

# MAG

## Magnetic Fields

revised August, 2021

(You will do two experiments; this one (in Rock 402) and the Magnetic Induction experiment (in Rock 403). Sections will switch rooms and experiments half-way through the lab.)

### Learning Objectives:

During this lab, you will

1. learn how to use a log-log plot to determine the exponent in a power law model.
2. estimate the uncertainty in directly measured quantities that is calculated from quantities that are uncertain.
3. test a physical law experimentally.

### A. Introduction

Magnetic fields can be created by electric currents and by ferromagnetic materials such as iron. However, even the fields created by ferromagnetic materials can be explained in terms of currents. These currents are due to electrons orbiting within individual atoms or electrons ‘spinning’ about their own axis.

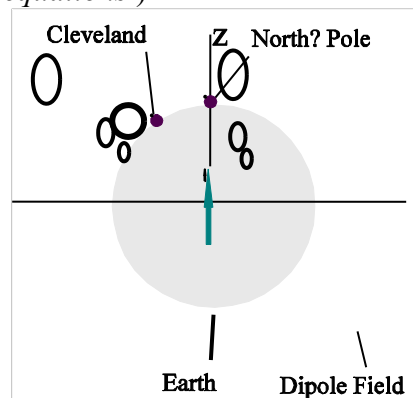
In this lab you will use one type of magnetic field sensor, a Hall Probe, to investigate the magnitudes and directions of the fields created by the Earth and by some common objects; a current-carrying wire, a coil and a small permanent magnet.

You must **complete and turn in a worksheet worth 30 points for Lab #5A; turn it in with your worksheet for Lab #5B, with all the graphs, and the cover sheet.** The worksheets are in Appendix XI.

### B. Theory

#### B.1. The Earth’s Magnetic Field

The magnetic field lines of the Earth are illustrated in Fig. 1. This is a dipole field, much like the dipole electric field that you examined in an earlier lab using the water tray and brass conductors. Near the north and south poles, the field points directly into or out of the Earth. Near the equator the field is parallel to the surface. Near Cleveland the Earth’s magnetic field has a north-south horizontal component and a much larger vertical component into the ground. The magnitude of the field is about 0.4 gauss or 0.00004 Tesla. (The various formulae and constants used in this manual assume that magnetic field is measured in Tesla with other quantities in appropriate SI units. However your equipment will report the field data in CGS units, gauss. Remember to convert to Tesla, with  $1 \text{ Tesla} = 10^4 \text{ gauss}$ , before using these equations.)



**Figure 1:** Earth’s Magnetic Field near Cleveland.

Note that the geographic North Pole in Fig. 1 is labeled as “North?” The question mark is included because the Earth’s geographic north pole is actually a magnetic south pole. (Also, the Earth’s magnetic poles seem to reverse every million years or so.)

## B.2. Long Straight Wires

A current  $I$  flowing in a long, straight wire creates magnetic field lines that are circles centered on the wire. The magnitude of the field outside the wire is

$$B = \mu_0 I / 2\pi r \quad (1)$$

where  $r$  is the distance radially out from the center of the wire and  $\mu_0 = 4\pi \times 10^{-7} \text{ T}\cdot\text{m/A}$ .

## B.3. Coils and Magnets

The magnetic field at a height  $z$  above the center of a coil of radius  $R$  is derived in Halliday, Resnick, and Walker (p. 702) as

$$B = \frac{\mu_0 i R^2}{2(R^2 + z^2)^{3/2}} \quad (2)$$

It follows that the magnetic field at a height  $z$  above the center of an  $N$ -turn coil of radius  $R$  is

$$B = \frac{\mu_0 N i R^2}{2(R^2 + z^2)^{3/2}} \quad (2a)$$

It is particularly instructive to examine the behavior of this field at heights much larger than  $R$ . For heights  $z \gg R$ , you can ignore the  $R^2$  term in the denominator compared to the  $z^2$  term and Eq. 2a reduces to

$$B = \frac{\mu_0 N i R^2}{2z^3} \quad (3)$$

So instead of the field falling off as the inverse square of distance, as it does for the electric field of a point charge, the magnetic field of a coil falls off as the inverse **cube** of the distance. The formula for the field in directions other than straight up is much more complex than Eq. 2a, with the field varying in both magnitude and orientation depending on the direction from the coil, but it still falls as  $1/r^3$  in any given direction.

One reason that this is such an interesting result is that the fields of permanent magnets are closely related to the field of a current-carrying coil, measured far from the coil. This is a dipole field and dipole fields; whether they are magnetic dipoles or electric dipoles, fall as the inverse cube of distance.

The fields of permanent magnets arise from the spins of electrons that make up the magnet. The field lines outside a permanent magnet have the same shape as the field lines from a current-carrying coil of wire if the coil has the same size and shape as the magnet. Even the magnitudes of these two fields can be made the same if the current through the coil is adjusted properly.

