A tangent magnetometer to measure the earth magnetic field

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A simple and low cost experiment is proposed for measuring the earth magnetic field. Results obtained with the system described here are compared to measurements performed using a commercial magnetometer. The value for the earth magnetic field north-south component, $B_Z = 24.6 \pm 0.3\ \mu$T, obtained with our system is in good agreement with measurements recorded by the commercial magnetometer, which vary around $30 \pm 5\ \mu$T. This experiment is of easy implementation and great educational value in an undergraduate laboratory course of electricity and magnetism, because it provides an application of the fundamental physics to the measurement of an ubiquous and important phenomenon.

Keywords: Magnetometer; earth magnetic field.

Se propone un experimento simple y de bajo costo para medir el campo magnético terrestre. Los resultados obtenidos con el sistema descrito se comparan con mediciones desarrolladas usando un magnetómetro comercial. El valor de la componente norte-sur del campo magnético terrestre, $B_Z = 24.6\pm0.3\ \mu$T, obtenido con nuestro sistema concuerda bien con las mediciones desarrolladas con el magnetómetro comercial, las cuales oscilan alrededor de $30 \pm 5\ \mu$T. Este experimento es de fácil implementación y de gran valor formativo en un curso de laboratorio de electricidad y magnetismo a nivel licenciatura, debido a que enfatiza la aplicación de la física fundamental a la medición de un fenómeno importante y muy conocido.

Descriptores: Magnetómetro; campo magnético terrestre.

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1. Introduction

It is well known that some planetary bodies of the solar system such as the Earth produce a magnetic field. The earth magnetic field has a pattern resembling a large dipole inside the planet, with an intensity varying from 3×10^{-5} T (0.3 Gauss) at the equator to 7×10^{-5} T (0.7 Gauss) near the poles [1]. The north-south direction of the earth magnetic field is tilted 11^0 with respect to the earth rotation axis [2].

An important feature to emphasize is that the earth magnetic field shows continue changes at short rate, due to magnetic storms that increase the ionization of some shells of the ionosphere produced by very high energy solar electromagnetic radiation burst. There are also some evidences of long rate variation in the magnetic field intensity. At the beginning of the 20th century, the scientists discovered one of the most surprising characteristics of the earth magnetic field, that is, the direction of polarity gradually changes with time [3].

The experiment described here was assembled because although most of the undergraduate students have knowledge of the physical aspects concerning the earth magnetic field, most of them are not acquainted with the experimental techniques to measure it, despite the strength of this field is quite enough for allowing an easy measurement.

In this experiment a low cost set-up is used, based on a magnetic needle and a set of simple electrical devices to measure the earth magnetic field. Finally, the results are compared to that obtained by using a commercial magnetometer (Magnetic Instrumentation Gaussmeter model 2100).

This experiment was performed as part of an undergraduate laboratory course of electricity and magnetism and proved to be of great educational value.

2. Theory

It is possible to measure the earth magnetic field by using a simple circuit. Applying the Biot-Savart law, the magnitude of the magnetic field B produced by a coil of N turns and radius R, in which a current I flows, is given by the expression

$$B(z) = \frac{\mu_0 NI}{2} \frac{R^2}{(R^2 + z^2)^{3/2}} \tag{1}$$

where z is the distance along the axis of the coil.

A simple way for measuring magnetic fields, *e.g.* the earth magnetic field, is using a magnetometer consisting in a simple coil and a compass. By using the fact that the compass in a magnetic field will orient in the direction of the resultant field, and determining the angle formed by the needle with the direction of the field under study, it is possible to obtain its value. This procedure is shown in Fig. 1, where B_E represents the magnetic field to be measured, B_C is the magnetic field produced by the coil of the magnetometer, and θ represents the angle formed by the needle of the magnetometer with respect to the direction of the field to be measured.

