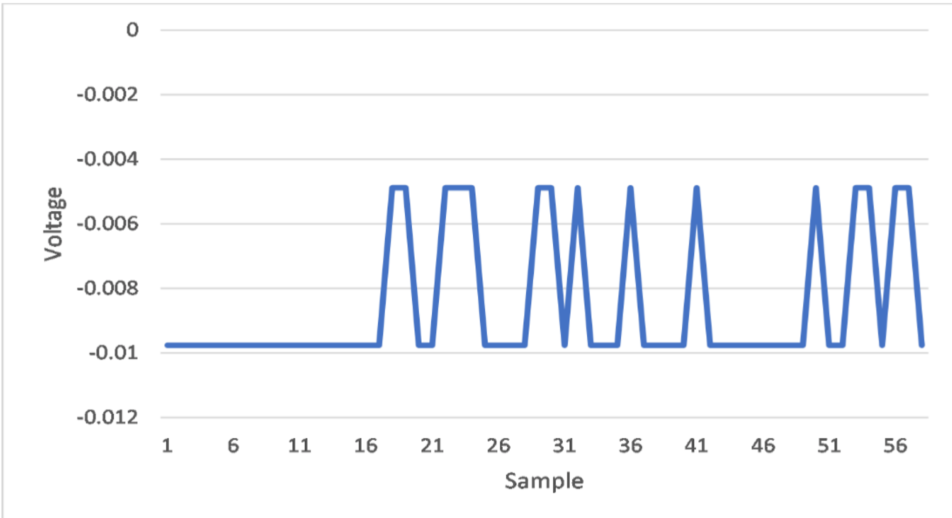

Figure 10. Example of digitization noise in the data.

The limit to the sensitivity is set by the digitization step size. We can see this by enlarging a quiet portion of the data shown in Figure 10. We see the digitization noise, 1bit at (-0.004882) – (-0.009765) = 0.0049 volts or 5 mV. The digitization level 1 LSB = 5 mV corresponds to 5 x 0.02 = 0.1°. This is the smallest deflection we can detect in the absence of any other sources of noise in the measurement process no matter how many samples we average together.

A more concerning problem is that over the long term, the output voltage drifts up and down with a spread of about 0.1 V. This leads to a systematic component to the total measurement uncertainty of ± 0.1V/2 or ±50 mV. This is about twice the measurement noise level of σ = ±23 mV we calculated earlier. This variation will significantly limit our sensitivity unless it averages-out over the many hours during which a geomagnetic storm occurs. In principle, it can be removed by fitting it with a polynomial of high-order and then subtracting this model from the data to 'flatten' the data. The result should be a s.d. for the baseline-corrected data that is close to the ±23 mV value we calculated from undisturbed data.

Now that we can digitally readout the battery-operated sensor, we want to put the sensor through some specific angular deflections and measure the output voltage over the range that the Hall sensor can operate with the magnet. To do this, create a rig where the sensor case can be smoothly turned through a series of angles. Figure 11 shows an example of this data where the sensor has been turned through the angular range from 10º to +10º relative to the zero 'Null' direction, which will nominally be Magnetic North.

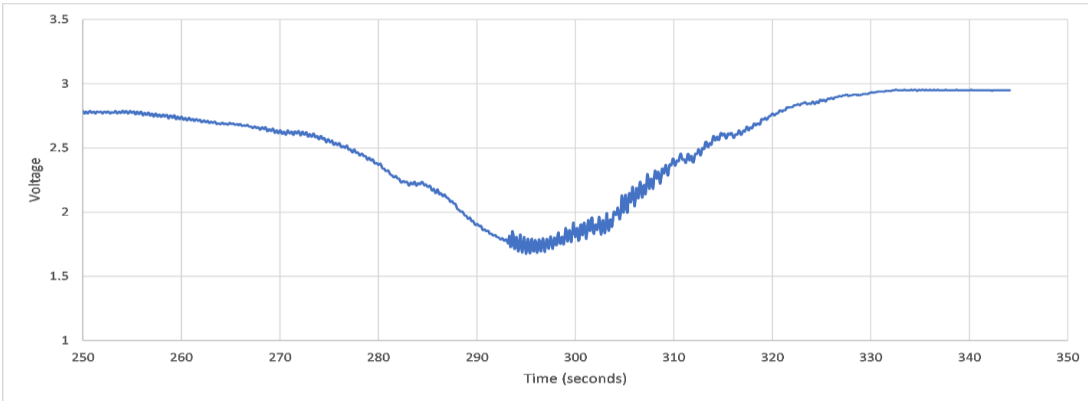

Figure 11. Example of smooth rotation of magnet and voltage output from the bottom-mounted Hall sensor. The wiggles are from the slight magnet oscillations during the move.

Table 4 was produced by taking measurements every 1º during the rotation with Point H as the null direction.