## C. Apparatus

### C.1. Magnetic Fields

You will be measuring the magnetic fields of four different objects. These are:

- i. the Earth, which will also serve to check and calibrate your use of the Hall Probe;
- ii. a bundle of  $N = 100$  “infinite” wires. These wires are actually part of a square coil of side  $L = 0.61 \text{ m}$ . This coil can simulate an infinite wire if you take measurements near the center of a side, far from the corners, and at spacings away from the wire bundle that are very short compared to the length of a side;
- iii. a 1600 turn round coil of radius  $R = 1.2 \text{ cm}$ ;
- iv. a disk-shaped permanent magnet similar in size and shape to the coil described above.

You will use a small compass and a dipmeter (a “vertical” compass) to measure the direction of a magnetic field. Use a power supply and DMM to furnish and monitor the currents through the two coils. For data acquisition and analysis, use the *LoggerPro* hardware and software.

## C.2. The Hall Probe

You will measure the magnitude of each magnetic field with a Hall probe connected to the LabPro interface. The theory behind a Hall probe is discussed in detail in your text but the basic principle is easy to explain. Moving charges (*or a current*) in a conductor feel a force when the conductor is placed in a magnetic field oriented perpendicular to the conductor. This force is perpendicular to the direction of the current flow, so charges will tend to pile up on the edges of a ribbon-like conductor. This piling up will continue until the electrostatic forces between these charges equals the force per charge due to the magnetic field. If you measure the *transverse potential* (*the potential perpendicular to the direction of current flow*) across the width of the ribbon conductor, you've effectively measured the magnetic field.

Note that a Hall probe only measures one component of the magnetic field, the component perpendicular to the ribbon conductor; this direction is marked with a white dot on your probe, as illustrated in Figure 2. Maximum field will be recorded when the white dot is facing the north pole of a magnet. Field components along the length or width of the probe are not detected. So to find the total field, one must either rotate the probe about two axes until the reading is maximized (*which then provides the magnitude and direction*) or take three mutually perpendicular readings ( $x, y, z$ ) to get the field components.

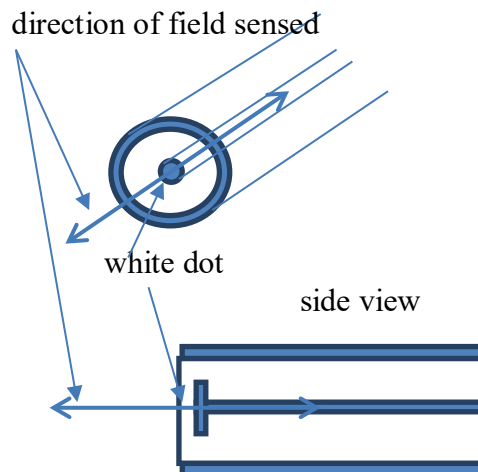


Figure 2: Hall probe directionality.

## D. Procedure and Analysis

### D.1. Hall Probe Calibration

Be sure that the probe is plugged into channel 1 of the LabPro interface and that the small switch on the probe box is set to **LOW** amplification. Start the *LoggerPro* program by double-clicking on its Windows desktop icon.

### D.2. Earth's Field

Near Cleveland, the Earth's magnetic field is  $0.4 \pm 0.1$  G and has components along the surface of the Earth, towards magnetic north, and into the ground. Note that the front entrance to the Rockefeller Building points roughly towards the west. This should help you locate magnetic north.

You will be able to find in the lab both a compass and a dipmeter, or possibly a combination instrument called a *dipneedle*. A compass is commonly used by people to find the direction of magnetic north, but few realize that it gives only one component of the Earth's field, a relatively minor component in Cleveland. The compass needle points along the component of the magnetic field parallel to the Earth's surface. The dipmeter is basically a vertical compass. When it is aligned in a north-south plane, the dipmeter

will indicate the actual direction of the Earth's field (*and not just the vertical component*). Check this yourself with the compass and dipneedle. You should find that the magnetic field in Cleveland is nearly vertical. The reason for this is illustrated in Fig. 1, where a dipole field is superimposed on a globe.

Be certain to **keep the compass and dipmeter away from any permanent magnets when making these measurements. You should also keep them away from each other since both the compass and the dipmeter are themselves magnetized.** Even if you are careful, it's possible that your compass and dipmeter will give faulty indications of the direction. This can happen if, for example, your steel lab table is slightly magnetized. Your TA will point out a "master" compass and dipmeter which are set up in a location where the stray fields are minimal; you can refer to these instruments for a reliable indication of the direction of the Earth's magnetic field.