Therefore, from the simple relation

$$\tan\theta = \frac{B_C}{B_E}, \tag{2}$$

the earth magnetic field B_E can be obtained. B_C is calculated from Eq. (1). Because of the value of the magnetic field

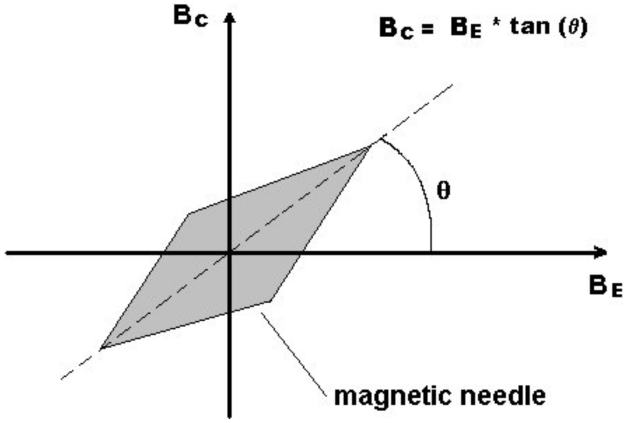

FIGURE 1. A schematic diagram of the principle of the tangent magnetometer. $\mathbf{B}_C$ and $\mathbf{B}_E$ represent the magnetic fields of both the coil and the earth. By measuring the angle of the magnetic needle it is possible to determine $\mathbf{B}_E$.

under study is obtained through the computation of the tangent function, this kind of device is called *tangent magnetometer*. However, due to the fact that the tangent function is extremely non-linear, this device has sensibility to detect fields only of the order of the earth magnetic field. Also, the inertial effects of the compass only allow the detection of static fields.

3. Material and methods

The system developed consisted of a simple RL circuit with a dc variable voltage power supply and an amperimeter connected in series. A schematic diagram of the system is shown in Fig. 2. The coil has 6.75 cm in radius and 320 turns, is made of 0.75 mm in diameter magnetic wire, which allows a maximum current of 2 A. The resistance was a commercial carbon one of 39 Ω and 0.5 Watts and was just to limit the current through the circuit.

Two photographs of the set-up used in the experiment are shown in Figs. 3 and 4, in two different positions to clearly show all of the details of the arrangement. As can be seen from the photographs, the coil was situated initially with its

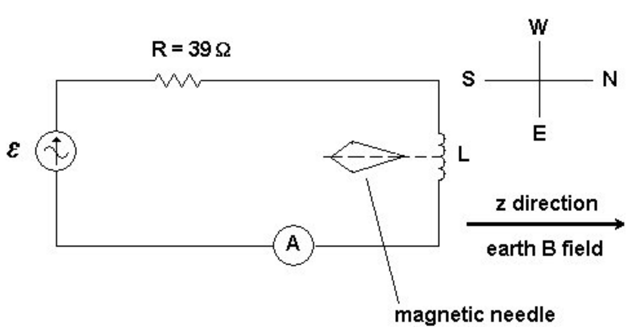

FIGURE 2. RL circuit layout employed in the experiment. The magnetic needle is oriented with its axis perpendicular to the axis of the coil, in the direction south-north of the earth magnetic field. A dc variable power source supplies a voltage from 0.1 – 3.0 V. An amperimeter in series register the current through the circuit.

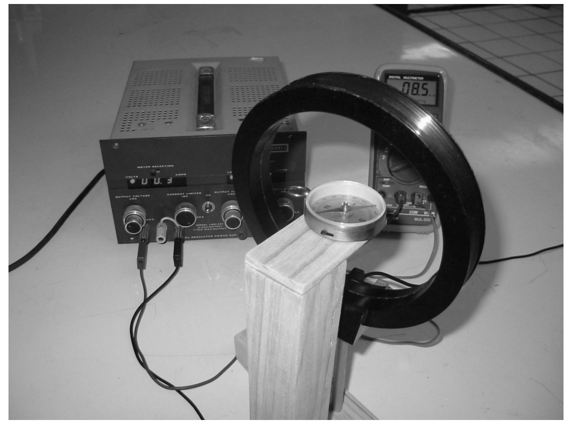

FIGURE 3. A first photograph of the experimental set-up used in this project.

