โครงการ

การเรียนการสอนเพื่อเสริมประสบการณ์

ชื่อโครงการ ผลของแท่งเหล็กเฟอร์โรที่มีต่อสนามแม่เหล็ก

The Effect of Ferromagnetic rod on the Magnetic Field

ชื่อนิสิต นายนันทนนท์ วิศิษฏ์พงศ์อารีย์ **เลขประจำตัว** 5833425723

ภาควิชา ฟิสิกส์

ปีการศึกษา 2561

คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย

The Effect of Ferromagnetic Rod on the Magnetic Field

Nanthanon Visitpongaree

Department of Physics, Faculty of Science
Chulalongkorn University

Submitted in partial fulfillment of the requirements for 2304499 Senior Project
Second Semester, Academic Year 2018

Project Title	The Effect of Ferromagnetic Rod on the Magnetic Field
Author	Mister Nanthanon Visitpongaree
Advisor	Assistant Professor Narumon Suwonjandee (Ph.D.)
Co-advisor	Assistant Professor Burin Asavapibhop (Ph.D.)
Department	Physics
Academic Year	2018

This report is submitted to the Department of Physics, Faculty of Science, Chulalongkorn University, in partial fulfillment of the requirements for the degree of Bachelor of Science.

This report has been approved by the committee:

....Chairman
(Assistant Professor Boonchoat Paosawatyanyong, Ph.D.)

Somrit Wongmanerod ....Committee
(Somrit Wongmanerod, Ph.D.)

ดร.นฤมล สุวรรณจันทร์ดี ....Advisor
(Assistant Professor Narumon Suwonjandee, Ph.D.)

ดร.บุรินทร์ อัศวพิภพ ....Co-advisor
(Assistant Professor Burin Asavapibhop, Ph.D.)

บทคัดย่อ

ชื่อโครงการ	ผลของแท่งเหล็กเฟอร์โรที่มีต่อสนามแม่เหล็ก
ชื่อนิสิต	นาย นันทนนท์ วิศิษฏ์พงศ์อารีย์
อาจารย์ที่ปรึกษา	ผู้ช่วยศาสตราจารย์ ดร.นฤมล สุวรรณจันทร์ดี
อาจารย์ที่ปรึกษาร่วม	ผู้ช่วยศาสตราจารย์ ดร.บุรินทร์ อัศวพิภพ
ภาควิชา	ฟิสิกส์
ปีการศึกษา	2561

วัสดุแม่เหล็ก สามารถแบ่งประเภทตามการตอบสนองของวัสดุต่อสนามแม่เหล็กภายนอก ได้เป็น วัสดุพารา-แมกเนติก วัสดุไดอะแมกเนติก และวัสดุเฟอร์โรแมกเนติก โดยที่วัสดุเฟอร์โรแมกเนติกเป็นวัสดุที่สามารถถูกดึงดูดด้วยแม่เหล็กได้ง่าย และทำให้วัสดุเฟอร์โรนั้นถูกทำให้มีความเป็นแม่เหล็กมากขึ้นอย่างถาวรได้ ตัวอย่างของวัสดุเฟอร์โรแมกเนติก เช่น เหล็ก นิกเกิล โคบอลต์ และโลหะผสมบางประเภท เมื่อวัสดุเหล่านั้นถูกวางอยู่ใกล้กับแม่เหล็ก แม่เหล็กจะทำให้สนามแม่เหล็กจากวัสดุเหล่านั้นเปลี่ยนแปลงไป โดยเราสามารถหาสนามแม่เหล็กได้จากการใช้เซ็นเซอร์แมกนิโตมิเตอร์ในสมาร์ตโฟน

ในการศึกษาสนามแม่เหล็กนี้ ได้มีการใช้ ไอโฟน 7+ ซึ่งเป็นสมาร์ตโฟนที่มีเซ็นเซอร์แม่เหล็ก รุ่น MAGNESIUM IC (U2402), model# HSCDTD601A-19[5] ในการหาขนาดและทิศทางของสนามแม่เหล็ก ในส่วนแรกเราจะทำการหาตำแหน่งของเซ็นเซอร์ในสมาร์ตโฟน หลังจากนั้นจะมีการศึกษาเกี่ยวกับข้อจำกัดในการใช้สมาร์ตโฟนเป็นเครื่องวัดสนามแม่เหล็ก จากนั้นเราจึงวัดสนามแม่เหล็กทั้งสามแกนในหลายตำแหน่งเนื่องจากแท่งแม่เหล็ก ในส่วนสุดท้ายนั้น เราจะหาสนามแม่เหล็กเนื่องจากวัตถุเฟอร์โรแมกเนติก

Abstract

Project title	The Effect of Ferromagnetic Rod on the Magnetic Field
Name	Mister Nanthanon Visitpongaree
Project advisor	Assistant Professor Narumon Suwonjandee (Ph.D.)
Project co-advisor	Assistant Professor Burin Asavapibhop (Ph.D.)
Department	Physics
Academic year	2018

The magnetic material can be classified by the response of material to the external magnetic field as the paramagnetic, diamagnetic or ferromagnetic material. The ferromagnetic material can be highly attracted to magnets and become permanently magnetized. Iron, nickel, cobalt, and some alloys are typical ferromagnetic materials. When they are placed near a strong magnet, this may alter the magnetic field. The change in the magnetic field is determined using a magnetometer sensor on a smart phone.

In this study, we will use the iPhone 7 plus which has magnetic sensors called the MAGNESIUM IC (U2402), model# HSCDTD601A-19[5] to determine the magnetic field lines. First, we locate the position of the probe of the sensor on the smartphone. Then, limitations of this method are also studied. We measure three components of magnetic field from a magnet at various positions. Finally, we determine the magnetic field due to the presence of ferromagnetic objects.

Acknowledgements

I would like to express my great appreciation to Assistant Professor Narumon Suwonjandee and Assistant Professor Burin Asavapibhop, my supervisors, for their great patient guidance in experiments and research writing. They also provided me an opportunity to explore the knowledge, language and culture by sending me to Guangzhou, China for workshop.

I would like to thank members of Particle Physics Research Laboratory for the comments and advices on my research.

I would like to offer my special thanks to Dr. Somrit Wongmanerod and Associate Professor Somchai Kiatgamolchai for the advices and apparatus of the sensor comparison experiment in my research.

Advice given by Mr. Chalermwut Chumnanchar, who is specialized in performing an electrical experiment, has been a great help in my experiments.

I am thankful to my family especially my mother and my sister who supported me in all aspects and Ms. Nichakarn Chatchumnun, my best friend, who always stands beside me and also being supportive.

I would also like to thank the hosts and creators of Toey Tiew Thai which is the most funniest TV program. This program always gives me happiness and also makes everyday special.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

The Jiangmen Underground Neutrino Observatory (JUNO) is a liquid scintillator neutrino experiment currently under construction at Kaiping, Jiangmen in Southern China. The JUNO international collaboration was established in July 2014 and the construction began on January 10, 2015. The experiment in JUNO will be started in 2020. The main goal of this experiment is to determine the neutrino mass hierarchy and the second goal is to determine the mixing angle.

Figure 1.1: The contruction area of JUNO's detector on the map

The construction site is located about 53 km from two nuclear reactors as shown in Fig. 1.1; Taishan and Yangjiang reactors, and located approximately 700 m underground to reduce muon-induced backgrounds. JUNO's detector consists of 2 main systems as shown in Fig. 1.2; central detector and veto system.

The central detector (CD) is a 35 m diameter acrylic sphere supported by a stainless-steel structure filling with linear alkylbenzene (LAB) as liquid scintillator. The sphere vessel is surrounded by two sizes of photomultiplier tubes which are 20" and 3" facing toward the center of sphere. The PMT grid is comprised of large and small PMTs aligned

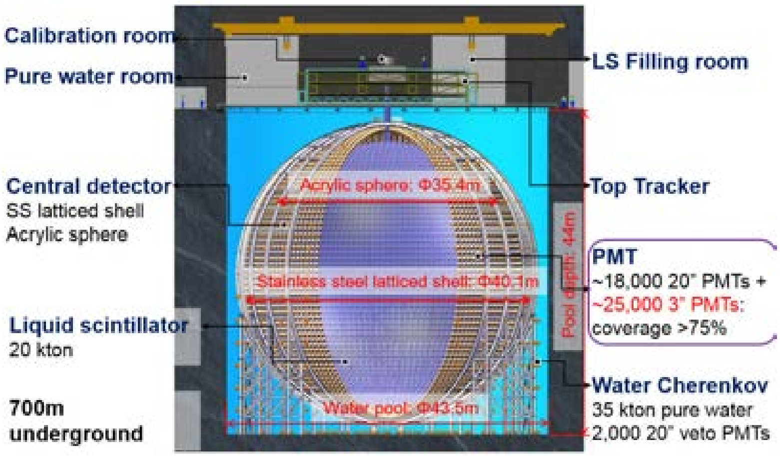


Figure 1.2: The construction diagram of JUNO's detector

in pattern as shown in Fig. 1.3. These PMTs detect light resulted from neutrino-induced interaction. This interaction is inverse beta decay as shown in Eq. 1.1. The main source of the electron antineutrino comes from both two nuclear reactors. Products from the inverse beta decay are a positron and a neutron which decay as two prompt photons and one delayed photons respectively.

$$\overline{\nu}_e + p \rightarrow e^+ + n \tag{1.1}$$

The veto system, which surrounds the central detector, consists of a water Cherenkov detector and a top tracker. A water Cherenkov detector is filled with the purified water and the photomultiplier tubes, on the stainless-steel supporting structure, which face away from the center of the central detector. This part is for detecting the Cherenkov light induced by muon traveling through water. A top tracker is made of scintillating strips that can detect the position of muon.

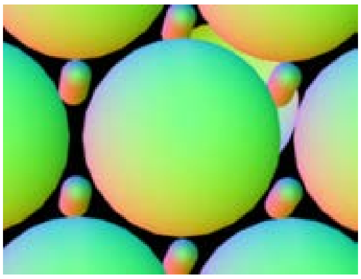


Figure 1.3: The alignment of two sizes of PMT

Figure 1.4: The 20 inches photomultiplier tube

Photomultiplier as shown in Fig. 1.4 is a photosensitive device which converts light into electrical signal. The PMT's efficiency decreases in a presence of magnetic field as shown in Fig. 1.5[8]. The Earth's magnetic field (EMF) at the JUNO's site is about 0.45 G which will affect the PMT's performance. In order to reduce the EMF, we will install a set of 32-circular coils forming a sphere of radius 21.64 m to surround the PMTs. The CD and veto system are inside a cylindrical concrete wall filled with purified water. There are metal reinforcing bars crossing each other inside the concrete wall. These reinforcing bars may affect the magnetic field produced by the spherical coil.

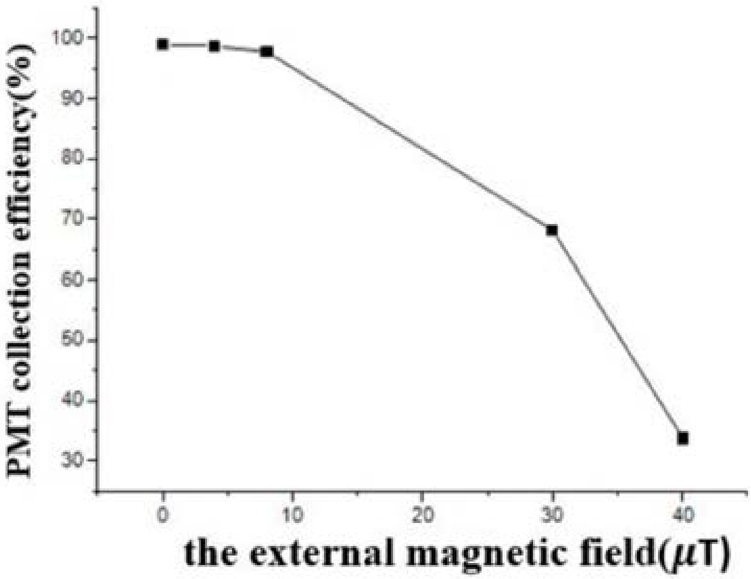


Figure 1.5: The efficiency of PMT as a function of magnetic field

Normally, the magnetic field is created by a current-carrying wire, but it can also be produced from the magnetization of the material. So, in this study, we determine the magnetic field due to the magnetic material especially the ferromagnetic object. In this experiment, we measure the magnetic field using the magnetic sensor from the smartphone which provides high sensitivity up to 10^{-7} Tesla.

1.2 Objectives

The objectives of this project aim for determining the magnetic field due to the presence of ferromagnets by using the smartphone. We have to know how to use the smartphone as a magnetic sensor by studying the following objectives.

1. Determine the sensor position in the smartphone for using the correct sensor position to measure the magnetic field.

2. Determine the magnetic field measurement compared between smartphone with the standard magnetic probe used in Physics Laboratory for verifying that smartphone measure the right magnitude of magnetic field.

3. Determine the magnetic field lines due to three magnets with the same and opposite polarities for determining the orientation of magnetic sensor.

4. Determine the magnetic field due to the presence of ferromagnets to study the behavior of the ferromagnets under the magnetized condition.

Chapter 2

Theoretical Background

In this chapter, we demonstrate the theory that used in the experiment. We use the Biot-Savart Law to calculate the magnetic field produced from the Helmholtz coil and the ferromagnetic materials.

2.1 Biot-Savart Law

The Biot-Savart Law is an equation that describes how the magnetic field is created when a current flows through a wire. We use Eq. 2.1 to calculate the strength of the magnetic field from the current-carrying circular wire as shown in Fig. 2.1.

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int \frac{d\vec{l} \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} \tag{2.1}$$

where μ_0 is a permeability of free space, I is a current through the wire, $d\vec{l}$ is an infinitesimal length of the wire carrying current I, $\vec{r}'$ is the position vector from the origin to the infinitesimal length $d\vec{l}$ and $\vec{r}$ is the position vector of measuring point.

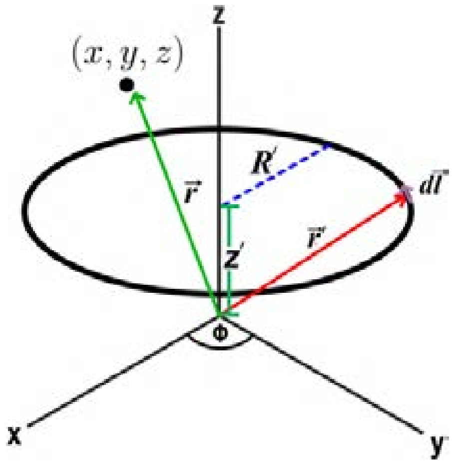


Figure 2.1: The magnetic field at any point (x, y, z) from a circular wire

In order to produce a region of nearly uniform magnetic field, we usually use the Helmholtz coil which consists of two identical circular coils that are placed symmetrically along a common axis. If the current flows through these identical circular coils in the same direction, the magnetic field at the midpoint between two identical coils will be twice as much of a single coil. To produce a uniform magnetic field, the distance between two identical coils must equal the radius of the circular coils as shown in Fig. 2.2.

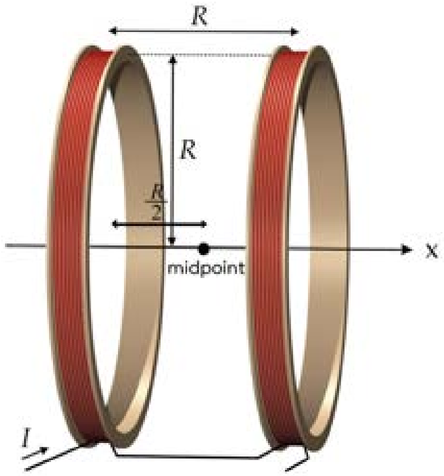


Figure 2.2: The Helmholtz coil configuration

The intensity of magnetic field at the midpoint $(\frac{R}{2})$ of the Helmholtz coil shown in Fig. 2.2 can be expressed as

$$B_{Helmholtz}(\frac{R}{2}) = 2B_{singlecoil} = (\frac{8}{5\sqrt{5}})(\frac{\mu_0 n I}{R}) \tag{2.2}$$

where I is a current through the coil, μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ $\frac{\mathrm{T \cdot m}}{\mathrm{A}}$), n is the number of the turns in each coil, and R is the coil radius.

2.2 Magnetization

This part describes how a material responds to an applied external magnetic field in the microscopic level. The foundation of the magnetization is the magnetic moment which all materials have different total magnetic moments. From those differences, all materials are classified as diamagnetic, paramagnetic ferromagnetic ferrimagnetic and antiferromagnetic materials.

2.2.1 Magnetic moment

The magnetic moment is a quantity that describes the magnetic field orientation and magnetic field strength of the object. Many objects around us have magnetic moment, such as subatomic particles, loops of electric current as shown in Fig. 2.3, general magnets, various molecules, and many astronomical objects.

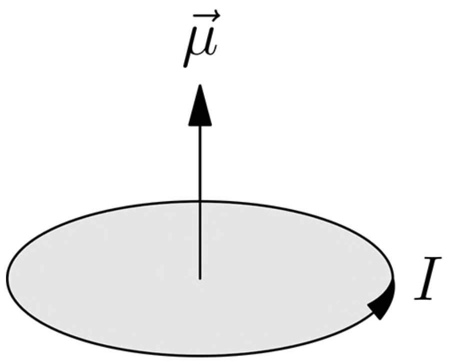


Figure 2.3: The loop of electric current has the magnetic moment

Generally, the magnetic moment refers to a magnetic dipole moment system. The magnetic moment ($\vec{\mu}$) can be considered to be a vector related to the torque ($\vec{\tau}$) on the dipole object due to an external magnetic field ($\vec{B}$). This torque is given by

$$\vec{\tau} = \vec{\mu} \times \vec{B} \tag{2.3}$$

Every portion in a volume of an object contributes the net magnetic moment ($\vec{m}$). Therefore, this magnetization field ($\vec{M}$) is defined to describe the induced magnetic dipole moments in a magnetic material.

$$\vec{M} = \frac{d\vec{m}}{dV} \tag{2.4}$$

where $d\vec{m}$ is the elementary magnetic moment and dV is the volume element.

For the loop of electric current, it behaves like the motion of electron in atom but in a different direction. This means the motion of electron in an orbit within the atom as shown in Fig. 2.4 produces the magnetic moment, so does the spin of electron that revolves its axis as shown in Fig. 2.5. Different materials have different number of subatomic particles. For this reason, the magnetic behavior of materials can be classified into these following groups: diamagnetism, paramagnetism, ferromagnetism, ferrimagnetism and antiferromagnetism. In this magnetic field experiment, we use only the ferromagnetic material because ferromagnetic object gives the highest magnetic field intensity among all types of magnetic materials.

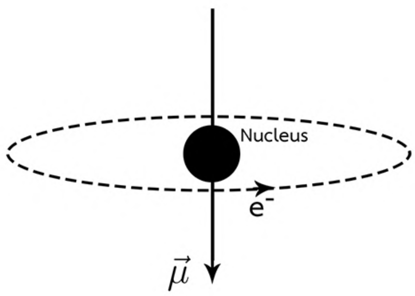


Figure 2.4: The motion of electron in an orbit of the atom

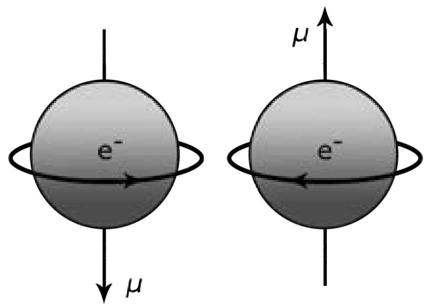


Figure 2.5: The electron spin around its own axis

2.2.2 Ferromagnetism

The magnetic moments in ferromagnetic materials tend to exhibit parallel alignment as shown in Fig. 2.6. This alignment results in large magnetization even in the absence of a magnetic field which is called the spontaneous magnetization. The magnitude of the spontaneous magnetization depends on the intrinsic spin magnetic moments of electrons. A related term is the saturation magnetization (M_S) which is the maximum induced magnetic dipole moment that can be obtained in an applied external magnetic field. At that point (H_S), magnetization is no further increase. Saturation magnetization is an intrinsic property which depends on the temperature.

From the Fig. 2.7, the relationship between the magnetization ($\vec{M}$) and the applied external magnetic field ($\vec{H}$) of ferromagnet is more complicated than the paramagnet and diamagnet. In paramagnet and diamagnet, magnetization does not retain even

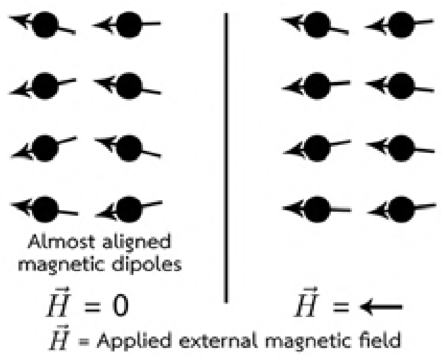


Figure 2.6: The magnetic dipoles align in the same direction to the $\vec{H}$-field even without the applied external magnetic field

though it reaches the saturation magnetization. Magnetization in ferromagnet has the retention of the magnetic dipole moments in the absence of $\vec{H}$-field at the retentivity point. This behavior is called hysteresis and a plot of the variation of magnetization with applied external magnetic field is called a hysteresis loop. The coercivity or coercive force is a measure of the reverse field needed to drive the magnetization to zero after being saturated. Ferromagnetic materials with high coercivity are called hard magnetic materials, and are used to make permanent magnets. On the other hand, materials with low coercivity are called soft magnetic materials. The susceptibility of ferromagnetic material also depends on the temperature like paramagnetic material but different tendency as shown in Fig. 2.8. The various hysteresis parameters are not just the intrinsic properties but depend on the domain state, stresses, grain size, and temperature.

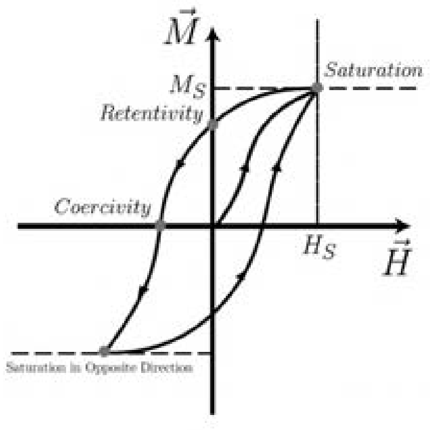


Figure 2.7: The hysteresis loop of ferromagnetic material

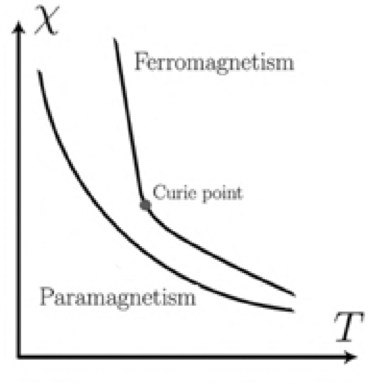


Figure 2.8: The relationship between the magnetic susceptibility (χ) and the temperature (T) of paramagnetism and ferromagnetism

2.2.3 Magnetic Domain

A magnetic domain is region within a magnetic material in which the magnetic moments of atoms are aligned in the same direction. In any magnetic material, there are many magnetic moments that are aligned differently. The different alignments of more than two groups of magnetic moment that adjoin each other will be separated as regions which are called domain walls. Magnetic domains act as miniature magnets within the material. Mostly, the magnetic domains are indicated by the arrows which refer to the magnetic field that points from the south pole to the north pole. When there is an external applied field passed through the magnetic material, the magnetic domains that have the same alignment will join together as shown in Fig. 2.9.

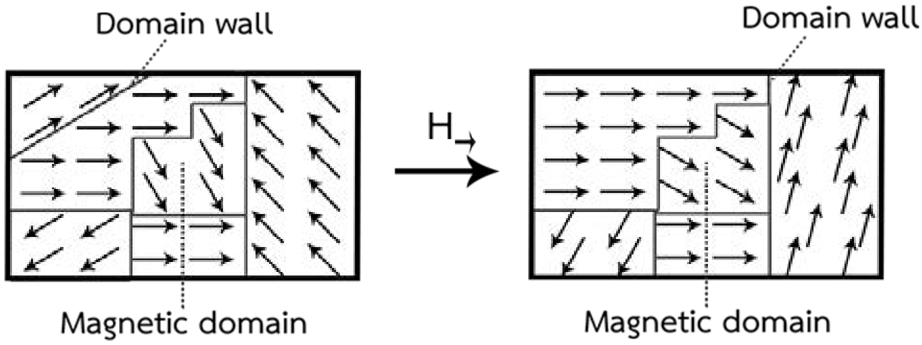


Figure 2.9: Rotation of orientation and increase in size of magnetic domains in response to an external applied field

The types of magnetic materials that their dipoles spontaneously align due to exchange interaction are the ferromagnetic, ferrimagnetic and antiferromagnetic materials. For paramagnetic and diamagnetic materials, their dipoles align in response to an external applied field but do not spontaneously align, which means they do not have magnetic domains.

2.2.4 Hall Effect

Hall effect is the most common magnetometer method. It works on the principle of the voltage detection where voltage can be detected across a thin conductive plate. The thin plate is supplied with the current which makes the charge carriers flow in a straight line from one side to the other side of the plate. When the magnetic field from the magnetic object passes perpendicularly through the element's plane. It will disturb the straight flow of the charge carriers due to a force called Lorentz force. That causes the electrons to deflect to one side whose will become a negative pole and the other side will become a positive pole. The different polarity between two sides can be measured as a voltage which will be converted as a magnetic field intensity. This method is illustrated as shown in Fig. 2.10 below.

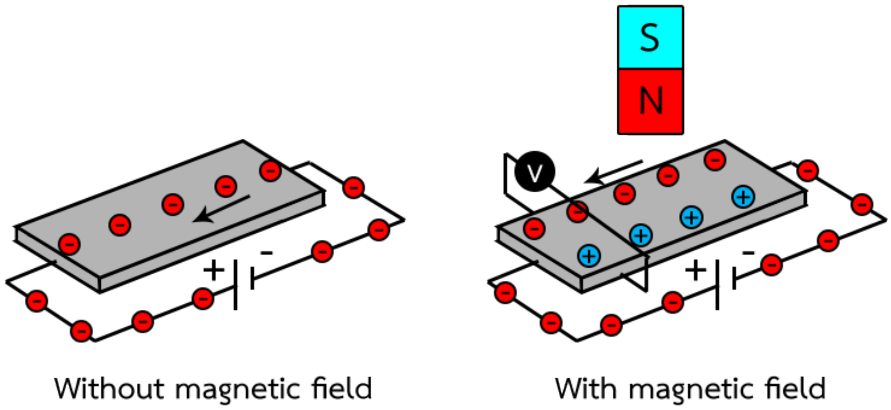


Figure 2.10: The Lorentz force on charge carriers due to the magnet

2.3 Measuring Earth's Magnetic Field Using a Smartphone Magnetometer

Article by Simen Hellesund

Simen Hellesund gives us a way to measure the magnetic field by using magnetic field measurement application in smartphone. Also, he has a method for eliminating bias due to internal magnetic fields from electronics inside the smartphone. He says there are plenty of applications available to access the magnetic field reading instantly.

The Location of Magnetic Sensor in Smartphone

Before he performs magnetic field measurement, he finds the approximate location of magnetic sensors in the smartphone. The way to find that location is to move a test magnet across the surface of the smartphone. The display of the magnetic measurement application will give the maximum magnetic field at the closest approach of the test magnet to the magnetic sensor.

Bias Due to Internal Magnetic Fields Elimination

The magnetic field measured by the sensor will be the sum of the Earth's magnetic field ($\mathrm{B_{EMF}}$) and the constant magnetic offset ($\mathrm{B_{offs}}$) in the smartphone:

$$B_{\mathrm{meas}} = B_{\mathrm{EMF}} + B_{\mathrm{offs}} \tag{2.5}$$

If the phone is flipped such that the magnetic field is measured in the opposite direction, which means the sign in the EMF term will change, the offset term will be the same:

$$B^{\pi}_{\mathrm{meas}} = -B_{\mathrm{EMF}} + B_{\mathrm{offs}} \tag{2.6}$$

The offset term can be eliminated by adding Eq. 2.5 and Eq. 2.6. You will get

$$B^{\pi}_{\mathrm{EMF}} = \frac{B_{\mathrm{meas}} + B^{\pi}_{\mathrm{meas}}}{2} \tag{2.7}$$

For our experiments, this bias elimination method is not suitable for magnetic field measurement in various positions. The method that we use will be explained in topic of Magnetic Field Due to the Presence of Ferromagnets in the next chapter which the set up, results and discussions will be demonstrated.

Chapter 3

Experimental Setup and Result

In this chapter, we explain the apparatuses used in this experiment and the information of the apparatuses. The procedures of the experiment are also described.

3.1 The List of Apparatus

There are five apparatuses used in the experiment consisting of smartphone, needle, Helmholtz coil, Regulator (Power supply) and Axial Hall probe with Sensor-CASSY.

3.1.1 Smartphone

In this experiment, we use the iPhone 7 plus as shown in Fig. 3.1 which has a length of 15.82 cm, a width of 7.79 cm and a thickness of 0.73 cm. The iPhone 7 plus has a magnetic sensor called the MAGNESIUM IC (U2402), model# HSCDTD601A-19 which can be used to measure the three components of the magnetic field in a very high sensitivity ranging from 10^{-7} to 10^{-2} T.

Figure 3.1: The iPhone 7 plus as a magnetic sensor device

"IPhone 7 Plus 32GB Black." T-Mobile,
https://www.t-mobile.com/cell-phone/apple-iphone-7-plus

3.1.2 Needle

The needle as shown in Fig. 3.2 is one of the magnetic material that produces the magnetic field around itself. It is used to locate the sensor position of the smartphone because the needle is a small rotational symmetry magnetic object. Using asymmetry or oversize object can cause the error in finding the sensor position.

