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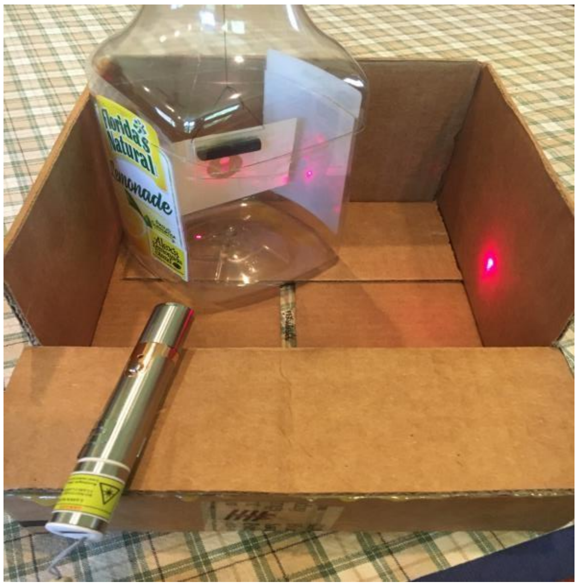
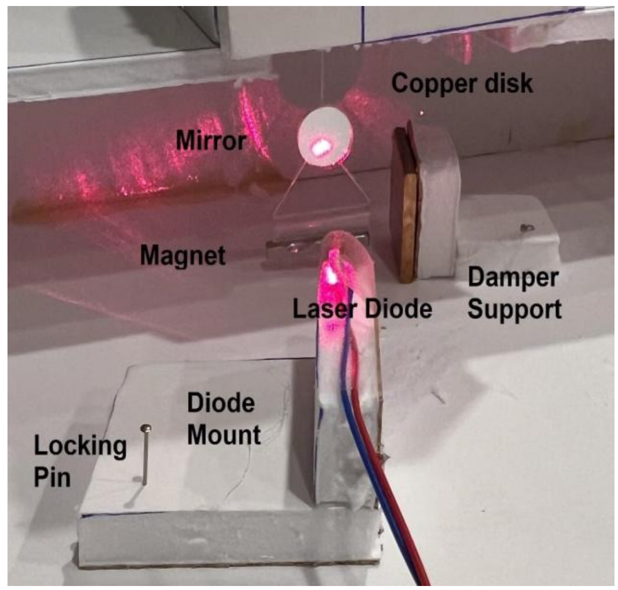
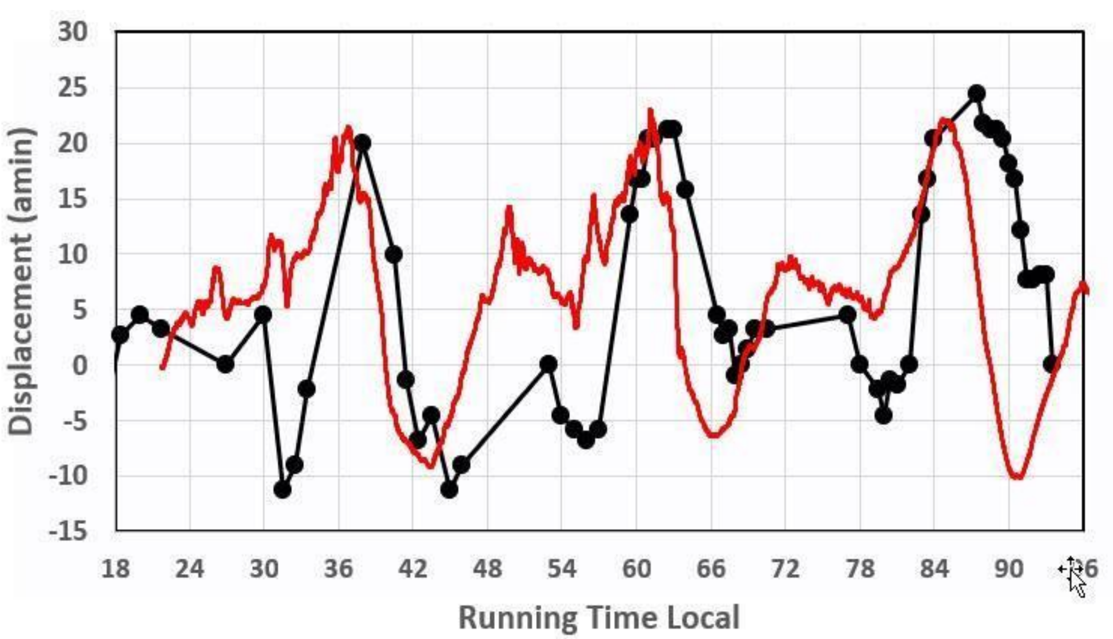




Soda Bottle Magnetometers for Space Weather Studies



Soda Bottle Magnetometers 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 sorts of devices used by scientists that 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 your own soda bottle magnetometer capable of detecting many of these 'magnetic storms' during severe space weather events. Several designs are featured as well as improvements that will increase their sensitivity.

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Cover art: (Top left) Simple design of a soda bottle magnetometer. (Top right) Improved design of a suspended mirror magnetometer with a laser diode light source. (Bottom) Data plot of magnetometer measurements (black dots and line) and actual data from the Fredericksburg Magnetic Observatory (red line) showing similarity in detection of the diurnal 'Sq' effect. (Credit: The Author).

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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. 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 sixth year of sunspot cycle number 25 with a maximum predicted to occur sometime in mid-2024. 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://www.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, soda bottle magnetometers are not sensitive enough to detect weak geomagnetic storms with Kp < 7, but they can be used to detect some of the stronger storms. The process requires careful analysis of the data. For severe storms with Kp>8, these events should be detectable in most locations across North America. These storm events, however, are rare and occur about once every six months during times when the Sun is active (called sunspot maximum). They are also unpredictable, so you need to carefully monitor space weather websites to see if a storm is likely in the next 24-48 hours.

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 Middle School NGSS Standards

Appropriate for magnetometer designs involving simple magnets.

MS-PS2-3 Ask questions about data to determine the factors that affect the strength of electric and magnetic forces.

MS-PS2-5 Investigate and evaluate the experimental design to provide evidence that fields exist between objects exerting forces on each other even though the objects are not in contact.

MS-PS2.B Electric and magnetic (electromagnetic) forces can be attractive or repulsive, and their sizes depend on the magnitudes of the charges, currents, or magnetic strengths involved and on the distances between the interacting objects.

6. 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>Current</u> – a flow of charged particles such as electrons and is measured in units called amperes

<u>Dynamo</u> – 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 thin gases and molecular 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.

Part II. The Basic Soda Bottle Magnetometer

Figure 1. Example of a simple soda bottle magnetometer.

1. Background

In 1741, George Graham (1674-1751) in London, and Anders Celsius (1701-1744) in Uppsala, Sweden began taking detailed hourly measurements of changes in the Earth's magnetic declination. It didn't take very long before Celsius and his assistant Olof Hiorter uncovered a correlation in the 6638 hourly readings between these disturbances and local auroral activity (see Aurora: The mysterious northern lights" Candace Savage 1994 Sierra Club Books; SF, p. 59-62). Moreover, comparing the records between Uppsala and London, it became quite apparent that the magnetic disturbances occurred at the same times at both locations. By 1805, the independently wealthy scientific traveler Alexander von Humboldt (1769-1859) had also noted these magnetic disturbances and called them ‘magnetic storms' since they caused the same gyrations of his compass needles as local lightning storms would do.

The first magnetometers were quite crude affairs. A human 'reader' would peer into a microscope at a needle on a graduated scale, which was little more than an ordinary compass. At half-hourly intervals, day and night, the position of the needle would be noted. By the 1840's networks of observatories amassed millions of these observations.

The basic operating principle is that a suspended magnet is free to move so that it is aligned with Earth's local magnetic field. As this field is disturbed and changes its direction, the suspended magnet will track the direction changes. By recording the orientation of the magnet over time like the bearings on a compass, you can then follow the changes in the local field.

Figure 2. A soda bottle magnetometer set up using an older design concept ca 2000.

The original design is based on the 'jam-jar' magnetometer devised by Ron Livesey of the BAA Auroral Section in the early 1980's (Journal of the British Astronomical Association 1983, v.93, p.17; Sky and Telescope 1989, v.78, p.426). The current design replaces the original design with more readily available components.

2. Materials

- ➢ One cleaned 2-liter soda or water bottle. Clear plastic; not tinted.
- ➢ Two feet of sewing thread.
- ➢ A small neodymium alloy bar magnet (About LxWxH = 30 mm x 5 mm x 5 mm)
- ➢ A 3x5 index card.
- ➢ A 25 mm piece of soda straw.
- ➢ A laser pointer or ‘cat toy’ with a red dot.
- ➢ A plastic, mirrored, dress sequin (1 cm dia.) Example:
- ➢ Hot glue gun
- ➢ A meter stick
- ➢ Small cardboard box
- ➢ Pine molding, about 18cm long. (hardware stores)
- ➢ Box cutter knife
- ➢ 100 mm length of clear packing tape

3. Construction

Constructing the Sensor and Magnetometer Housing

Step 1) The soda bottle needs to have smooth sides not corrugated or curved. This avoids optical distortion of the light after it reflects from the mirror. Clean the bottle thoroughly, removing the label and glue from the outside.