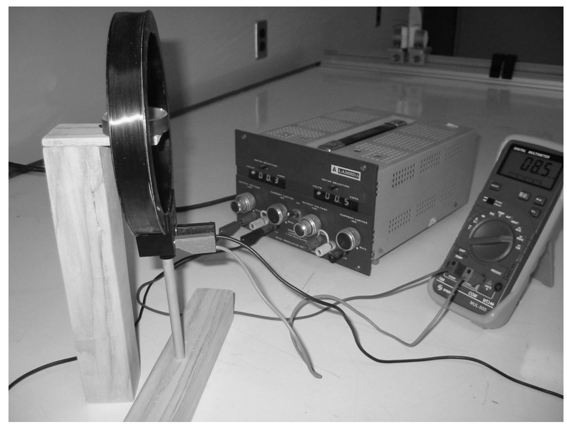

FIGURE 4. A second photograph of the experimental set-up, in a different position as in Fig. 3, to clearly show all of the details of the arrangement.

longitudinal axis perpendicular to the direction north-south of the local (21°07'22" N and 101°41'00" W) earth magnetic field (z direction). The alignment of the coil was obtained by using a magnetic needle. Then the magnetic needle was fixed on a non-magnetic base (wood) to avoid magnetic disturbances, and situated in the center of the coil ($z = 0$) and parallel to the z direction of the earth magnetic field. With the experimental arrangement in this condition a current was allowed to circulate through the circuit, producing a deflection in the magnetic needle according to Eq. (2).

The voltage produced by a dc regulated power supply (0–20 V Lambda power supply, model LQD-421) was swept from 0.1 to 3.0 Volts. Then, the current circulating through the RL circuit and the angle of deflection of the magnetic needle were measured for each value of voltage by a digital multimeter (model Fluke) and the magnetic needle itself, respectively. With these values, and using Eqs. (1) and (2), the magnitude of the local earth magnetic field was calculated. The experimental results are shown in Table I and Fig. 5. The slope of Fig. 5 represents the value of the local earth magnetic field in the z direction.

TABLE I. Values recorded for the current and the angle for the three different experiments, for each voltage applied.

Voltage (V)	**i** (mA) (Exp. #1)	**Angle** (°) (Exp. #1)	**i** (mA) (Exp. #2)	**Angle** (°) (Exp. #2)	**i** (mA) (Exp. #3)	**Angle** (°) (Exp. #3)
0.1			1.9	14	1.7	12
0.2			2.6	19	3.4	22
0.3			5.3	35	4.9	30
0.4			6.2	38	7.3	40
0.5	7.2	40	9.6	50	9.9	48
0.6	8.8	45	10.8	52	12.5	54
0.7	10.0	49	13.0	60	13.8	56
0.8	11.2	52	14.8	64	15.3	58
0.9	13.7	57	16.2	66	17.9	62
1.0	14.6	59	18.7	69	20.2	66
1.5	22.5	70				
2.0	30.0	75				
2.5	38.6	78				
3.0	46.4	80				