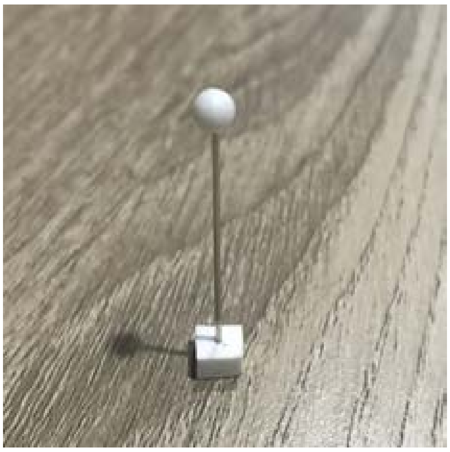


Figure 3.2: The needle is stabbed in the eraser for supporting the needle to stay perpendicularly to the plane

3.1.3 Helmholtz coil

This Helmholtz coil as shown in Fig. 3.3 is from the e/m experiment model TG-13 by UCHIDA YOKO. There are 130 turns on each coil with radius of 0.15 m. The external power supply is needed to supply the current to the coil.

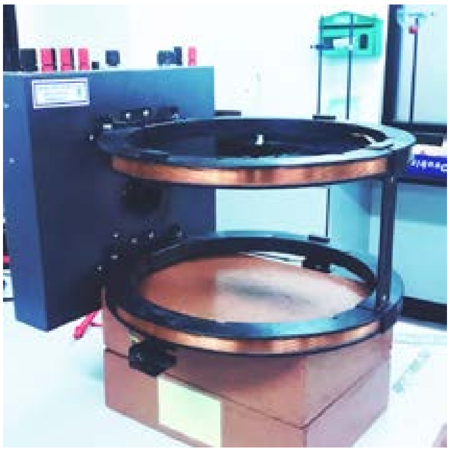


Figure 3.3: This Helmholtz coil

3.1.4 Regulator

The regulator as shown in Fig. 3.4 is an electrical device that supplies the electrical power to an electrical load or Helmholtz coil in this case. In this experiment, we use the EPS regulator with an output voltage of 0 to 30 V at 3 A current with an overload protection.

Figure 3.4: The regulator supplies the current to the Helmholtz coil

3.1.5 Axial Hall Probe with Sensor-CASSY

This probe as shown in Fig. 3.5 is commonly used to measure the axial magnetic field that is parallel to the sensor axis, along with the Sensor-CASSY shown in Fig. 3.6. The Sensor-CASSY is an interface device for recording measurement data and usually display the data on the screen of computer.

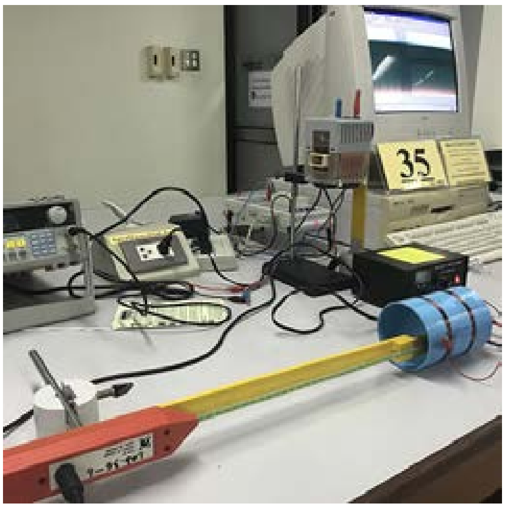


Figure 3.5: The Axial Hall probe

Figure 3.6: The Sensor-Cassy

3.2 Verification of Magnetic Sensor on the Smartphone

We want to determine the magnetic field of the ferromagnetic material when it is magnetized by an external magnetic field. In this study the magnetic sensor from the smartphone which provides up to 10^{-7} T is used as a magnetic probe. The comparison of this sensor, the experimental set up and measurement are described in this topic.

3.2.1 Sensor Position in the Smartphone

At first, we do not know where sensor of the smartphone is located, so we have to find the method. However, we can find the sensor position by moving the magnetic material on the surface of smartphone. When magnetic material approaches the sensor, smartphone will give the maximum magnetic field intensity. In this experiment, we use the needle as shown in Fig. 3.2 as a magnetic material. (Warning: Too much intensity of magnetic field can damage the smartphone)

Procedure

1. Move the needle over the smartphone and observe the maximum magnitude, so we know the cursory area of the sensor position.

2. Make coordinate plane on a piece of paper above the sensor area as shown in Fig. 3.7 and move the needle in a step of 1 mm in both x and y direction (must always be perpendicular to the surface) around on the sensor area of the smartphone.

3. Locate the position that gives the maximum magnitude of magnetic field as compared to other positions.

Figure 3.7: The area on the smartphone which is used to locate the sensor position

Result

Fig. 3.8 shows a graph between the magnetic field intensity varied with the position along the x-axis. From the graph, the position along the x-axis that gives the maximum intensity of magnetic field is 9.0 ± 1.0 mm.

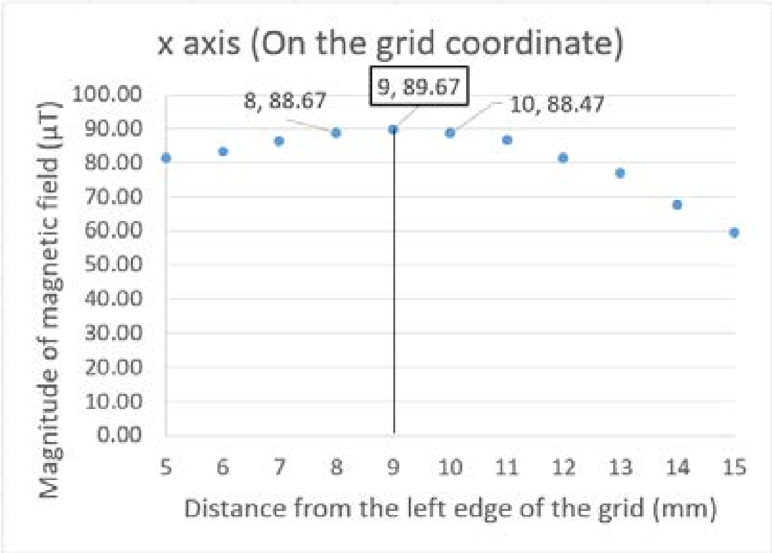


Figure 3.8: The graph between the magnetic field varied with the position along the x-axis

Fig. 3.9 shows a graph between the magnetic field intensity varied with position along the y-axis. From the graph, the position along the y-axis that gives the maximum intensity of magnetic field is 11.0 ± 1.0 mm.

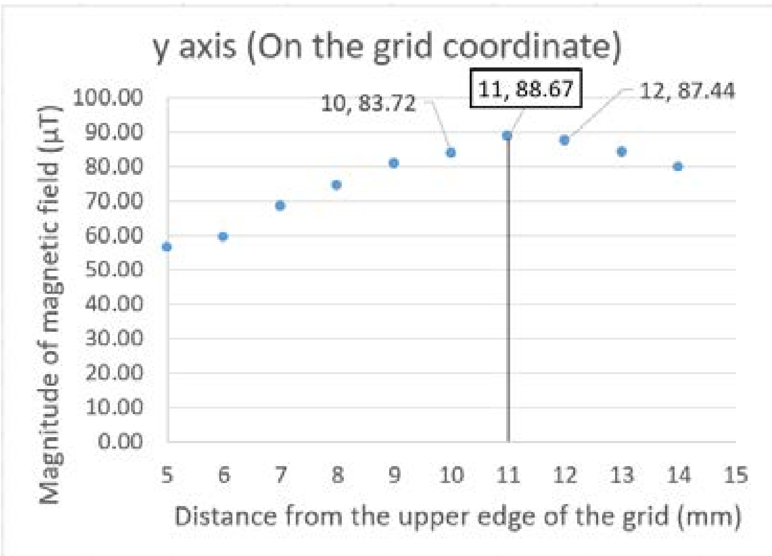


Figure 3.9: The graph between the magnetic field varied with the position along the y-axis

This measured value includes the magnetic field from the needle and the Earth's magnetic field. The EMF subtraction is not necessary in this experiment because we observe only the maximum intensity of magnetic field and this happens when the magnetic material approaches the sensor.

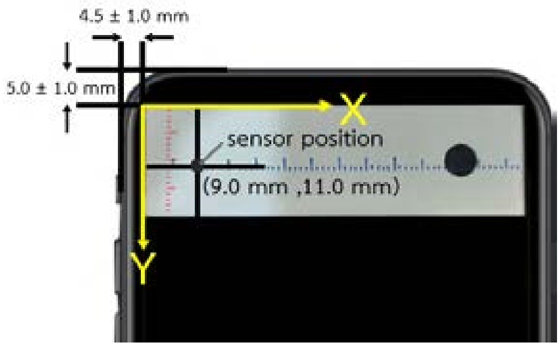


Figure 3.10: The sensor location in the smartphone

From Fig. 3.10, the distance from left side of smartphone to the origin of the Cartesian coordinate plane on a paper is about 4.5 $\pm$ 1.0 mm. The distance from top of smartphone to the origin of the Cartesian coordinate plane on a paper is about 5.0 $\pm$ 1.0 mm. Therefore, we add the distance from the edge of the smartphone to the sensor position in each axis. The magnetic sensor of the iPhone 7 plus is located 13.5 $\pm$ 2.0 mm away from the left side of smartphone and 16.0 $\pm$ 2.0 mm away from the top of smartphone.

After we have located the sensor position, we want to verify if this magnetic sensor measures the correct magnetic field intensity. We compare the measurement of magnetic field produced by Helmholtz coil from smartphone and magnetic probe used in Physics Laboratory to the analytical and numerical calculation of Biot-Savart's law .

3.2.2 Magnetic Field Comparison

We perform an experiment to verify whether the magnetic sensor of the smartphone measures the correct magnitude of magnetic field. We compare the z-component magnetic field from analytical calculation of Biot-Savart's law and numerical calculation by C programming with the measurement of the magnetic probe in laboratory and smartphone.

Procedure

In this experiment, we measure the magnetic field from the Helmholtz coil as shown in Fig. 3.11 along the z-axis and on the plane of z = 6.0 cm.

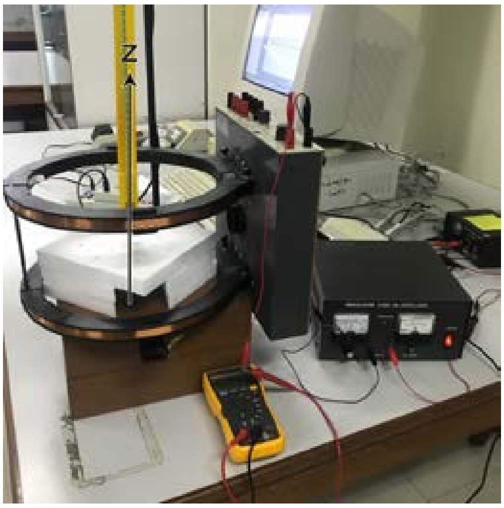


Figure 3.11: Experimental setup for magnetic field comparison

1. Measure the Earth's magnetic field with smartphone.

2. Measure the magnetic field along the z-axis of the Helmholtz coil as shown in Fig. 3.12 using the smartphone and read the current supplied to the coil on the regulator.

3. Use the magnetic probes from Physics Laboratory to measure the magnetic field from the same Helmholtz coil at the same position in step 1.

4. Calculate the magnetic field produced from the Helmholtz coil using the analytical calculation and numerical calculation by C programming of Biot-Savart's law. Then, compare with the ones obtained from the smartphone sensor and mangetic probe from laboratory.

5. Repeat step 1-4 by measuring the magnetic field on the plane of z = 6.0 cm at the positions as shown in Fig. 3.13.

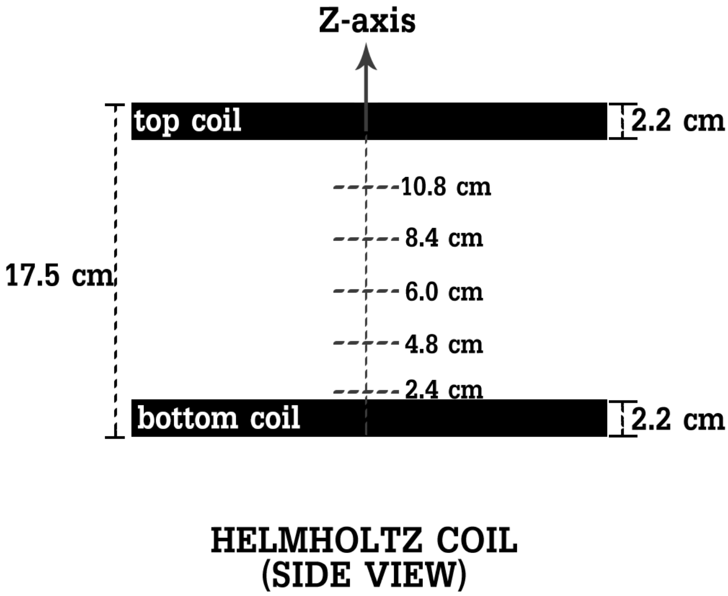


Figure 3.12: The measurement position along the z-axis of the Helmholtz coil (Side view)

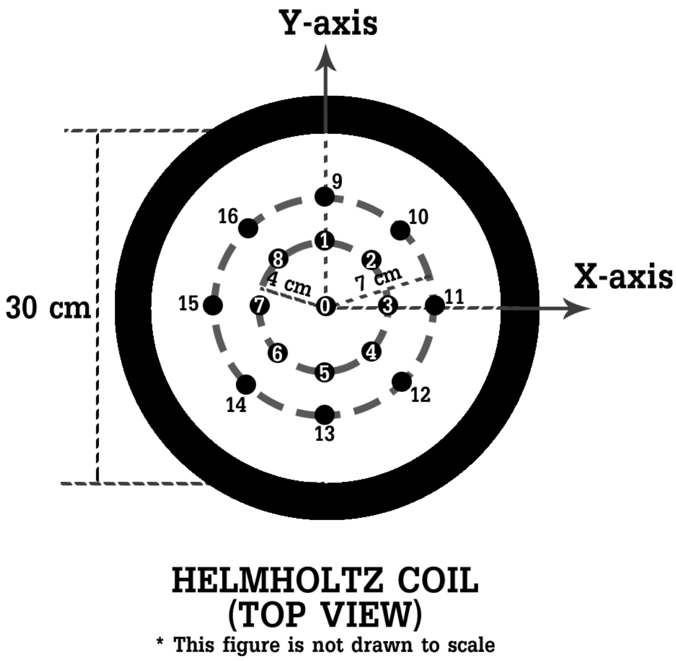


Figure 3.13: The measurement position on the plane of z = 0.060 m of the Helmholtz coil (Top view)

For the measurement by smartphone, it can measure three components of magnetic field. The Earth's magnetic field is always included in the measurement so it is necessary to measure the EMF before measuring the magnetic field from Helmholtz coil.

For the measurement by magnetic probe in laboratory, we set the reference level for the background noise the software before measuring.

For the analytical calculation from Biot-Savart's law, we calculated only the z-component magnetic field along the z-axis of the Helmholtz which is given by

$$B_z = \frac{N\mu_0 I}{(\frac{5}{4})^{3/2}a} \tag{3.1}$$

where μ_0 is a permeability of free space ($4\pi \times 10^{-7}\ \frac{\mathrm{Tm}}{\mathrm{A}}$), I is a current through each coil, N is the number of turns on each coil (130 turns) and a is the mean radius of the coils in meters (0.15 m).

For the numerical calculation by C programming, we solve the Biot-Savart equation as the single circular coil to obtain three components of the magnetic field at any point. Then, we use the Simpson's rule which is a method for numerical approximation of definite integrals to find the approximation of magnetic field from superposition of many coils. The program needs the parameters of the radius of each coil, the current of each coil and the position of each coil as an input array.

Result

Magnetic field along z-axis of the Helmholtz coil

From table 3.1 and 3.2 below, the measurement of z-component magnetic field along z-axis of the Helmholtz coil from the smartphone is more accurate than the value obtained from the Sensor-CASSY when comparing with the results from analytical and numerical calculation. The magnetic field is quite stable along the z-axis except at the z = 2.4 cm which is slightly lower than others for the calculation from the code.

Table 3.1: The comparison of the z-component magnetic field along the z-axis of the Helmholtz coil with current of 1.0 A

The Magnetic Field along z-axis Produced by Helmholtz Coil				
I = 1.0 A (*EMF is removed from the measurement)				
z (cm)	**Calculation**		**Measurement***	
	Analytical (μT)	Numerical (μT)	Laboratory (μT)	Smartphone (μT)
2.4	779.3	750.9	600	724.1
4.8		767.8	640	738.1
6.0		769.6	620	741.4
8.4		769.6	640	743.6
10.8		769.8	620	739.8
Range of percentage error when comparing to analytical calculation (%)			17.88 - 23.01	4.58 - 7.08

Table 3.2: The comparison of the z-component magnetic field along the z-axis of the Helmholtz coil with current of 1.5 A

The Magnetic Field along z-axis Produced by Helmholtz Coil				
I = 1.5 A (*EMF is removed from the measurement)				
z (cm)	**Calculation**		**Measurement***	
	Analytical (μT)	Numerical (μT)	Laboratory (μT)	Smartphone (μT)
2.4	1168.9	1126.3	960	1072.5
4.8		1151.3	950	1095.4
6.0		1154.3	960	1094.8
8.4		1154.4	950	1096.2
10.8		1154.7	960	1079.4
Range of percentage error when comparing to analytical calculation (%)			26.81 - 28.09	9.33 - 12.37

Magnetic field on the plane of z = 6.0 cm of the Helmholtz coil

From the table 3.3 below, the measurement of z-component magnetic field on the plane of z = 6.0 cm of the Helmholtz coil from the smartphone is more accurate than the values obtained from the Sensor-CASSY when comparing with the numerical calculation by C programming. From the numerical calculation, the z-component magnetic field is quite stable.

Table 3.3: The comparison of the z-component magnetic field on the plane of z = 6.0 cm of the Helmholtz coil with current of 1.0 A

The Magnetic Field on the Plane of z = 6.0 cm Produced by Helmholtz Coil						
I = 1.0 A (*EMF is removed from the measurement)						
Radius (cm)	**Position**	**x (cm)**	**y (cm)**	**Smartphone**		
				Numerical (μT)	Laboratory (μT)	Smartphone (μT)
0	**0**	**0.0**	**0.0**	769.6	590	716.5
4	**1**	**0.0**	**4.0**	773.5	600	714.7
	2	**2.8**	**2.8**	773.4	580	715.6
	3	**4.0**	**0.0**	773.3	570	716.0
	4	**2.8**	**-2.8**	773.4	610	716.6
	5	**0.0**	**-4.0**	773.5	580	715.5
	6	**-2.8**	**-2.8**	773.5	590	713.7
	7	**-4.0**	**0**	773.6	540	713.9
	8	**-2.8**	**2.8**	773.5	580	713.4
7	**9**	**0.0**	**7.0**	774.0	570	700.9
	10	**4.8**	**4.8**	774.0	560	704.6
	11	**7.0**	**0.0**	773.5	540	703.6
	12	**4.8**	**-4.8**	774.0	570	701.2
	13	**0.0**	**-7.0**	774.0	510	701.1
	14	**-4.8**	**-4.8**	774.3	550	699.9
	15	**-7.0**	**0.0**	774.1	550	693.2
	16	**-4.8**	**4.8**	774.3	550	693.2
Range of percentage error when comparing to numerical calculation (%)					21.13 - 30.19	6.89 - 10.47

All the raw data obtained from the numerical calculation and smartphone are shown in the Appendix A.

After we have verified this magnetic field sensor of the smartphone, we can use this device to measure the three components of any magnetic field.

3.2.3 Magnetic Field Line Determination

The magnetic sensor in the iPhone 7 plus is used to determine the three components of magnetic field in microtesla units and determine the magnetic field lines from the magnet.

Procedure

1. Draw 36 square grids of 5×5 cm^2 on a sheet of paper of 30×30 cm^2 and place it on the table for determining the magnetic field line.

2. Measure the three components of magnetic field on this plane without any magnetic materials nearby to determine the Earth's magnetic field (EMF) at that location.

3. Place three magnets with a spacing of 15 cm apart from each other under the table with the same and opposite polarities as shown in Fig. 3.14. Each magnet has a size of $1.9 \times 4.9 \times 0.5$ cm^3.

4. Measure the three components of magnetic field at every point on the plane due to magnets and the EMF as shown in Fig. 3.15.

5. Determine the magnetic field produced from the magnets by subtracting the data obtained from step 4 with the one from step 2 in each component.

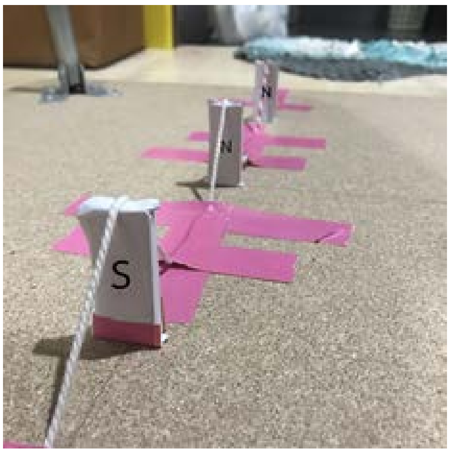


Figure 3.14: Placing three magnets under the table

Figure 3.15: Measuring the magnetic field due to magnets on the plane

Result

In this experiment, we want to determine the magnetic field lines from the magnets by measuring the three components of the magnetic field on the plane whose size is a square grid of 5×5 cm^2 on a sheet of paper of 30×30 cm^2. Then, we place the magnetic sensor at each point of the grid throughout the plane to measure the magnetic field. This method does not only determine the magnetic field lines from the magnet but also the orientation of the magnetic sensor of the smartphone by using the known-pole magnet. We use the three known-pole magnets with a spacing of 15 cm apart from each other under the table with the same and opposite polarities. Fig. 3.16 shows a vector plot of the magnetic field lines from three magnets with the same and opposite polarities.

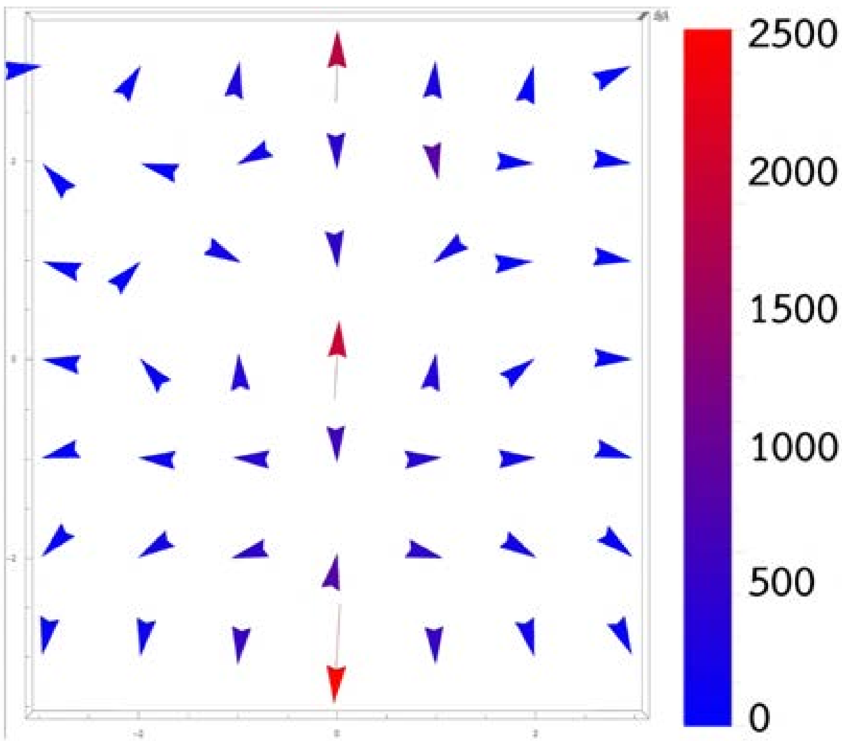


Figure 3.16: The magnetic field lines of the three known-pole magnets

We can use the magnet that we know the polarity of it to find the orientation of magnetic sensor. The magnetic field measurement application which called Teslameter in smartphone can determine three components of magnetic field which are coordinate system (B_x,B_y,B_z). We do not know that each component of magnetic field is obtained from which magnetic sensor and orientation of the smartphone. To determine this coordinate system, we use the magnet which we know that the magnetic field point toward from north to south pole then we face the north pole toward around the surface of the smartphone. When we face the north pole from left to right side of the surface of the smartphone, we get the positive value in x-component magnetic field. When we face the north pole from back to front of the smartphone, we get the positive value in z-component of magnetic field. When we face the north pole from bottom to top of the smartphone, we get the positive y-component magnetic field. From all of these results, we can conclude that the coordinate system of the magnetic sensor of the Teslameter application is drawn in Fig. 3.17.

Figure 3.17: The coordinate system of the magnetic sensor of the iPhone 7 plus

After we determine the magnetic field lines of the magnet and the coordinate system of the magnetic sensor. We can use the coordinate system to determine the value and vector of magnetic field of the ferromagnetic rod.

3.2.4 Magnetic Field Measurement at Single Point While Smartphone is Rotating

We want to check that the total magnetic field on the point should be the same value no matter how smartphone orientation changes if the sensor stays still at that position.

Procedure

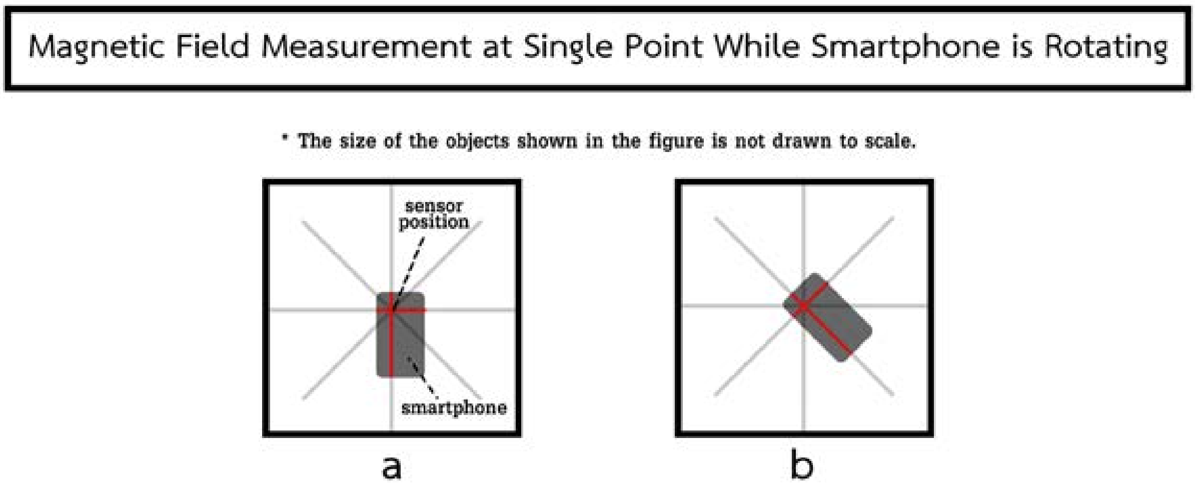


Figure 3.18: The procedure configurations in Magnetic Field Measurement at Single Point While Smartphone is Rotating

1. Draw lines crossing each other as shown in Fig. 3.18a.

2. Place the smartphone sensor on a point at line crossing each other as shown in Fig. 3.18a.

3. Measure the magnetic field at that position with different orientations of the phone by rotating the smartphone sensor about that position every 45° in clockwise direction as shown in Fig. 3.18b.

Result

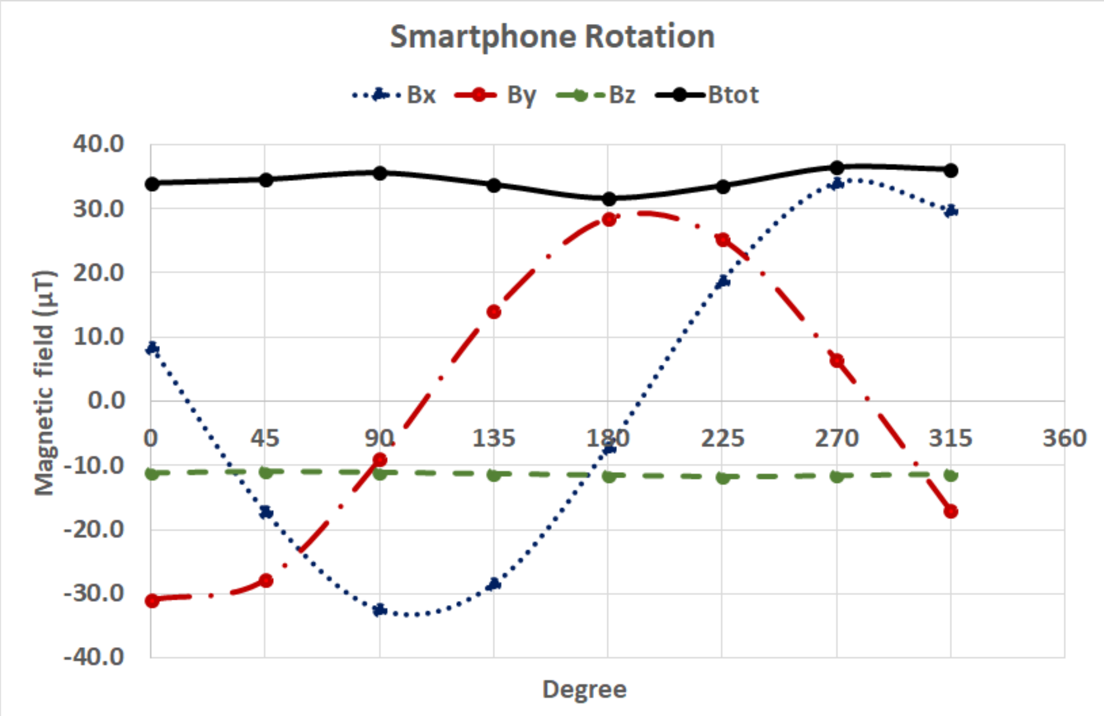


Figure 3.19: The graph of the magnetic field in each component and the total magnetic field for different angle

From 3.19, we can see that total magnetic field is quite stable within 30 - 40 μT. When comparing the magnetic field in x and y component between 0° and 180°, you can see that the B_x gives the positive value at 0°. At 180°, B_x gives the negative value in the same magnitude. This also happens in B_y.