Step 2) Slice the bottle in half about 1/3 of the way from the top. Pierce a small hole in the center of the cap. Fill the bottom of the bottle with the sand. This will make the magnetometer steadier and resistant to unwanted vibration.

Figure 3. The parts to the current magnetometer design including the assembled SENSOR and the bottle cut into two pieces.

Step 3) Build the SENSOR by cutting the index card so that when it is suspended inside the bottle, it does not touch the sides. Hot glue the small bar magnet to the center of the top edge of the card. Do not use magnets commonly found in novelty stores which are clay-based and flexible. These 'refrigerator magnets' actually are pressed in complex ways and do not have a well-defined N-S polarity. Instead, we have used an inexpensive neodymium alloy bar magnet, which is exceptionally strong for its size and mass.

Step 4) Hot glue a piece of soda straw to the top of the magnet, and thread the sewing thread through the straw to make a small triangular loop. Glue the mirror spot to the front of the bar magnet and with a marker pen, put a dot near its center. We have found that any highly reflective foil or other material works better than a glass mirror, which was part of the original jam-jar design. If you visit a fabric store, it is common to find reflective 'bangles', which are normally sewn onto evening dresses to add sparkle. These are light weight, inexpensive, and at 1cm, are the perfect size.

Figure 4. Close up of the bar magnet sensor assembly.

Step 5) Tie an 18 cm piece of sewing thread to the loop of string through the soda straw. Thread the other end of this suspension thread through the inside of the top part of the severed coke bottle, and through the threaded part where the bottle cap screws-on. Feed the remaining suspension thread through the inside of the bottle cap. Figure 4 shows the completed SENSOR assembly.

Step 6) Rejoin the top part of the bottle with its bottom, making sure that the SENSOR card is free to swing and that the magnet remains parallel to the floor and table top. You might have to adjust the string through the straw so that the card hangs vertically with the mirror perpendicular to the floor, otherwise the reflected beam will strike the screen closer to the floor. With the clear packing tape, tape the top and bottom of the bottle together carefully. Adjust the length of the suspension thread so that the bar magnet and mirror spot hang below the tape seam to avoid optical distortion in generating the light spot.

Figure 5. The fully assembled magnetometer.

<u>Constructing the Light Source</u>

For added stability, the soda bottle assembly will be mounted inside a small cardboard box at one of the corners. The next step will be to create a shelf onto which the laser pointer can be fastened so that its beam is centered at the middle of the mirror. These low-wattage lasers are generally called Cat Pointers or Cat Toys and can be found at a price of about $8.00 from many suppliers. It is a LED-based pointer that can be re-charged using a USB connection and charges in 1.5 hours. Its collimated beam reaches 15 meters under dark conditions and about three meters in daylight. The little silver button on top controls its functions: Press once for the flashlight, twice for the red pointer light, three times for blue light, and four times to turn it off.

Step 7) Place the soda bottle unit in a corner of the box and tape, or use the glue gun to attach it securely as shown in Figure 6. Depending on the construction of the box, it may be necessary to hot glue the bottom tabs so that they lie firmly and do not spring up at the edges. Alternately, cut a piece of cardboard that exactly fits the bottom of the box and hot glue it so that you have a firm and solid floor to the box. Any springiness will cause the soda bottle to move and upset the sensitive geometry of the measurement process.

Step 8) Use the box cutter to carefully remove the top flaps to the box so that only the bottom and four sides remain. Save the pieces for later use.

Figure 6. The magnetometer mounted inside a box for stability.

Step 9) Orient the box so that the suspended magnet is oriented along the magnetic North-South axis. This will be the normal 'Null' orientation of the magnet and mirror.

We now need to create a shelf in the corner opposite the soda bottle whose height is precisely calculated to be high enough that the laser pointer spot strikes the exact center of the mirror.

Step 10) With a millimeter ruler, carefully measure the height, H, of the center of the mirror above the floor of the box (Example: H=70 mm). Now measure the thickness of the floor, F, of the box to the point where it meets the table. (Example: F=6 mm). We now know the height of the center of the mirror above the table (Example: H+F = 76 mm).

Step 11) With the laser pointer on, rotate the pointer until the on-off switch is conveniently at the top and measure the height of the center of the beam's exit hole, B, from the bottom edge of the pointer. (Example: B = 4 mm) This is how far above the shelf the beam axis will be as it travels to the center of the mirror.

Step 12) Measure the thickness, T, of the cardboard in the box (Example: T=3 mm).

Step 13) On the corner of the box, use the box cutter to trim each wall forming the corner to a height above the table equal to H+F – B – T (Example: 76-7 = 69 mm). When the shelf of thickness T is attached to this slot and the laser pointer with a beam position at B is attached, the center of the beam will be at a height of H+F-B-T+T+B = H+F above the table, which is the height of the center of the mirror found in Step 10.

Step 14) From a piece of scrap cardboard, cut a rectangular piece 90 mm wide that spans the back wall to form the shelf. Seat this shelf on the three sides of the box but do not glue yet.

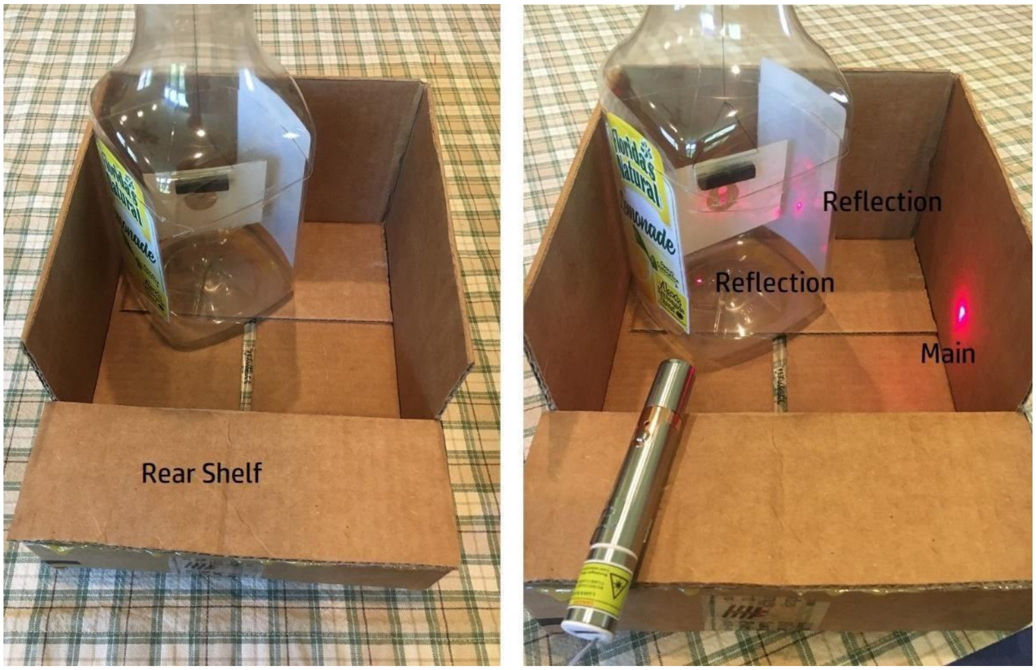

Figure 7. Constructing a shelf inside the box for the laser pointer. **Left**: The completed shelf; **Right**: The laser pointer is positioned to reflect a beam into the side wall.

Step 15) Turn on the laser pointer and, placing it on the shelf, verify that its beam is centered on the mirror. You may have to remove a few millimeters on the box walls to match the height exactly. When finished, hot glue this shelf to the box as shown in Figure 7A.

Step 16) You will notice in Figure 7B that when you turn the laser on and place it on the shelf with its beam directed at the mirror, multiple laser spots are produced as the beam passes through the plastic of the bottle. When you position the laser pointer on the left side of the shelf, there will be one bright beam that strikes the right-hand wall of the box.

This is the beam whose position we will measure. The distance from the mirror to the box wall is too small to provide significant measurement accuracy, so we need to cut a window on the side of the box that spans the full width of the box. This allows the beam to move across a wide range of angles. The location of the center of the window can be judged from the location of the spot on the wall. Allow a 25 mm tall window centered on the beam position height.

Figure 8. The laser pointer mounted securely, and a window cut into the projection wall for the exit beam.