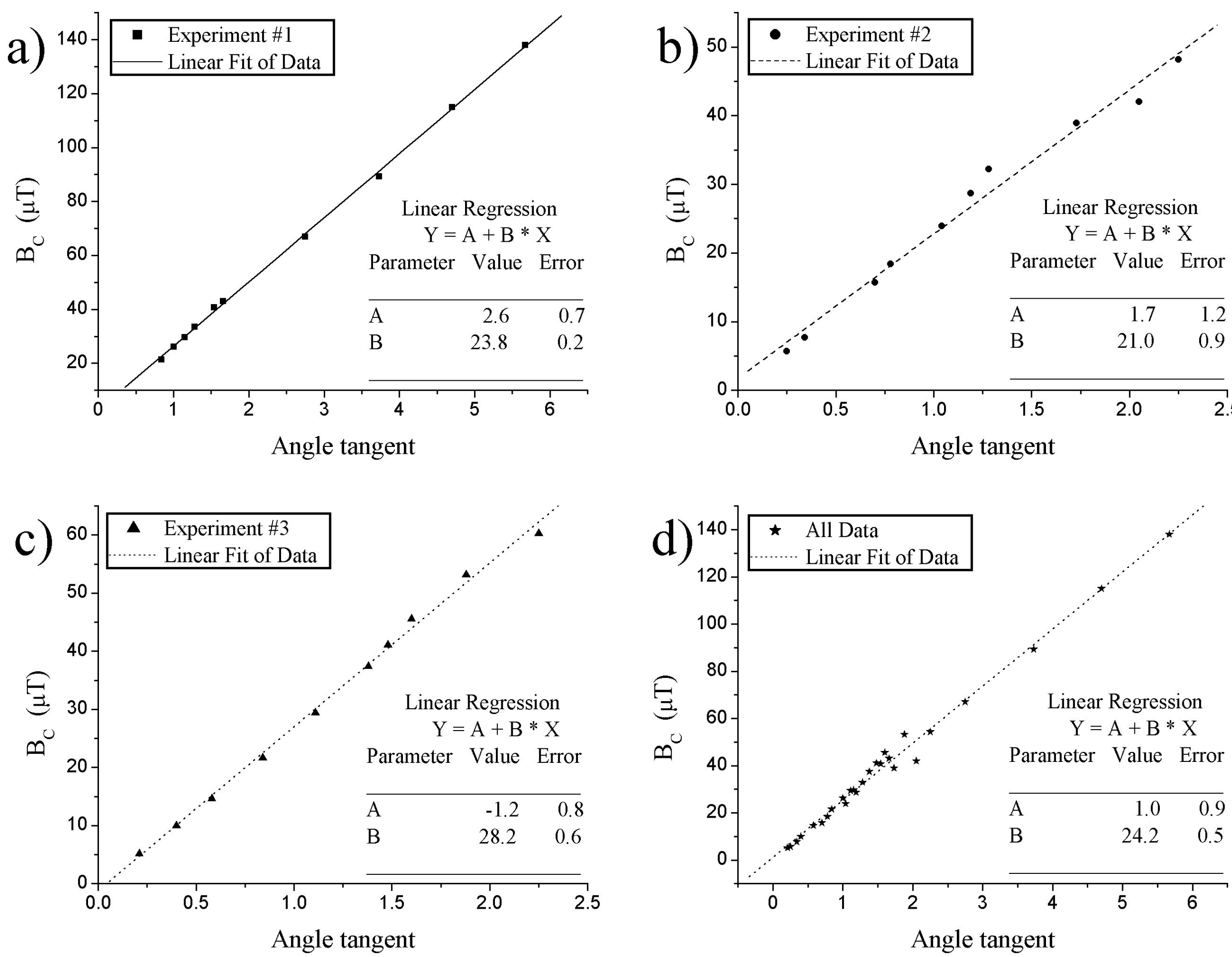

FIGURE 5. Results of (a) the first, (b) the second and (c) the third experiment, respectively. The slopes of the linear fits give the values of the local earth B_z field. (d) All of the data together.