Table 4. Calibration data for bottom-mounted sensor with no damping.

Angle Label	Magnet Deflection (East=+)	Deflection from Null	Voltage (mV)
A	50.5	39.5	2.866 weak noise
B	57	33	2.80 Noise gone...just LDB
C	63	27	2.70
D	68	22	2.55
E	73.4	16.6	2.34
F	79	11	2.06
G	85	+5	1.85
H	90	0	1.78
I	95	-5	1.89
J	100.5	-10.5	2.08
K	106	-16	2.28
L	112	-22	2.45
M	118	-28	2.55
N	124.5	-34.5	2.70
O	130.5	-40.5	2.76

The graph in terms of deflection angle is as follows is shown in Figure 12 and 13.

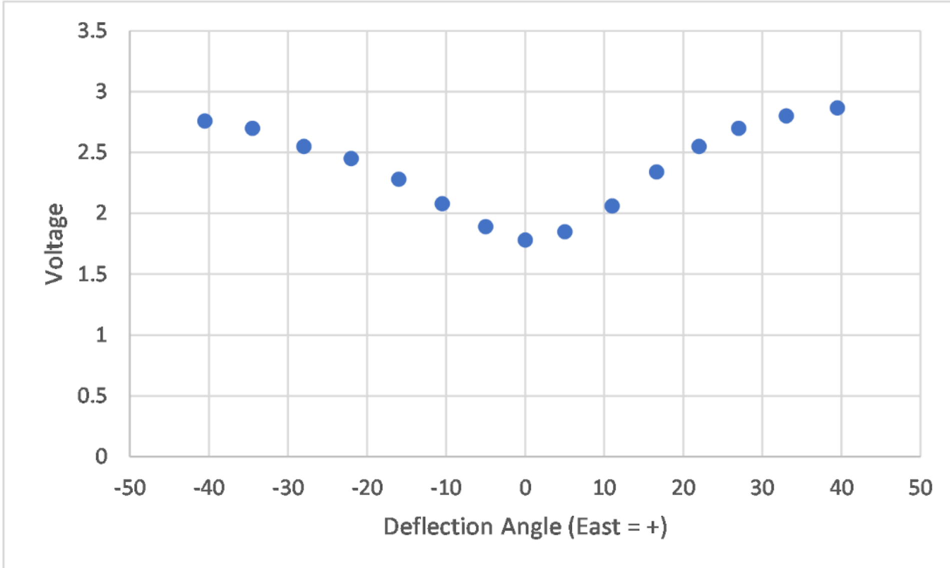

Figure 12. Voltage versus deflection angle.

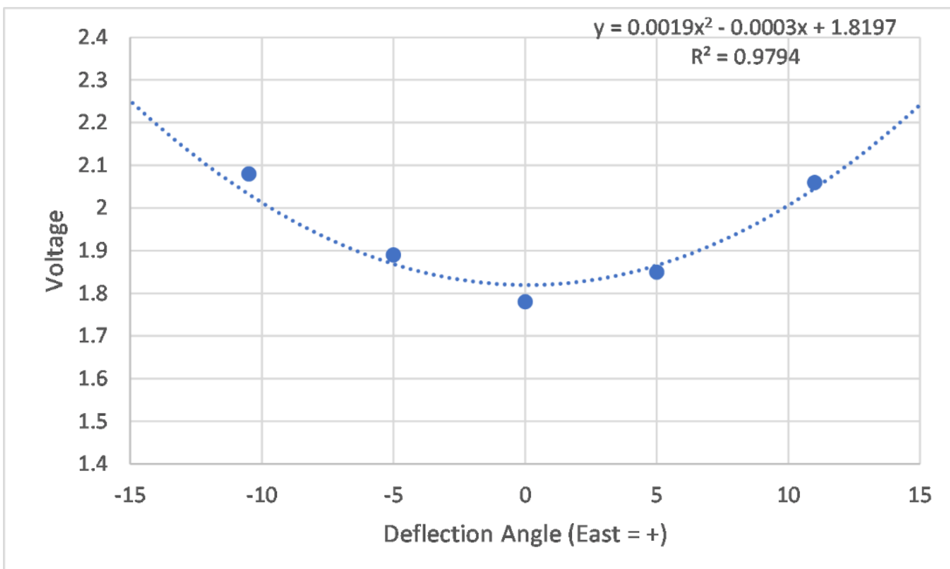

Figure 13. Correlation for small angle deflections typical of geomagnetic storms.

This is a pretty good fit but very sparce in the 1° domain in which we are interested. The voltage change between the null direction and a deflection of 5° is only about 70 mV and is even less for angles lower than 1°. Because the curve is so flat, without amplification we will not see weaker storms with deflections below this.

Table 5. High resolution data.

