University of Tasmania

Second-year laboratory work

KYA212

Induction and the Earth's Magnetic Field

July 29, 2025

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Safety

General information regarding lab safety can be found on POLUS, the lab website, whereas experiment-specific safety considerations are listed here.

Hazards

The magnetic induction apparatus utilises a spring-loaded mechanism to rotate through the coil through 180 degrees very quickly. The mechanism can pose a pinch point hazard, so ensure to keep your fingers away from the mechanism when loading or during release.

A risk assessment for this activity has been undertaken and approved by the relevant university authority; it can be accessed here.

Summary

A changing magnetic flux creates a measurable electric current in a loop of wire. One way of creating a change in magnetic flux is by changing the orientation of the loop with respect to a constant field **B**. In this experiment, the strength and orientation of the Earth's magnetic field is measured by observing the electrical response produced during a 180° rotation of a coil of wire (and hence the device being colloquially known as the "π-flipper").

Experiment objectives and learning outcomes

> The primary objective of this experiment is to measure the vertical and horizontal components of the Earth's magnetic field within the laboratory and outside.

Following this experiment, it is expected that you will:

- Gain practical experience with applying Faraday's laws of induction.
- Work with operational amplifier ("op-amp") circuitry.

Introduction

Earth is surrounded by an immense magnetic field called the magnetosphere. This field plays an important role in making the planet habitable. Aside from providing the basis for compass navigation, it protects the atmosphere from stripping by the solar wind and shields us from the radiation effects of coronal mass ejections and cosmic rays from deep space.

Background

Pre-lab exercises

Pre-lab questions can be found sprinkled through the introductory section. These are to be completed and submitted *before* you commence a new experiment. The information needed to complete the exercises is contained in the experiment background section, your course notes, or in the appendices; however, your own independent research is highly encouraged. Make sure to include references where material has been foraged from elsewhere; this is not only "good form", but making notes of this kind - where to find useful information - is essential should you need to return to the origin of some information.

Context

This field is generated by dynamic geophysical processes at the centre of our planet. Since these processes are constantly changing, the field itself is in continual flux, it's strength changing over time. Given the importance of the magnetosphere, understanding it's behaviour through persistent and repeatable measurements is important. Many Low Earth orbiting (LEO) satellite missions have been commissioned to do just that starting with MAGSAT (Magnetic field Satellite) in the 1970s and more recently, ESA's Swarm mission. However, the University of Tasmania does not hold a stake in the European Space Agency so in this experiment we will use a much simpler apparatus to measure the local magnetic field.

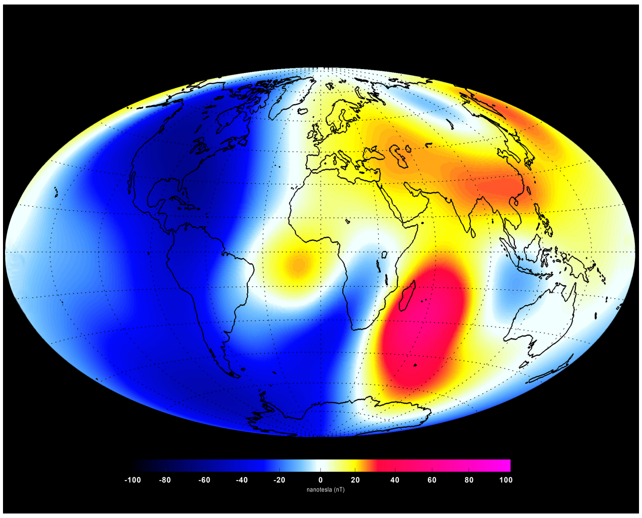

Figure 1: Changes to the Earth's magnetic field over a 6-month period from January to June 2014 as measured by the ESA Swarm satellite constellation. Red areas show where the magnetic field is strengthening while blue areas show weakening [1].

The magnetosphere is believed to be in the range of 3-4 billion years old but humans have only really known about it since the 1600s when William Gilbert published his work "De Magnate". This postulated that the Earth itself generated its own magnetic field, and that it had a similar configuration to a magnetized sphere. By observing the orientation of small needles placed at various spots around such a sphere, he verified that his hypothesis was able to explain much of the mysterious behaviour of real compasses. In 1832, Carl Freidrich Gauss provided the first absolute measurement of the horizontal component of the geomagnetic field using a simple apparatus consisting of two bar magnets, something to suspend the magnets, a ruler, a clock and two weights.