In some case, we can not always use the same orientation of the smartphone in every position of the magnetic field measurement due to the other object that place nearby. From the discussions, we can change the orientation of the smartphone by rotating the smartphone at 180° to measure at that point which still gives almost the same magnitude of magnetic field but in opposite sign. Rotation of the smartphone in the 180° is the compromise option to get the value of magnetic field at the difficult position.

3.3 Magnetic Field Due to the Presence of Ferromagnets

In this experiment, we use the circular ferromagnetic rod which has a length of 59.0 cm and a diameter of 1.2 cm to study the magnetic field lines when the rod is magnetized in different conditions. We expand 36 square grids of 5×5 cm^2 in the topic of Magnetic Field Line Determination to 100 square grids to place the rod and magnet for magnetizing and measure the magnetic field in the measurement area of 5×5 points of the center of the plane.

All of these preparation can reduce the error from measurement by smartphone:

Location

The experimental location must be the place where there is not any magnetic object nearby. The place must not be changed until you finish all the experiments because the Earth's magnetic field at each point in the space does not equal.

Sensor calibration

In some conditions, the sensor may not give the actual magnetic field. The best way to calibrate the sensor is to turn off and turn on the smartphone. Then, open the magnetic field measurement application, the magnetic field still not give the actual magnetic field until flipping in all three axes of the smartphone.

EMF cancellation & Bias due to the internal magnetic fields elimination

In order to measure the magnetic field from the magnetic object, the result from measuring the magnetic object does not only come from the magnetic field of that object but also come from the Earth's magnetic field and the internal magnetic field due to the magnetic material in smartphone. So, we have to measure the EMF ($B_E + B_{offs}$) first and measure the magnetic field object ($B_{Object} + B_E + B_{offs}$). Then, we subtract the $B_{Object} + B_E + B_{offs}$ by the $B_E + B_{offs}$. We will finally get the magnetic field from only the magnetic object. This method is developed from the Simen Hellesund's method of elimination.

Time duration

The Earth's magnetic field is also change slightly randomly over time. Therefore, the time duration between the EMF measurement process and the magnetic object measurement must not be too long.

3.3.1 Magnetic Field Measurement with and without Ferromagnet

We want to know whether the magnetic field decreases when the magnetic object obstructs by comparison each configuration.

Procedure

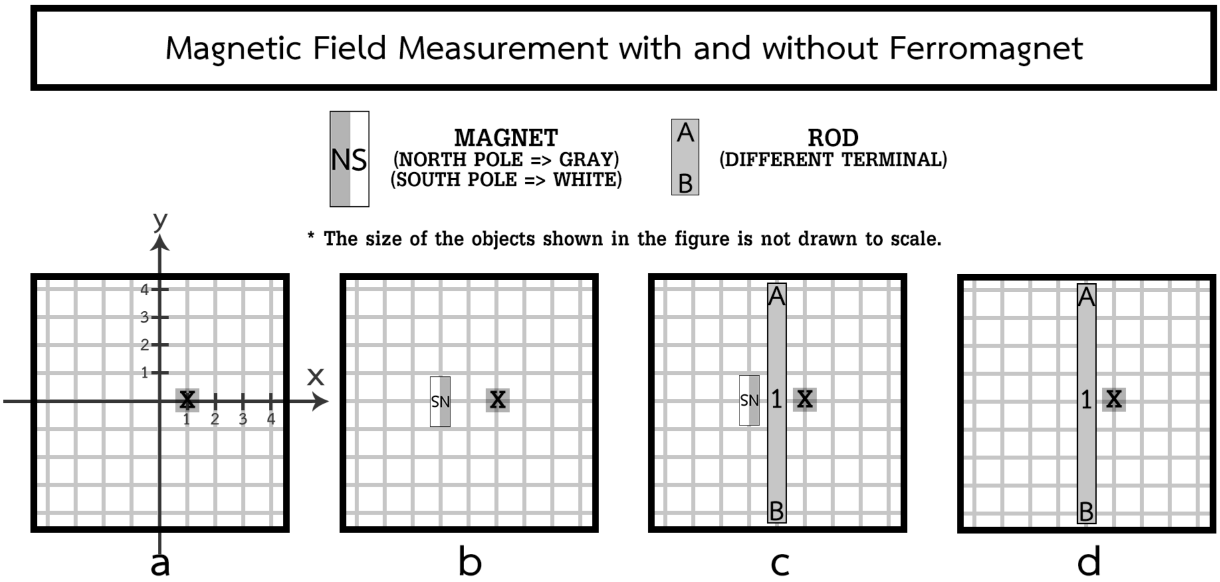


Figure 3.20: The procedure configurations in Magnetic Field Measurement with and without Ferromagnet

1. Measure the Earth's magnetic field at point X as shown in Fig. 3.20a.

2. Place the magnet at x = -1. Then, measure the magnetic field due to the magnet at point X as shown in Fig. 3.20b.

3. Place the rod at x = 0 parallel to the y-axis. Then, measure the magnetic field due to the magnet and the rod at point X as shown in Fig. 3.20c.

4. Remove the magnet. Then, measure the magnetic field due to the rod at point X as shown in Fig. 3.20d.

Result

From the 3.4, when comparing the magnetic field from B_M to B_M+B_R in both magnetizing condition, you can see that the total magnetic field of B_M+B_R is lesser than B_M because magnetic field line from the magnet is attracted to the rod which is a ferromagnetic material. High-permeability material can highly attracts the magnetic field line from any source to itself.

Table 3.4: The values of magnetic field from the different configurations in the topic of Magnetic Field Measurement with and without Ferromagnet

Magnetic field in Microtesla Unit						
Magnetizing	**Step**	**Measurement**	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
SN	**1**	B_E	2.9	-30.4	-11.0	32.5
	2	B_E+B_M	187.4	-26.3	-28.6	191.4
		B_M	184.5	4.1	-17.6	185.4
	3	B_E+B_M+B_R	74.1	-17.1	-18.3	78.2
		B_M+B_R	71.2	13.3	-7.2	72.8
	4	B_E+B_R	-35.9	-18.8	-7.2	41.2
		B_R	-38.7	11.6	3.8	40.6
NS	**1**	B_E	2.5	-30.8	-10.5	32.7
	2	B_E+B_M	-198.2	-37.5	-1.5	201.7
		B_M	-201.0	-7.1	9.6	201.4
	3	B_E+B_M+B_R	-136.9	-23.0	-8.1	139.1
		B_M+B_R	-139.8	7.4	3.0	140.0
	4	B_E+B_R	-19.0	-20.1	-9.8	29.4
		B_R	-21.9	10.3	1.2	24.2

B_E : The Earth's magnetic field
B_M : The magnetic field due to the magnet
B_R : The magnetic field due to the ferromagnetic rod

3.3.2 Magnetization Retention

In these sets of experiments, there are two sets of experiments; magnetizing only one time and magnetizing every time when we change the position of the rod. We want to know if the magnetization in the rod remains the same for a time. We magnetize the rod with the magnet only one time, then take the magnet out, and after that we change the position of the rod.

Procedure of one time magnetizing

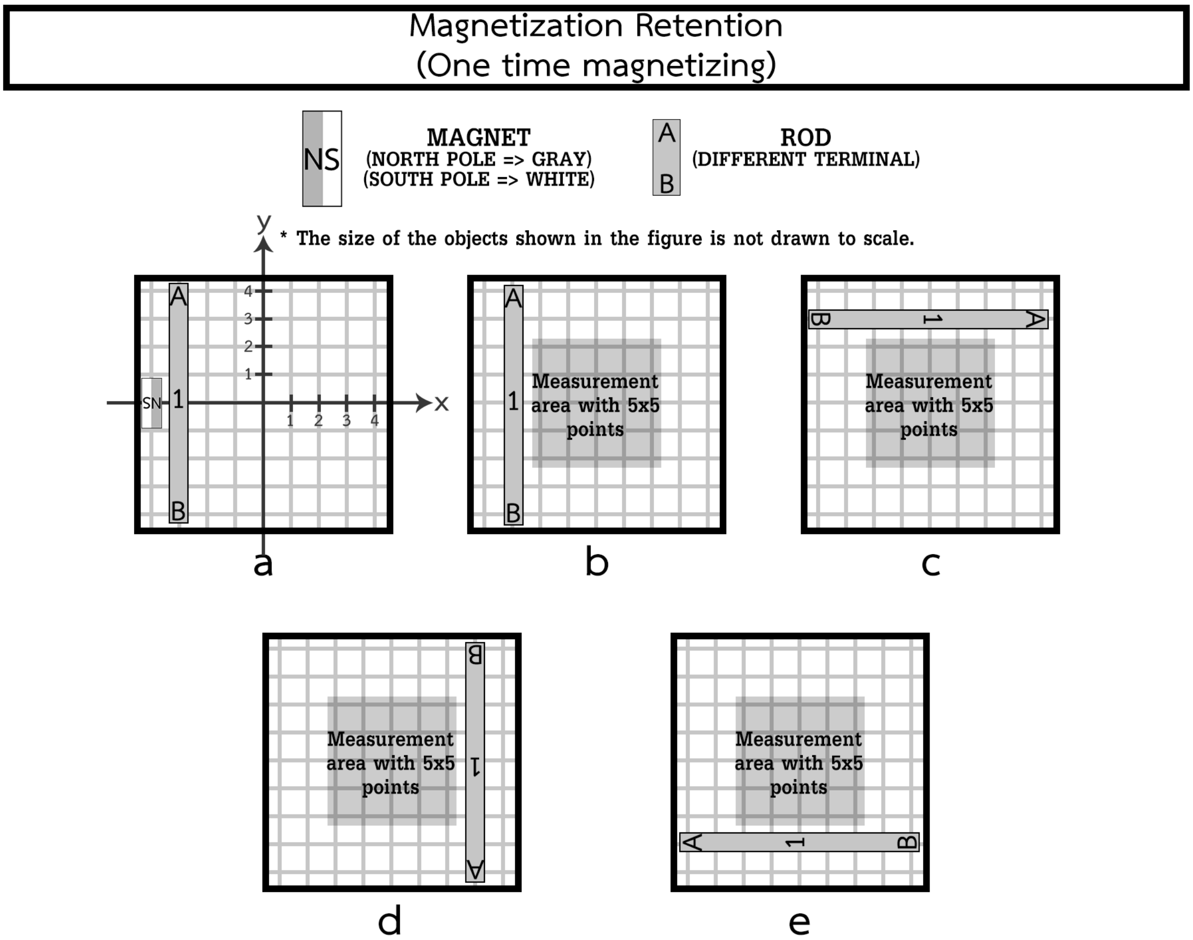


Figure 3.21: The procedure configurations in Magnetization Retention (one time magnetizing)

1. Measure the Earth's magnetic field at the measurement area of 5 × 5 points.

2. Place the magnet at x = -4 by facing north pole toward the rod and place the rod at the x = -3. Both objects are placed parallel to the y-axis as shown in Fig. 3.21a.

3. Magnetize the rod with the magnet for about 60 minutes.

4. Take the magnet out and then measure the magnetic field due to the magnetized rod in the measurement area as shown in Fig. 3.21b.

5. Change the position of the rod to y = 3 as shown in Fig. 3.21c and then measure the magnetic field due to the magnetized rod in the measurement area.

6. Repeat step 5 by changing the position of the rod to x = 3 as shown in Fig. 3.21d and to y = -3 as shown in Fig. 3.21e.

All the results which consist of the values and the vectors of magnetic field from the experiments will be shown in Fig. B.1 to Fig. B.5 the Appendix B.

Procedure of magnetizing every time the rod's position is changed

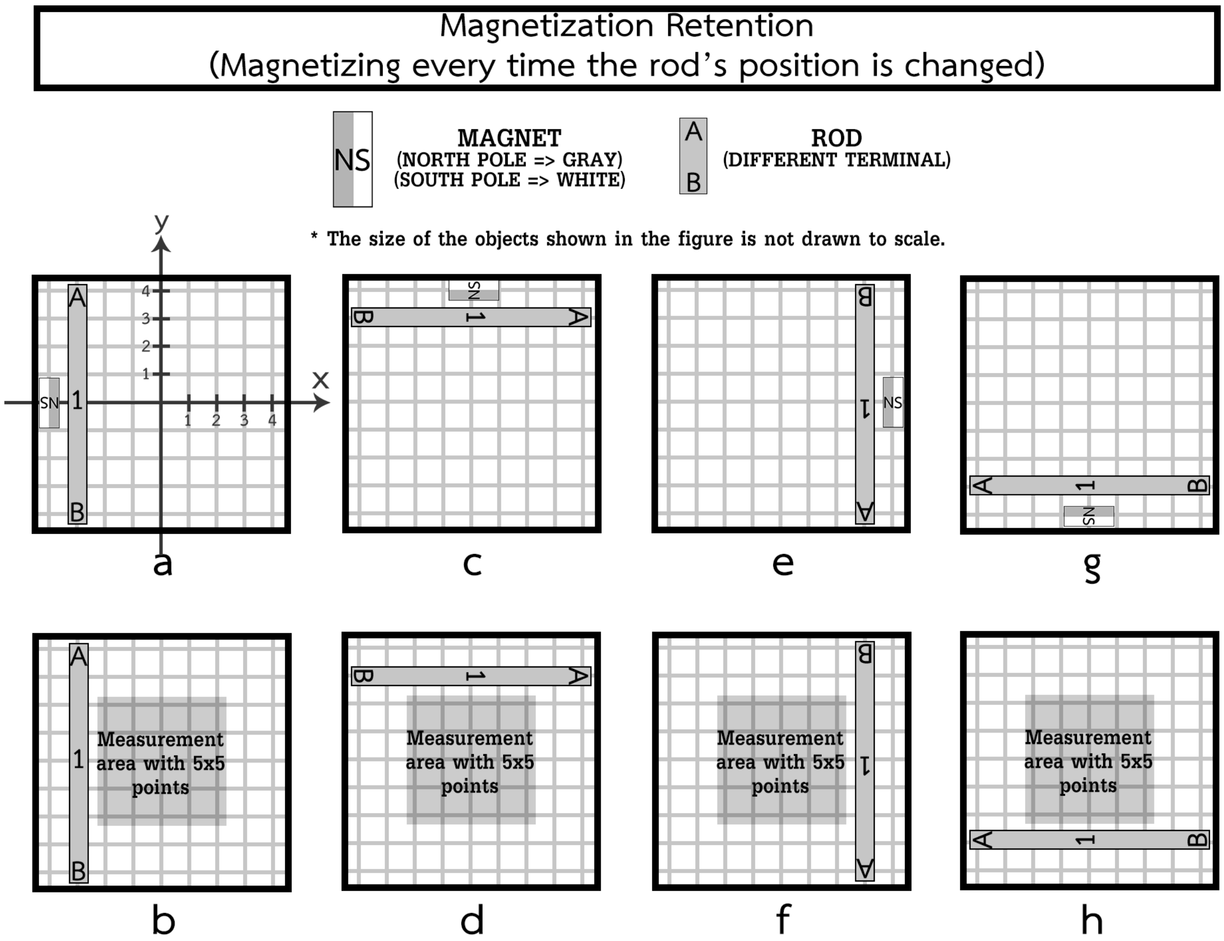


Figure 3.22: The procedure configurations in Magnetization Retention (magnetizing every time the rod's position is changed)

1. Measure the Earth's magnetic field at the measurement area of 5 × 5 points.

2. Place the magnet at x = -4 by facing north pole toward the rod and the rod at the x = -3. Both objects are placed parallel to the y-axis as shown in Fig. 3.22a.

3. Magnetize the rod with the magnet for about 60 minutes.

4. Take the magnet out and then measure the magnetic field due to the magnetized rod in the measurement area as shown in Fig. 3.22b.

5. Change the position of the rod to y = 3 parallel to the x-axis then magnetize the rod as shown in Fig. 3.22c and then measure the magnetic field due to the magnetized rod in the measurement area as shown in Fig. 3.22d.

6. Repeat the step 5 by changing the position of the rod to x = 3 parallel to the y-axis, then magnetize the rod as shown in Fig. 3.22e. For Fig. 3.22g, move the rod to y = -3 parallel to the x-axis. We will get the results from Fig. 3.22f and Fig. 3.22h.

All the results which consist of the values and the vectors of magnetic field from the experiments will be shown in Fig. B.6 to Fig. B.10 the Appendix B.

Result of Magnetization Retention

All results of magnetic field measurement, we already subtract the Earth's magnetic field. Therefore, all of the magnetic field measurements are purely the magnetic field from the rod. On the result's figure in the Appendix B, we demonstrate the magnetic field from the rod as B_R which comes from the B_{R+E} subtracted by the B_E. Every point in the measurement area contain four values of magnetic field which are the x-component, y-component, z-component and the total magnetic field in the microtesla unit. Due to smartphone size, in some condition like Fig. Fig. 3.22e, the smartphone cannot place in the same orientation. So, we have to rotate the smartphone 180° which will give almost the same amount of magnetic field but the opposite sign then we just change the sign of that value. (We have already proven this in the topic of Magnetic Field Measurement at Single Point While Smartphone is Rotating)

We compare the results from having the rod at the bottom of the measurement area. From comparison of vectors of the magnetic field in Fig. 3.23 and Fig. 3.24 in the next page, we can see that magnetic field line from both figures having the same pattern of magnetic field which means there is no need to magnetize the rod every time. The duration of magnetization retention is long enough for the duration of an experiment which is not more than 1-2 hours. It is necessary to keep the rod in the place where there is no magnetic object nearby.

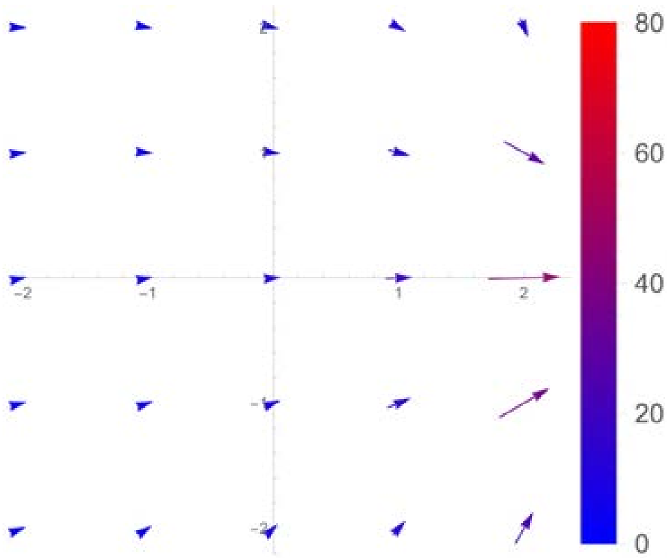


Figure 3.23: The vectors of the magnetic field due to the magnetized rod of Magnetization Retention (One time magnetizing) from Fig. 3.21d

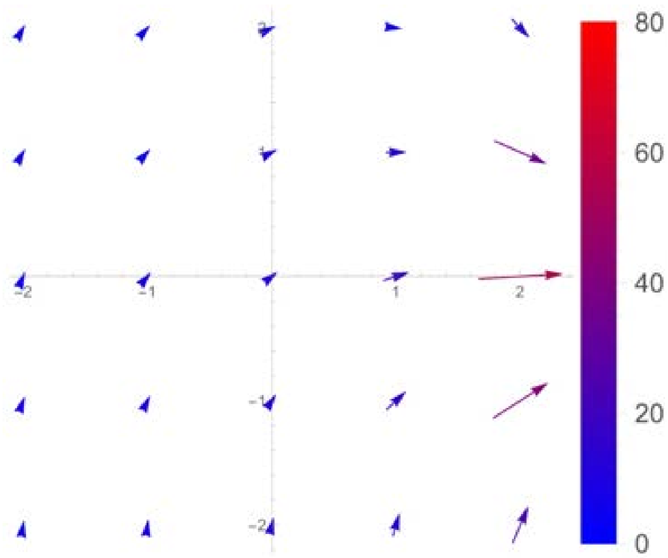


Figure 3.24: The vectors of the magnetic field due to the magnetized rod of Magnetization Retention (Magnetizing every time the rod's position is changed) from Fig. 3.22f

3.3.3 The Superposition of the Magnetic Field from Two Rods

In this set of experiments, we want to determine the magnetic field line from two rods which are magnetized in the same condition but placing at different location. We also measure the magnetic field from each rod to determine whether the summation of each component of magnetic field obtained from one rod and another rod will equal to the magnetic field measurement of two rods.

Procedure

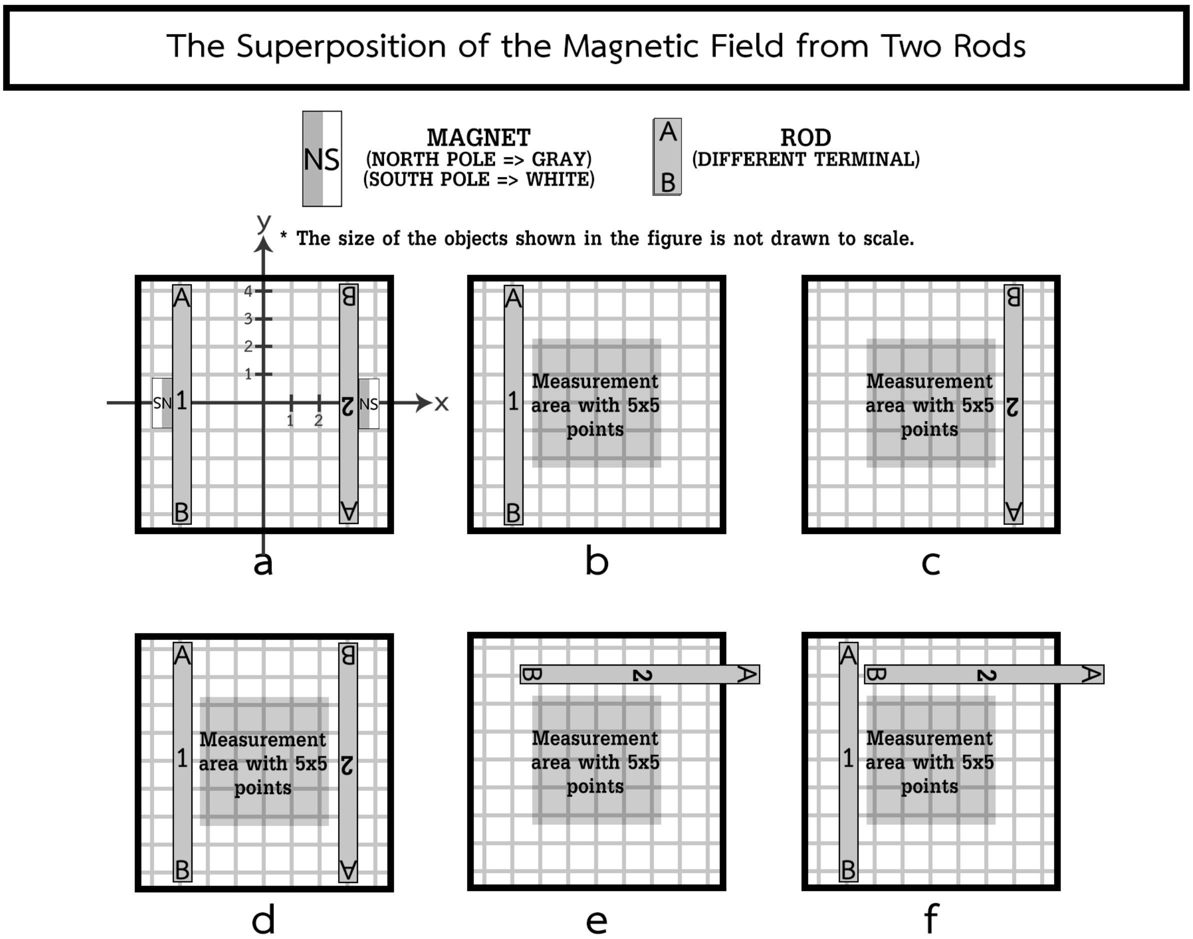


Figure 3.25: The procedure configurations in The Superposition of the Magnetic Field from Two Rods

1. Measure the Earth's magnetic field at the measurement area of 5 × 5 points.

2. Place the magnets at x = -4 and x = 4 and the rods at the x = -3 and 3 which each magnet faces the north pole toward to the rod. All objects are places parallel to

y-axis as shown in Fig. 3.25a. Then, magnetize two rods for about 60 minutes.

3. Take out the magnets and the rod on the right then measure the magnetic field due to the magnetized rod on the left in the measurement area as shown in Fig. 3.25b.

4. Take the rod on the left out, then place the second rod on the right at x = 3 parallel to y-axis, after that measure the magnetic field due to the magnetized rod on the right as shown in Fig. 3.25c.

5. Place the first rod on the left back at x = -3 parallel to y-axis then measure the magnetic field due to two magnetized rods in the measurement area as shown in Fig. 3.25d.

6. Take the first rod on the left out, then move the second rod to the top of the measurement area at y = 3 parallel to the y-axis, after that measure the magnetic field due to the magnetized rod on top as shown in Fig. 3.25e.

7. Place the first rod on the left back at x = -3 parallel to y-axis then measure the magnetic field due to two magnetized rods as shown in 3.25f.

All the results which consist of the values and the vectors of magnetic field from the experiments will be shown in Fig. B.11 to Fig. B.16 in the Appendix B.

Result

When we sum the magnetic field of the result from Fig. 3.25b and Fig. 3.25c, it should be equal to Fig. 3.25d. It also happens to Fig. 3.25f, if you sum the result from Fig. 3.25b and Fig. 3.25e. As shown in Fig. 3.26 and Fig. 3.27a below, which come from the subtraction of summation of each rod with two rods, you can see that all the values in Fig. 3.26 are almost zero. This means the superposition of two rods come from the magnetic field obtained from each rod but not in Fig. 3.27 at the top-left corner. This may come from the magnetizing between two rods at the top-left corner because in Fig. 3.27 , you can see that the values obtained by the subtraction in the corner of the top-left are not nearly zero. In order to confirm this magnetizing between two rods, the magnetic field measurement of the first rod on the left is necessary after performing the procedure in Fig. 3.25e.

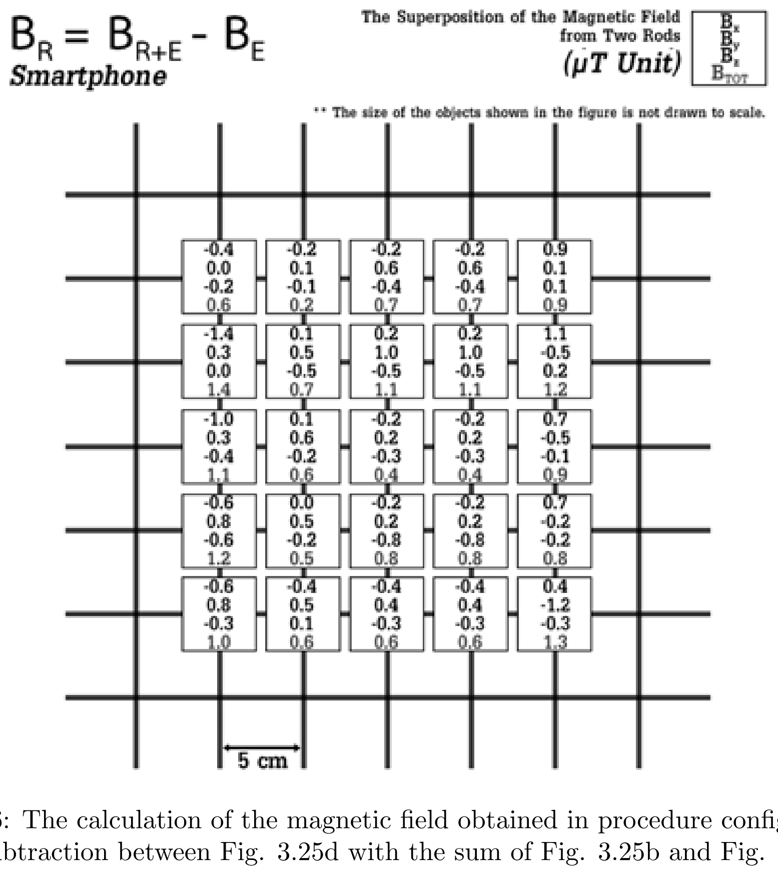
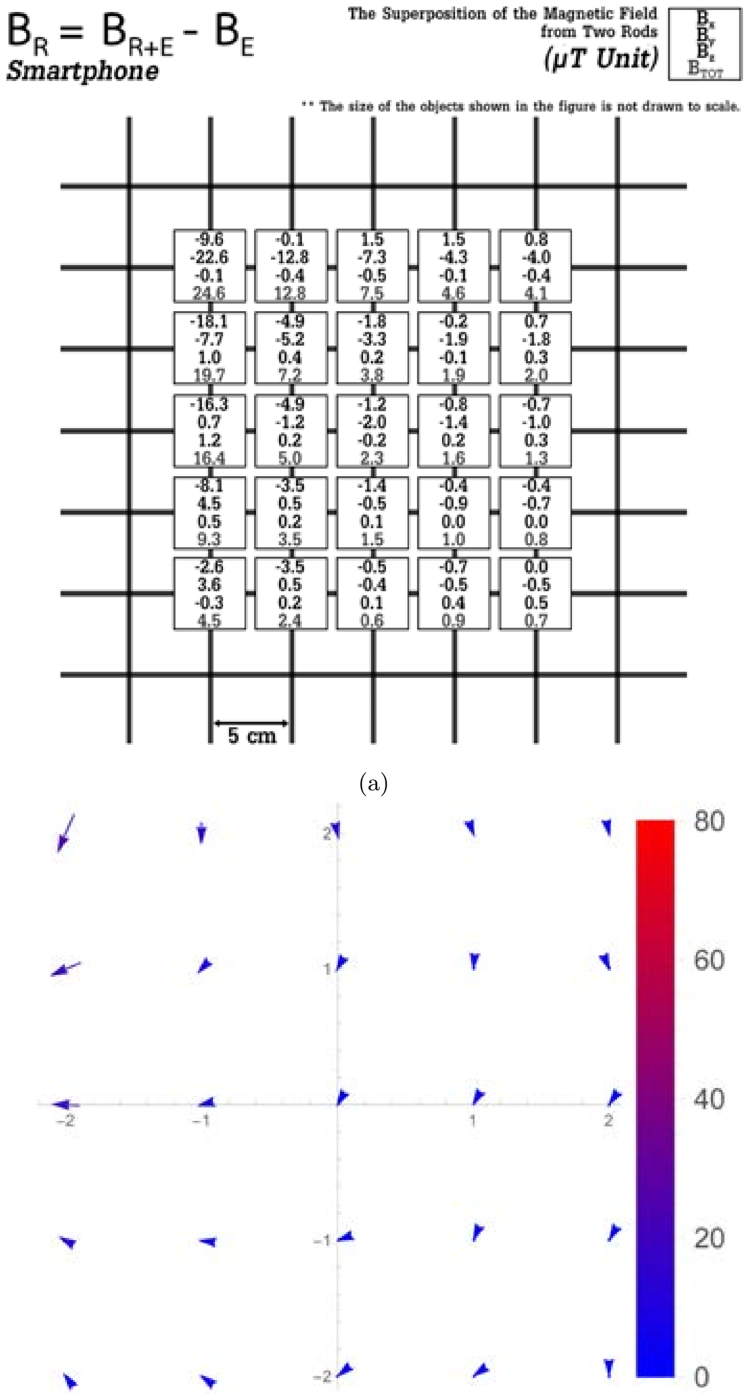


Figure 3.26: The calculation of the magnetic field obtained in procedure configuration of the subtraction between Fig. 3.25d with the sum of Fig. 3.25b and Fig. 3.25c.