Deflection	Calib4
-5	2.019
-4	2.000
-3	1.985
-2	1.965
-1	1.960
0	1.950
1	1.945
2	1.956
3	1.960
4	1.970
5	2.000

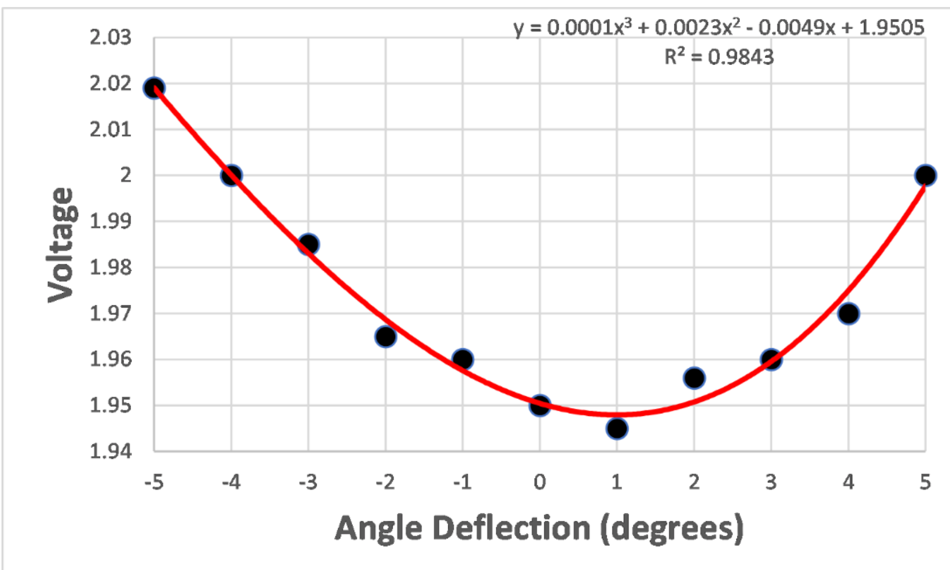

Figure 14. Additional data for smaller angular steps.

Table 5 and the graph in Figure 14 shows that the axis of the magnet is offset by about 1° East from the reference Null direction. Between deviations of zero and 1° where many geomagnetic storm events occur, the amplitude is only +/-5 mV. (i.e. 1.945 at null vs 1.950 at 1°). When compared to the digitization level of 1 LSB = 5 mV (0.1°) found previously, these weak storms would be undetectable. Stronger storms that produce 1° or more deflections would be detectable at S/N > 3-sigma.

Part III. Improved design with magnetic damping.

According to Lenz's Law, when a magnet passes over a conducting surface, the magnetic field induces currents in the conductor that produce an opposite-polarity magnetic field in the conductor. This magnetic field works against the passing magnet to slow it down. Magnetic damping via these eddy currents is a major ingredient to magnetic breaking in trains and even roller-coaster rides[1].

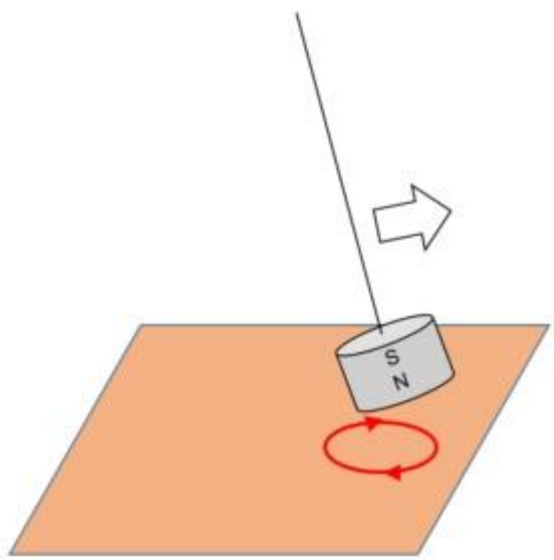

Figure 15. Moving magnet creates eddy currents in the conductor that provide magnetic breaking.

We will use this idea by adding a copper plate near the S-pole of the magnet.

1. Material

- Copper bar.
- Foamboard.

2. Procedure

Step 1) Cut one piece of foamboard 2 cm x 2 cm x 9 mm.

[1] https://nationalmaglab.org/education/magnet-academy/watch-play/interactive/foucault-s-disk

Step 2) Cut a 2 cm x 2 cm piece of copper from the stock bar. This will require a hacksaw and a vise, which are common in most home hobbyist workshops.

Step 3) Hot glue the copper piece to the 2 cm x 2 cm foam board piece.