Unlike the magnetic fields we are used to in everyday life, the Earth's magnetic field is not a result of a permanent magnet at the centre of the planet. The temperature there is too high for this. Instead, it is driven by the thermal convection of the liquid iron in the outer core region. However, to first order, we can treat the Earth like a magnetic dipole whose poles are slightly offset from the north and south geographic poles. This results in a magnetic field on the Earth's surface, B_E, which varies in strength and direction from place to place. An important observable property of B_E is that it has a vertical component, known as the dip, that increases with geomagnetic latitude. Another observable is the difference between magnetic and geomagnetic north (or south). This difference is termed the magnetic variation or magnetic declination. Both angles are observed to vary with time, and the rate and periodicity of this "secular variation" provides important clues to the processes which create the magnetic field.

Faraday's Law of Induction

Understanding how magnetic fields and electrical circuits interact to produce an electromotive force (EMF) underpins this experiment.

Faraday's law of induction was developed in 1831 after a series of experimental observations. This law describes how an electric current produces a magnetic field and, conversely, how a magnetic flux generates an electric current.

Prelab 1 *An illustrative exercise*

In what ways can the magnetic flux change?

[1] https://earth.esa.int/eogateway/missions/swarm

For a single conducting loop, Faraday's law states that the EMF is given by the rate of change of magnetic flux (Φ_B).

$$\varepsilon = -\frac{d\Phi_B}{dt} \tag{1}$$

Prelab 2

Consider a flat, circular coil of n turns, each of the same radius r, in a uniform magnetic field $\vec{B}$. The coil is places perpendicular to $\vec{B}$, i.e. the unit vector $\vec{\hat{A}}$ normal to the circular area enclosed by the coil is parallel to $\vec{B}$. Now suppose the coil is rotated through an angle θ during time τ at a constant angular velocity, so that $\vec{\hat{A}}$ ends up anti-parallel to $\vec{B}$. During this rotation, a voltage ε is induced across the coil. Once the rotation stops, the voltage drops back to zero. Starting from Faraday's law of induction, show that for $\theta = 180^o$

$$\int_0^\tau \varepsilon dt = 2\pi n r^2 B \tag{2}$$

In this experiment, the magnetic field is supplied by the Earth. The horizontal (H) and vertical (Z) components of this field vary depending on longitude and latitude.

Prelab 3

At what locations on Earth would you expect unreliable measurements of the Horizontal and Vertical components of the magnetic field? What steps could you take to circumvent this problem?

Prelab 4

Consider the schematic in Figure 3 together with Equation 4. By applying Ohm's Law and the definition of capacitance to the input and output sides of the circuit, derive the relationship between the input and output voltages.?

Prelab 5

Thinking about the equations you have derived in Exercise 2 and Exercise 4, show that the magnetic field can be obtained from

$$B = \frac{V_{out} RC}{2\pi r^2 n} \tag{3}$$

Apparatus

To do this experiment, you will need the following components. A labelled diagram of the setup is shown in figure 2.

1. A **wire coil**, which forms the core of π-flipper is a continuous length of wire with ≈ 1000 turns and a mean diameter of about 15.5 cm. It is mounted on a spring-loaded shaft attached to a square wooden frame on a tripod. The apparatus can be wound up and released using a simple ratchet mechanism. When released, it rotates through 180° (hence the name, "π-flipper") in about 0.2 seconds. At the end of the flip, the ratchet locks it back in place to avoid and bouncing of the coil.
2. A **D.C. battery pack** is used power the operational amplifier. Importantly, it is portable, allowing you to take the apparatus outside. If we used an electronic power supply, we would need quite a long extension lead!!