(a)

(b)

Figure 3.27: (a) The values and (b) the vectors of calculation of the magnetic field obtained in procedure configuration of the subtraction between Fig. 3.25f with the sum of Fig. 3.25b and Fig. 3.25e.

3.3.4 Magnetizing the Rod with Different Polarity Conditions by Using One Magnet

In this set of experiments, we place the rod parallel to y-axis in the middle of the measurement area. So, we can determine the magnetic field line around the rod with 4 × 5 points. We magnetize the rod by sticking the magnet at middle of the rod as four different conditions which are sticking the north pole side on the left and right and the south pole on the left and right.

Procedure

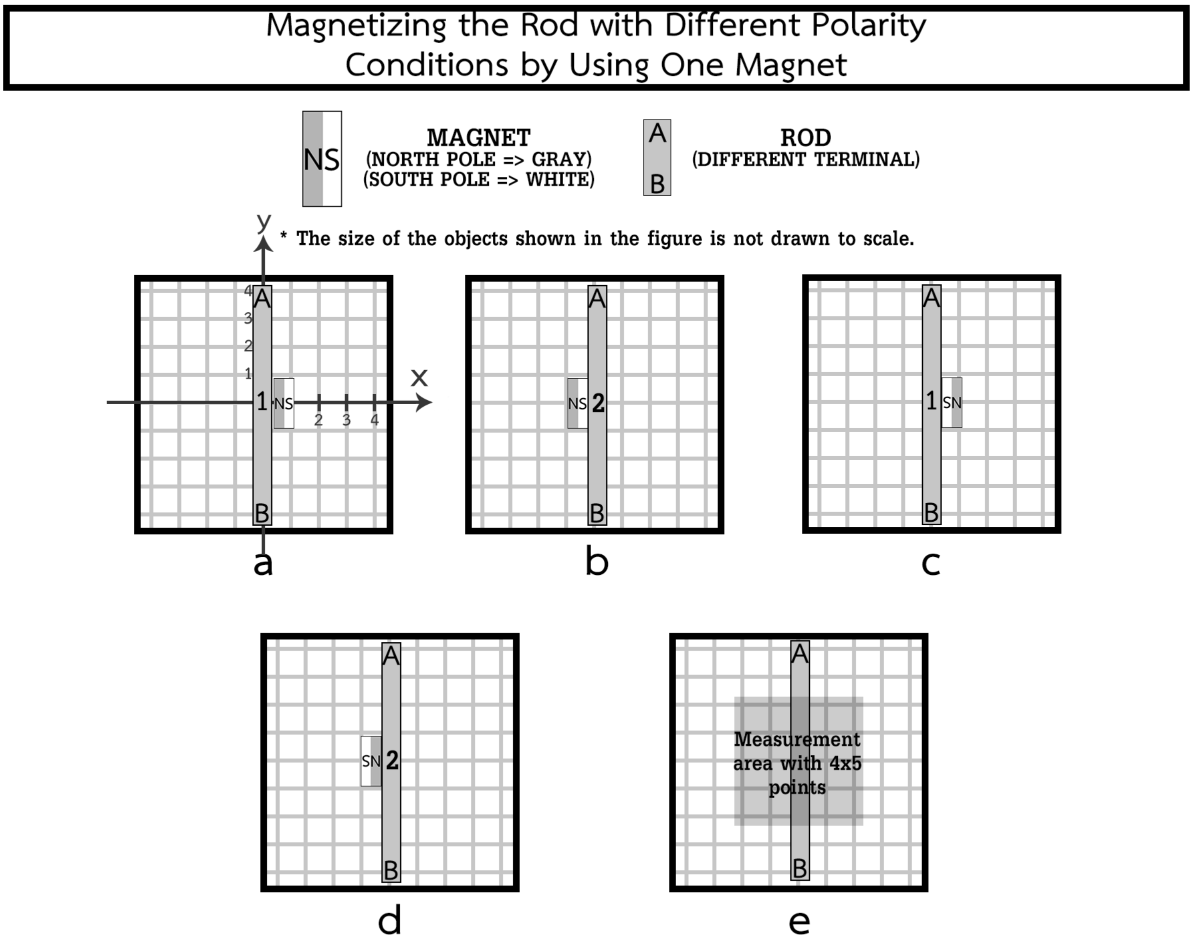


Figure 3.28: The procedure configurations in Magnetizing the Rod with Different Polarity Conditions by Using One Magnet

1. Measure the Earth's magnetic field at the measurement area of 4 × 5 points.
2. Place the rod at the x = 0 parallel to the y-axis then magnetize the rod by sticking

the north pole magnet on the right side of the rod for about 60 minutes as shown in Fig. 3.28a.

3. Take the magnet away then measure the magnetic field due to the magnetized rod in the measurement area as shown in Fig. 3.28e.

4. Repeat step 2 and 3 by changing the magnetizing conditions which in Fig. 3.28b, the rod is magnetized by sticking the south pole magnet on the left side of the rod, in Fig. 3.28c, the rod is magnetized by sticking the south pole magnet on the right side of the rod and in Fig. 3.28d, the rod is magnetized by sticking the north pole magnet on the left side of the rod.

All the results which consist of the values and the vectors of magnetic field from the experiments will be shown in Fig. B.17 to Fig. B.21 in the Appendix B.

Result

From Fig. 3.29 to Fig. 3.32, we can see that the magnetic field line that the rod produced in different conditions on the left side is almost a mirror version of magnetic field line on the right side of the rod. The middle of the rod will have the opposite polarity to the one from the magnet that is initially stuck to the rod. From the condition of using north pole magnet to magnetize the rod as shown in Fig. 3.29 and Fig. 3.32, the magnetic field points out from both ends of the rod then points toward to middle of the rod. We can infer that both ends of the rod are the south pole and the middle of the rod is north pole. For Fig. 3.30 and Fig. 3.31, both ends of the rod are the north pole and the middle of the rod is south pole.

You can see that the rod does not produce the same intensity of the magnetic field because of the property of ferromagnetic material. The ferromagnetic material remembers all the magnetizing and change from the previous magnetizing just a little bit. If the rod does not get enough external magnetic field intensity, the magnetization will not completely change the direction that it should be.

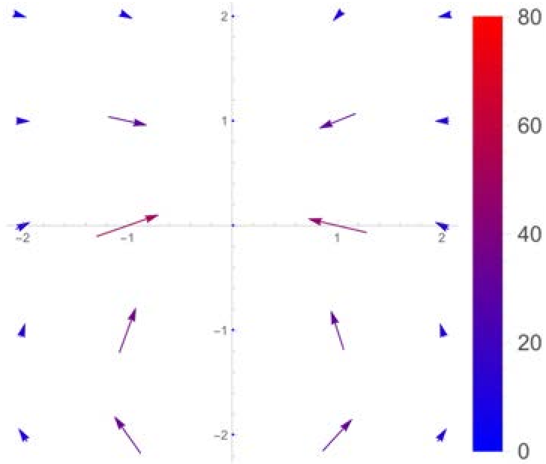


Figure 3.29: The vectors of the magnetic field due to the rod magnetized by sticking the north pole magnet on the right side of the rod as shown in the procedure configuration in Fig. 3.28a

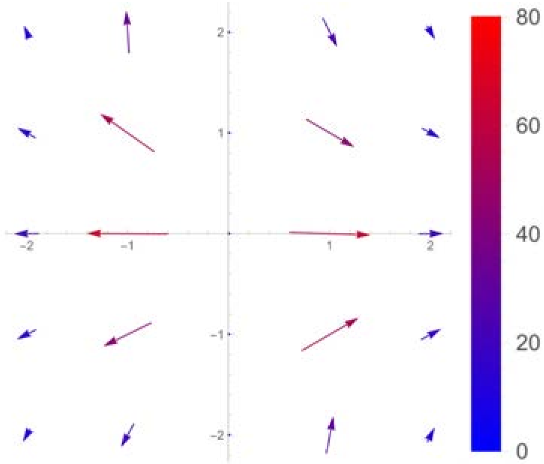


Figure 3.30: The vectors of the magnetic field due to the rod magnetized by sticking the south pole magnet on the left side of the rod as shown in the procedure configuration in Fig. 3.28b

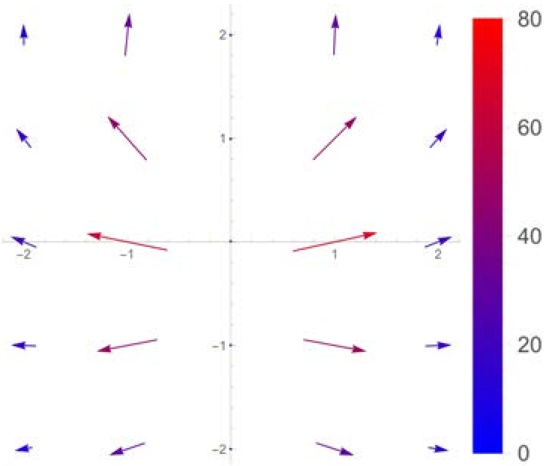


Figure 3.31: The vectors of the magnetic field due to the rod magnetized by sticking the south magnet on the right side of the rod as shown in the procedure configuration in Fig. 3.28c

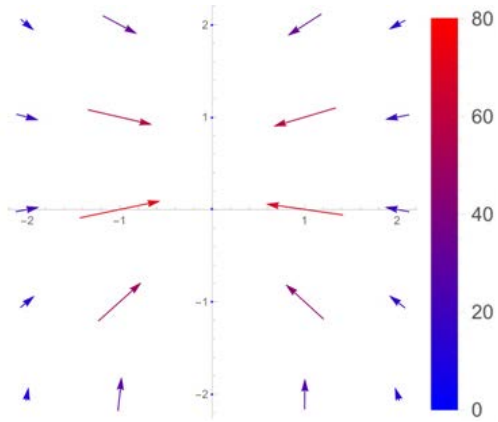


Figure 3.32: The vectors of the magnetic field due to the rod magnetized by sticking the north magnet on the left side of the rod as shown in the procedure configuration in Fig. 3.28d

3.3.5 Magnetizing the Rod by Using Two Magnets

In this experiment, we want to check whether the same rod, which we use in Magnetizing the Rod with Different Polarity Conditions by Using One Magnet, can be magnetized at any position on the rod. Also, we want to confirm the result in Magnetizing the Rod with Different Polarity Conditions by Using One Magnet.

Procedure

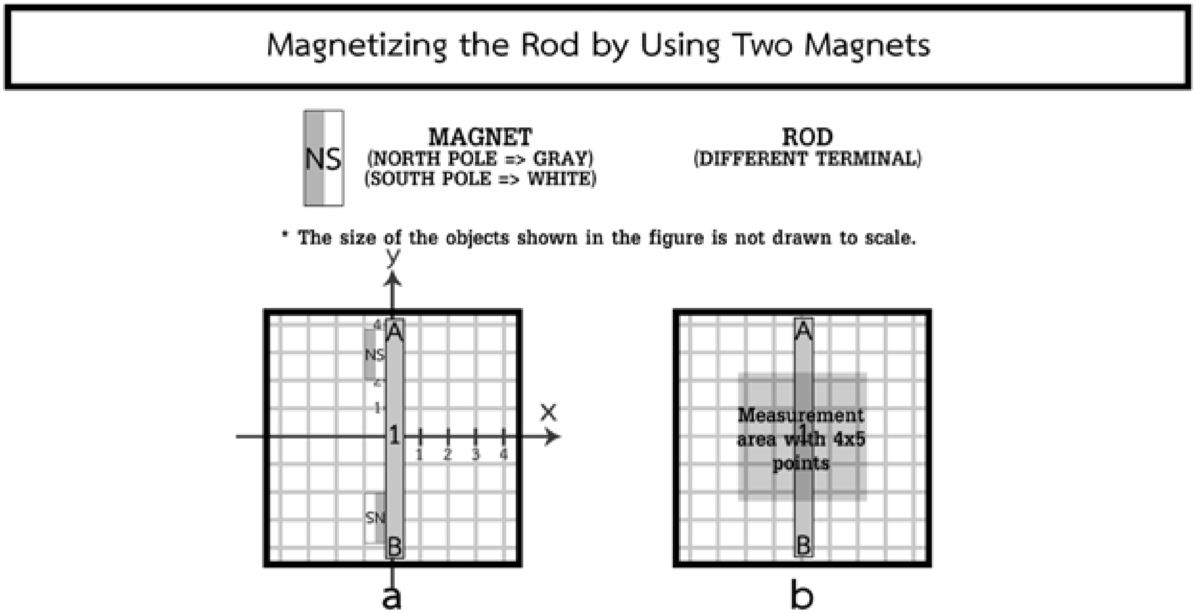


Figure 3.33: The procedure configurations in Magnetizing the Rod by Using Two Magnets

1. Measure the Earth's magnetic field at the measurement area of 4 $\times$ 5 points.

2. Place the rod at the x = 0 parallel to y-axis then magnetize the rod for about 60 minutes by sticking two magnets on the left side of the rod with different polarity of magnets facing to the rod as shown in Fig. 3.33a.

3. Take the magnets out then measure the magnetic field in the measurement area as shown in Fig. 3.33b.

All the results which consist of the values and the vectors of magnetic field from the experiments will be shown in Fig. B.22 to Fig. B.23 in the Appendix B.

Result

From the magnetic field line shown in Fig. 3.34, we can see that the rod acts like a single magnet that has A terminal of the rod as a north pole and B terminal of the rod as a south pole. The polarity of the rod is the opposite polarity to the polarity that magnet face toward to the rod which is the result we observe in topic of Magnetizing the Rod with Different Polarity Conditions by Using One Magnet.

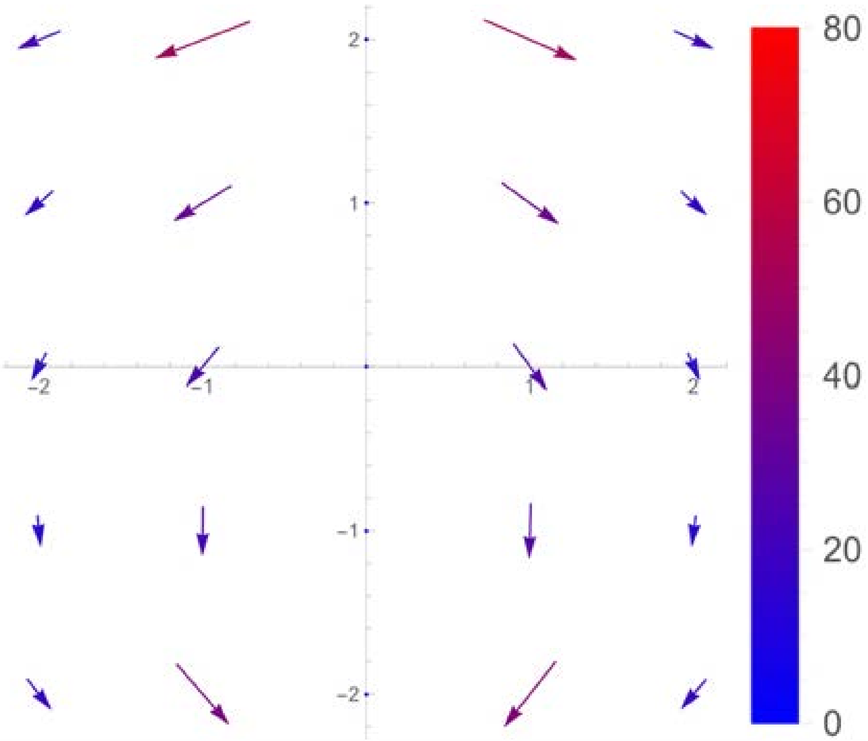


Figure 3.34: The vectors of the magnetic field due to the rod magnetized by sticking the magnets on the left side of the rod as shown in the procedure configuration in Fig. 3.28a

Chapter 4

Conclusion

In this project, we want to know the magnetic field lines due to the magnetized ferromagnetic rod. Instead of using the magnetic probe in the Physics Laboratory, we use the magnetic sensor from the iPhone 7 plus. First, we perform the experiment to locate the sensor position which results that the sensor of the smartphone is located 13.5 $\pm$ 2.0 mm away from the left side of the body and 16.0 $\pm$ 2.0 mm away from top of the body. We also perform a magnetic field measurement using a Helmholtz coil as a magnetic field source. Then, we compare the magnetic fields measured from the magnetic probe in laboratory and magnetic sensor in smartphone to the calculated value using Biot-Savart's law. The results show that the range of percentage error of the measured values from smartphone and laboratory probe when comparing to the calculated one are 4.58 - 7.08 % and 17.88 - 23.01 %, respectively. This means the smartphone is more reliable than the magnetic probe in laboratory because the sensitivity of magnetic field measurement from smartphone is better than the one from the magnetic probe in laboratory.

Once, we verify that the smartphone is reliable and can be used as a magnetic field measurement device, we use the smartphone to determine the magnetic field line from magnet and magnetized ferromagnetic rod. We measure the magnetic field from the rod which is magnetized under different conditions by using magnet. The results show that when the rod is magnetized by north pole magnet no matter on which side of the rod, the surface of the rod on that area will have south pole and vice versa. This means the rod will have an opposite polarity to the polarity of magnet that face in. The vectors of the magnetic field show that the magnitude of magnetic field from both sides of the rod have almost the same values.

Appendix A

The raw data of magnetic field is obtained by smartphone and numerical calculation of C programming from Magnetic Field Comparison in section of Verification of Magnetic Sensor on the Smartphone. There are two sets of experiment from Magnetic Field Comparison which are Magnetic field along z-axis of Helmholtz Coil and Magnetic field on the plane at z = 0.060 m of Helmholtz Coil. Fig. A.1 below demonstrates the position of z-axis from the reference position. Fig. A.2 below demonstrates the position number and the radius from center on the plane of z = 0.060 m of Helmholtz Coil.

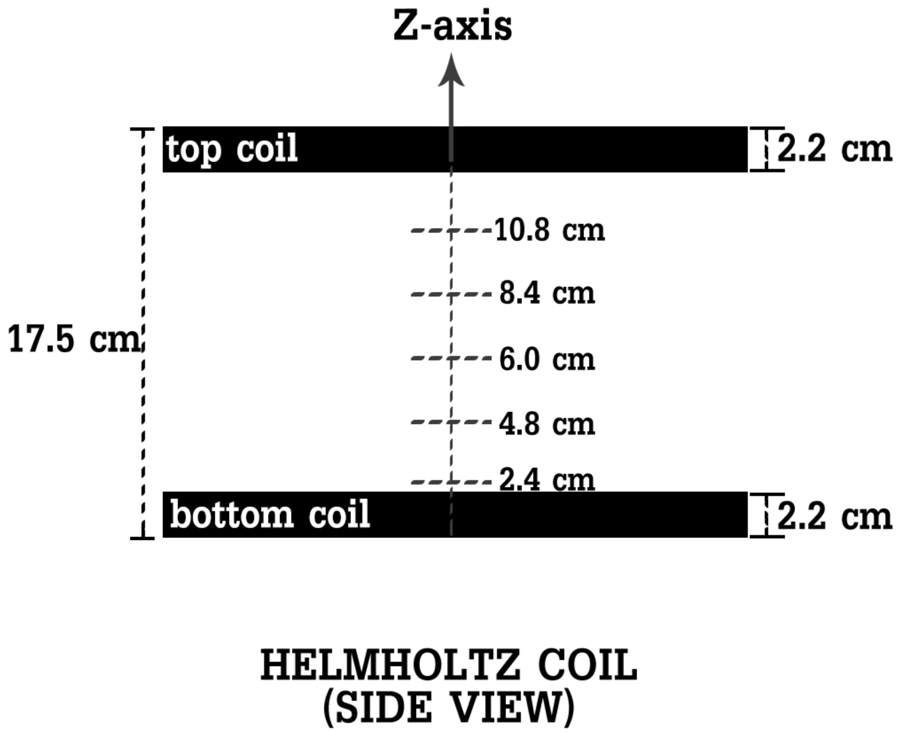


Figure A.1: The measurement position along the z-axis of the Helmholtz coil (Side view)

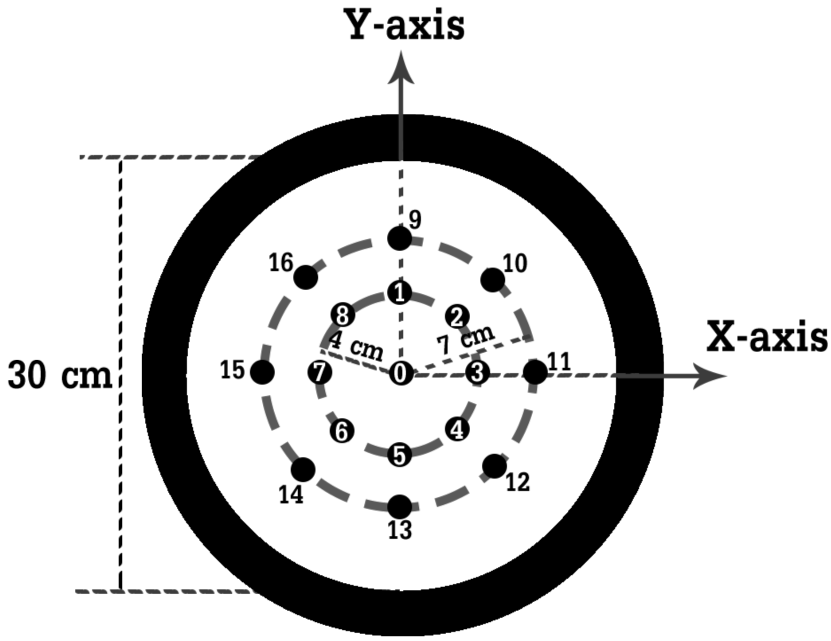


Figure A.2: The measurement position on the plane of z = 0.060 m of the Helmholtz coil (Top view)

Magnetic field along z-axis of Helmholtz Coil

Table A.1: The Earth's magnetic field measured by smartphone at different positions along the z-axis of the Helmholtz coil in set A

The Earth's Magnetic Field				
z (cm)	**Smartphone**			
	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
2.4	38.4	6.3	-25.0	46.3
4.8	38.2	6.8	-25.4	46.4
6.0	37.8	7.3	-26.2	46.6
8.4	38.5	8.4	-25.9	47.2
10.8	38.6	9.6	-26.2	47.6

Table A.2: The magnetic field measured by smartphone at different positions along the z-axis of the Helmholtz coil with current of 1 A in set A (EMF is included)

The Magnetic Field along z-axis Produced by Helmholtz Coil (I = 1.0 A) (EMF is included)				
z (cm)	**Smartphone**			
	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
2.4	39.0	23.3	714.8	716.2
4.8	41.4	12.4	718.2	719.5
6.0	41.2	8.9	715.2	716.4
8.4	39.9	4.2	712.2	713.3
10.8	41.2	2.7	697.9	699.1

Table A.3: The magnetic field measured by smartphone at different positions along the z-axis of the Helmholtz coil with current of 1 A in set A (EMF is excluded by subtracting table the value from A.1 by table A.2)

The Magnetic Field along z-axis Produced by Helmholtz Coil (I = 1.0 A) (EMF is excluded)				
z (cm)	**Smartphone**			
	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
2.4	36.9	4.7	-24.9	44.8
4.8	36.7	9.1	-26.5	46.2
6.0	36.4	9.6	-26.6	46.1
8.4	41.4	9.6	-25.7	49.7
10.8	38.6	8.9	-25.5	47.1

Table A.4: The Earth's magnetic field measured by smartphone at different positions along the z-axis of the Helmholtz coil in set B

The Earth's Magnetic Field				
z (cm)	**Smartphone**			
	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
2.4	42.2	22.9	1054.5	1055.6
4.8	44.9	17.8	1069.7	1070.8
6.0	40.2	14.7	1068.2	1069.1
8.4	47.9	5.3	1069.7	1070.8
10.8	40.5	-5.4	1047.0	1047.8

Table A.5: The magnetic field measured by smartphone at different positions along the z-axis of the Helmholtz coil with current of 1.5 A in set B (EMF is included)

The Magnetic Field along z-axis Produced by Helmholtz Coil (I = 1.5 A) (EMF is included)				
z (cm)	**Smartphone**			
	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
2.4	5.3	18.2	1079.4	1079.6
4.8	8.2	8.7	1096.2	1096.3
6.0	3.8	5.1	1094.8	1094.8
8.4	6.5	-4.3	1095.4	1095.4
10.8	1.9	-14.3	1072.5	1072.6

Table A.6: The magnetic field measured by smartphone at different positions along the z-axis of the Helmholtz coil with current of 1.5 A in set B (EMF is excluded by subtracting the value from table A.5 by table A.4)

The Magnetic Field along z-axis Produced by Helmholtz Coil (I = 1.5 A) (EMF is excluded)				
z (cm)	**Smartphone**			
	$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
2.4	0.6	17.0	739.8	740.0
4.8	3.2	5.6	743.6	743.6
6.0	3.4	1.6	741.4	741.4
8.4	1.4	-4.2	738.1	738.1
10.8	2.6	-6.9	724.1	724.1

Magnetic field on the plane at z = 0.060 m of Helmholtz Coil

Table A.7: The Earth's magnetic field measured by smartphone at different positions on the plane of z = 0.060 m of the Helmholtz coil in set C

The Earth's Magnetic Field							
Radius (cm)	**Position**	**x (cm)**	**y (cm)**	**Smartphone**			
				$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
0.0	**0**	**0.0**	**0.0**	37.8	6.5	-25.7	46.2
4.0	**1**	**0.0**	**4.0**	36.5	6.8	-25.9	45.3
	2	**2.8**	**2.8**	37.4	6.2	-26.4	46.2
	3	**4.0**	**0.0**	38.1	7.3	-26.5	47.0
	4	**2.8**	**-2.8**	37.9	6.9	-26.1	46.5
	5	**0.0**	**-4.0**	38.2	6.8	-26.2	46.8
	6	**-2.8**	**-2.8**	37.5	6.7	-25.8	46.0
	7	**-4.0**	**0.0**	36.5	6.1	-25.5	44.9
	8	**-2.8**	**2.8**	38.7	7.1	-26.0	47.2
7.0	**9**	**0.0**	**7.0**	37.6	6.2	-26.1	46.2
	10	**4.9**	**4.9**	39.0	6.3	-26.4	47.5
	11	**7.0**	**0.0**	38.5	6.2	-25.9	46.8
	12	**4.9**	**-4.9**	37.6	6.9	-26.7	46.6
	13	**0.0**	**-7.0**	37.2	7.3	-26.9	46.5
	14	**-4.9**	**-4.9**	36.4	8.3	-25.4	45.2
	15	**-7.0**	**0.0**	37.5	6.9	-26.1	46.2
	16	**-4.9**	**4.9**	38.1	6.7	-26.4	46.8

Table A.8: The magnetic field measured by smartphone at different positions on the plane of z = 0.060 m of the Helmholtz coil with current of 1.0 A in set C (EMF is included)

The Magnetic Field on the Plane of z = 0.060 m Produced by Helmholtz Coil (I = 1.0 A) (EMF is included)							
Radius (cm)	**Position**	**x (cm)**	**y (cm)**	**Smartphone**			
				$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
0.0	**0**	**0.0**	**0.0**	42.5	5.4	716.5	717.8
4.0	**1**	**0.0**	**4.0**	40.4	4.4	714.7	715.9
	2	**2.8**	**2.8**	41.6	3.8	715.6	716.8
	3	**4.0**	**0.0**	49.7	1.3	716.0	717.7
	4	**2.8**	**-2.8**	48.5	5.7	716.6	718.3
	5	**0.0**	**-4.0**	54.4	6.9	715.5	717.6
	6	**-2.8**	**-2.8**	51.9	9.6	713.7	715.6
	7	**-4.0**	**0.0**	36.1	1.1	713.9	714.8
	8	**-2.8**	**2.8**	37.8	2.7	713.4	714.4
7.0	**9**	**0.0**	**7.0**	39.8	6.0	700.9	702.1
	10	**4.9**	**4.9**	48.4	2.4	704.6	706.3
	11	**7.0**	**0.0**	60.3	-3.2	703.6	706.2
	12	**4.9**	**-4.9**	69.3	-11.9	701.2	704.7
	13	**0.0**	**-7.0**	56.4	-6.4	701.1	703.4
	14	**-4.9**	**-4.9**	50.6	-4.0	699.9	701.7
	15	**-7.0**	**0.0**	42.8	-0.5	693.2	694.5
	16	**-4.9**	**4.9**	31.6	12.2	693.2	694.0

Table A.9: The magnetic field measured by smartphone at different positions on the plane of z = 0.060 m of the Helmholtz coil with current of 1.0 A in set C (EMF is excluded by subtracting the value from table A.8 by table A.7)