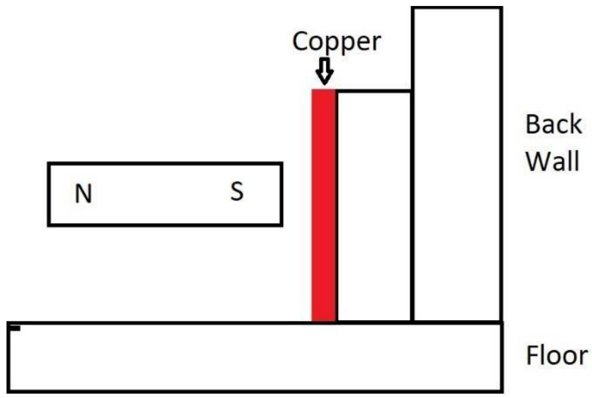

Figure 16. Construction and mounting of copper piece.

Step 4) Hot glue this assembly inside the sensor box, opposite the South-pole of the sensor magnet. When the magnet is pointing due-North with the Hall sensor directly below the North pole of the magnet, the magnet is perpendicular to the copper face and about 1/8 inch from the S-pole of the magnet as shown in Figure 16. The final assembly should look like Figure 17.

Figure 17. Magnetic damper installed near bottom-mounted magnet sensor. Note that when the magnet is in the Null position pointing due-North (magnetic), the magnet axis is perpendicular to the copper plate damper.

Part IV. Improved design with a regulated power supply

In the previous designs, the output from the Hall sensor was read out on a multimeter and the power supply was a single 6-volt lantern battery. This is a bare-bones configuration that requires human supervision to record the data on the magnet sensor position encoded in the output 'millivolts.' Also, during the kind of constant operation necessary for tracking one or more geomagnetic storms, the drain on the battery will cause a constant change in the output voltage that will mask the changes from the Hall sensor. This improved design fixes both problems.

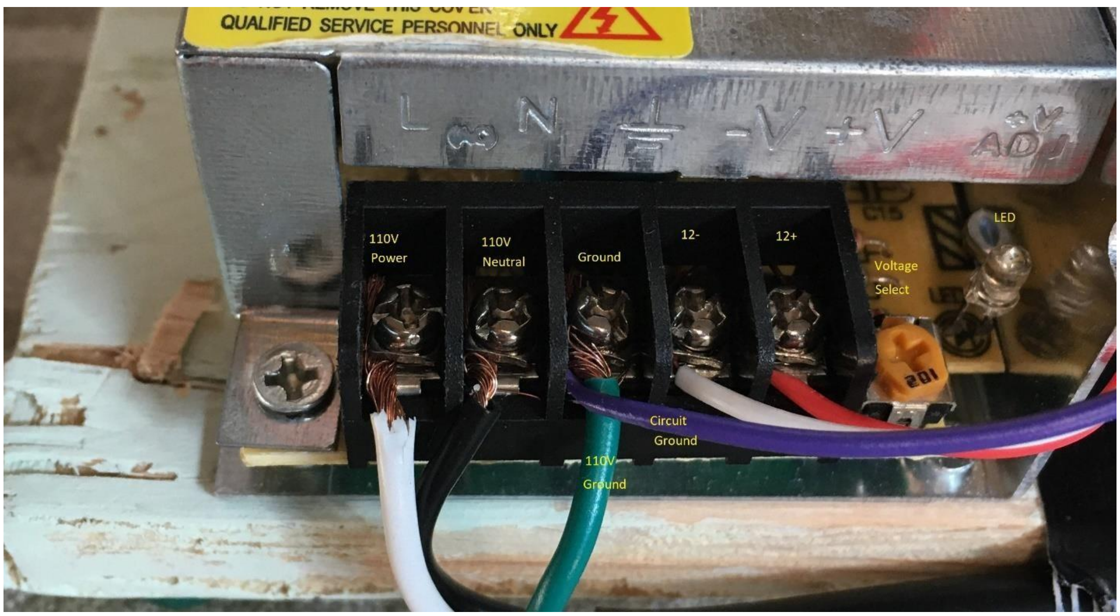

Figure 18. Example of a regulated power supply with output adjustment screw.

We will replace the battery with an inexpensive, regulated power supply that produces a constant 12 V DC output. This is 'stepped down' to 6 V using a simple voltage divider. The TRCE power supply can be adjusted to produce 12.00 VDC to within 0.5% (i.e. +/- 60 mV).

1. Materials

- 1x Power supply 15VDC regulated –TRCElectronkics.com; MornSun #LM1523B15; Input 85-305 VAC, output 15.0 VDC, Max 1.00 amps; $9.71 - https://www.trcelectronics.com/View/Mornsun/LM15-23B15.shtml

- Data logger – 1x DataQ Instruments; DI-188 Data acquisition computer interface; $49.00; +/-10 v input; 12-bit ADC, 100 sec/sample to 8000 samples/sec, USB-port connection; includes WinDaq software. https://tinyurl.com/65xczvau
- 1x Solderless breadboard - 400 Point Solderless.
- 2x 470-Ohm resistors.
- 1x 330-Ohm resistor.
- Breadboard jumpers as needed.