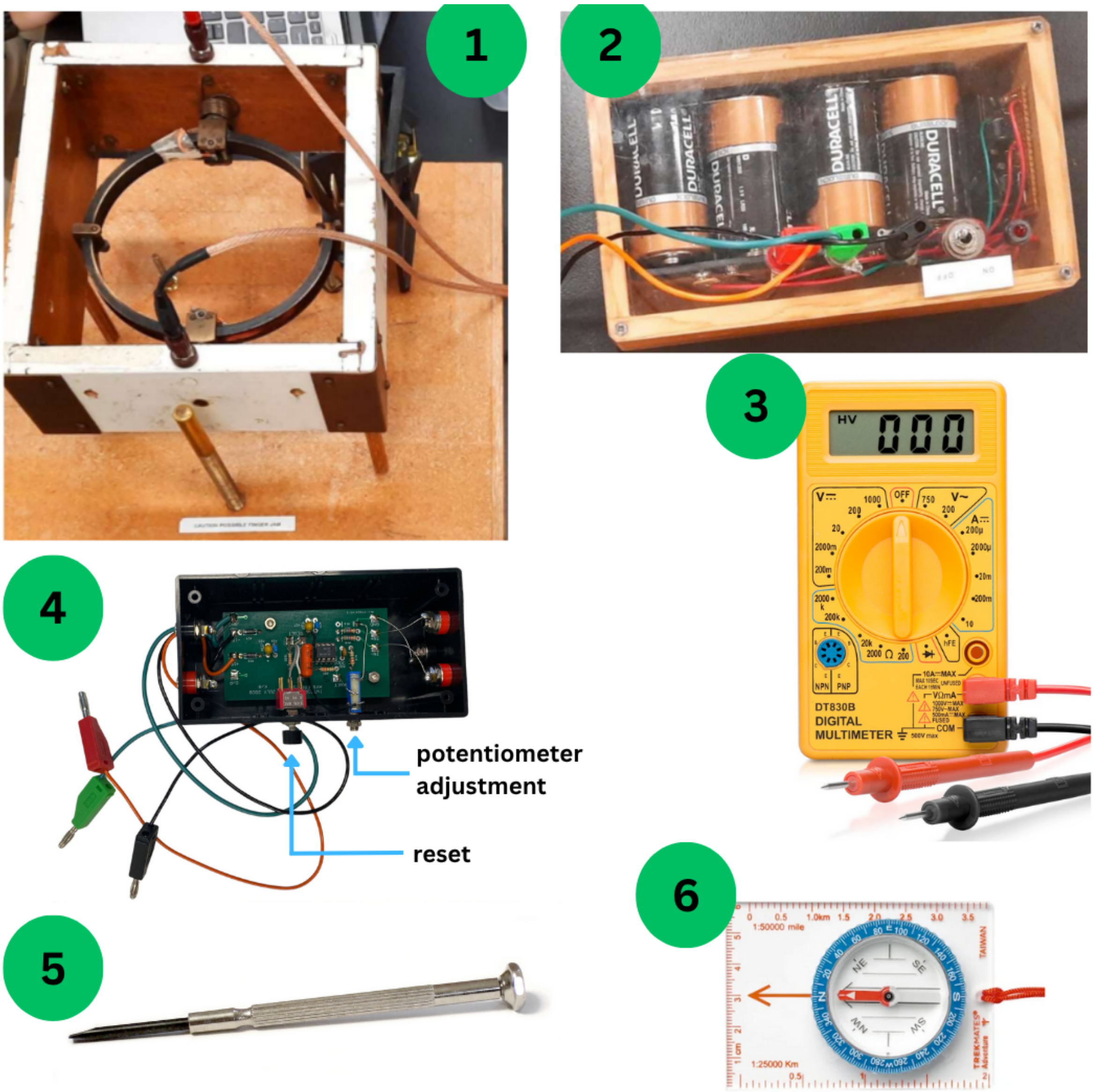

Figure 2: Components used to measure the Earth's magnetic field

3. A **Voltmeter** is supplied for reading the output signal of the op-amp.

4. An **integrating amplifier** is used to measure the EMF produced when the coil flips. This integrating amplifier requires some careful attention to both understand and operate, with details on both of these provided in the reference section of POLUS.

   In this experiment, the op-amp accepts input voltage V_{in}, amplifies it and shows the integrated output across V_{out}. Amplification of this signal requires external power. A positive and negative voltage applied to the appropriate pins of the op-amp provide a power on the order of 10-20 volts. The supplied battery pack allows you to connect a supply of $+V$ to the V_+ port and a $-V$ supply to the V_- port.

   NOTE: that the battery pack must be earthed locally with the inputs of the op-amp in order to provide a common ground potential.