The Magnetic Field on the Plane of z = 0.060 m Produced by Helmholtz Coil (I = 1.0 A) (EMF is excluded)							
Radius (cm)	**Position**	**x (cm)**	**y (cm)**	**Smartphone**			
				$\mathbf{B_x}$	$\mathbf{B_y}$	$\mathbf{B_z}$	$\mathbf{B_{tot}}$
0.0	**0**	**0.0**	**0.0**	4.7	-1.1	742.2	742.2
4.0	**1**	**0.0**	**4.0**	3.9	-2.4	740.6	740.6
	2	**2.8**	**2.8**	4.2	-2.4	742.0	742.0
	3	**4.0**	**0.0**	11.6	-6.0	742.5	742.6
	4	**2.8**	**-2.8**	10.6	-1.2	742.7	742.8
	5	**0.0**	**-4.0**	16.2	0.1	741.7	741.9
	6	**-2.8**	**-2.8**	14.4	2.9	739.5	739.6
	7	**-4.0**	**0.0**	-0.4	-5.0	739.4	739.4
	8	**-2.8**	**2.8**	-0.9	-4.4	739.4	739.4
7.0	**9**	**0.0**	**7.0**	2.2	-0.2	727.0	727.0
	10	**4.9**	**4.9**	9.4	-3.9	731.0	731.1
	11	**7.0**	**0.0**	21.8	-9.4	729.5	729.9
	12	**4.9**	**-4.9**	31.7	-18.8	727.9	728.8
	13	**0.0**	**-7.0**	19.2	-13.7	728.0	728.4
	14	**-4.9**	**-4.9**	14.2	-12.3	725.3	725.5
	15	**-7.0**	**0.0**	5.3	-7.4	719.3	719.4
	16	**-4.9**	**4.9**	-6.5	5.5	719.6	719.7

Table A.10: The magnetic field along the z-axis (x = 0 m , y = 0 m) in microtesla from numerical calculation

z (m)	B_x	B_y	B_z
0.000	0.11	0.00	707.23
0.001	0.11	0.00	709.66
0.002	0.11	-0.00	712.03
0.003	0.11	-0.00	714.36
0.004	0.10	0.00	716.63
0.005	0.10	0.00	718.84
0.006	0.10	0.00	721.01
0.007	0.10	0.00	723.11
0.008	0.10	-0.00	725.17
0.009	0.10	-0.00	727.17
0.010	0.10	0.00	729.12
0.011	0.09	-0.00	731.01
0.012	0.09	0.00	732.85
0.013	0.09	-0.00	734.64
0.014	0.09	0.00	736.37
0.015	0.09	0.00	738.05
0.016	0.09	-0.00	739.68
0.017	0.09	-0.00	741.26
0.018	0.08	0.00	742.78
0.019	0.08	-0.00	744.25
0.020	0.08	0.00	745.67
0.021	0.08	0.00	747.04
0.022	0.08	0.00	748.36
0.023	0.08	0.00	749.63
0.024	0.08	-0.00	750.85
0.025	0.07	-0.00	752.02
0.026	0.07	-0.00	753.14
0.027	0.07	-0.00	754.22
0.028	0.07	0.00	755.25
0.029	0.07	0.00	756.23
0.030	0.07	-0.00	757.17
0.031	0.06	-0.00	758.07
0.032	0.06	-0.00	758.92
0.033	0.06	0.00	759.73
0.034	0.06	-0.00	760.50
0.035	0.06	0.00	761.23
0.036	0.06	-0.00	761.93
0.037	0.06	-0.00	762.58
0.038	0.06	-0.00	763.19
0.039	0.05	-0.00	763.77
0.040	0.05	0.00	764.32
0.041	0.05	0.00	764.83
0.042	0.05	-0.00	765.31

z (m)	B_x	B_y	B_z
0.043	0.05	0.00	765.75
0.044	0.05	-0.00	766.17
0.045	0.05	0.00	766.55
0.046	0.04	0.00	766.91
0.047	0.04	-0.00	767.24
0.048	0.04	-0.00	767.55
0.049	0.04	-0.00	767.82
0.050	0.04	0.00	768.08
0.051	0.04	0.00	768.31
0.052	0.04	-0.00	768.52
0.053	0.04	-0.00	768.71
0.054	0.03	0.00	768.88
0.055	0.03	-0.00	769.03
0.056	0.03	0.00	769.17
0.057	0.03	-0.00	769.29
0.058	0.03	-0.00	769.39
0.059	0.03	0.00	769.48
0.060	0.03	-0.00	769.55
0.061	0.03	0.00	769.62
0.062	0.03	0.00	769.67
0.063	0.02	-0.00	769.71
0.064	0.02	-0.00	769.74
0.065	0.02	-0.00	769.77
0.066	0.02	0.00	769.78
0.067	0.02	0.00	769.79
0.068	0.02	0.00	769.79
0.069	0.02	-0.00	769.79
0.070	0.02	0.00	769.79
0.071	0.02	0.00	769.78
0.072	0.01	-0.00	769.76
0.073	0.01	-0.00	769.75
0.074	0.01	0.00	769.73
0.075	0.01	-0.00	769.71
0.076	0.01	-0.00	769.69
0.077	0.01	-0.00	769.67
0.078	0.01	0.00	769.66
0.079	0.01	-0.00	769.64
0.080	0.01	-0.00	769.62
0.081	0.01	0.00	769.60
0.082	0.00	0.00	769.59
0.083	0.00	0.00	769.58
0.084	0.00	-0.00	769.57
0.085	0.00	0.00	769.56

z (m)	B_x	B_y	B_z
0.086	0.00	0.00	769.56
0.087	-0.00	0.00	769.55
0.088	-0.00	-0.00	769.55
0.089	-0.00	0.00	769.56
0.090	-0.00	-0.00	769.56
0.091	-0.00	0.00	769.57
0.092	-0.01	-0.00	769.58
0.093	-0.01	-0.00	769.59
0.094	-0.01	-0.00	769.60
0.095	-0.01	-0.00	769.62
0.096	-0.01	-0.00	769.64
0.097	-0.01	-0.00	769.66
0.098	-0.01	-0.00	769.67
0.099	-0.01	0.00	769.69
0.100	-0.01	0.00	769.71
0.101	-0.01	-0.00	769.73
0.102	-0.02	-0.00	769.75
0.103	-0.02	0.00	769.76
0.104	-0.02	-0.00	769.78
0.105	-0.02	-0.00	769.79
0.106	-0.02	-0.00	769.79
0.107	-0.02	0.00	769.79
0.108	-0.02	-0.00	769.79
0.109	-0.02	-0.00	769.78
0.110	-0.02	0.00	769.77
0.111	-0.02	0.00	769.74
0.112	-0.03	0.00	769.71
0.113	-0.03	-0.00	769.67
0.114	-0.03	-0.00	769.62
0.115	-0.03	0.00	769.55
0.116	-0.03	-0.00	769.48
0.117	-0.03	0.00	769.39
0.118	-0.03	-0.00	769.29
0.119	-0.03	-0.00	769.17
0.120	-0.03	0.00	769.03
0.121	-0.04	0.00	768.88
0.122	-0.04	0.00	768.71
0.123	-0.04	-0.00	768.52
0.124	-0.04	-0.00	768.31
0.125	-0.04	-0.00	768.08
0.126	-0.04	-0.00	767.83
0.127	-0.04	0.00	767.55
0.128	-0.04	0.00	767.24
0.129	-0.05	0.00	766.91
0.130	-0.05	-0.00	766.56

z (m)	B_x	B_y	B_z
0.131	-0.05	-0.00	766.17
0.132	-0.05	0.00	765.75
0.133	-0.05	0.00	765.31
0.134	-0.05	-0.00	764.83
0.135	-0.05	-0.00	764.32
0.136	-0.05	0.00	763.78
0.137	-0.06	-0.00	763.20
0.138	-0.06	0.00	762.58
0.139	-0.06	0.00	761.93
0.140	-0.06	-0.00	761.24
0.141	-0.06	-0.00	760.51
0.142	-0.06	-0.00	759.74
0.143	-0.06	0.00	758.92
0.144	-0.07	-0.00	758.07
0.145	-0.07	0.00	757.17
0.146	-0.07	0.00	756.23
0.147	-0.07	0.00	755.25
0.148	-0.07	-0.00	754.22
0.149	-0.07	0.00	753.14
0.150	-0.07	-0.00	752.02
0.151	-0.08	-0.00	750.85
0.152	-0.08	0.00	749.63
0.153	-0.08	0.00	748.36
0.154	-0.08	-0.00	747.04
0.155	-0.08	0.00	745.67
0.156	-0.08	-0.00	744.25
0.157	-0.08	0.00	742.78
0.158	-0.09	0.00	741.26
0.159	-0.09	0.00	739.68
0.160	-0.09	0.00	738.06
0.161	-0.09	-0.00	736.37
0.162	-0.09	0.00	734.64
0.163	-0.09	-0.00	732.85
0.164	-0.10	0.00	731.01
0.165	-0.10	0.00	729.12
0.166	-0.10	0.00	727.17
0.167	-0.10	-0.00	725.17
0.168	-0.10	0.00	723.12
0.169	-0.10	0.00	721.01
0.170	-0.10	0.00	718.84
0.171	-0.11	0.00	716.63
0.172	-0.11	0.00	714.36
0.173	-0.11	-0.00	712.04
0.174	-0.11	-0.00	709.66
0.175	-0.11	0.00	707.23

Table A.11: The magnetic field along the x-axis (y = 0 m , z = 0.060 m) in microtesla from numerical calculation

x (m)	B_x	B_y	B_z
0.000	0.03	-0.00	769.55
0.001	-0.01	0.00	769.55
0.002	-0.04	0.00	769.56
0.003	-0.07	0.00	769.57
0.004	-0.11	0.00	769.59
0.005	-0.14	0.00	769.61
0.006	-0.17	-0.00	769.64
0.007	-0.19	0.00	769.67
0.008	-0.22	0.00	769.72
0.009	-0.24	-0.00	769.76
0.010	-0.26	0.00	769.82
0.011	-0.27	0.00	769.87
0.012	-0.28	0.00	769.94
0.013	-0.29	-0.00	770.01
0.014	-0.29	-0.00	770.08
0.015	-0.28	0.00	770.16
0.016	-0.27	0.00	770.25
0.017	-0.26	-0.00	770.34
0.018	-0.23	-0.00	770.43
0.019	-0.20	-0.00	770.53
0.020	-0.16	0.00	770.64
0.021	-0.12	0.00	770.74
0.022	-0.06	0.00	770.86
0.023	-0.00	0.00	770.97
0.024	0.07	-0.00	771.09
0.025	0.15	0.00	771.22
0.026	0.25	0.00	771.34
0.027	0.35	0.00	771.47
0.028	0.46	0.00	771.61
0.029	0.59	0.00	771.74
0.030	0.73	0.00	771.88
0.031	0.88	0.00	772.02
0.032	1.05	0.00	772.16
0.033	1.23	0.00	772.30
0.034	1.43	0.00	772.45
0.035	1.64	0.00	772.59

x (m)	B_x	B_y	B_z
0.036	1.87	-0.00	772.74
0.037	2.11	0.00	772.88
0.038	2.37	-0.00	773.02
0.039	2.65	-0.00	773.17
0.040	2.95	-0.00	773.31
0.041	3.27	-0.00	773.45
0.042	3.61	0.00	773.58
0.043	3.98	0.00	773.72
0.044	4.36	-0.00	773.85
0.045	4.77	-0.00	773.98
0.046	5.20	-0.00	774.10
0.047	5.66	0.00	774.21
0.048	6.14	-0.00	774.32
0.049	6.65	0.00	774.43
0.050	7.19	-0.00	774.52
0.051	7.75	-0.00	774.61
0.052	8.35	-0.00	774.69
0.053	8.98	-0.00	774.76
0.054	9.64	0.00	774.82
0.055	10.33	0.00	774.87
0.056	11.06	0.00	774.91
0.057	11.82	-0.00	774.93
0.058	12.62	-0.00	774.94
0.059	13.46	0.00	774.93
0.060	14.34	-0.00	774.91
0.061	15.26	-0.00	774.87
0.062	16.22	-0.00	774.81
0.063	17.23	-0.00	774.73
0.064	18.28	-0.00	774.63
0.065	19.37	0.00	774.51
0.066	20.52	0.00	774.36
0.067	21.72	0.00	774.19
0.068	22.97	-0.00	773.99
0.069	24.27	0.00	773.76
0.070	25.62	0.00	773.50

Table A.12: The magnetic field along the y-axis (x = 0 m , z = 0.060 m) in microtesla from program

y (m)	B_x	B_y	B_z
0.000	0.03	-0.00	769.55
0.001	0.03	-0.03	769.56
0.002	0.03	-0.07	769.56
0.003	0.03	-0.10	769.58
0.004	0.03	-0.13	769.60
0.005	0.03	-0.17	769.63
0.006	0.03	-0.19	769.66
0.007	0.03	-0.22	769.70
0.008	0.03	-0.25	769.75
0.009	0.03	-0.27	769.80
0.010	0.03	-0.28	769.86
0.011	0.03	-0.30	769.92
0.012	0.03	-0.31	769.99
0.013	0.03	-0.31	770.06
0.014	0.03	-0.31	770.14
0.015	0.03	-0.31	770.23
0.016	0.03	-0.30	770.32
0.017	0.03	-0.28	770.41
0.018	0.03	-0.26	770.51
0.019	0.03	-0.23	770.62
0.020	0.03	-0.19	770.73
0.021	0.03	-0.14	770.84
0.022	0.03	-0.09	770.96
0.023	0.03	-0.03	771.08
0.024	0.03	0.05	771.21
0.025	0.03	0.13	771.34
0.026	0.03	0.22	771.47
0.027	0.03	0.33	771.61
0.028	0.03	0.44	771.75
0.029	0.03	0.57	771.89
0.030	0.03	0.71	772.03
0.031	0.03	0.86	772.18
0.032	0.03	1.03	772.33
0.033	0.03	1.21	772.48
0.034	0.03	1.41	772.63
0.035	0.03	1.62	772.78

y (m)	B_x	B_y	B_z
0.036	0.03	1.85	772.93
0.037	0.03	2.10	773.08
0.038	0.03	2.36	773.24
0.039	0.03	2.64	773.39
0.040	0.03	2.94	773.53
0.041	0.03	3.26	773.68
0.042	0.03	3.61	773.83
0.043	0.03	3.97	773.97
0.044	0.03	4.36	774.11
0.045	0.03	4.76	774.24
0.046	0.03	5.20	774.37
0.047	0.03	5.66	774.50
0.048	0.03	6.14	774.61
0.049	0.03	6.65	774.73
0.050	0.03	7.19	774.83
0.051	0.03	7.76	774.93
0.052	0.03	8.36	775.02
0.053	0.03	8.99	775.10
0.054	0.03	9.65	775.17
0.055	0.03	10.35	775.23
0.056	0.03	11.08	775.27
0.057	0.03	11.85	775.30
0.058	0.03	12.65	775.32
0.059	0.03	13.49	775.33
0.060	0.03	14.37	775.31
0.061	0.03	15.30	775.28
0.062	0.03	16.26	775.23
0.063	0.03	17.27	775.17
0.064	0.03	18.33	775.08
0.065	0.03	19.43	774.96
0.066	0.03	20.58	774.83
0.067	0.03	21.78	774.67
0.068	0.03	23.04	774.48
0.069	0.03	24.34	774.26
0.070	0.03	25.71	774.01

Table A.13: The magnetic field on the plane at z = 0.060 m at any (x,y) in microtesla from numerical calculation

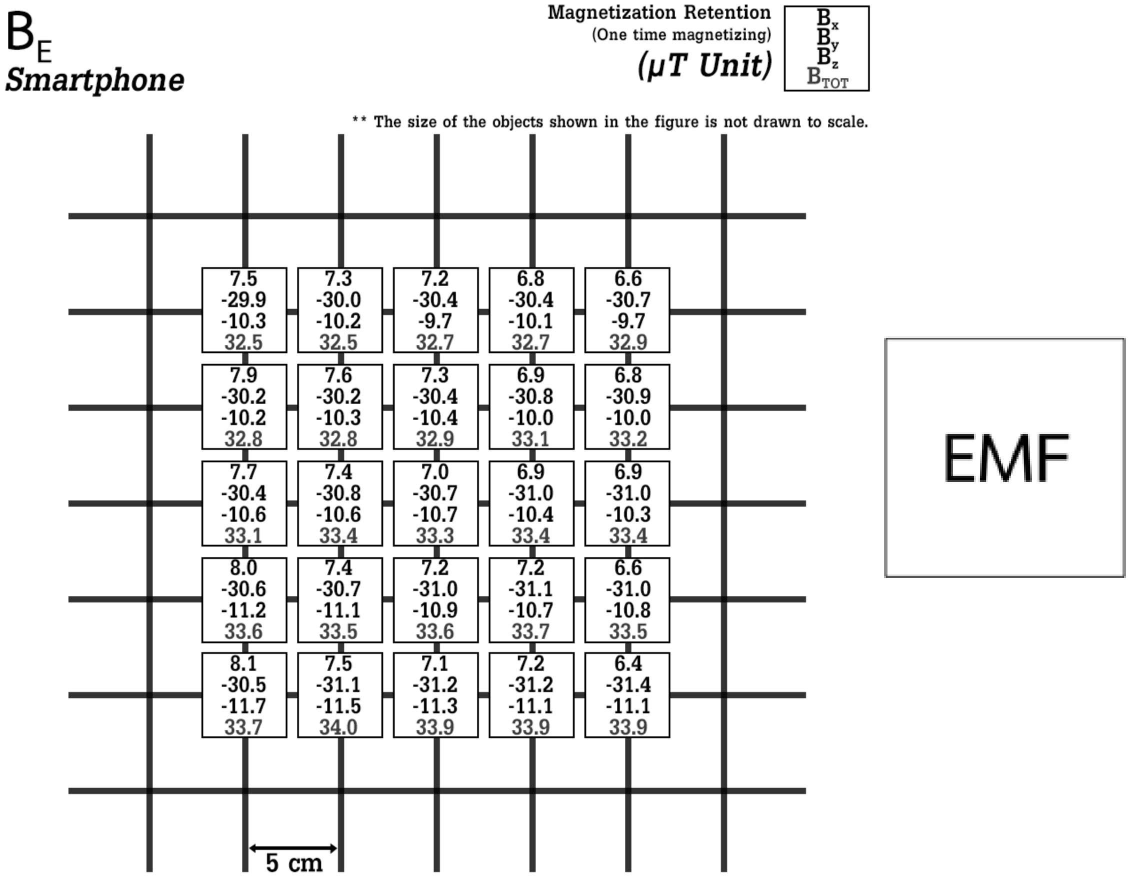
x (m)	y (m)	B_x	B_y	B_z
-0.070	-0.001	-25.70	-0.37	774.10
-0.070	0.000	-25.69	0.00	774.10
-0.070	0.001	-25.70	0.37	774.10
⋮	⋮	⋮	⋮	⋮
-0.049	-0.050	-17.98	-18.37	774.08
-0.049	-0.049	-17.48	-17.50	774.26
-0.049	-0.048	-16.99	-16.66	774.43
⋮	⋮	⋮	⋮	⋮
-0.049	0.048	-16.99	16.66	774.43
-0.049	0.049	-17.48	17.50	774.26
-0.049	0.050	-17.98	18.37	774.08
⋮	⋮	⋮	⋮	⋮
-0.040	-0.001	-2.92	-0.07	773.62
-0.040	0.000	-2.92	-0.00	773.62
-0.040	0.001	-2.92	0.07	773.62
⋮	⋮	⋮	⋮	⋮
-0.028	-0.029	-2.09	-2.19	773.65
-0.028	-0.028	-1.97	-1.99	773.54
-0.028	-0.027	-1.86	-1.81	773.44
⋮	⋮	⋮	⋮	⋮
-0.028	0.027	-1.86	1.81	773.44
-0.028	0.028	-1.97	1.99	773.54
-0.028	0.029	-2.09	2.19	773.65
⋮	⋮	⋮	⋮	⋮
0.000	-0.071	0.03	-27.13	773.73
0.000	-0.070	0.03	-25.71	774.01
0.000	-0.069	0.03	-24.34	774.26
⋮	⋮	⋮	⋮	⋮
0.000	-0.041	0.03	-3.26	773.68
0.000	-0.040	0.03	-2.94	773.53
0.000	-0.039	0.03	-2.64	773.39
⋮	⋮	⋮	⋮	⋮
0.000	-0.001	0.03	0.03	769.56
0.000	0.000	0.03	-0.00	769.55
0.000	0.001	0.03	-0.03	769.56

x (m)	y (m)	B_x	B_y	B_z
⋮	⋮	⋮	⋮	⋮
0.000	0.039	0.03	2.64	773.39
0.000	0.040	0.03	2.94	773.53
0.000	0.041	0.03	3.26	773.68
⋮	⋮	⋮	⋮	⋮
0.000	0.069	0.03	24.34	774.26
0.000	0.070	0.03	25.71	774.01
0.000	0.071	0.03	27.13	773.73
⋮	⋮	⋮	⋮	⋮
0.028	-0.029	2.14	-2.19	773.45
0.028	-0.028	2.02	-1.99	773.35
0.028	-0.027	1.90	-1.81	773.24
⋮	⋮	⋮	⋮	⋮
0.028	0.027	1.90	1.81	773.24
0.028	0.028	2.02	1.99	773.35
0.028	0.029	2.14	2.19	773.45
⋮	⋮	⋮	⋮	⋮
0.040	-0.001	2.96	-0.07	773.31
0.040	0.000	2.95	0.00	773.31
0.040	0.001	2.96	0.07	773.31
⋮	⋮	⋮	⋮	⋮
0.049	-0.050	18.01	-18.37	773.81
0.049	-0.049	17.51	-17.50	773.98
0.049	-0.048	17.02	-16.66	774.14
⋮	⋮	⋮	⋮	⋮
0.049	0.048	17.02	16.66	774.14
0.049	0.049	17.51	17.50	773.98
0.049	0.050	18.01	18.37	773.81
⋮	⋮	⋮	⋮	⋮
0.070	-0.001	25.63	-0.37	773.50
0.070	0.000	25.62	0.00	773.50
0.070	0.001	25.63	0.37	773.50

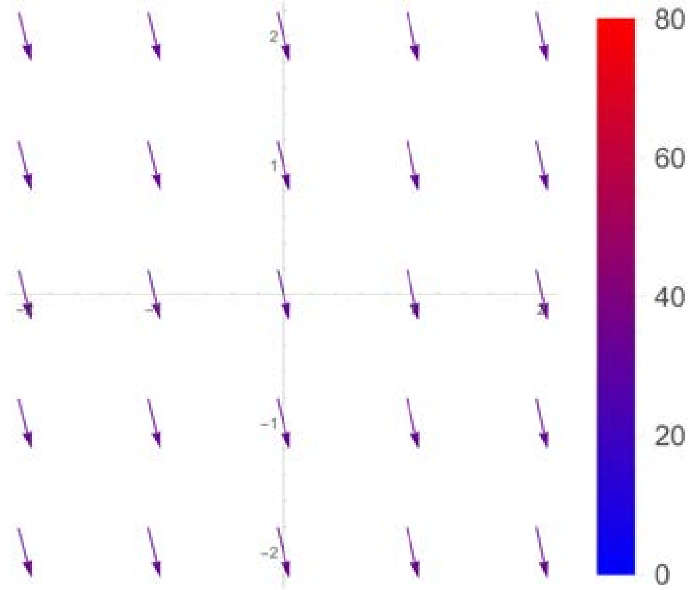
Appendix B

In this Appendix, there are four sets of experiments in section of Magnetic Field Due to the Presence of Ferromagnets: (1) Magnetization Retention, (2) The Superposition of the Magnetic Field from Two Rods, (3) The Superposition of the Magnetic Field from Two Rods and (4) Magnetizing the Rod with Different Polarity Conditions by Using One Magnet. Each experiment is shown as two types of figure which are the values and the vectors of magnetic field obtained by using the magnetic sensor in smartphone.

All results in Magnetization Retention (One time Magnetizing)

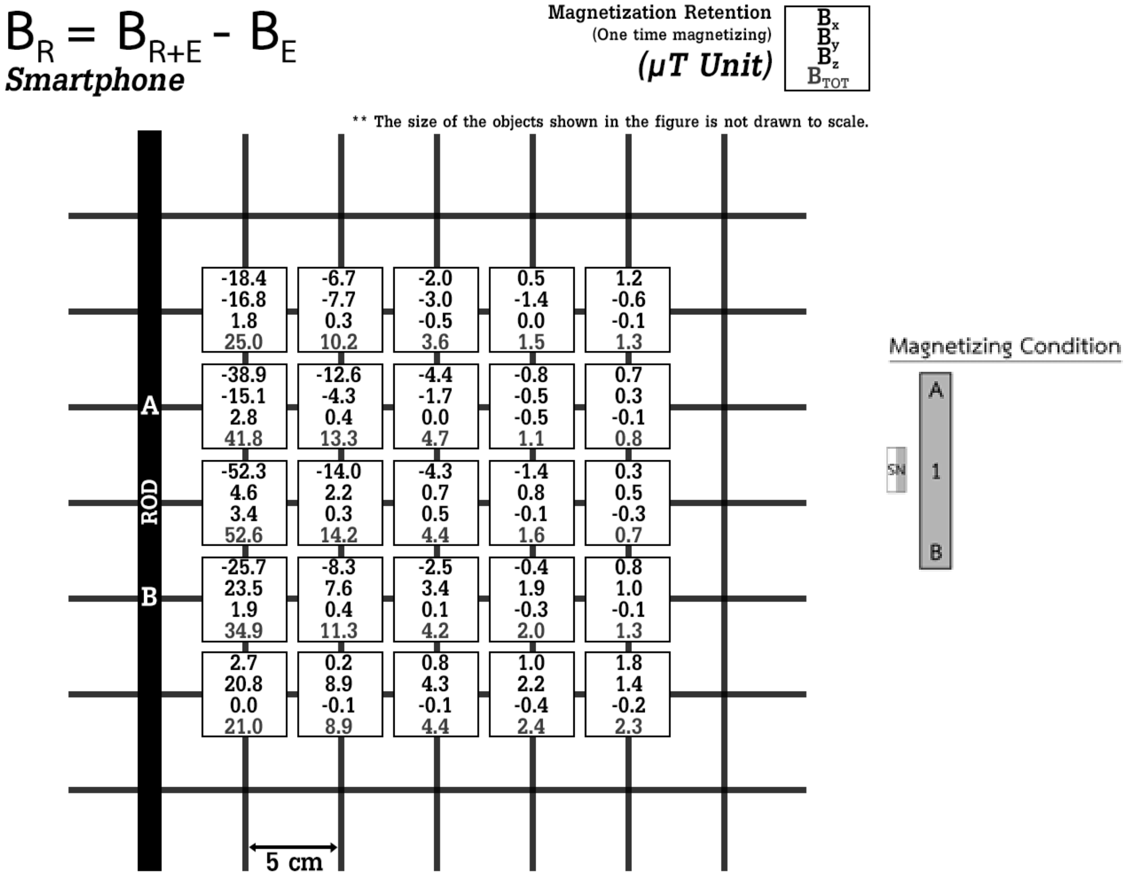


(a)

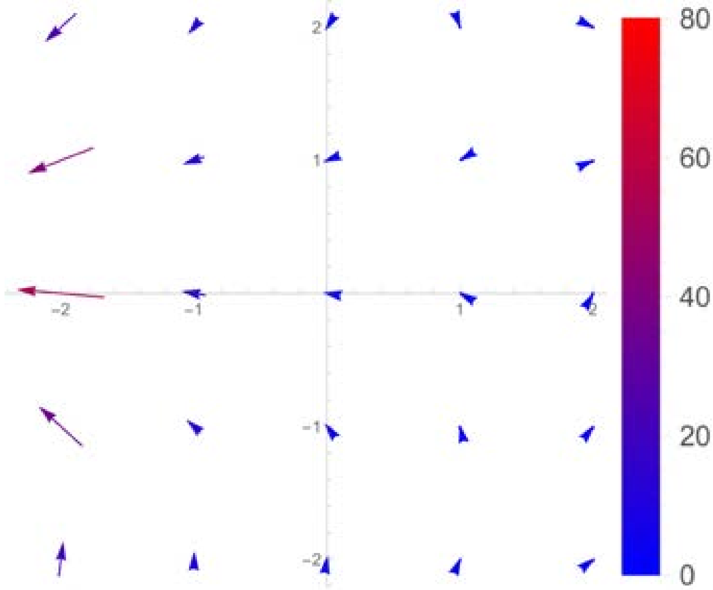


(b)

Figure B.1: (a) The values and (b) the vectors of the Earth's magnetic field of Magnetization Retention from Fig. 3.21

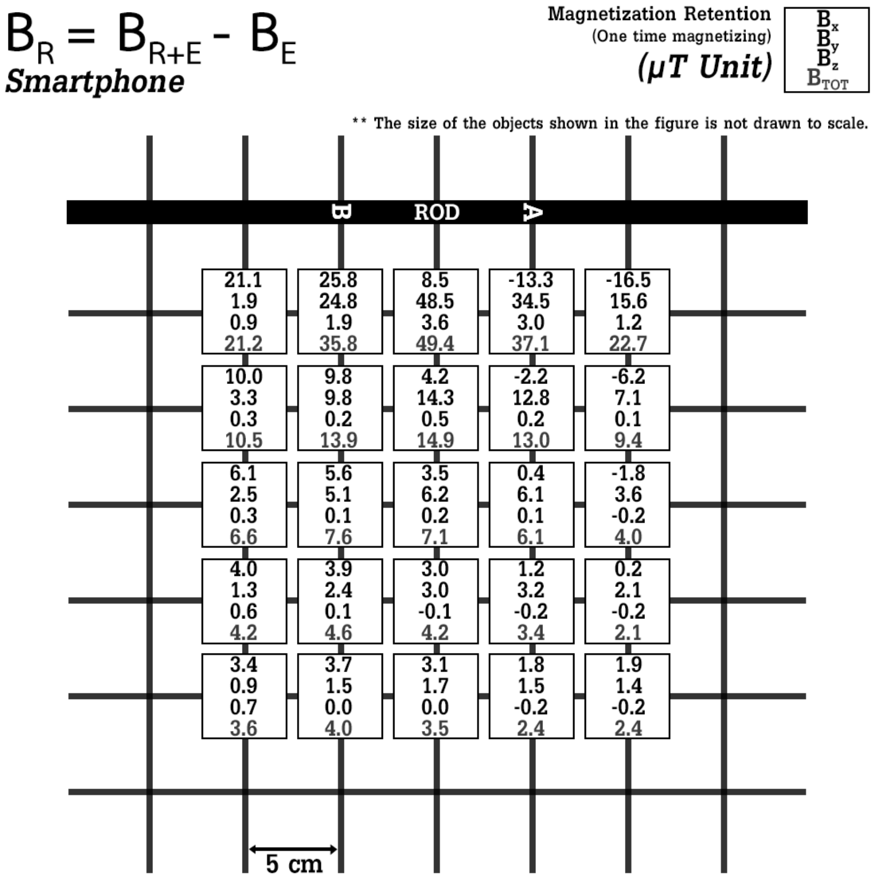


(a)