2. Procedure

Step 1) With a voltmeter placed across the +V and -V terminals of the power supply, check that the supply is providing 12.000 V to the nearest millivolt. If not, adjust the Voltage Select screw shown in Figure 37 until the voltmeter reads this value.

Step 2) The Hall sensor works with an input voltage in the range from 4.5 to 6.0 V so we can select 5.0 V in the mid-range. A voltage divider consisting of 330 Ohm and 470 Ohm resistors in series with the +12 V and -12 V supply. The voltage across the 330 Ohm resistor and V- will be 5.0 V within 5% (±0.1 volts) if 1% resistors are used. This voltage will remain stable at ±0.5% because the supply is regulated. The voltage provided by the divider across resistor R2 will be

V = 12 x R2/(R1 + R2)

For R1=470 Ohms and R2 = 330 Ohms this will give V = 12 x (330/(470+330)) = 5 V which is the desired voltage for the Hall sensor. Alternatively, with R1=R2 the voltage divider will provide 6.0V as an output. This is the combination used in this design with R1=R2=470 Ohms. The reason for this is that when the Hall sensor is attached, its internal resistance slightly lowers the output voltage on the now-loaded power supply so by using a 6V divider, the lowered voltage will still be above the 4.5 V operating limit of the Hall sensor.

Step 3) Next, we connect the 6 V+ (pin 1) and 6V- (pin 2) ends of the Hall sensor to the new 6 V regulated power supply from the voltage divider. The output from the Hall sensor (pin 3) is attached to the multimeter V+ ‘input’ lead and the other ‘common’ lead is attached to the -12 V ground line. Figure 19 shows this set-up.

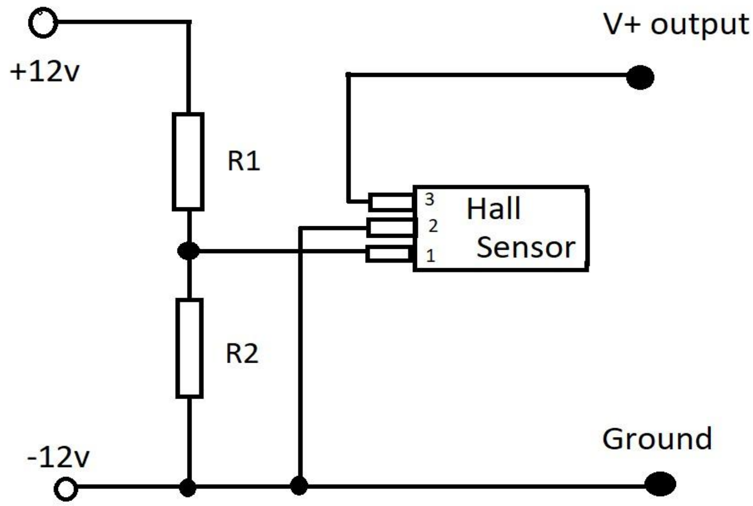

Figure 19. Diagram for 12v regulated power supply with voltage divider (5V or 6V) and sensor.

Part V. Improved design with output amplifier

1. How it Works

The previous design in Part II measured the absolute position of the magnet suspended over a single Hall sensor with no amplification of the output. This produced a large offset voltage of -4.9 V, which dominated the range of the analog-to-digital converter output. Since we are looking for millivolt changes, this large voltage offset swamps the output with useless information and robs us of sensitivity. A solution to this is to use two side by side Hall sensors configured so that it only measures the difference in their outputs. This sensor design is shown in Figures 20 and 21. The Hall sensors are then connected to a device called an instrumentation amplifier, which will amplify the outputs from the two Hall sensors and compute their difference. This difference can be rescaled using a gain adjustment resistor Rg, and the output recentered using an offset adjustment potentiometer so that the digitizer now records only the relative motion of the magnet over the sensors. Also, a dedicated 5V regulated power supply is used at half the cost of the 12-volt power supply used in the previous Hall sensor design.

2. Materials

- Bestol A1302 Ratiometric Linear Hall Effect Sensor (Amazon: $11.99 for pack of 10) https://tinyurl.com/yc6rzs34
- AD623AN amp. Mouser, $7.77 https://tinyurl.com/5d67uhn9
- 5V power supply, $8.99, https://tinyurl.com/3s65drzw
- DataQ DI-188 digitizer.
- Solderless breadboard - Small Breadboard 400 Point Solderless.
- Breadboard jumpers.
- 1,000 Ohm Potentiometer.
- 11,000 Ohm resistor.
- Bar magnet   (NdFeB).
- Glue gun.
- Foam board.
- 1-foot thread.
- Four sewing pins.
- Soldering iron and solder.
- Copper bar.