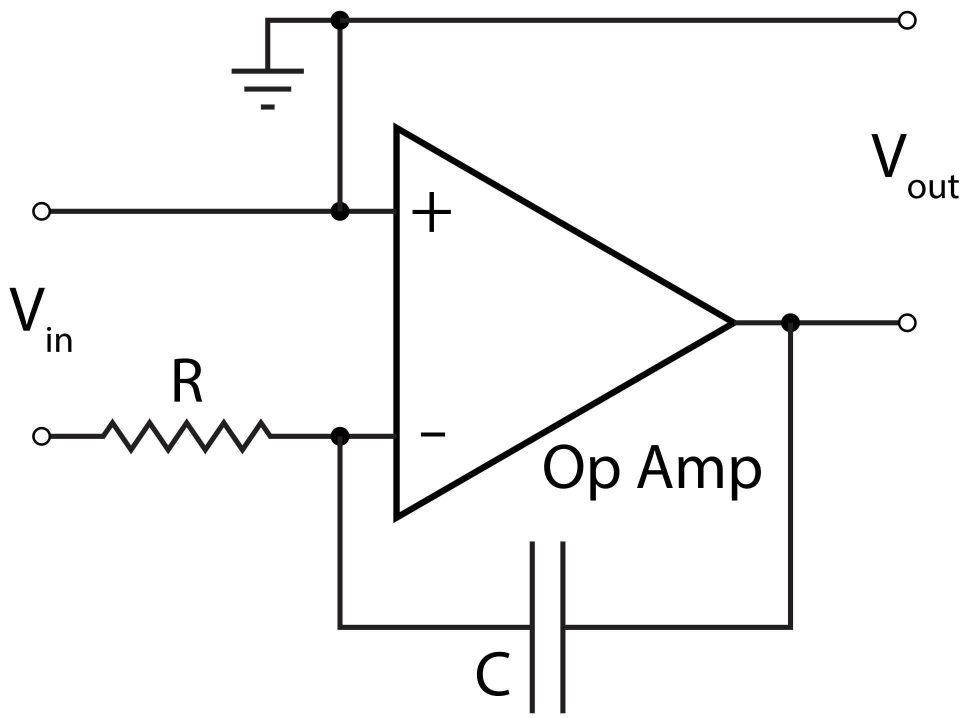

Figure 3: Schematic of an integrating amplifier. The power supply, reset button, drift adjustment, and additional resistive and capacitive components that protect the circuit are not shown.

   In the ideal case, the op-amp keeps the voltage difference between the input pins zero, and draws no current. With no additional resistance or inductive losses, the amplification factor is given by

$$\text{Gain} = \frac{1}{\text{RC}} \tag{4}$$

   Integrator drift: an annoying aspect of the op-amp is it's tendency to drift. Drift is the shifting of the amplifier output's offset voltage primarily due to temperature fluctuations. This causes the output voltage to incrementally increase. The op-amps you have for this experiment contain a potentiometer which can be adjusted using a screwdriver to effectively cancel-out the output drift. It is unlikely you will be able to remove the drift completely. However, a small drift that occurs on timescales larger than the time for the coil to flip should not significantly impact your results.

5. A flathead **screwdriver** is required for adjusting the trim-pot which must be adjusted to minimise drift of the integrating amplifier.

6. A **compass** is provided to facilitate the alignment the pi-flipper to external magnetic fields.

Experiment

With the apparatus described and the relevant physics discussed, it is now time to design and execute an experiment that achieves the Experiment Objectives.

Exercise 1

With the apparatus provided, formulate an experiment which will allow you to measure the vertical and horizontal components of the Earth's magnetic field. Ensure that your formulation includes a plan for the execution of the experiment, in addition to a plan for any analysis of your measurements.
In planning, it will help to think about the following:

- How will you connect the components in order to measure the voltage created from the movement of the coil through the Earth's magnetic field?
- How will you align the coil so that you measure the maximum and values of the horizontal and vertical components of the magnetic field?What should V_{out} be when facing magnetic East and West.
- You should take two sets of data; one inside the lab and outside the lab. Why? Where might be a good outside location?
- What are local magnetic effects? How might these affect your results?
- Is the integrator repeatable? Test thoroughly for repeatability. Is it accurate? How can we minimise drift?

Once you have a clear plan, discuss it with a demonstrator.

Analysis

At this point, you should have two sets of data. One for inside the laboratory and one for outside.

Exercise 2

1. Using your data, calculate Z, H, and the dip angle (the angle between B_E and the horizontal, increasing downward) at Hobart. Compare your values to the International Geomagnetic Reference Field[2]. Include all uncertainties and show your propagation of errors.
2. Compare your indoor and outdoor measurements. Do they agree within the errors? Identify what you think are the major likely sources of deviation.
3. At the longitude and latitude of Hobart and based on your data, do you think the measurement of the Horizontal or Vertical component of the magnetic field is more sensitive to coil alignment? Justify your answer. Are there locations on Earth where this situation would be reversed?

There are many online versions, for example https://wdc.kugi.kyoto-u.ac.jp/igrf/

References

Appendix