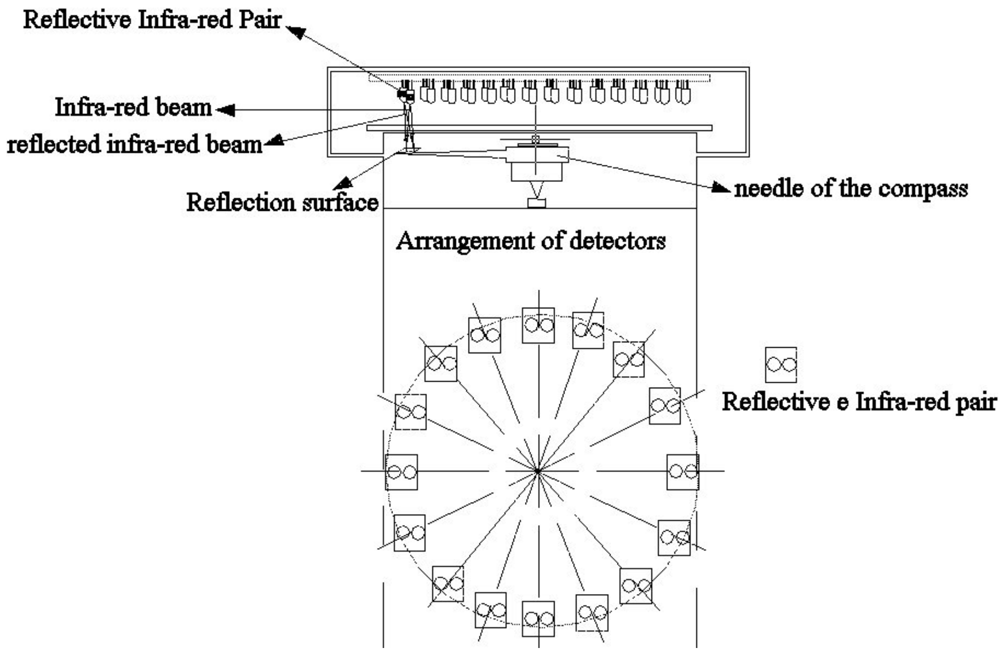

FIGURE 6. A system composed of a set of photodiodes in a circular arrangement, proposed as an alternative to measure the deflection angle on the needle of the compass. Depending on the photodiode activated the position of the needle is indicated.

On the other hand, it is important to strength that to avoid magnetic interferences, the whole experimental set-up must be mounted on a non-magnetic base. In this experiment a wood table without metallic screws was used.

Finally, we describe some general features concerning a possible computerized version of this experiment. To computerize the experimental set-up the voltage applied to the RL circuit can be easily controlled from the computer. Also, most of digital multimeters have a RS232 interface, which allows computerized acquisition of the current throughout the circuit. On the other hand, the automatic registration of the deflection angle of the needle of the compass is probably the most problematic thing in such project. As shown in Fig. 6, a system composed of a set of photodiodes is proposed as an alternative. This detection system is formed by a set of photodiodes in a circular arrangement distributed according to the required precision. The photodiodes work by emitting an infra-red beam which is reflected on the surface of the needle and then received again by the photodetector. Depending on the photodiode activated, the position of the needle is indicated.

4. Results and conclusions

The values of the magnetic field of the coil B_c are shown in Fig. 5, calculated from Eq. (1), as function of the tangent of θ, for each value of voltage. In Figs. 5a, 5b, and 5c are shown the measurements of the earth magnetic field performed in three different experiments during a period of about one month. For each experiment the set-up was completely dismounted and mounted again. Figure 5d shows all the data obtained, demonstrating a good reproducibility. The dots represent the experimental values while the straight line is a linear fit to the data. A function of the form $y = A + Bx$ was tried. The slopes obtained in Figs. 5a, 5b, and 5c were $B = 23.8 \pm 0.3$ μT, 21.0 ± 0.9 μT, and 28.2 ± 0.6 μT, respectively, which gives the local earth magnetic field in the z direction with an average of 24.3 ± 0.6 μT. This value agrees well with the fit to the whole data, 24.2 ± 0.5 μT, shown in Fig. 5d.

On the other hand, Table II shows the mean values of current and angle measured for each voltage applied to the coil. The calculated mean values for the coil $\mathbf{B}_C$ field is also shown. However, as can be seen from Table I there are discrepancies in the values registered for the current through the coil and the angle formed by the magnetic needle for the same voltage. These systematic uncertainties are shown in Table II and are associated, mainly, to the uncertainty and instability of the variable power supply and the error in the measurement of the angle. Figure 7 shows a plot of the magnetic field of the coil as function of the tangent of θ, using the values in Table II, including the systematic uncertainties. As in the previous data, a linear fit of the form $y = A + Bx$ was tried, giving a slope of $B = 24.6 \pm 0.3$ μT.