Step 17) Next, we have to affix the laser pointer to the shelf so that its orientation does not shift when we move the magnetometer unit or switch on and off the pointer. The first orientation is in the plane of the shelf. To stabilize this, use two pieces of square pine molding cut to the same length as the laser pointer as shown in Figure 8. You only need about 1 foot and may be able to wrangle a free piece from a hardware store scrap barrel!

Step 18) Some effort may be required to find a location in the classroom that is undisturbed, and where this set-up can be arranged so that the magnetometer and reflected spot are in convenient positions on a table or other flat surface near a wall. The geometry of the magnetometer and recording screen must be kept fixed during the entire measurement series.

4. Calibration and Sensitivity

Step 19) It is important that when you adjust the location of the sensor card inside the bottle that its edges do not touch the inside of the bottle. Be sure that the mirror spot is above the seam and the taping region of this seam, so that it is unobstructed and free to spin around the suspension thread.

Step 20) A reflected spot can be cast on a wall within 1 meter of the center of the bottle. This allows a one-centimeter change in the light spot position to equal 1/4 degree in angular shift of Magnetic North. Because magnetic storms produce shifts up to 1 or more degrees for some geographic locations, you will need to measure angular shifts smaller than 1/4 degrees. By increasing the distance from 1 meter to 7 meters, the laser spot will track angular displacements of 0.1-degrees or less and allow weaker storms to be detected.

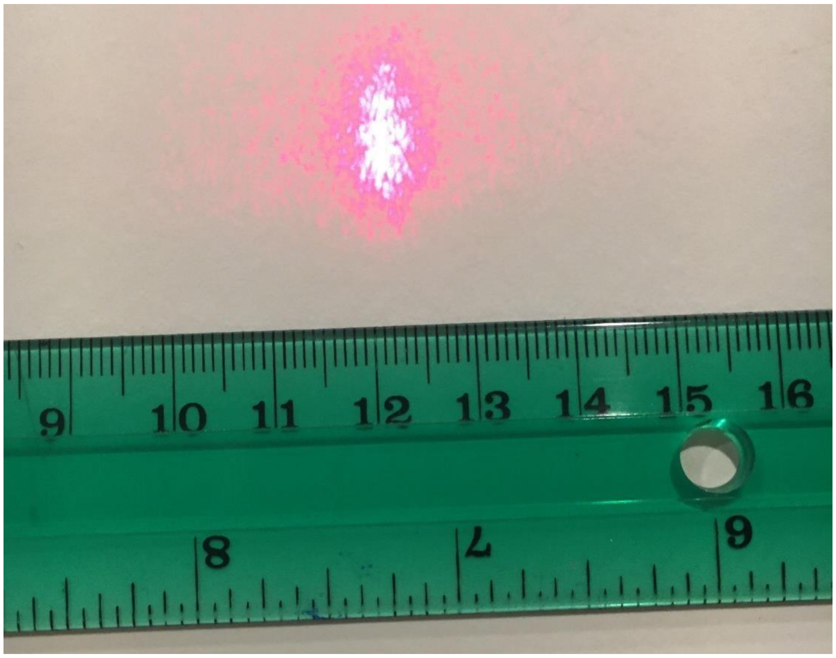

Figure 9. Example of the laser spot at 1 meter showing shape.

Step 21) Typically, intense magnetic storms last between 3 to 12 hours. To begin a measuring session, note the location of the spot on the wall by a small pencil mark. Record the magnetic activity every few hours by measuring the distance between this reference spot and the current spot whose position you will mark, and note the date and the time of day. Measure the distance to the reference mark and the new spot in centimeters. Convert this into degrees of deflection for a 1-meter distance by multiplying by 1/4 degrees for each centimeter of displacement. For longer distances use 0.25 degrees x (1/L) where L is the distance to the spot in meters. For example, at L=5 meters, a 1cm shift corresponds to 0.25 x (1/5) = 0.05 degrees of angle. You can check that this magnetometer is working by comparing the card's pointing direction with an ordinary compass needle, which should point parallel to the magnet in the soda bottle. You can also note this direction by marking the position of the light spot on the wall as shown in Figure 9.

Step 22) If you must move the soda bottle, you will have to note a new reference mark for the light spot and then resume measuring the new deflections from the new reference mark as before. Most of the time there will be few detectable changes in the spot's location, so you will have to exercise some patience. However, as we approach sunspot maximum there should be several good storms each month, and perhaps as often as once a week. Large magnetic storms are accompanied by major aurora displays, so you may want to use your magnetometer in the daytime to predict if you will see a good aurora display after sunset if you live at latitudes above 60º North.

This magnetometer is sensitive enough to detect cars moving on a street outside your room. Also, by moving a large mass of metal...say 10 kg of iron nails...at distances of 1 meter to 5 meters from the magnet, you can measure the amount of deflection you get on the spot, and by plotting this, you can attempt to recover the 'inverse-cube' law for magnetism. This would be an advanced project for middle-school students, but they would see that magnetism falls off with distance, which is the main point of the plotting exercise.

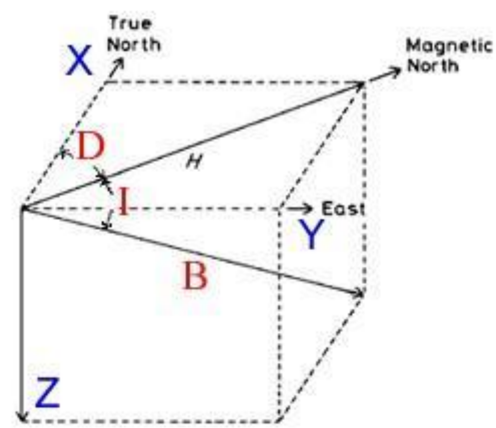

Figure 10. The geometry of Earth's magnetic field. Slight changes in Angle D are measured by the magnetometer.

Magnetic storms often produce deviations of several degrees or more at geographic latitudes on Earth near the Arctic Circle. For the mid-latitudes of North America (New York City, San Francisco, etc.) positional shifts in the 3 to 5 cm range should be seen. Because all of the magnetometer measurements are detecting angle differences, magnetic storm events can only be seen clearly in relation to at least several previous 'null' measurements of the field direction. The null position needs to be clearly determined so that the onset, climax and termination of the magnetic storm can be discerned in the data.

To follow the overall change in the angular variations during a storm, the optimal sample rate is approximately 30 minutes so that 10 - 20 points can trace out the envelope of the disturbance.

Part III. Magnetometer sans Soda Bottle

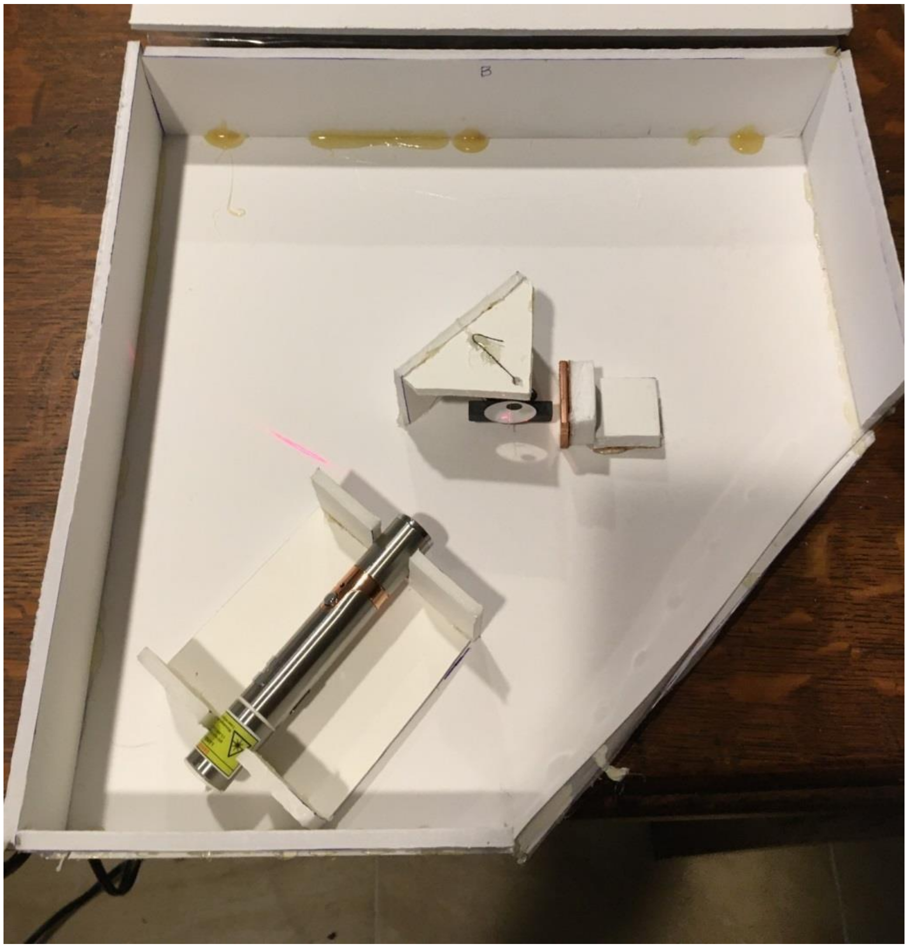

Figure 11. Completed magnetometer design.