**Use the Hall probe to measure the magnetic field of the Earth. Point the Hall probe in several random directions. Stop the scan and LoggerPro should choose a scale that displays all of the data. Start another scan and point the Hall probe dot in the direction of the Earth's field - almost straight down but slightly north. Confirm that you have the probe pointing in the correct direction by varying the probe direction to maximize the magnitude of the reading.** Remember to keep the probe away from any magnets.

Once you think you have the probe pointed in the direction of the Earth's field (*by maximizing the reading*), **rotate the probe 180° about the long axis of the plastic tube.** This reverses the direction of the white dot and should cause the reading to reverse sign. Ideally the readings should change from plus to minus  $0.4 \pm 0.1$  G or vice versa but they probably won't. It is likely that you will

observe an overall change of  $0.8 \pm 0.2$  G when you flip the probe but that the scan won't be centered about 0. This behavior is due to small, irreproducible electrical offsets in the interface electronics. The Hall probe signal is very small, tens of millivolts. While the gain of the probe and the amplification of the electronics is quite consistent (*1/32 volt per G*) there are gradual, random drifts in the interface circuitry that are interpreted by the computer as adding to or subtracting from the field reading. These drifts can appear to be as large as a few G per hour but are much smaller over the time of any single measurement you will make.

The experiments in this lab are set up so that you can easily subtract off this offset as well as the Earth's field from each set of data. So while it is possible to recalibrate the probe or simply subtract off this offset from your data for the Earth's field, this is not required.

**Try several flips to align the probe parallel and opposite to the Earth's field, pausing for about 5 seconds in each position to generate a "square" wave on the LoggerPro scan.** If when you flip the probe back and forth, you don't see an overall change in field of about  $0.8 \pm 0.2$  G, you may have other problems; you have either not located the true direction of the Earth's field, your probe is seriously miscalibrated or you aren't using it correctly. **Ask a TA for assistance before proceeding.**

### D.3. Long Wire

**Connect the large square coil being used to simulate a long straight wire in series with a 13.8 V power supply and a DMM set to read current on a 10 A scale. Before you turn the power supply on make sure your DMM is in series with the coil and NOT in parallel.** (It may take the current a minute or so to stabilize at about 1.3 A after you turn on the power supply, as the coil heats up and its resistance increases.) This coil only simulates an infinite wire if you **take**

measurements close to the bundle of wires near the center of one leg of the square; don't measure near the corners.

Referring to Figure 3 and to the photograph posted on the lab web site or on Canvas, start by **holding the coil in a vertical plane, resting one side of the square on the table, and use your small compass to investigate the direction of the magnetic field a few cm from a vertical section of the wire bundle. Do this near the center of a section of the loop and not close to the corners.** Remember to **hold the compass horizontally as you move it in a circle around the wires to follow the magnetic field.** This should prove to you that the field lines form circles around the wire.

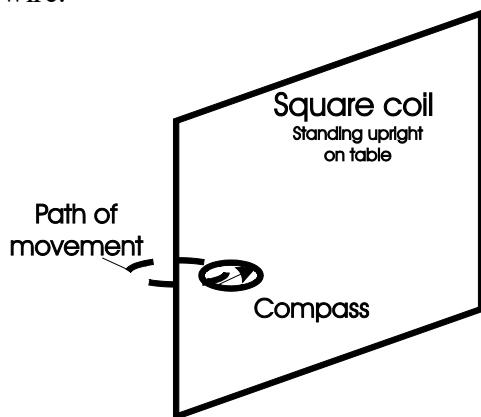


Figure 3: Path of  $\mathbf{B}$  for “infinite” wire.

Now lay the coil flat on the lab table. Mount your Hall Probe (with the dot pointing up) in the aluminum support structure that you will find at your lab station, checking that the probe is at roughly the same height as the center of the wire bundle. (This is a little tricky because the cross-section of the probe is elliptical at its measurement end but round everywhere else. The holder has elliptical holes that require inserting the probe in one orientation and then rotating it  $90^\circ$  before locking it in position by LIGHTLY tightening a plastic bolt.) Take your readings outside the coil near the center of a long straight section of

the loop. Refer to the photo on the lab web site or on Canvas for guidance.

You will need to **measure the magnitude of the field at distances of 1.5, 3, 5, 8, and 12 cm from the wire bundle and then acquire one more data point with the coil current turned off.** These distances should be measured with a ruler from the center of the bundle of wires that make up the coil to the center of the white dot on the Hall Probe. It is better to move the coil rather than the Hall probe, so that the probe is not affected by any local variations in the magnetic field due, for example, to the steel tables or nearby magnets. You can **take all 5 data points in one 60 second or so sweep of the program, pausing at each distance long enough to see a clear plateau on the computer monitor.** Set the vertical scale in LoggerPro to a range of -1 to +12 G. (Setting these values takes LoggerPro off autoscale. You can change these numbers if you feel it is useful; they were chosen purposely to cover such a wide range that everyone should see something on their first try.)