The value obtained for the local earth magnetic field $\mathrm{B}_z = 24.6 \pm 0.3$ μT, using this simple tangent magnetometer has been compared with that obtained by using a commercial magnetometer (Magnetic Instrumentation Gaussmeter model 2100), whose measurement of the z component of the local earth magnetic field fluctuates around 30 μT. On the other

TABLE II. Mean values for the current and the angle obtained combining the three different experiments, for each voltage applied. The calculated coil $\mathbf{B}_C$ field is also shown.

Voltage (V)	**i** (mA)	**Angle** (°)	$\mathbf{B}_C$ (μT)
0.1	1.8 ± 0.1	13 ± 1	5.4 ± 0.3
0.2	3.0 ± 0.4	21 ± 2	8.9 ± 1.2
0.3	5.1 ± 0.2	33 ± 3	15.2 ± 0.6
0.4	6.8 ± 0.6	39 ± 1	20.3 ± 1.8
0.5	8.9 ± 1.1	46 ± 4	26.5 ± 3.3
0.6	10.7 ± 1.3	50 ± 4	31.9 ± 3.9
0.7	12.4 ± 1.6	55 ± 4	37.0 ± 4.7
0.8	13.8 ± 1.7	58 ± 4	41.1 ± 5.1
0.9	15.9 ± 1.5	62 ± 3	47.4 ± 4.5
1.0	17.8 ± 2.2	65 ± 4	53.0 ± 6.6
1.5	22.5 ± 2.3	70 ± 4	67.1 ± 6.8
2.0	30.0 ± 2.1	75 ± 4	89.4 ± 6.3
2.5	38.6 ± 2.4	78 ± 4	115.0 ± 7.2
3.0	46.4 ± 2.8	80 ± 4	138.3 ± 8.3

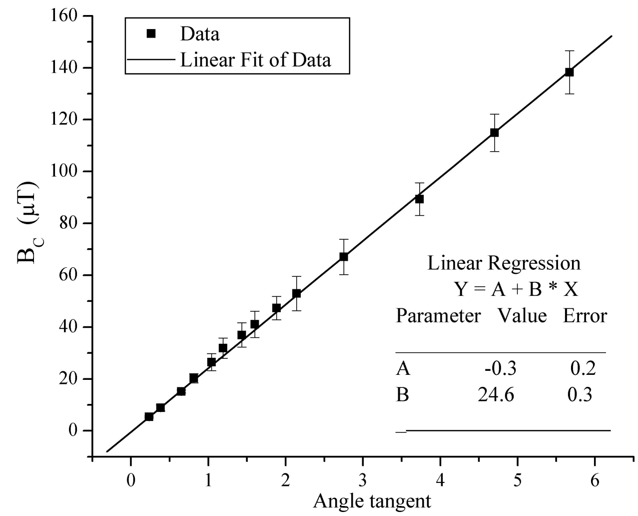

FIGURE 7. Results of the three experiments together. The uncertainties take into account the systematic errors in the experiment. The value obtained for the local earth B_z field, 24.6 ± 0.3 μT, agrees very well with the expected value.

hand, it is important to emphasize that the earth magnetic field not only vary with the latitude, but also variations in time are observed. Using the commercial gaussmeter fluctuations have been observed sometimes in the local earth magnetic field down to 20 μT up to 40 μT. A comparison of these values with that of the experiment described here shows that, despite being a simple device, the tangent magnetometer provides measurements of the earth magnetic field in good agreement with the expected values.

Finally, the magnetometer developed is a very low cost device, with enough accuracy to measure fields of the order of the earth field and has demonstrated to be enough simple to exhibit the physics involved in the experiment and of easy implementation in a laboratory course of electricity and magnetism at undergraduate level.

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