1. Background

The basic soda bottle magnetometer constructed in Part II demonstrated the basic principles of a torsion-beam magnetometer and implemented them with a very low-cost design requiring only an inexpensive ‘cat toy’ laser pointer to provide the light beam. The design, however, was cumbersome, suffered from multiple reflections and produced an exit beam distorted by its passage through the transparent plastic of the soda bottle. In this experiment, these deficiencies will be circumvented by constructing a proper enclosure for the magnetometer sensor, and providing a significantly less distorted laser spot from which to make the displacement measurements.

2. Materials

- ➢ Small bar magnet (3 mm x 3 mm x 25 mm, NdFeB-alloy).
- ➢ Foam Board.
- ➢ Laser pointer (cat toy).
- ➢ Hot glue gun.
- ➢ Metric yardstick.
- ➢ Plastic straw.
- ➢ 5 or 6 sewing needles.
- ➢ 30cm length of sewing thread.
- ➢ Box cutter with fresh, sharp blade to make clean cuts.
- ➢ Reflective mirror dress sequin.

3. Construction

Step 1) Cut two pieces of foam board 30 cm square to form the top and bottom of the magnetometer case.

Step 2) Cut two rectangular sides A & C that are 5 cm x 30 cm; Cut a second pair of rectangles B & D that are 5 cm x 29.5 cm.

Step 3) With the hot glue gun, assemble sides A, B and C on top of the bottom sheet. Side B should fit between sides A and C. Do not assemble Side D yet.

Step 4) To form the cradle for the laser pointer, cut three pieces of foam board; one Base piece 8cm x 8cm and two pieces A and B measuring 8 cm x 3.8 cm.

Step 5) Measure the diameter of the laser pointer (ex. 1.6 cm)

Step 6) On each of the A and B pieces, draw a midline at 3.8 cm. Cut a rectangular slot the width of the laser pointer and 2 cm long centered on the midline. The completed unit should resemble Figure 12. Note that the on/off button controlling the pointer is conveniently rotated into the ‘up’ position. The bottom of the cradle should be flush with the table top surface with no rocking.

Figure 12. The laser pointer assembly.

Step 7) The next ingredient is the mirrored magnet sensor. 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. Hot glue a mirror sequin to one side of the magnet so that the edge does not extend below the edge of the magnet. The final unit should resemble Figure 13. When the magnet is suspended by the thread, it should hang vertically with the mirrors perpendicular to the floor. This will allow the reflected laser beam spot to scan parallel to the floor and the bottom of the magnetometer box.

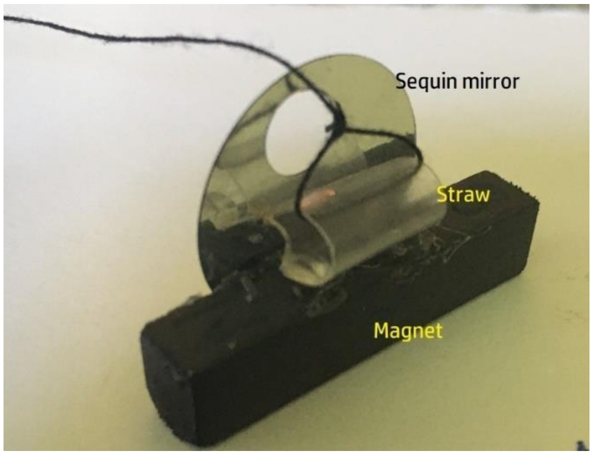

Figure 13. The magnet and mirror assembly.

Step 8) Now we need to suspend the magnet inside the box independent of whether the lid is on or off, so it cannot be merely suspended through a hole in the top. We have to create a suspension framework attached to the bottom of the box that will not block the beam spot as it oscillates from the eastern side of magnetic north to the western side. Figure 14 shows one design for such a framework using foam board elements.

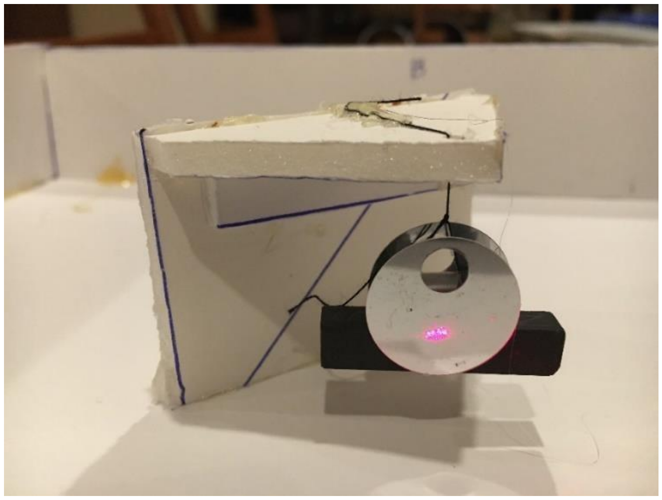

Figure 14. The magnet suspension system with a laser spot illuminating the mirror.

It consists of an equilateral triangle with side lengths of 5 cm hot glued at its base to a second piece measuring 3.8 cm x 6.4 cm. A third piece measuring 4 cm x 1 cm has been glued to reinforce the joint. A small hole is punched near the apex of the triangle and the sensor thread is fed through this hole. With the laser on, the suspended sensor is adjusted in height until the spot is centered on the mirror. The sensor thread is then hot glued to permanently fix the sensor at this height. Because the sensor unit only has a mass of about 7 grams depending on the magnet used, the suspension framework is strong enough to prevent any deflections.

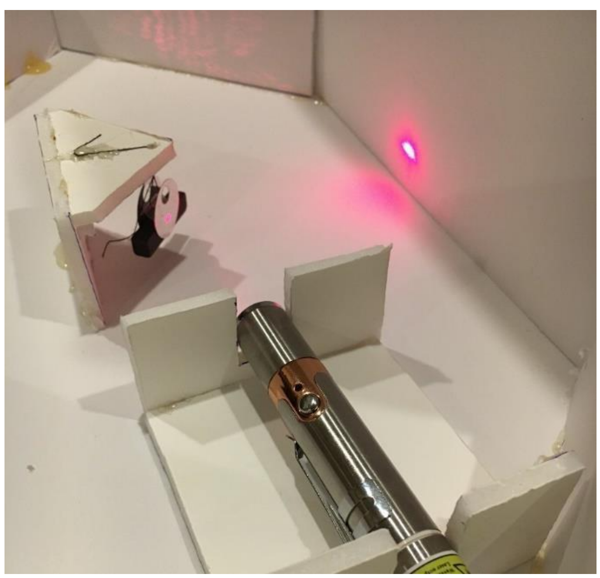

Figure 15. Laser spot projected onto a piece of foam board placed over the box opening.

Step 9) With the sensor in place, orient the magnetometer box so that the sensor is aligned with the opposite wall of the box. Move the laser cradle so that the laser spot exits the box near the corner of the opening. You can use a scrap piece of foam board as a projection screen. Hot glue the cradle in place but see the note in Step 13 for an alternate cradle installation that may be more convenient.

Step 10) With the laser cradle in place as shown in Figure 15, we now trim the top lid of the box to remove excess foam board so that we have access to the laser pointer. After checking that the top lid fits properly, use several pins to secure the lid in place. Do not hot glue the lid because you may need access to the sensor at some future date. The pins allow you to easily remove the lid and reinstall it.

Step 11) The last step will be to install a transparent window over the opening. This will allow the laser spot to exit the box but will prevent air currents from entering the box and setting the sensor into oscillation. A common source of transparent plastic is plastic 'clamshell' boxes used for salads or bakery goods. These can be found at little or no cost at many stores. The completed magnetometer is shown in Figures 16.

Figure 16. The completed magnetometer with lid raised piano-style to reveal the interior.

Step 12) Close the magnetometer box and secure the lid with sewing needles. Orient the box with the laser spot activated so that the spot exits the box near the middle of the window. Looking through the window with the laser off, note the orientation of the magnet and draw a reference line on top of the box aligned with the magnet. This is the nominal direction of Magnetic North (in the Northern Hemisphere). Label the axis with an arrow directed towards the North Magnetic Pole. You can also use a smartphone 'compass' app to identify this direction using its 'magnetic bearing' and not its 'true north' bearing. You now need to position this device so that the laser spot strikes a wall on which a meter stick has been affixed with tape. It may be difficult to find such a wall given the fixed geometry of the laser in the device.