3. Construction

The electrical schematic is shown in Figure 22. The instrumentation amplifier is an AD623AN device that can be purchased at Mouser Electronics. The two Hall sensors are A1302 devices used in the previous design and that can be purchased for $11 for a pack of 10.

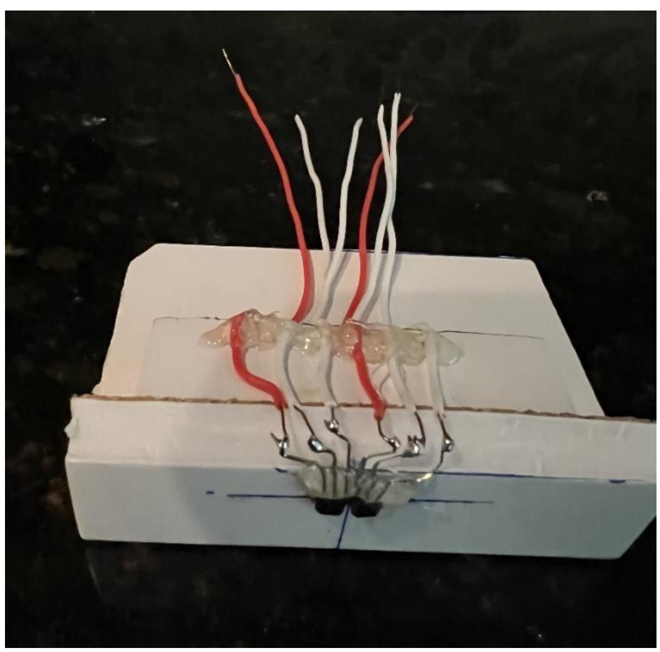

Figure 20. Hall sensors mounted side-by-side.

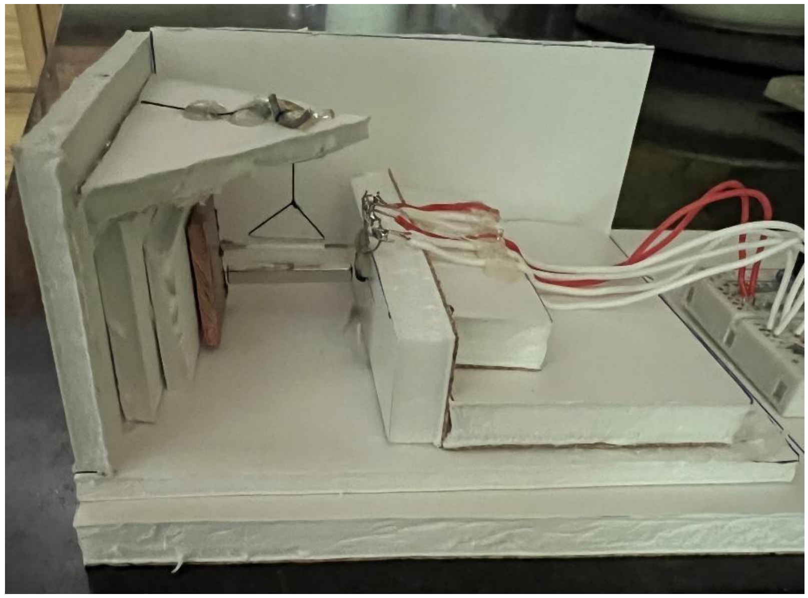

Figure 21. Preferred installation of Hall sensors in front of suspended magnet with the magnet's North pole facing the Hall sensors and the South pole facing the copper motion damper.

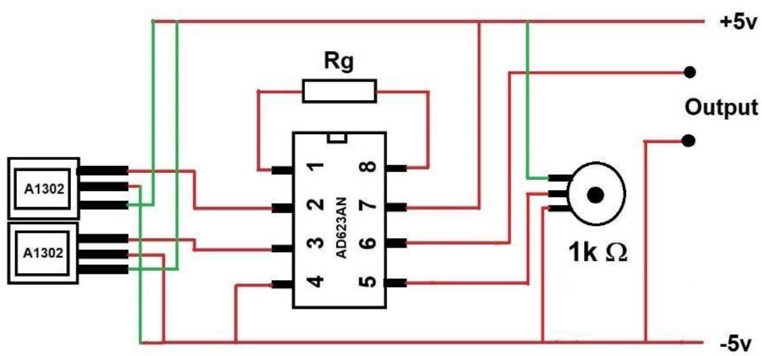

Figure 22. Electrical diagram of system. Green lines jump over the red lines and are not connected to them.

The suspended magnet is free to move in the horizontal plane with its North pole facing the Hall sensors and the South pole facing the copper disk that is used as the magnetic damper for the oscillations. The Hall sensors are mounted side-by-side with their faces opposite the magnet. Hot glue can be used to carefully attach the sensors to the mounting wall but should not cover the sensor faces so that the magnet pole can be brought within 1/8" of the sensor faces. Extension leads can then be carefully soldered to the sensor leads and plugged into the solderless component board. An example of the electrical connections is shown in Figure 23.