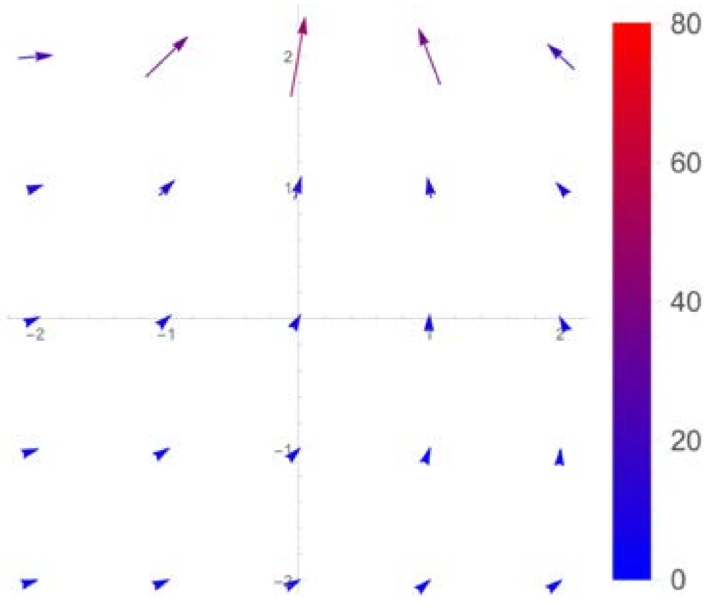


(b)

Figure B.2: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.21b

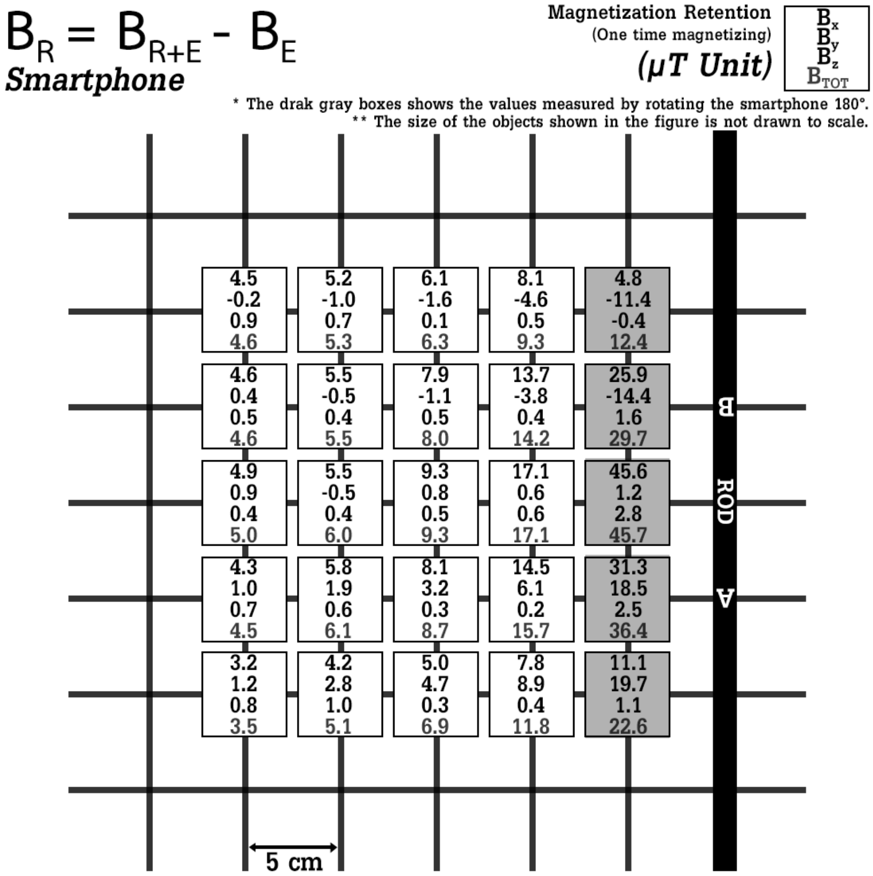


(a)

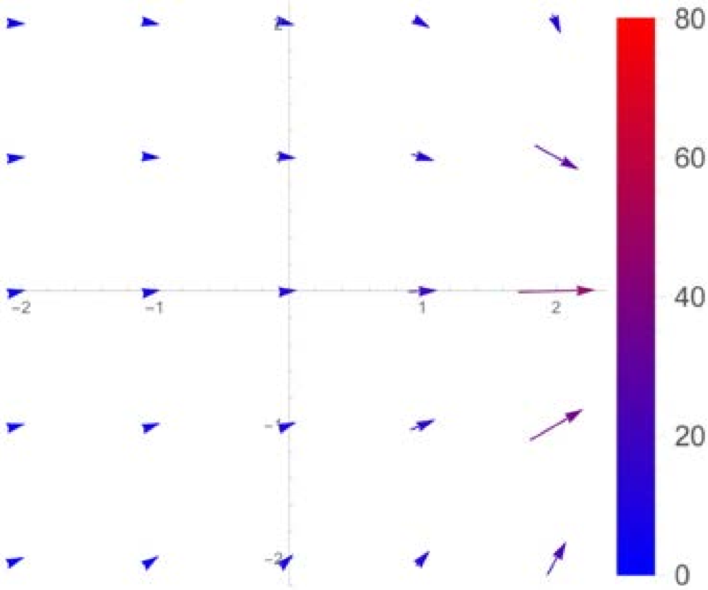


(b)

Figure B.3: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.21c

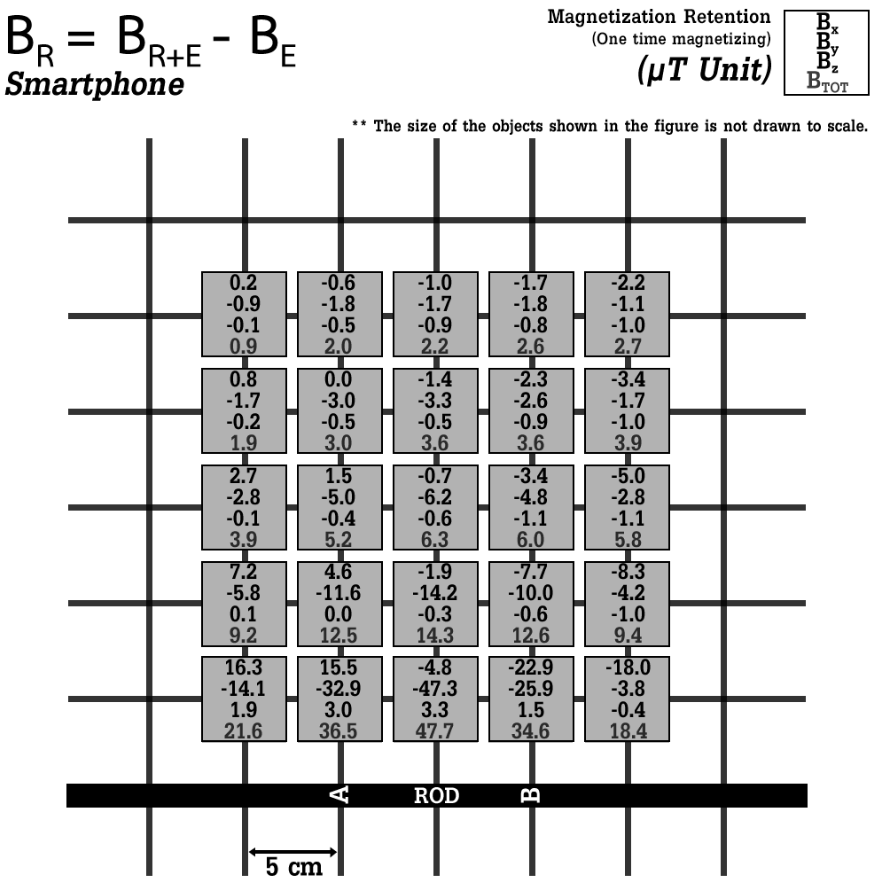


(a)

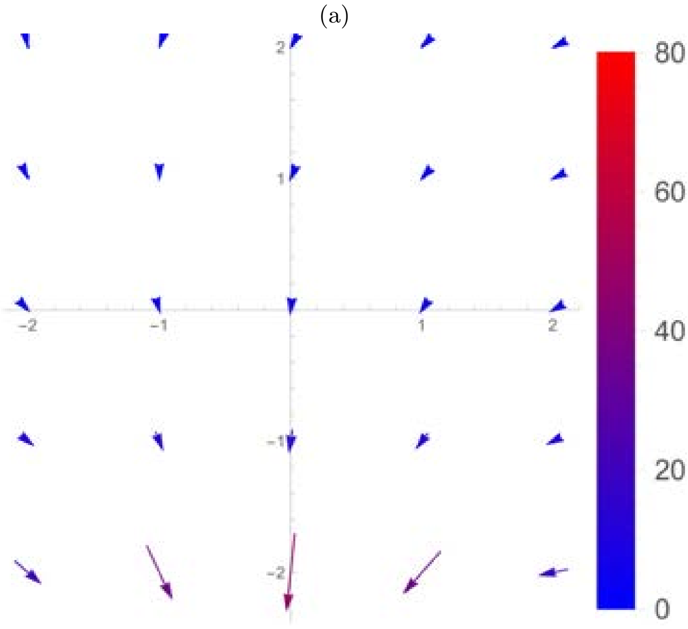


(b)

Figure B.4: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.21d



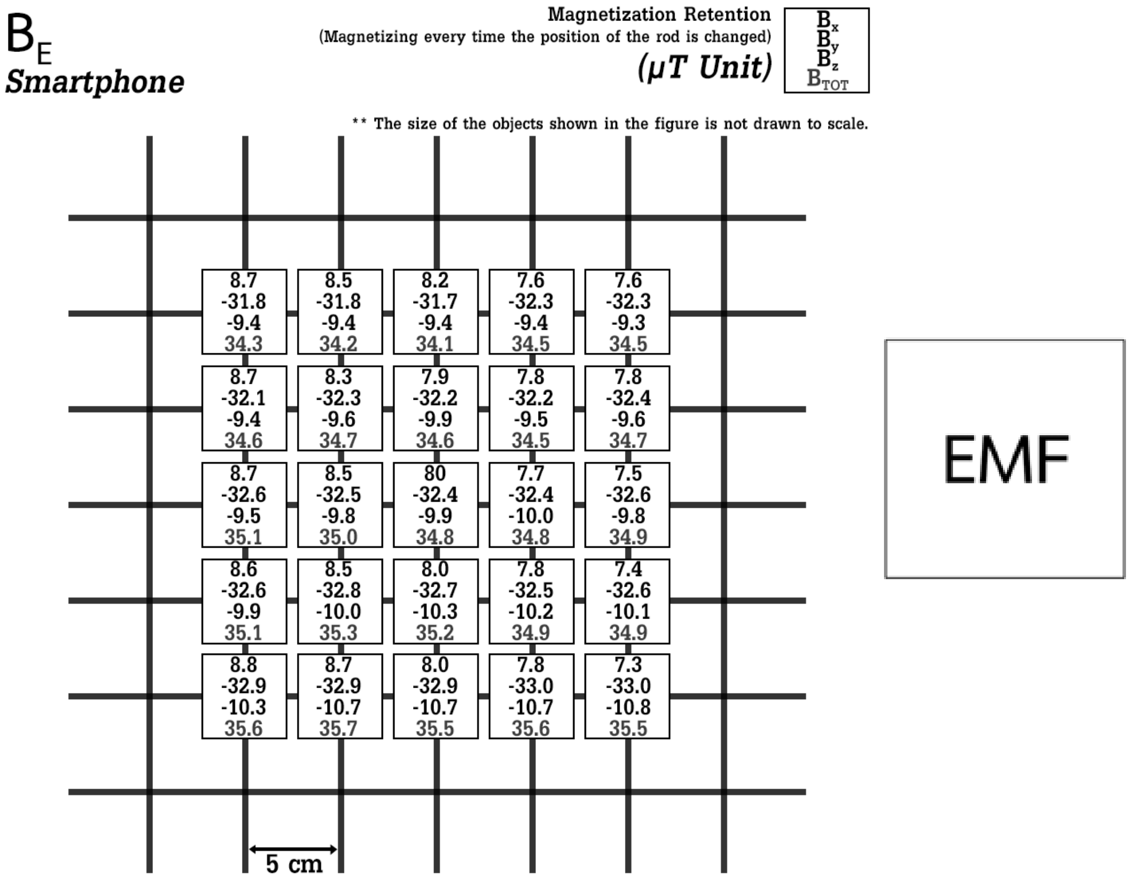
(a)



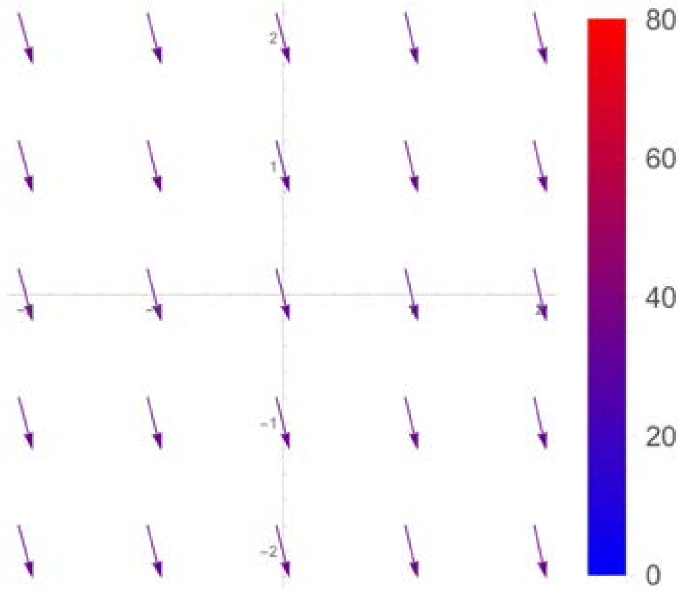
(b)

Figure B.5: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.21e

All results in Magnetization Retention (Magnetizing every time the posion of the rod is changed)

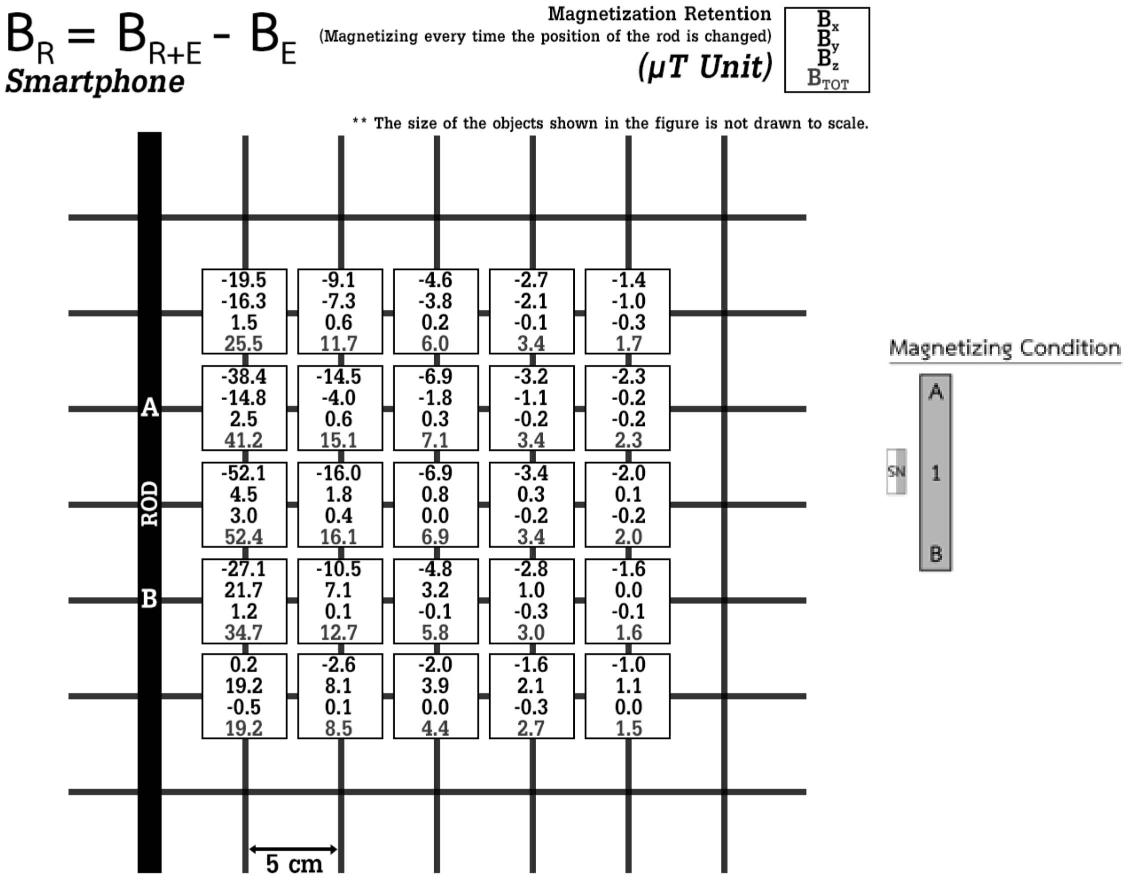


(a)

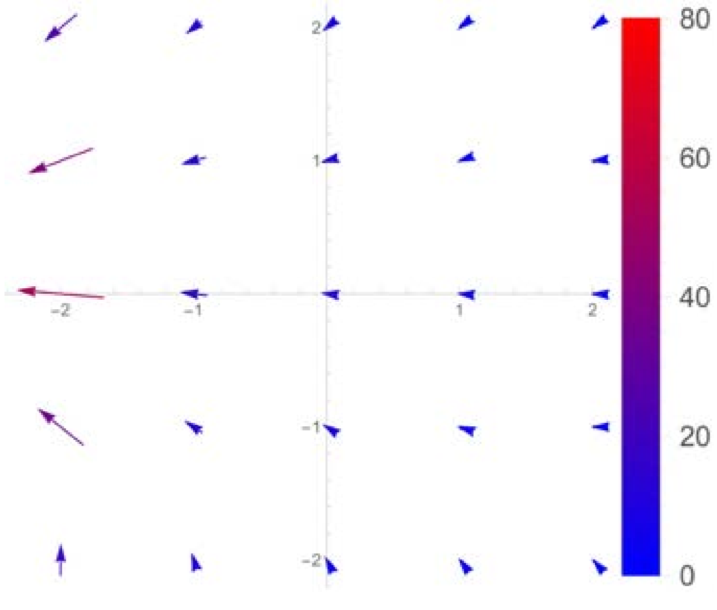


(b)

Figure B.6: (a) The values and (b) the vectors of the Earth's magnetic field of Magnetization Retention from Fig. 3.22

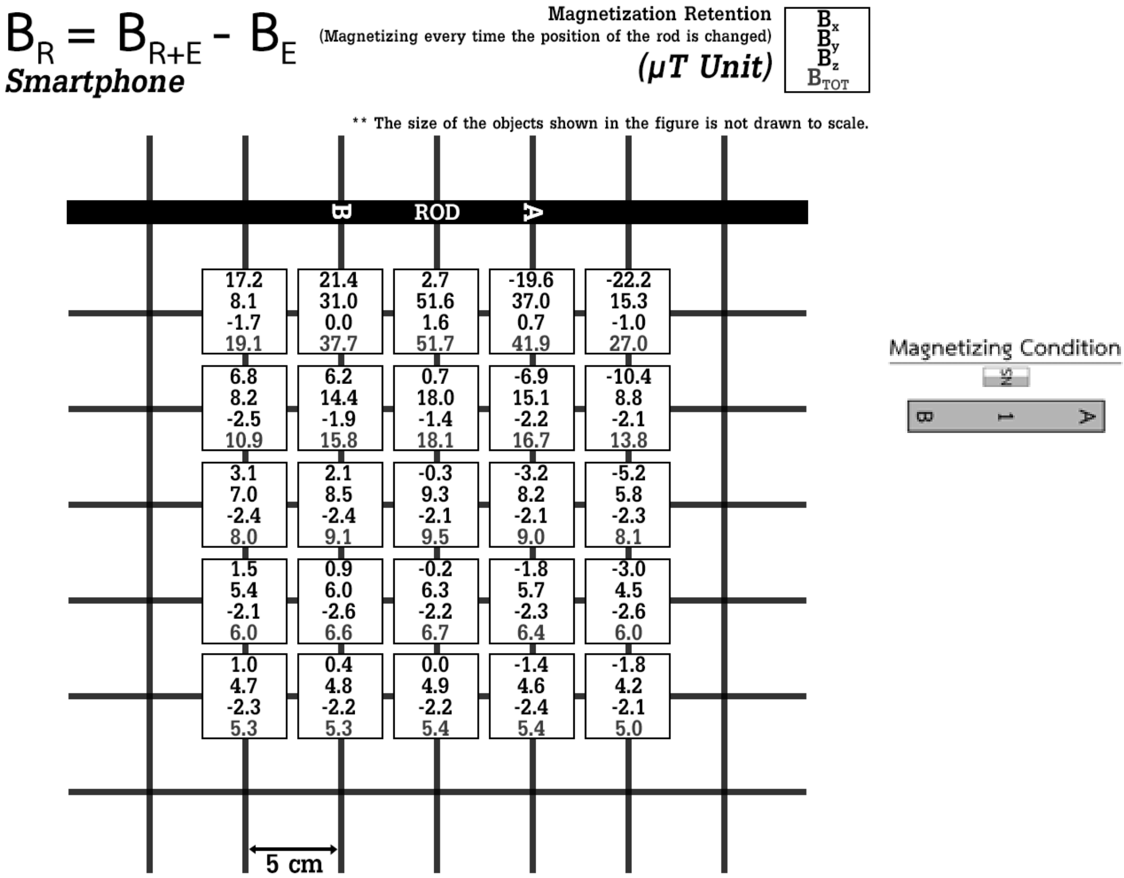


(a)

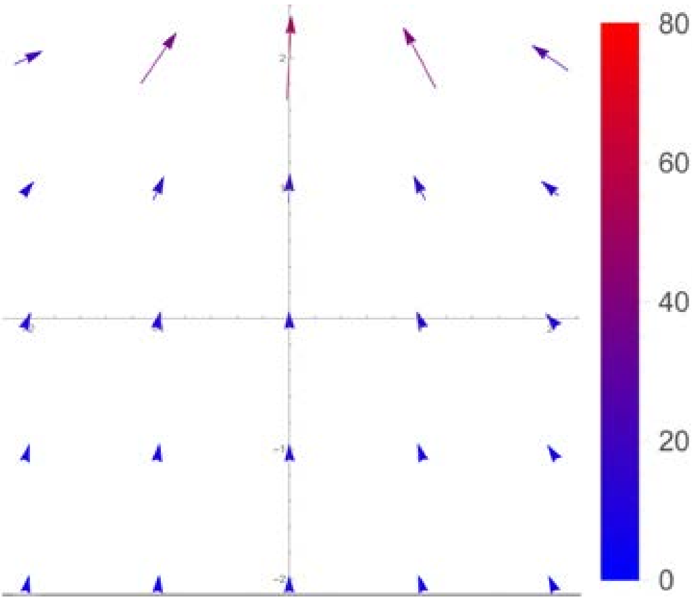


(b)

Figure B.7: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.22b

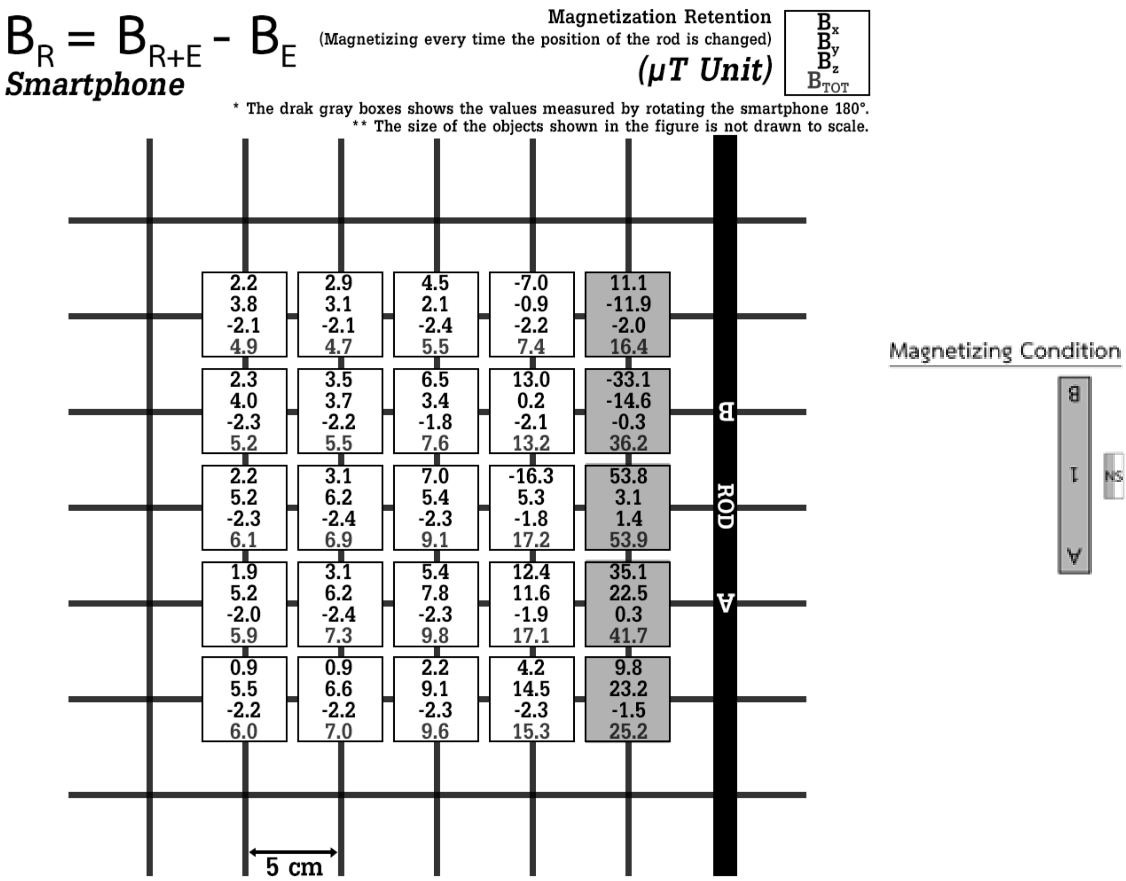


(a)

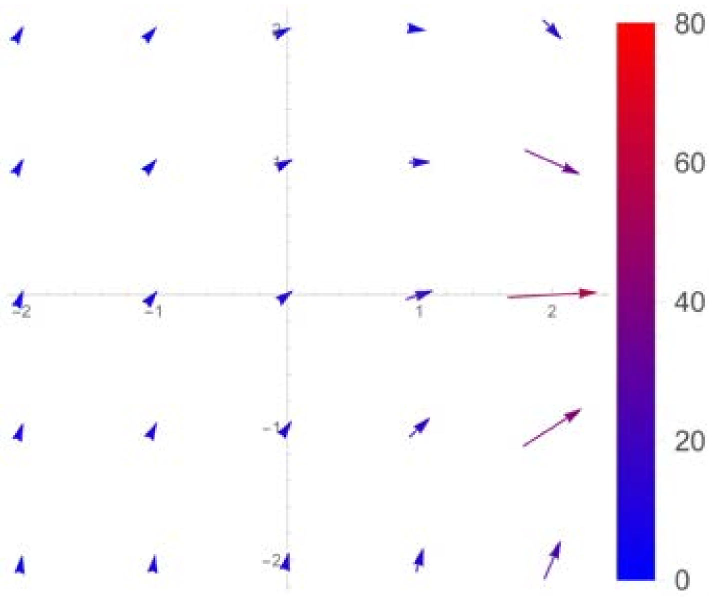


(b)

Figure B.8: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.22d



(a)



(b)