An alternative design is to not glue the laser cradle to the bottom of the box in Step 9. First find a wall and a convenient table for the magnetometer. With the laser pointer turned on, move the cradle around until its spot reflected off of the mirror passes through the device window and strikes the desired wall at a convenient location. With two or four sewing pins, pin the cradle securely to the bottom of the box.

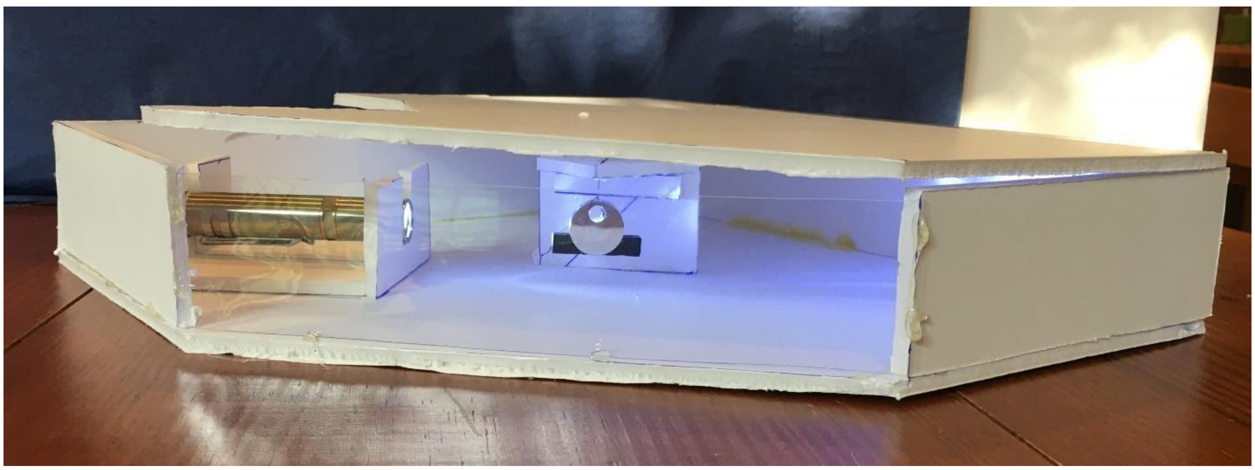

Figure 17. A side view through the window.

4. Taking Measurements

Step 1) Because of the use of foam board, the completed magnetometer has a mass of only about 125 grams (about 4 ounces). To stabilize the box for measurements, place a medium-sized book on the roof of the box.

Step 2) Find a location where you can set up the magnetometer that will be generally undisturbed for several days. Orient the magnetometer box so that the laser spot exits the box near the midline of the window and can be seen on a wall parallel to the magnetometer window and about 1-meter distant as shown in Figure 18. Alternatively, move the laser pointer cradle until the beam spot strikes the wall at a desired location. **For best sensitivity, the spot distance should be greater than about 5 meters.**

Step 3) Set the magnetometer sensor into an oscillation along the horizontal plane. Note how the spot moves on the wall and orient the metric meter-ruler along this line so that the rest position of the spot is at about the midpoint of the meter stick. During a geomagnetic storm, the spot will be displaced from this rest ’50 cm’ position.

Figure 18. Here the magnetometer has been placed on a desk. The ‘wall’ consists of a piece of foam board propped up by books on a chair. The red laser spot may be slightly distorted by imperfections in the reflective mirror surface and transmission through the window. Better-quality laser pointers will have better quality beam spots so some experimentation and fine-tuning may be required to get the best results. Identify a fixed feature in the projected spot and use that to indicate the displacement of the beam.

5. Calibration

The calibration process for this design is similar to that of the standard soda bottle magnetometer design. At 1 meter, the laser spot is shown in Figure 19. It has a very rough shape and this is the main source of the uncertainty in determining its position along the meter stick. With practice one can make this measurement to an accuracy of about 1 mm.

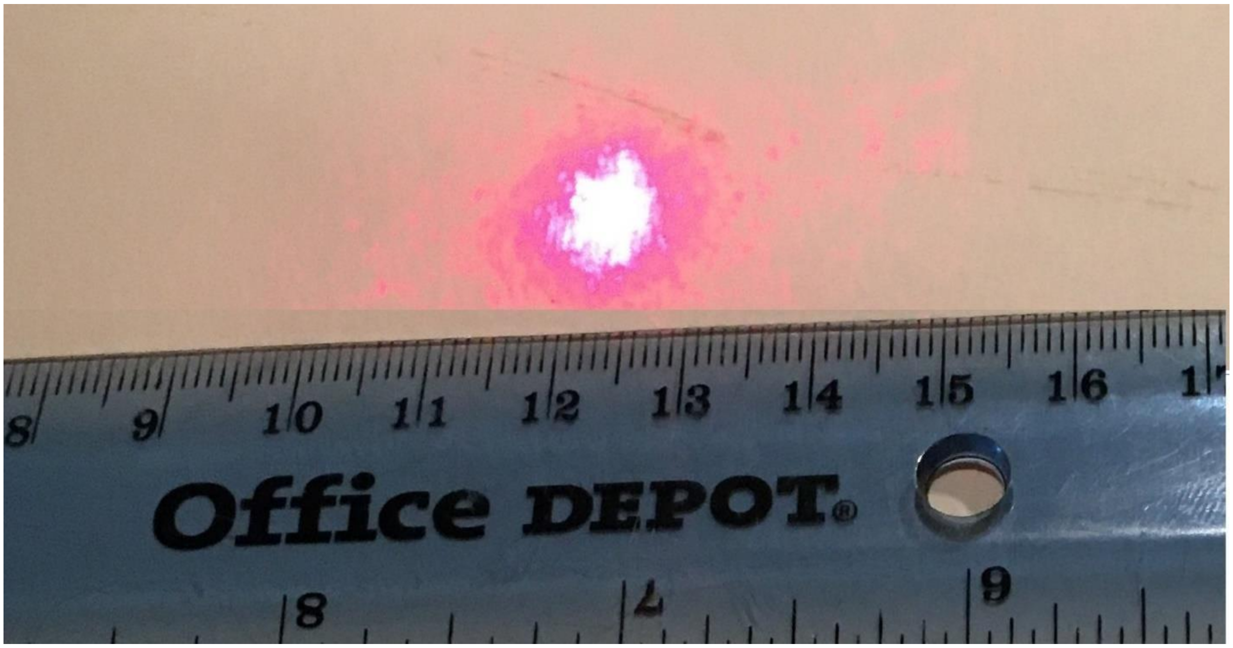

Figure 19. Laser with box closed and beam through the plastic window at a distance of 1-meter.

The average diameter of the bright core of the spot is 5 mm but ranges from 4 mm to 6 mm. The angular scale from simple geometry is 1 cm @ 1 m = 0.57^o so the geometric center of the spot is uncertain to about 1 mm or $\pm 0.057^o$. For a longer spot distance of L=x meters, the uncertainty in the spot position will be $\pm 0.057^o/L$, which will make the device more sensitive to weaker storm events. For example, at L=5 m, the position uncertainty is ±0.01 degree or equivalently ±6 arcminutes.

Part IV. 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 produces 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 braking in trains and even roller-coaster rides[1].

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

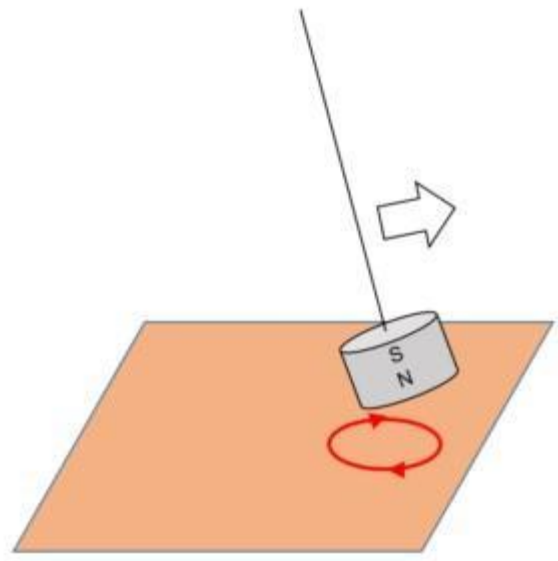

Figure 20. Moving magnet creates eddy currents in the conductor that provide magnetic breaking.

We will use this idea by adding a copper plate under the magnet[2].

1. Material

- Copper bar
- Foam board

2. Construction

Step 1) Cut two pieces of foam board 2 cm x 2 cm.

Step 2) Cut a 2 cm x 2 cm piece of copper from the stock bar.

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

2 https://www.physicslens.com/braking-of-a-magnetic-pendulum-with-copper-plate/

Step 4) Hot glue the second foam board piece to the back of the first piece opposite the copper disk as shown in Figure 21.