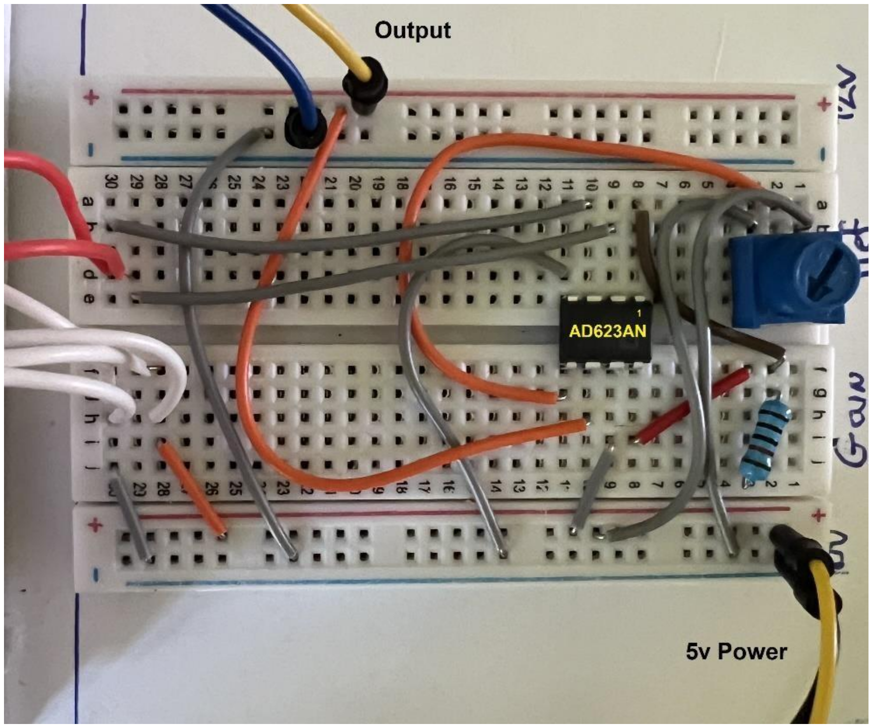

Figure 23. Electrical board with connections.

It is important to follow the pin designations of the AD623AN and the A1302 devices carefully. The single resistor Rg in the circuit should nominally be 11,000 Ohm to provide a gain of 10 for the output. The gain is sensitive to the value of this resistor Rg such that increasing the resistance will decrease the gain and decreasing the resistance will increase the gain. Alternately, Rg can be replaced by a 30,000 Ohm potentiometer if variable gain is desired.

The output from the amplifier was fed to a DataQ DI-188 digitizer and coupled to a laptop via a USB cable. The laptop runs the DataQ acquisition software, which controls the sampling cadence and converts the data into a .csv file, which can be opened and processed using Excel. The details for this data acquisition and analysis setup can be found in the guide '*A Photocell Magnetometer for Space Weather Studies'.*