Figure B.9: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.22f

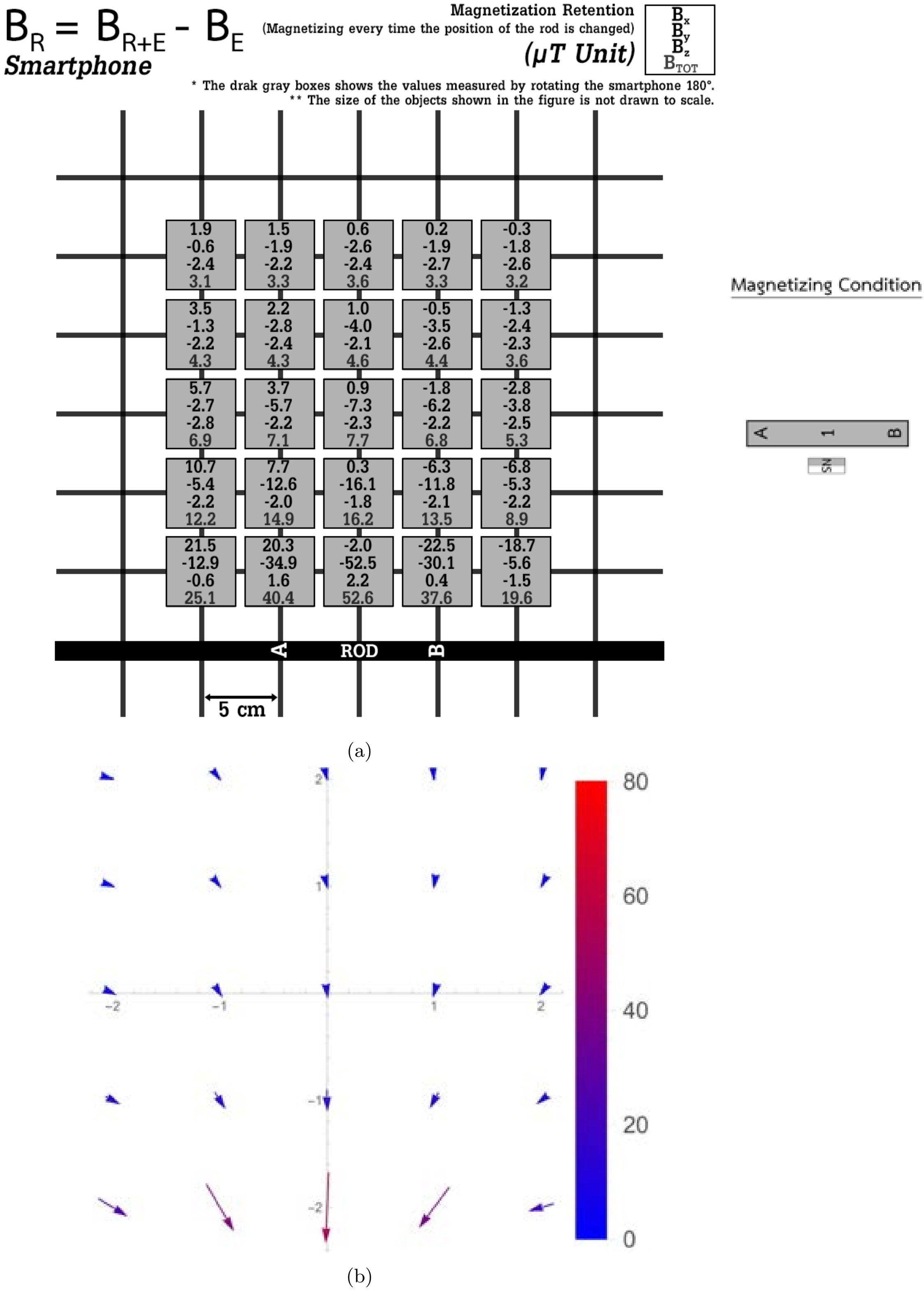


Figure B.10: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod of Magnetization Retention from Fig. 3.22h

All results in The Superposition of the Magnetic Field from Two Rods

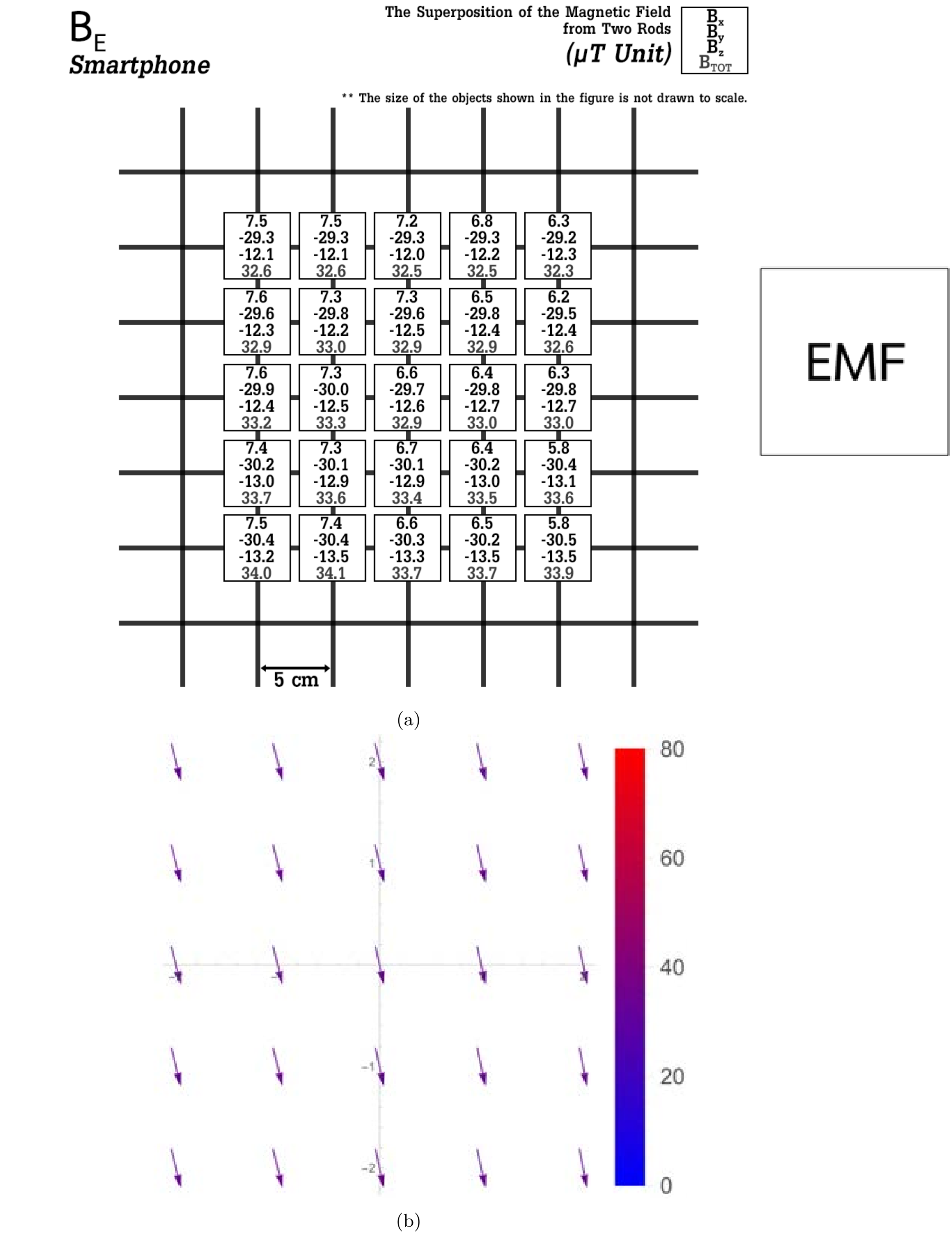
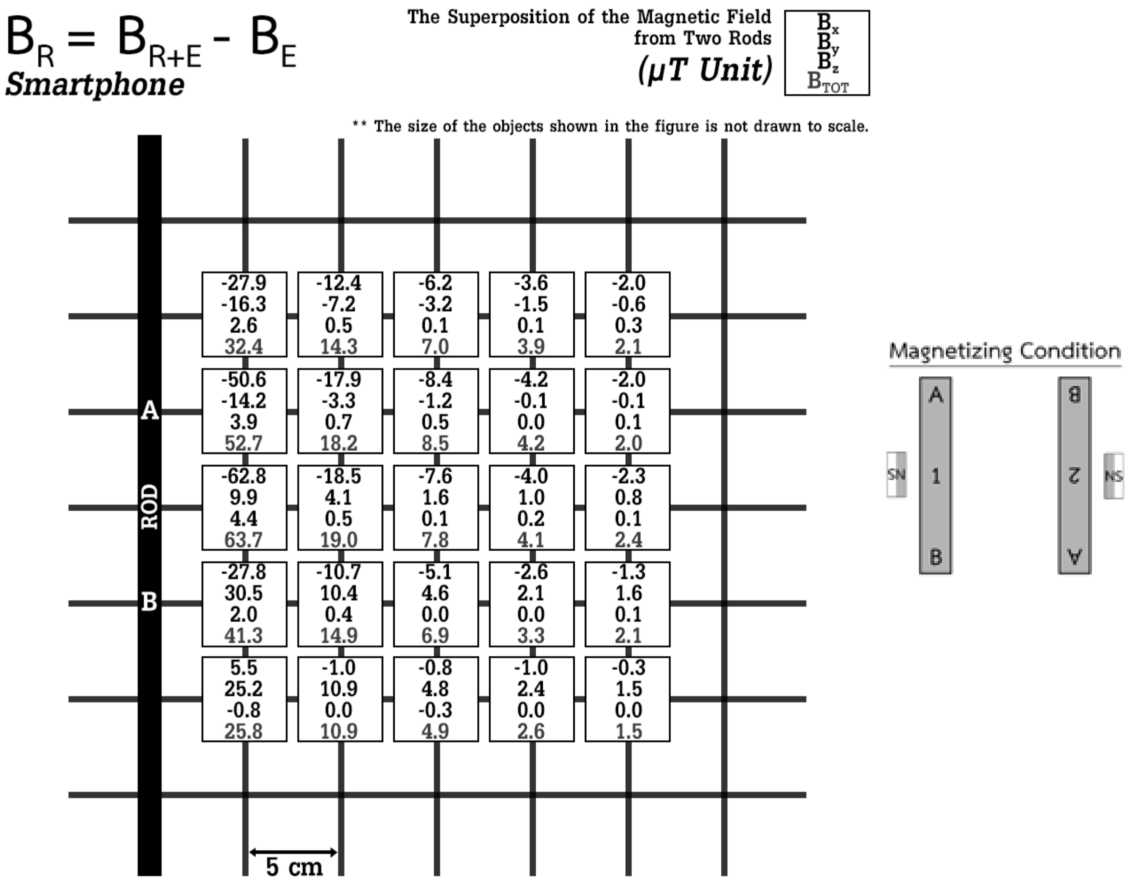
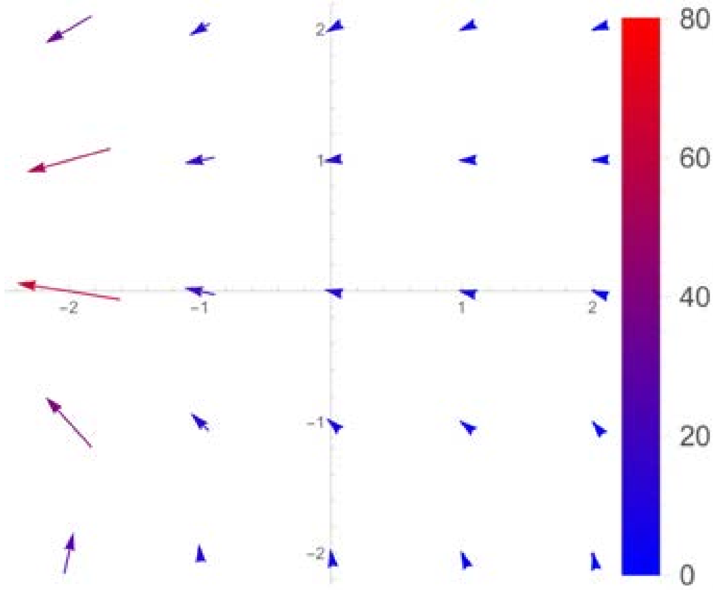


Figure B.11: (a) The values and (b) the vectors of the Earth's magnetic field of The Superposition of the Magnetic Field from Two Rods from Fig. 3.25

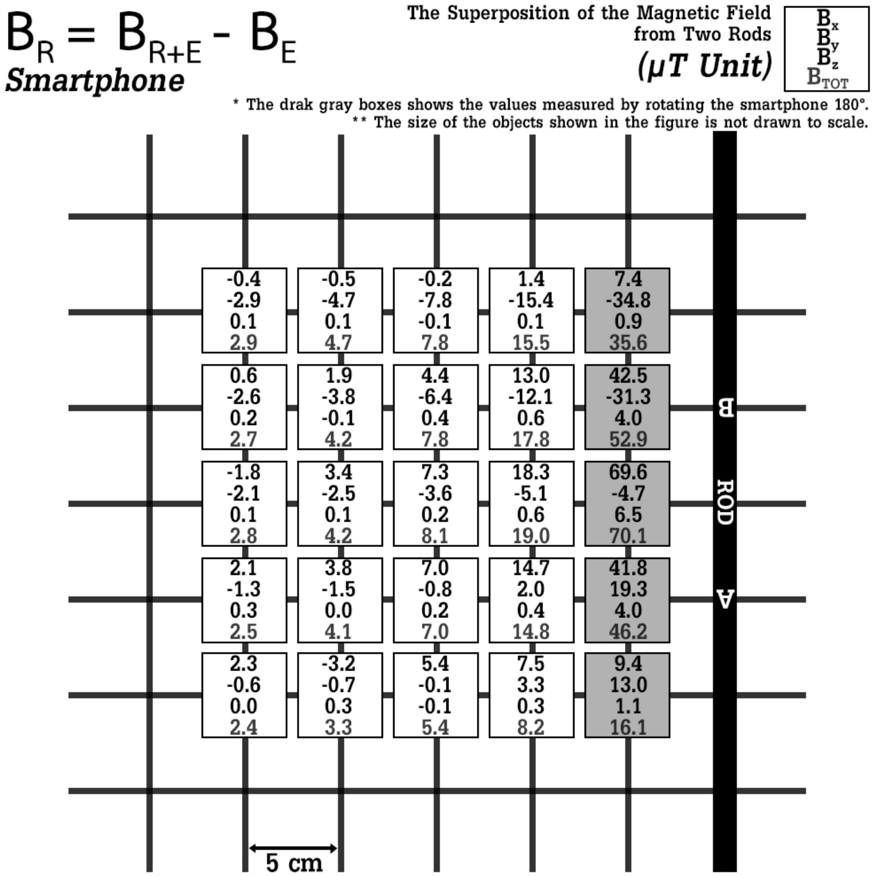


(a)

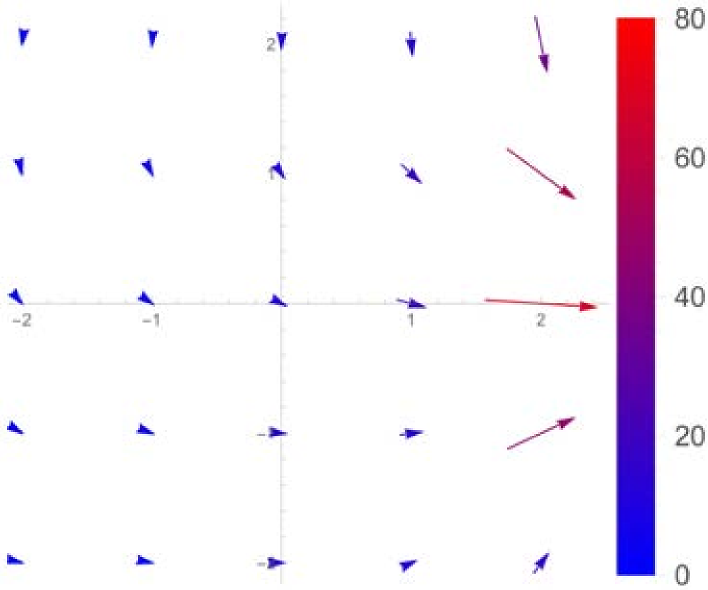


(b)

Figure B.12: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod The Superposition of the Magnetic Field from Two Rods from Fig. 3.25b

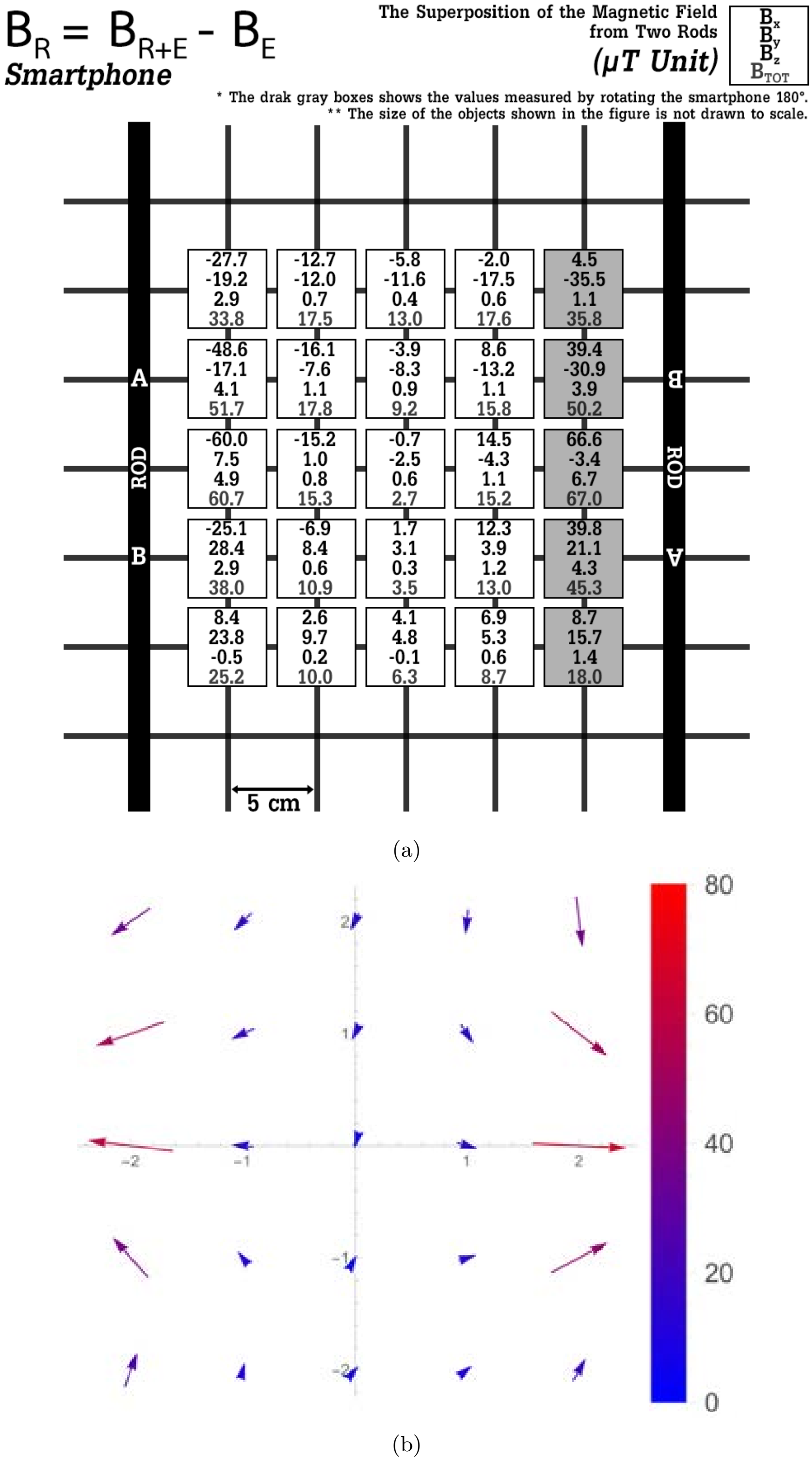


(a)



(b)

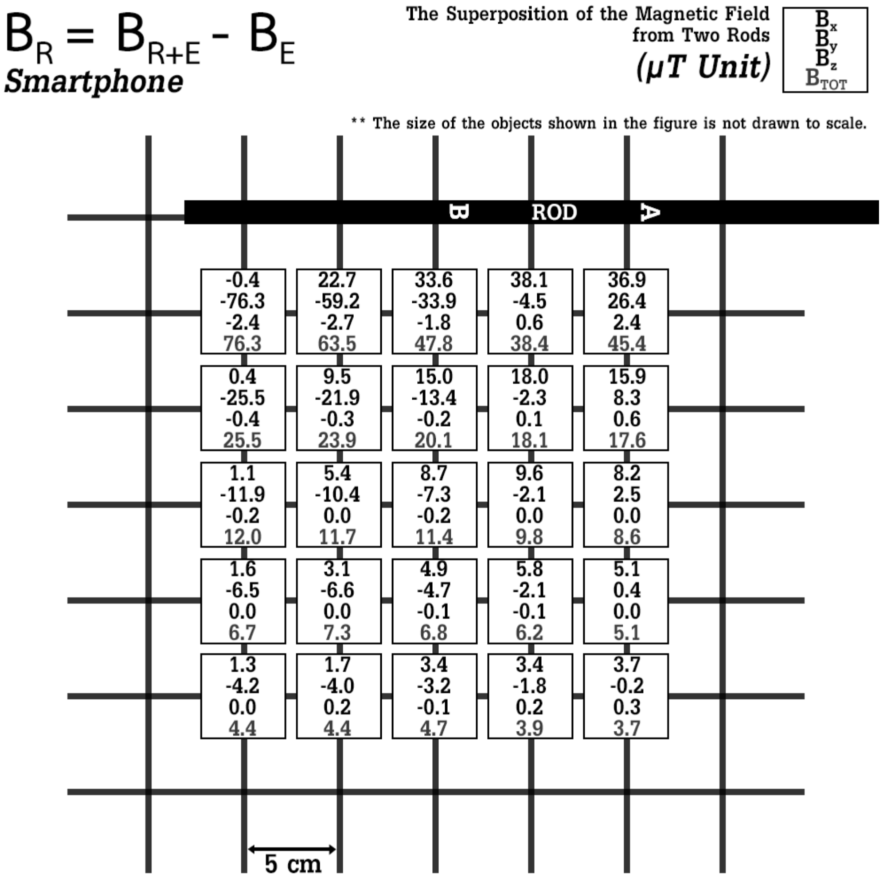
Figure B.13: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod The Superposition of the Magnetic Field from Two Rods from Fig. 3.25c



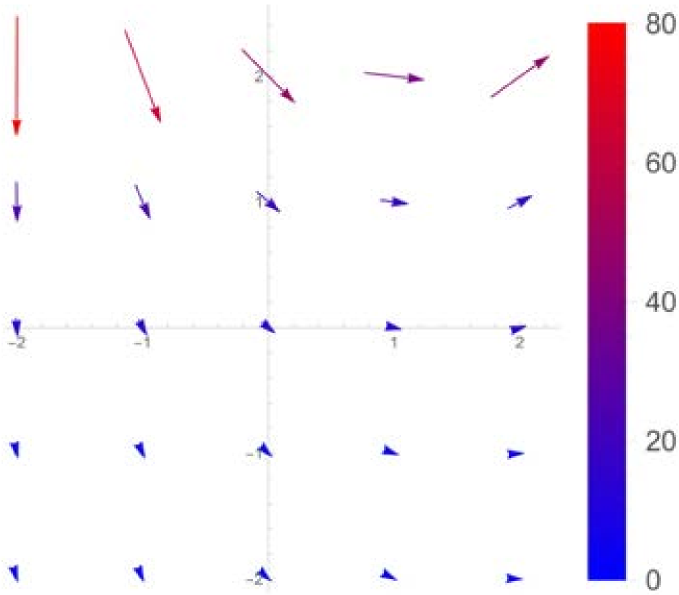
(a)

(b)

Figure B.14: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods The Superposition of the Magnetic Field from Two Rods from Fig. 3.25d

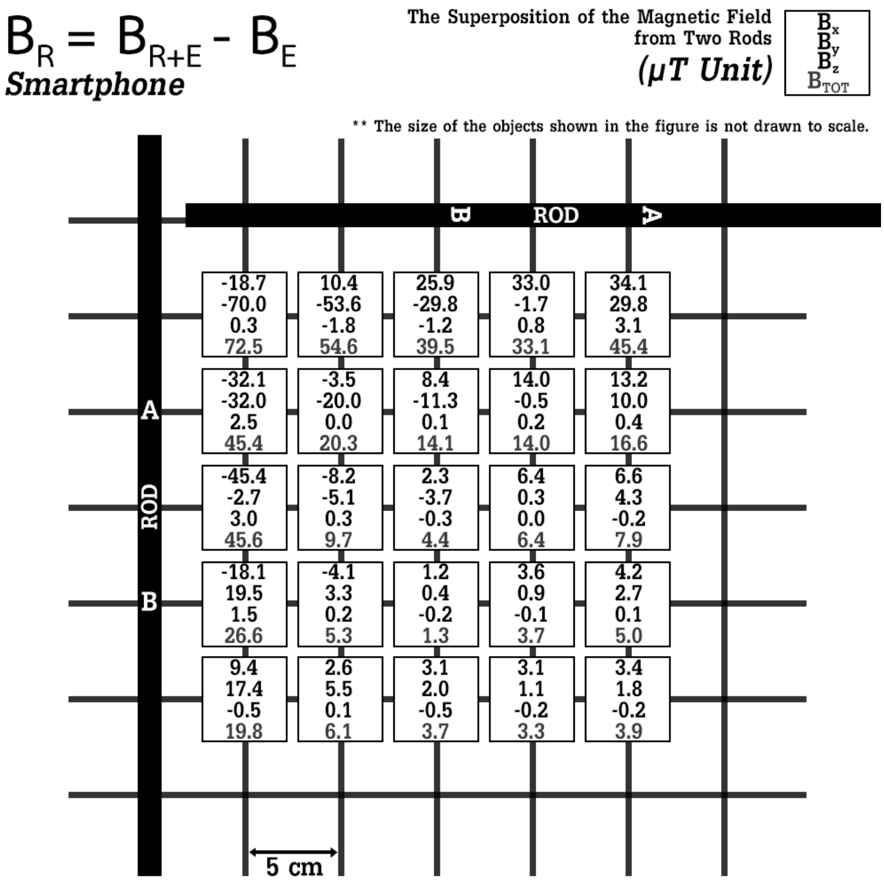


(a)

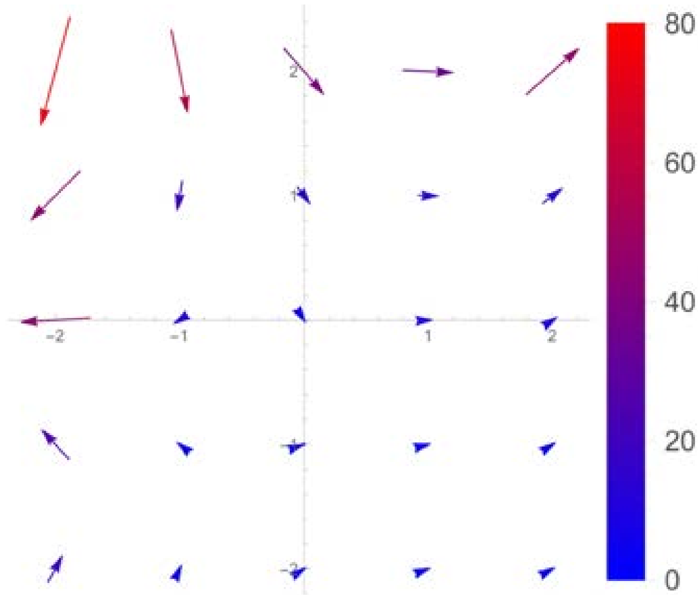


(b)

Figure B.15: (a) The values and (b) the vectors of the magnetic field due to the magnetized rod The Superposition of the Magnetic Field from Two Rods from Fig. 3.25e



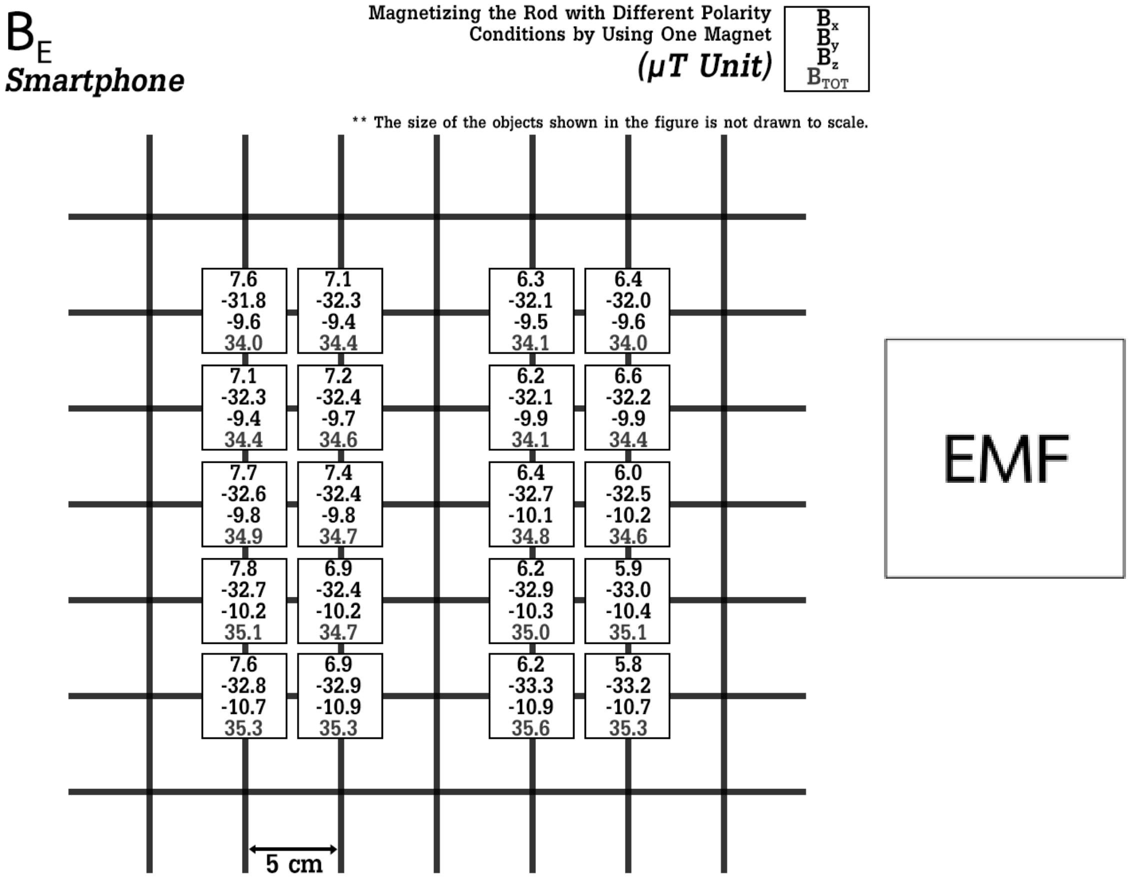
(a)