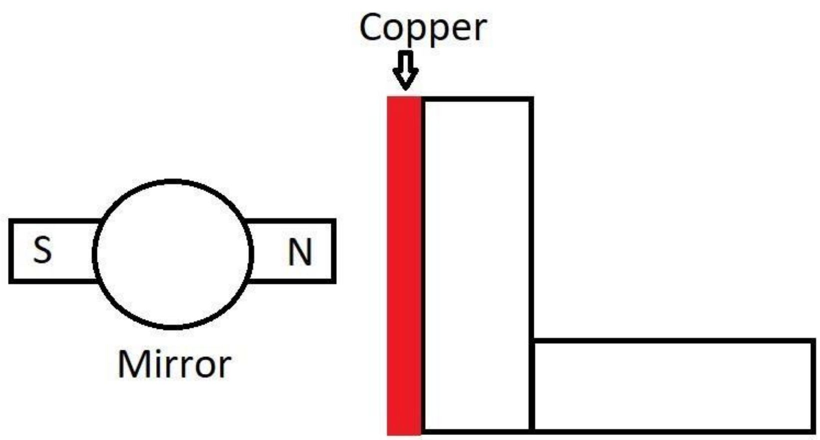

Figure 21. Sideways view of the construction and mounting of the (red) copper piece. The circle represents the reflective mirror attached to the side of the bar magnet.

Step 5) Use sewing pins to anchor this assembly opposite the N-pole of the sensor magnet so that when the magnet is pointing North, the copper face is about 3 mm from the magnet as shown in Figure 21. The final assembly should look like Figure 22.

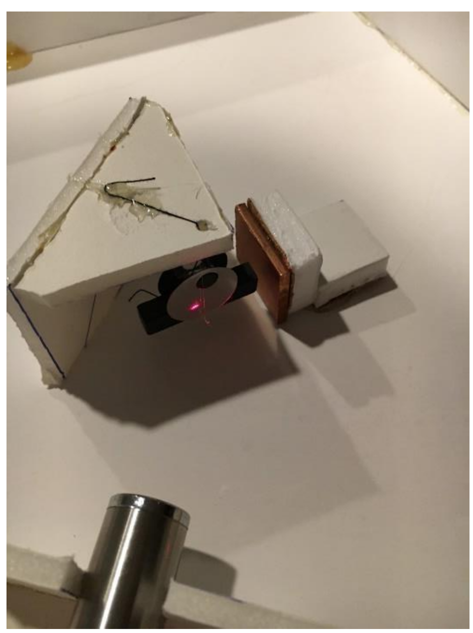

Figure 22. Magnetic braking system with laser activated in the Null (North) orientation.

If a piece of copper is too expensive or unavailable, you can experiment by using a series of copper pennies soldered together at their edges to form a 3-penny linear string. Each penny must be in electrical contact with its neighbor in order for the damping currents to flow inside the copper properly.

Part V. Improved design with a laser diode and magnetic braking

The best design shown in Figure 23 replaces the original soda bottle design with a handmade box made from common photographic foam board and adds a magnetic damper to replace the air-displacement 'card' mechanism for rapidly reducing the oscillations of the magnet. Also, the laser pointer is replaced by a simple laser diode LED light that can be switched on and off without disturbing the system.

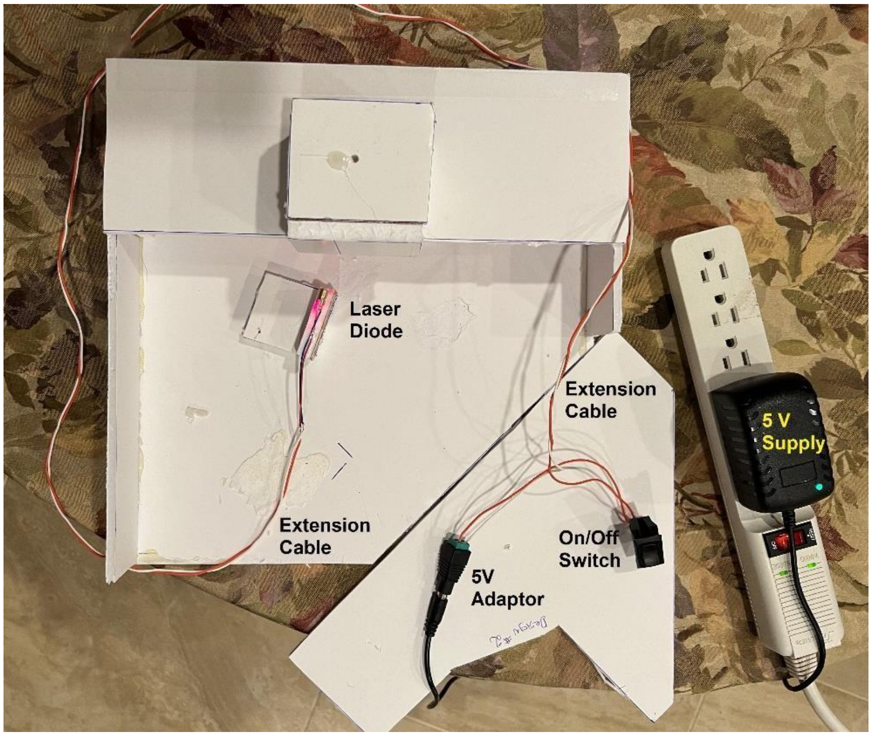

Figure 23. Completed laser diode system.

1. Materials

- ➢ Bar magnet (NdFeB-alloy).
- ➢ Laser Diode 5 V, 5 mW red.
- ➢ 5 V, 3 A power supply. ➢ On/Off switch

- Copper bar.
- Foam Board.
- Hot glue gun.
- Metric yardstick.
- Plastic straw.
- 5 or 6 sewing needles.
- 30 cm length of sewing thread.
- Box cutter.
- Mirror sequin.

2. Construction

The basic construction details are identical to those described in Part III and consist of creating a flat box with a depth of about 4 cm to provide vertical room for the sensor magnet mounting and the laser diode as shown in Figure 23 and Figure 24. There are three sub-assemblies for this magnetometer: The laser diode support, the magnet system, and the damper system.

3. Incorporating the Laser Diode

As a replacement for the laser pointer in an earlier design, you can use a laser diode with an on/off switch and remote power supply to avoid any disturbances to the magnet, which was a problem for the laser pointer configuration. Each time the laser pointer was switched on and off for a measurement it caused mirror movement. Also, the laser pointer had to be periodically removed to re-charge it. The current configuration avoids these problems entirely.

The laser diode has a pair of blue and red wires. The blue wire connects to the negative terminal of the power supply and the red wire to the positive terminal. A switch can be added in series with the red wire. To improve isolation, the diode wires should be attached to 1 m wires so that the power supply and on/off switch are vibrationally isolated from the sensor system. Alternately, the power supply can be plugged directly into a spare power strip and the power strip's on/off switch can be used.

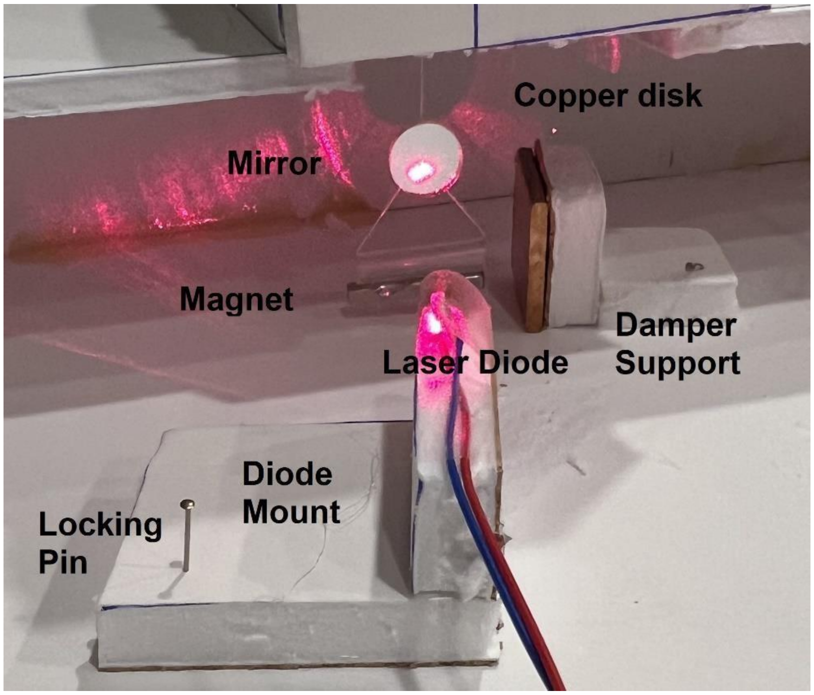

Figure 24. Example of a simple laser diode mounting.

4. Improved Magnet Sensor System

In this version of the basic design, use a small, compact, and intense neodymium bar magnet rather than a heavier and weaker alnico magnet. This is a basic suspension system used in typical soda bottle systems. However, in many cases the suspended assembly tends to lean forwards, which projects the laser spot onto the floor of the instrument box. To keep the mirror properly aligned perpendicular to the floor, attach the mirror as shown in Figure 25 at the vertex of the thread triangle.