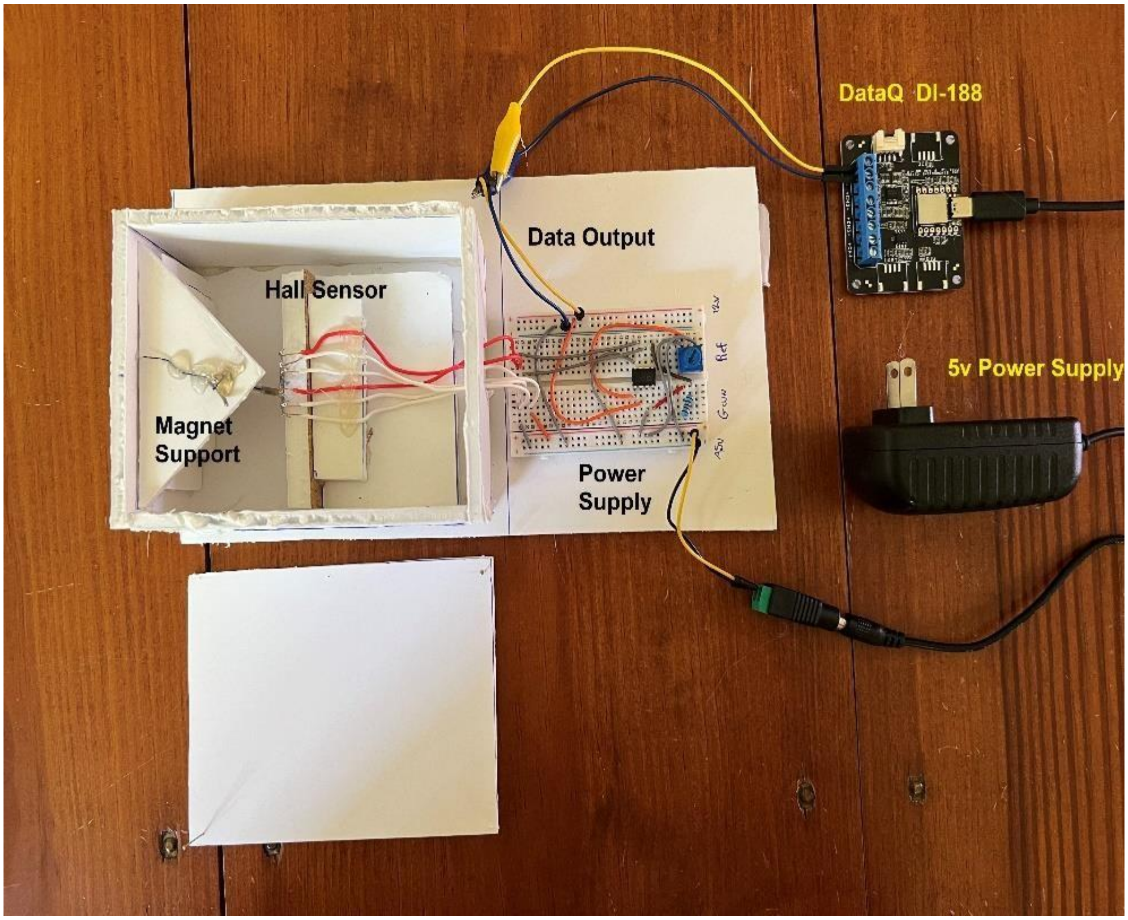

Figure 24. Final set up for the system.

4. Observations

Detecting the diurnal Sq current

A selection of digitized test data taken with this system between June 5-9, 2023, during a time when geomagnetic conditions were near Kp=1. The Hall sensor data shown in Figure 25 were obtained at the slowest cadence available for the DI-188 digitizer of 1-second, exported to an Excel program, and then averaged into 1-minute bins beginning at a local time of 9:54 pm (01:54 UT) and continuing through 4:55am (08:55 UT) on June 9. The units on the graph are in millivolts relative to an average Null level with the sensor magnet at the midpoint between the two sensors.

The corresponding D-component data from the Fredericksburg Magnetic Observatory (FRD) were downloaded from the USGS Geomagnetism website[2]

[2] https://geomag.usgs.gov/plots/

and aligned with the Hall magnetometer data. The FRD data is expressed in milli-arcminutes relative to the average Null value for this sequence of D-component measurements. The overlap between the two data sets is almost perfect with the Hall sensor system able to easily detect the Sq current effect traced by the FRD data. From a comparison of the two scales, the linear regression calibration constant is about 1.0 mV/milli-arcminute with R^2=0.87. The typical noise in the Hall measurement is about s = ±50 mV corresponding to a measurement accuracy for the D component of σ = ±0.05 arcminutes or more conveniently σ = ±3 arcseconds. The peak-to-peak amplitude of the Sq effect is about 1.0 arcminutes. In the future, data will be given in this document for a geomagnetic storm event to benchmark detectability.

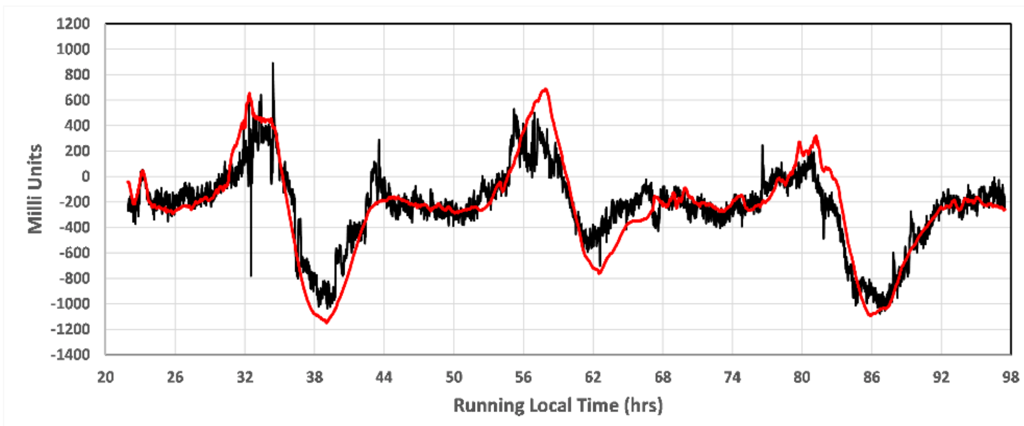

Figure 25. Comparison of dual Hall sensor output (black) and FRD (red) for three-day detection of Sq current variation.

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NP-2023-5-070-GSFC