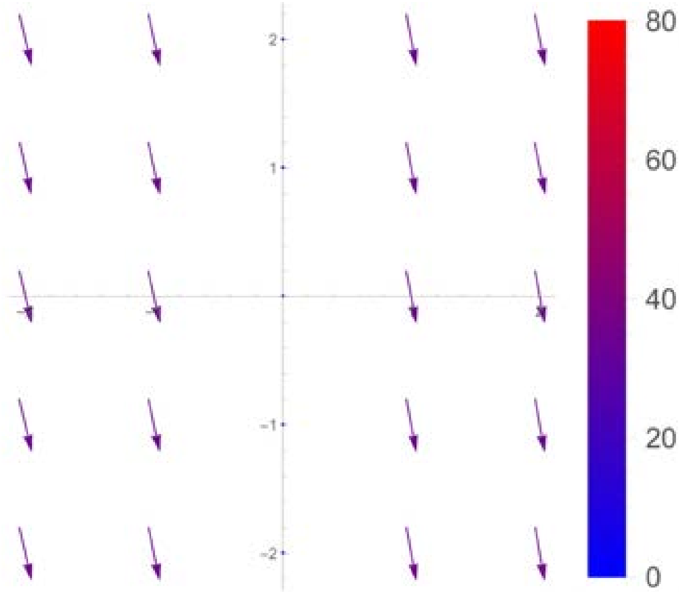
(b)

Figure B.16: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods The Superposition of the Magnetic Field from Two Rods from Fig. 3.25f

All results in Magnetizing the Rod with Different Polarity Conditions by Using One Magnet



(a)



(b)

Figure B.17: (a) The values and (b) the vectors of the Earth's magnetic field of Magnetizing the Rod with Different Polarity Conditions by Using One Magnet from Fig. 3.28

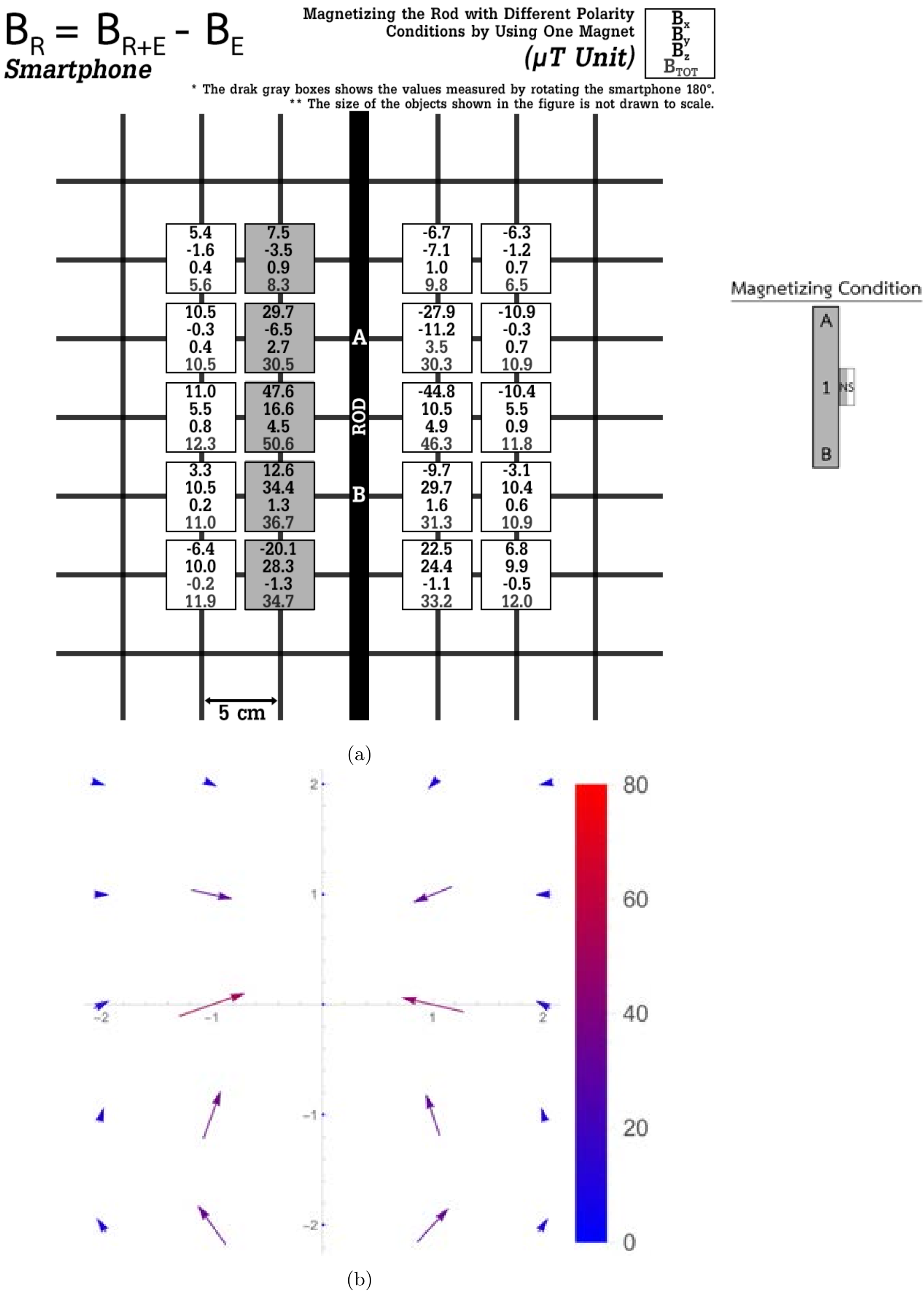
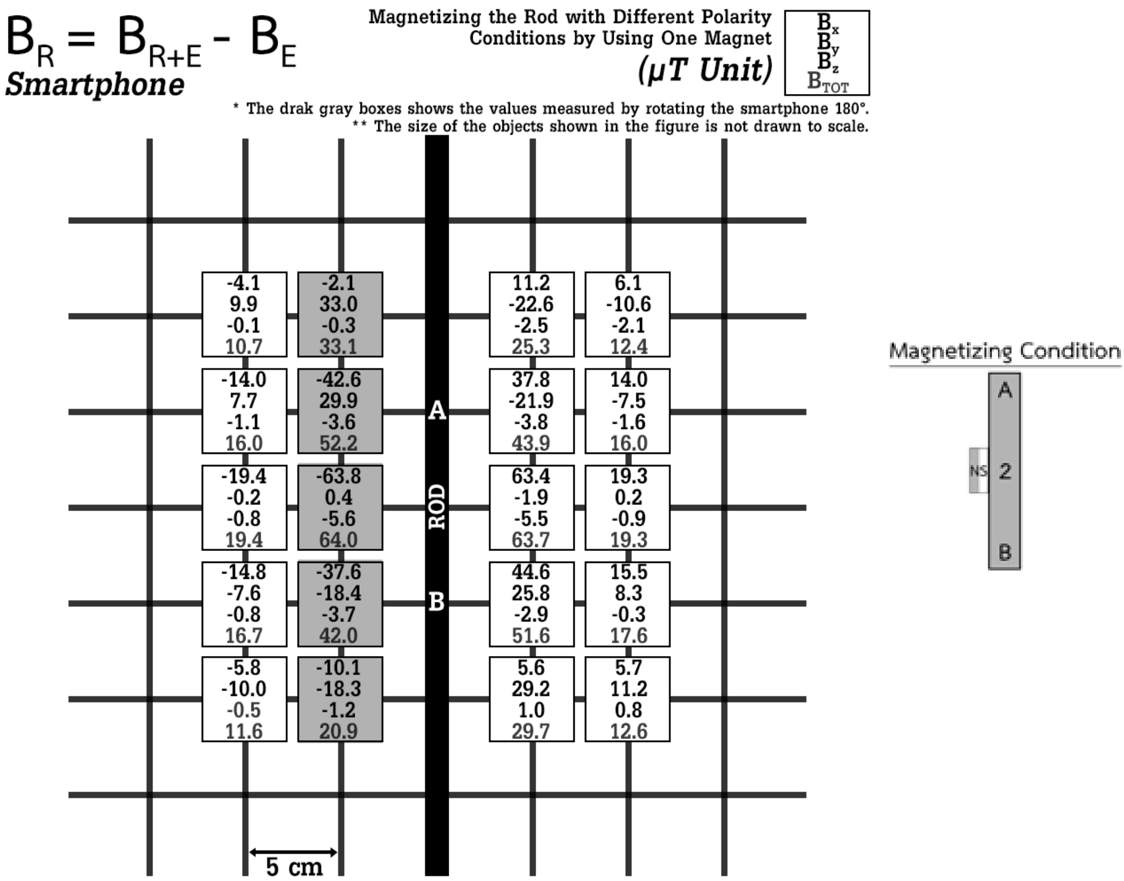
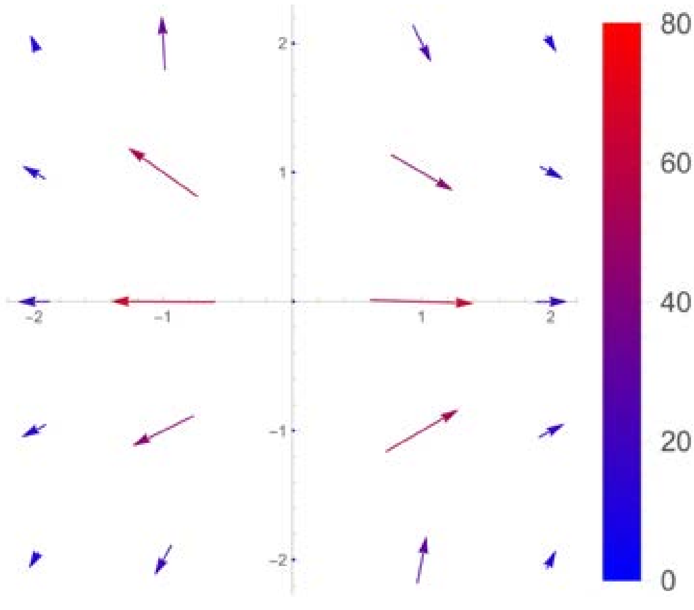


Figure B.18: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods Magnetizing the Rod with Different Polarity Conditions by Using One Magnet in condition from Fig. 3.28a after taking the magnet out

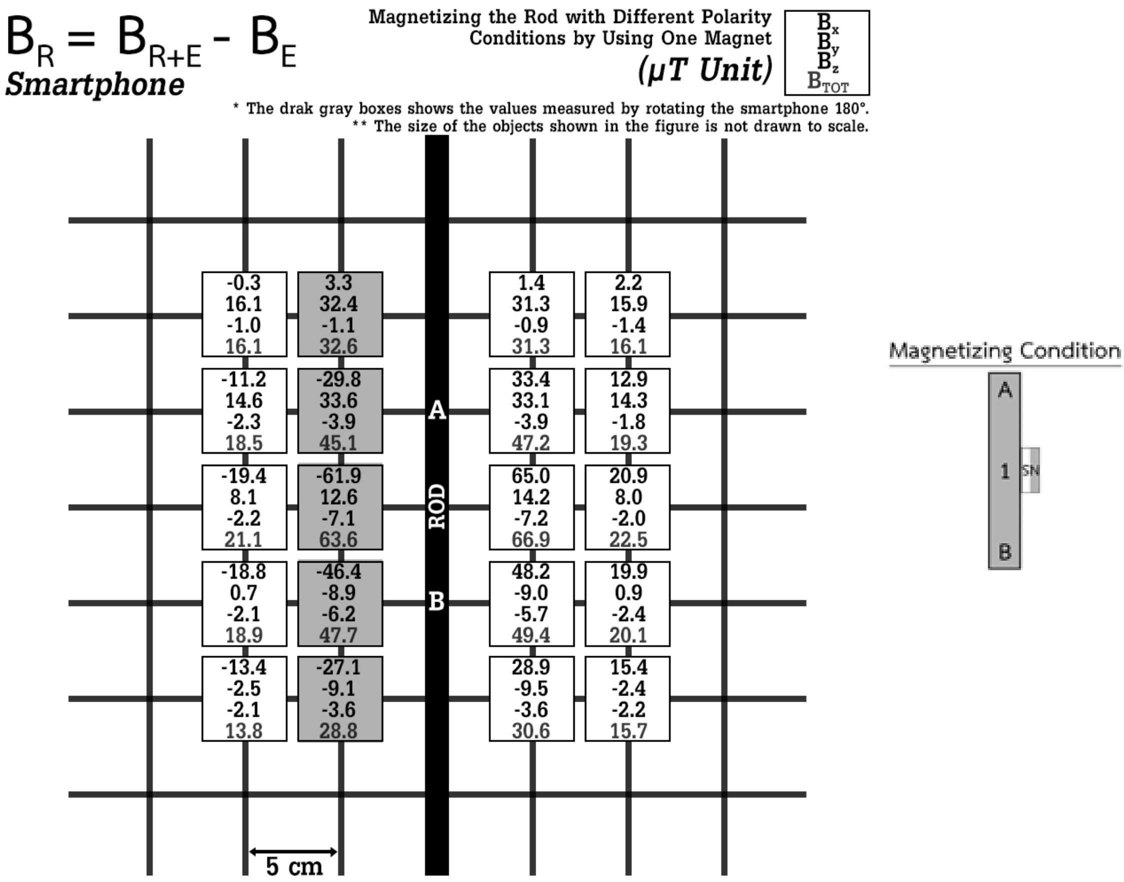


(a)

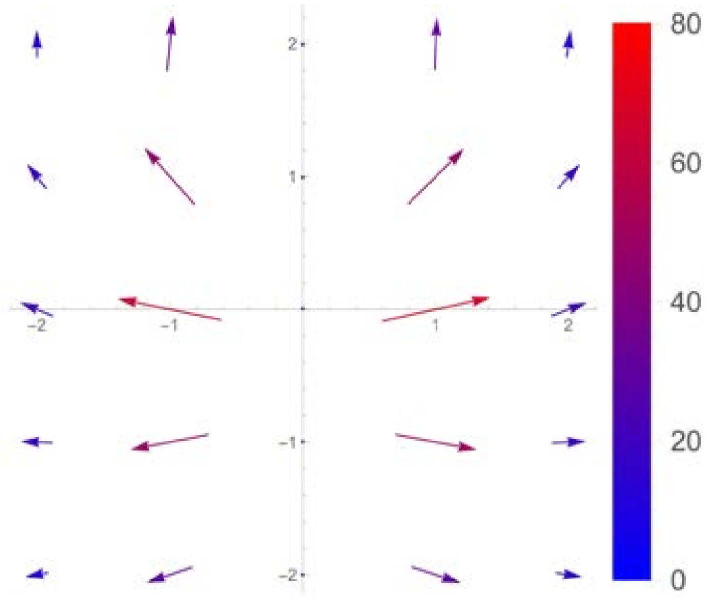


(b)

Figure B.19: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods Magnetizing the Rod with Different Polarity Conditions by Using One Magnet in condition from Fig. 3.28b after taking the magnet out

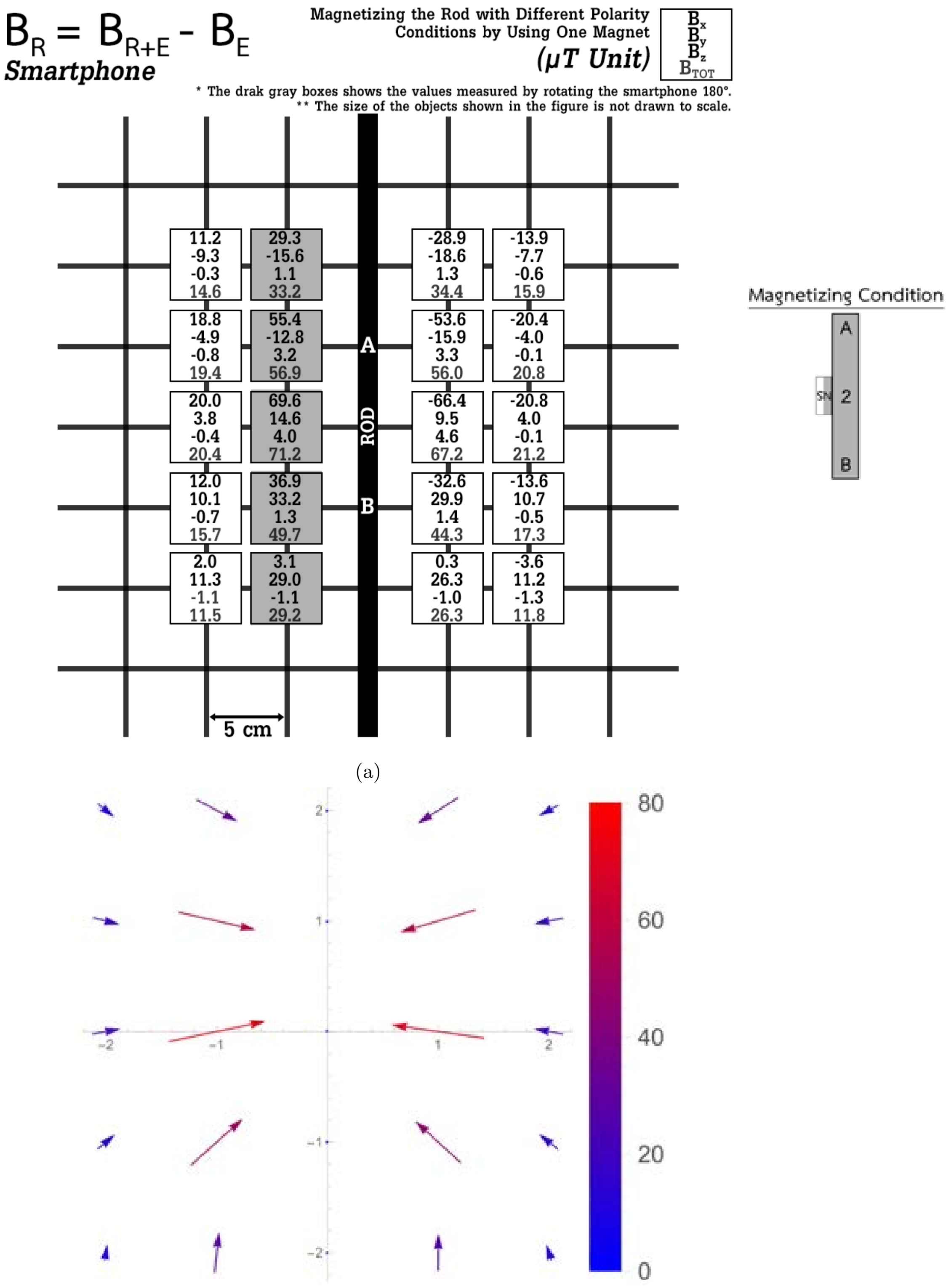


(a)



(b)

Figure B.20: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods Magnetizing the Rod with Different Polarity Conditions by Using One Magnet in condition from Fig. 3.28c after taking the magnet out

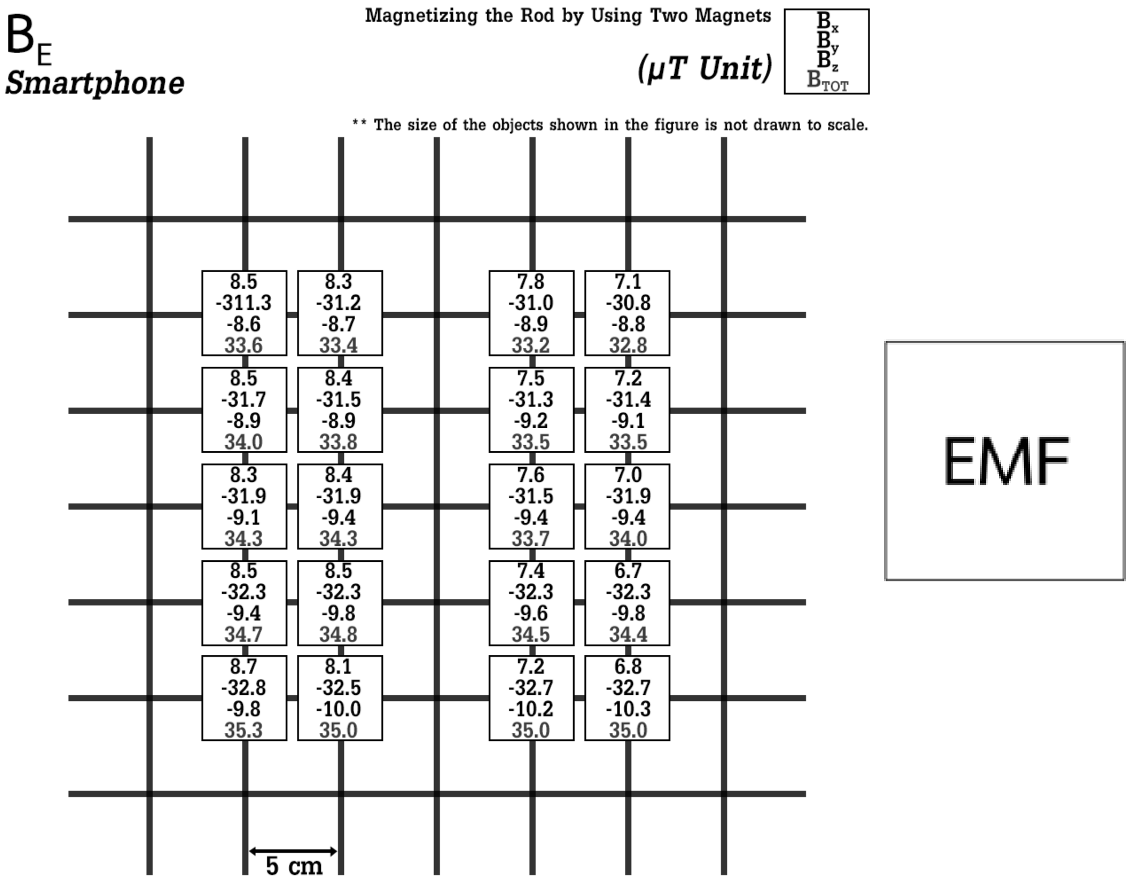


(a)

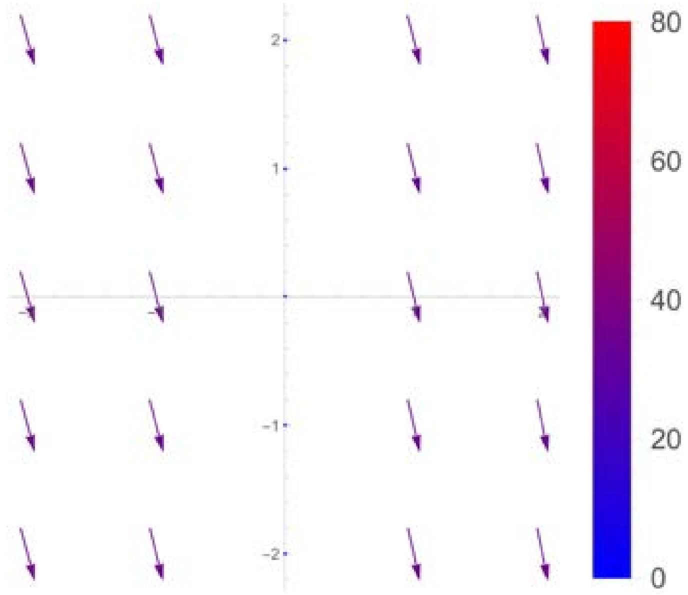
(b)

Figure B.21: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods Magnetizing the Rod with Different Polarity Conditions by Using One Magnet in condition from Fig. 3.28d after taking the magnet out

All results in Magnetizing the Rod by Using Two Magnets

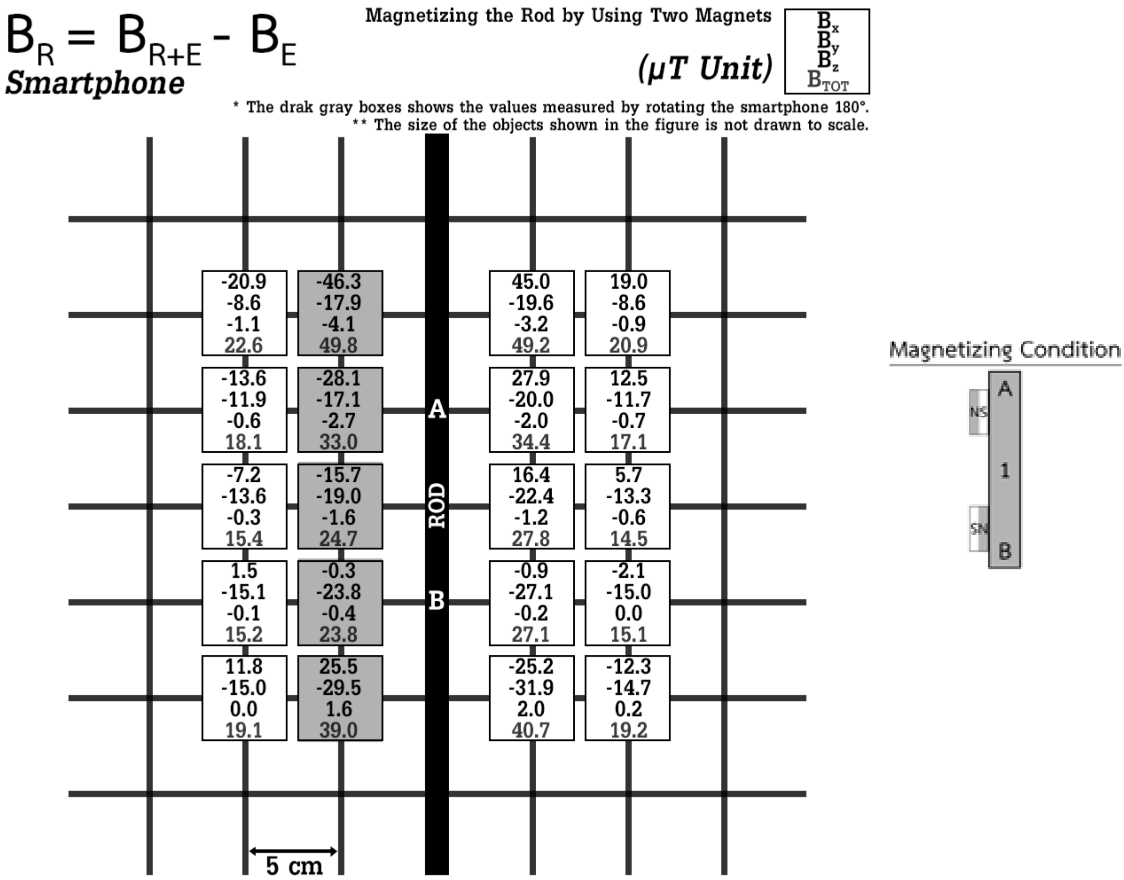


(a)

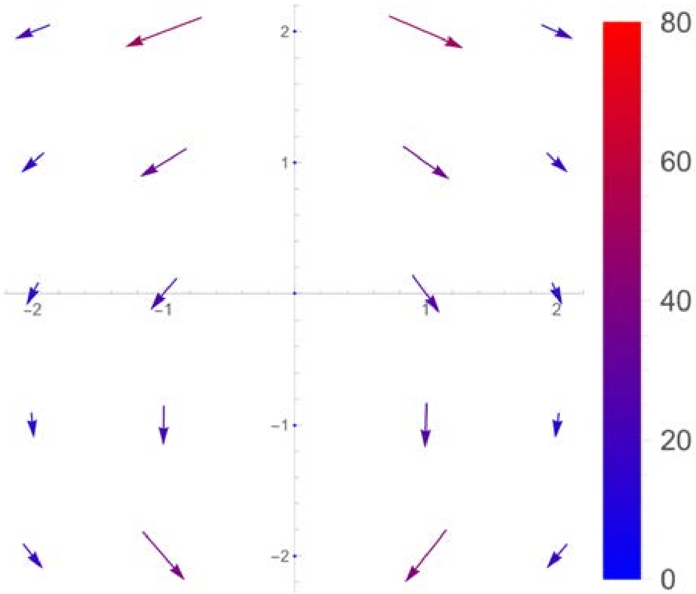


(b)

Figure B.22: (a) The values and (b) the vectors of the Earth's magnetic field of Magnetizing the Rod by Using Two Magnets from Fig. 3.33



(a)



(b)

Figure B.23: (a) The values and (b) the vectors of the magnetic field due to the magnetized rods Magnetizing the Rod by Using Two Magnets from Fig. 3.33b

References

[1] Drake, A. (2018). *Magnetic properties of materials*. Retrieved from http://www.kayelaby.npl.co.uk/general_physics/2_6/2_6_6.html

[2] Feynman, R. P., Leighton, R. B., & Sands, M. L. (1963). *The Feynman lectures on physics*. Reading, Mass: Addison-Wesley Pub. Co.

[3] Griffiths, D. J. (1999). *Introduction to electrodynamics*. Upper Saddle River, N.J: Prentice Hall.

[4] Hellesund, S. (2018). *Measuring Earth's Magnetic Field Using a Smartphone Magnetometer*. Retrieved from https://arxiv.org/abs/1901.00857

[5] IFIXIT. 2019. iPhone 7 Plus magnetic field sensor. [ONLINE] Available at: https://www.ifixit.com/Answers/View/497941/iPhone+7+Plus+magnetic+field+sensor. [Accessed 4 July 2019].

[6] K&J Magnetics. (2017). iPhone Magnetic Measurements. [ONLINE] Available at: https://www.kjmagnetics.com/blog.asp?p=iphone-fun. [Accessed 7 July 2019].

[7] RotoView. (2019). Magnetometer in Smartphones and Tablets. [ONLINE] Available at: https://www.rotoview.com/magnetometer.htm. [Accessed 4 July 2019].

[8] Yan, Y., Songwadhana, J., Khosonthongkee, K., Limphirat, A., & Payapol, T. (2018). EMF Shielding of One Set of Circular Coils with Slight Distortion. *Journal of Physics Conference Series*, 1144(1), 012022.doi:10.1088/1742-6596/1144/1/012022

[9] WIKIPEDIA. 2019. Magnetic domain. [ONLINE] Available at: https://en.wikipedia.org/wiki/Magnetic_domain. [Accessed 4 July 2019].