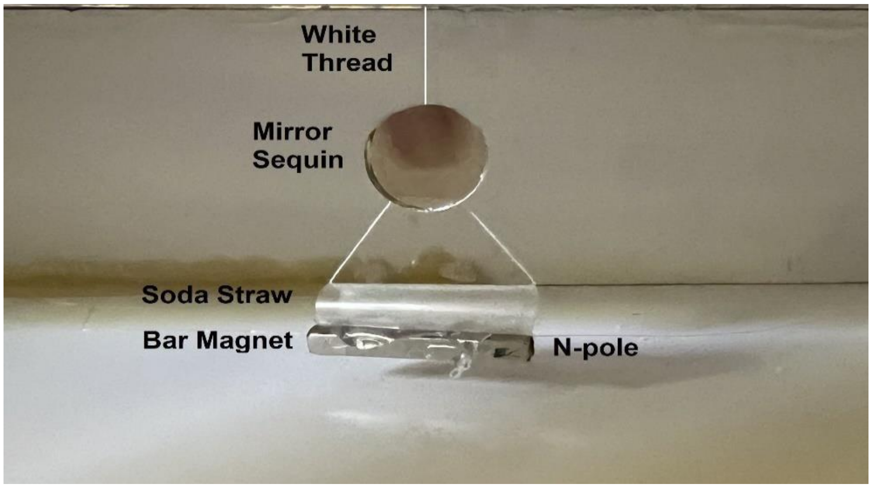

Figure 25. Magnet assembly.

5. Magnetic Damping

Cut a 2 cm x 2 cm piece of copper from the stock bar and hot glue the copper piece to a 2 cm x 2 cm foam board piece. With a pair of sewing pins, secure the foam support to the bottom of the box once the orientation of the magnetometer and magnet has been established for the best beam location in the room. The damper assembly should be opposite the N-pole of the sensor magnet so that when the magnet is pointing North, the copper face is about 1/8 inch from the magnet as shown in Figure 25. Alternatively, the copper piece can be placed opposite the South Pole of the magnet.

If a piece of copper is too expensive or unavailable, you can experiment by using a series of copper pennies soldered together at their edges to form a 3-penny linear string, as in Part IV. Each penny must be in electrical contact with its neighbor in order for the damping currents to properly flow inside the copper.

After checking that the top lid fits properly, use several pins to secure the lid in place. Do not hot glue the lid because you may need access to the sensor at some future date. The pins allow you to easily remove the lid and reinstall it, while the lid prevents any stray air currents from disturbing the magnet. Look through the window with the laser off and note the orientation of the magnet. Draw a reference line on the top of the box that is aligned with the magnet. This is the nominal direction of Magnetic North (in the Northern Hemisphere). You can also use a smartphone 'compass' app to identify this direction using its 'magnetic bearing' and not its 'true north' bearing. When completed, and with the laser on, you should see a bright spot positioned just above the markings on a meter stick placed horizontally on a wall as shown in Figure 26. In this instance, the location of the center of the spot is at the '53.7 cm' marking during geomagnetically quiet conditions. During a magnetic storm, the spot position should move many centimeters from this Null position.

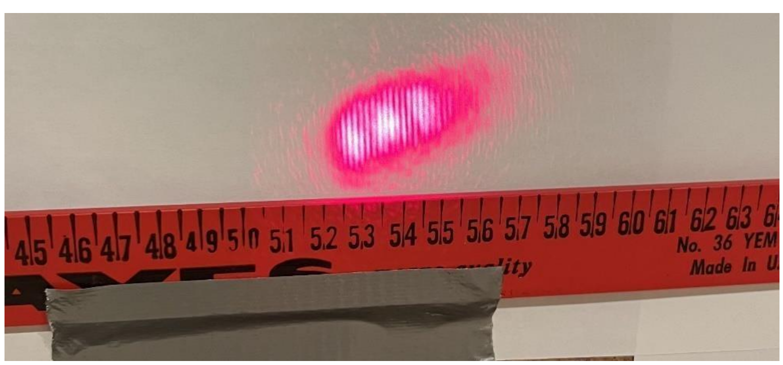

Figure 26. Example of laser spot projected onto screen 7.7-meters from the magnet. Note the vertical interference fringes (dark lines) crossing the elliptical laser spot.

6. Sensitivity

At 5 volts, the inexpensive laser diode produces a very bright beam, and can easily throw a spot across >10 m of separation. By adding a second mirror to the beam as it exits the instrument as shown in Figure 27, the laser beam can be re-directed into a much longer path (to the right) than simply the opposite wall of the room. The Author's rectangular basement room had dimensions 5 m x 10 m.

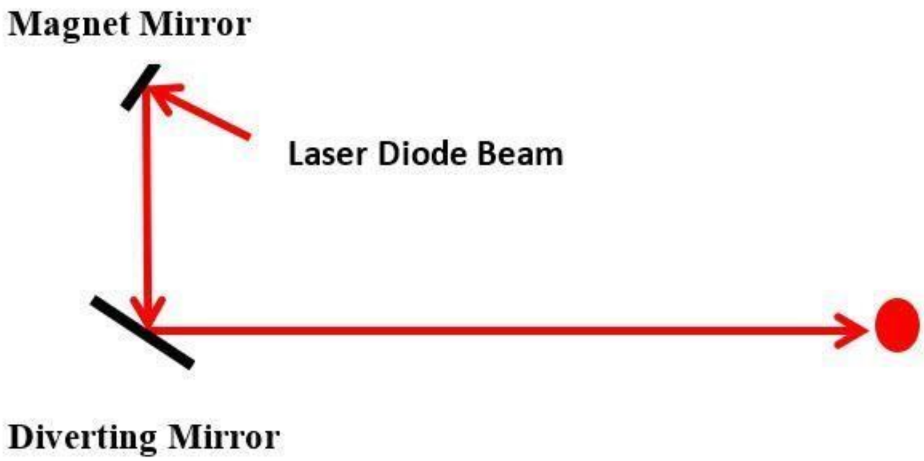

Figure 27. Set up for redirecting the laser spot to a longer distance.

An ordinary dressing mirror was propped up with a chair, which allowed the 3.5 m beam distance to be extended to 7.7 m along the room's major dimension. This includes the 0.5m distance of the magnet mirror to the diverting mirror, and the 7.2 m distance from the center of the diverting mirror to the far wall. The spot diameter at this distance has an elliptical shape shown in Figure 26 due to the near-45^o tilt of the diverting mirror along the horizontal axis. The center of the spot can be gauged to a 2 mm resolution in position.

The resolution of this device can be determined by carefully shifting the magnet by 1^o using a protractor and a pair of lines drawn on a large piece of paper. The suspended magnet was positioned at the vertex of the angle, and the entire magnetometer was picked up and repositioned to the 1^o segment to gauge the angle. At a distance of 7.7 m, this one-degree shift corresponded to 160mm so a 2 mm resolution in position corresponds to about 0.8 arcminutes. Using trigonometry, the predicted resolution for 2mm at a distance of 7.7 m is 0.85 arcminutes so the two methods give comparable results.

7. Observations

Two kinds of phenomena can be detected with this magnetometer design when long spot distances more than five meters are used for best sensitivity.

The Diurnal Sq Current

Solar heating of the ionosphere produces a circulating current of charged ions that flow in a pattern concentric with the direction to the sun in the sky. This pattern is physically many thousands of kilometers in diameter. This current produces its own magnetic field that reduces the strength of Earth's magnetic field at ground-level. When the sun is at Local Noon, an observer will detect the maximum magnetism change. At sunrise and sunset, the effect is minimal. At night the effect vanishes completely. This diurnal Solar Quiet or 'Sq' current happens every day, and is the most intense during the summer solstice when the Noon sun is the highest in the sky.

Figure 28 was obtained from a series of half-hour to hour cadence measurements using the 7.7 m beam distance. The angular scale at this distance corresponds to 0.5 arcminutes/millimeter. The spot position can be measured to an accuracy of ±2 mm or ±1 arcminute and is motionless during the measurement process.