Before your scan is complete, **turn off the current and let LoggerPro acquire another plateau.** Prior to analyzing this data, you should **subtract the value of this reading from your other measurements.** This will eliminate the effect of the vertical component of the Earth's magnetic field and any offset in the interface electronics.

The LoggerPro software provides a convenient means for determining the average value of each plateau. LoggerPro also provides an error estimate based on the variations in the scan during a plateau. **Click and hold the left mouse button while you wipe the cursor over the region of interest. Then click on ANALYZE / STATISTICS.** The program will calculate the information you need and paste it into the figure. You should **move the textboxes to convenient**

locations, save the figure to the L: drive, and **include it with your worksheet.**

**Plot  $B$  vs.  $r$  in Origin as described below and use Origin to check the functional relationship between field and distance.** (*Remember to subtract off the value with no current in the coil before making your plot.*) Since you already know that theory predicts the field should fall off as  $1/r$ , you might be tempted to plot  $B$  vs.  $1/r$  and show that you get a straight line - but **don't do this**. Experimentalists don't always know the answer before they start taking data (*and the theory isn't always right*). You should use a better technique that lets you check whether **any** power law fits the data. This can be done by **making a log-log plot of  $B$  as a function of  $r$ .** (*Plot  $B$  vs.  $r$ , then double click on each axis and change type from linear to log10. It really doesn't matter if you use the natural log or log-base 10 but use the latter here because it lets you produce easier-to-read axes on your plot, with labels such as 0.01 m, 0.1 m, etc.*) If the data appears linear on such a plot, then it can be described by a power law. The slope of a linear fit gives you the exponent of the power law. Theory predicts that for an infinite wire this slope should be -1. **Do this fit and show it on your graph. Include the graph with your worksheet. Remember to include error bars in your plot and to report an error estimate for the value of the power law that you find.** (*Origin will calculate this latter error estimate for you!*)

#### D.4. Coils

Referring to the photograph on the lab web page or on Canvas for guidance, **set up the Hall probe in its aluminum support for measuring the magnetic fields of your coil. Mount the small round coil glued to a gray plastic bar into this same aluminum holder. Align the Hall probe 5 cm directly above the center of the coil before lightly tightening the screws that hold them each in place.**

The coil should be connected to the 13.8 V power supply through a DMM to monitor the current. The *LoggerPro* scale should initially be set at -1 to +2 gauss. After the current stabilizes (*at about 0.13 A*), **start a *LoggerPro* scan and measure the vertical component of the magnetic field as you move the coil straight down in steps of 2 cm, until it is 13 cm below the probe. After taking the 13 cm data but before the scan is finished, turn off the current and acquire another plateau. You will need to subtract the value of this plateau from your other data before doing any analysis,** to eliminate the effects of electrical offsets and the Earth's magnetic field.

**Plot  $B$  vs.  $r$  in Origin.** To test if the field falls off as the inverse cube of  $r$ , as predicted by Eq. 3, **convert both of your plot's axes to log<sub>10</sub> scales, do a linear fit and see if the slope is -3. Include this plot and fit with your worksheet.**

#### D.5. Disk Magnet

**Replace the coil with the disk magnet, check that the Hall probe is centered over the magnet and set the *LoggerPro* scale, initially, to -1 to 15 gauss. Repeat all of the measurements and analysis that you performed for the coil.** You will not be able to "turn off the current" that creates the field for the permanent magnet. Instead, **after taking your 13 cm data lower the magnet as far as it will go, quickly remove it from the aluminum holder and let *LoggerPro* acquire a plateau. Subtract the value of this plateau from your other data before starting your analysis.**

**Compare the dependence of  $B$  on  $r$  for the magnet and the coil.** (*If you wish, you may plot both sets of data, for the coil and the magnet, on a common x-axis. To do this, you need to have all of this data in one table. Highlight the x and both y columns before selecting PLOT-SCATTER-SCATTER or*

*highlight nothing, select PLOT-SCATTER-SCATTER and then use the resulting window to choose your x and y columns, clicking the down arrows to expand the dialog, and clicking the ADD button to add these sets of data onto your plot. To determine which dataset will be used for a linear fit or other operation, activate your plot, go to DATA and highlight the appropriate selection.)* The linear fits for the coil and magnet should both have slopes close to -3. This demonstrates the equivalence of the magnetic fields of current loops and permanent magnets. The offset between these curves is just due to the difference in effective currents. You could make these curves overlap if you increased the current through the coil, which would probably cause it to overheat and burn, or simply multiplied the field of the coil by an appropriate constant. This is not required.

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