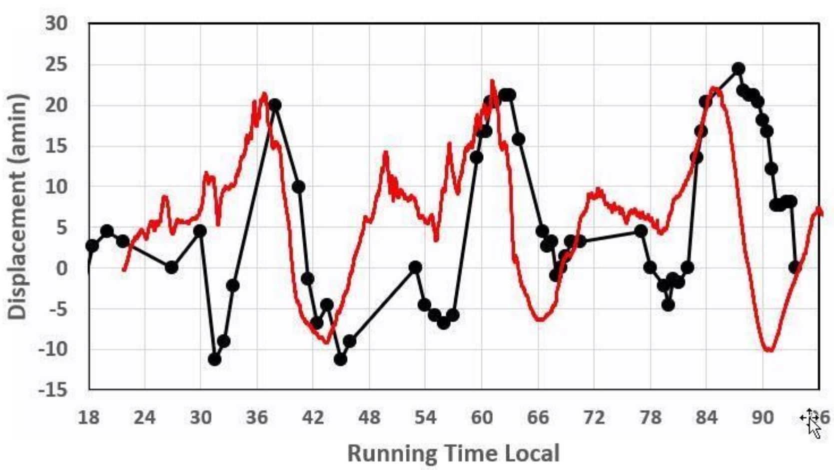

Figure 28. FRD D-component (red) and soda bottle data (black).

The large variations in Figure 28 are not due to wind or breezes in the closed room and appear to be genuine diurnal daytime features of the local, magnetic environment. The geomagnetic Sq current displacement amplitude measured at the Frederiksberg Magnetic Observatory (FRD) also follows a diurnal pattern that is at its largest displacement of about 1 arcminute in the hours just after local Noon. It is clear from Figure 28 and the coincidence between the FRD and soda bottle measurements that this device can detect the Sq effect. This is good news for educators because classroom hourly studies will be able to detect at least the Sq effect, which can then be related to space weather phenomena and the ionosphere.

Geomagnetic Storms

These events caused by space weather are infrequent even during conditions of sunspot maximum. It is best to consult a space weather service on your smartphone or at the NOAA Space Weather Prediction Center[3], and check the 'Estimated Planetary Index' display, which shows the level of activity of the geomagnetic field. When conditions exceed Kp=6 or 7, start making periodic measurements of the location of the laser spot along the meter stick.

You are looking for a long-term multi-hour trend in the spot moving progressively farther from the rest 'null' position of the laser spot. The maximum displacement is a measure of the severity of the geomagnetic disturbance at your latitude. At lower latitudes such as New York City or San Francisco, the maximum displacements during a strong storm with Kp=8 may be more than ten centimeters. At higher latitudes closer to the auroral zone, such as Bangor, Maine or Detroit, Michigan, the displacement could be dozens of centimeters depending on how far the meter stick/wall is from the magnetometer.

Strong magnetic storms produce shifts of $\Delta D \geq 1^o$ for some geographic locations. However, typical values for ΔD for the weaker and more numerous storms will likely be in the range from $0.5^o < \Delta D < 1^o$. The detection limit for this system suggests that under good conditions this system can detect geomagnetic storms with Kp > 5. The detection will be strongly latitude-dependent because Kp is generally measured at high latitudes in the auroral zone, and will produce weaker changes at mid-latitudes for the same value of Kp.

As an example, on July 14, 2000, the detection of a solar flare was followed by a halo, or Earth-directed, coronal mass ejection (CME) in SOHO LASCO coronagraph data starting at 10:54 UTC. This CME reached Earth on 15 July causing a geomagnetic storm on 15-16 July which would reach a peak Kp index of 9+ in the late hours of 15 July corresponding to an extreme-level, or G5, geomagnetic storm. Figure 29 shows the Kp index history of this storm, which caused minor damage to power transformers and satellites.

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[3] https://www.swpc.noaa.gov/

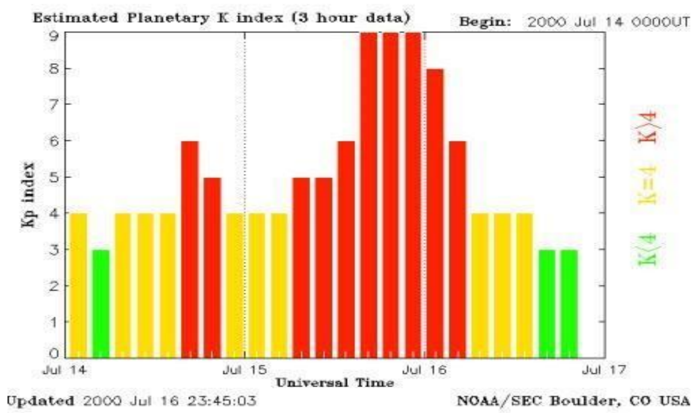

Figure 29. Kp Indices for the July 15, 2000 Bastille Day Storm.

The once-in-a-sunspot-cycle storm data were collected with a 5 m separation between the magnet and the meter stick. Figure 30 shows a pre-storm level near 11.5° with a strong deviation to 13.2° at about 20:06 UT. There is considerable activity between 20:00 UT July 15 and 00:00 UT July 16. This matches the severe activity shown in Figure 47 with Kp>8. So geomagnetic storms of this magnitude seen at the latitude of Kensington, Maryland (+39°N) register a deviation of about 2° on a 5 m separation. Clearly, the soda bottle laser spot needs to be measured with a longer distance between the magnet and the display screen in order to detect the weaker geomagnetic storms at mid-latitudes. However, at latitudes closer to the aurora belt in Canada, smaller separations near 1 m should be adequate for detecting the stronger geomagnetic storms. These are precisely the storms that lead to the most spectacular aurora borealis, which is why this soda bottle design was pioneered by aurora photographers to give them advanced notice that an aurora would be visible in the next 24 hours.

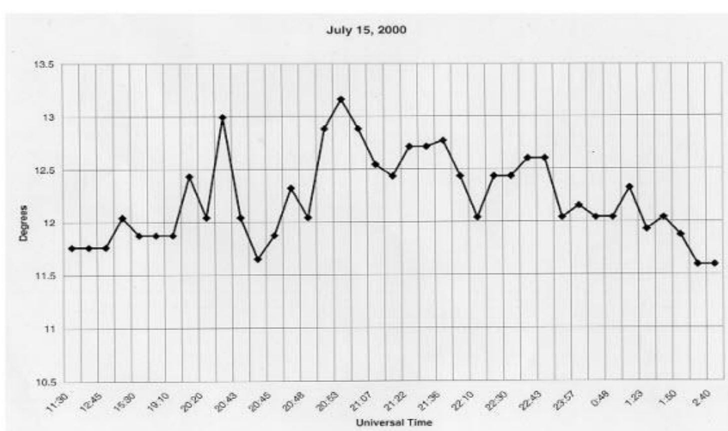

Figure 30 Soda bottle data recorded during the peak of the Bastille Day storm[4]. The linear measure along the meter stick has been converted to angular measure for convenience.

[4] https://spacemath.gsfc.nasa.gov/NASADocs/magbook2002.pdf page 38.

8. Automatic Data-taking

Soda Bottle magnetometer designs are notorious for being very human-intensive when it comes to logging the data. Ideally, you would want a system that can be left alone in your basement and that automatically records the spot location along the meter stick at some pre-set cadence.

Data recording by camera

One solution is to set up a camera on a tripod pointed at the nominal Null position of the spot with enough field-of-view to encompass the extremes of the spot movement. With the laser diode continuously ON, the camera would be set to take one image every 15 minutes. The collection of images would then be downloaded to a laptop and opened with a photo viewer so that you can swipe quickly from one to the next. An Excel spreadsheet would be open in the lower half of the laptop screen so that you could enter the spot position in the appropriate column and row. Each day, about 100 images would be taken and would have to be processed into the spreadsheet, but the image taking would be unattended so your effort would only be in reviewing the images and recording the spot positions.

Although this approach sounds plausible, smartphone cameras and apps only allow up to 10-second delays in taking successive images using apps called 'self-timers' for one-shot delays. Apps are available such as 'Time Lapse Camera' or 'Time Lapse Camera & Videos'. You can adjust the video duration, frame delay, and video quality. After recording, you'll find your MP4 files in the gallery, from where you can use video processing software to grab individual frames from the video stream. The cost for this solution is just the cost of a tripod and camera adaptor, which would be under $20.00.

Data recording by electro-mechanical interface.

Another, hypothetical, approach to automating the data taking is to create a computer-controlled interface. A photodiode light sensor would be attached to a platform on a rotating screw. The screw would be advanced using a stepper motor controlled by an Arduino, which is a programmable microprocessor. The Arduino 'sketch' program would control the motion of the screw that would drive the photodiode stage as it scans along the meterstick. The output from the photodiode would be an analog voltage input into the Arduino, which would be read-out by the same sketch driving the motor. After each step and turn of the screw, the program would test the voltage value from the photodiode to see if it is the maximum voltage value. If not, the stepper motor advances the screw one turn and repeats the test until it finds a maximum value. This is where the center of the laser spot is located producing the highest output voltage on the photodiode, and this value along with the screw turn count and elapsed time, would be saved to memory. Later, this data could be read-out into an Excel spreadsheet. The cost for this solution would be about $30.00, primarily for the hardware, stepper motor and Arduino Uno microprocessor.

Given the likely sensitivity of this basic soda bottle design, it seems unwise to invest very much in automating the data-taking operation. Sometimes the simple solution, though time-consuming, can be the best practical solution!

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