Experiment 5B Biot-Savart's Experiment

Navrit Bal - njsb2 - 12958319

01/04/14

Contents

0.1 Introduction

This experiment explores how magnetic fields produced by varying shapes of conductors (straight lines and loops) changes over various displacements (axial, radial and tangential). There is a special case of the 2 Helmholtz coils which are used to create a near homogeneous magnetic field which are explored at the end.

0.2 Objectives

1. Measure magnetic field due to current carrying conductors including loops
2. Measure axial magnetic field of an air solenoid
3. Measure radial and tangential magnetic field of a coil
4. Measure axial magnetic field of a pair of Helmholtz coils

0.3 Apparatus and method

The method in the lab script was followed exactly unless otherwise explicitly mentioned. Please refer to the lab script for further details where necessary.

0.4 Results

All symbols used in this report match the convention of the lab report unless otherwise explicitly stated for ease of matching. All error estimations have been graphically included, however due to the scale, they are not necessarily visible but are there. For example, with every graph with the magnetic field strength measured, the error in that measurement was universally $\pm 0.03mT$ and is therefore often relatively much smaller than the variation in the measurements. The errors on the measured data are all due to the precision of the equipment in use and will be discussed later on. This is with the exception of the magnetic field strength which also has an amount of random error which cannot be reasonably quantified and so has not been. This is typically the reason why some of the results are slightly outside of the expected range. All blue lines are the measured data which will match the corresponding data in the lab book, the red lines are all the predicted values from the various corresponding equations.

0.4.1 Measure magnetic field due to current carrying conductors including loops

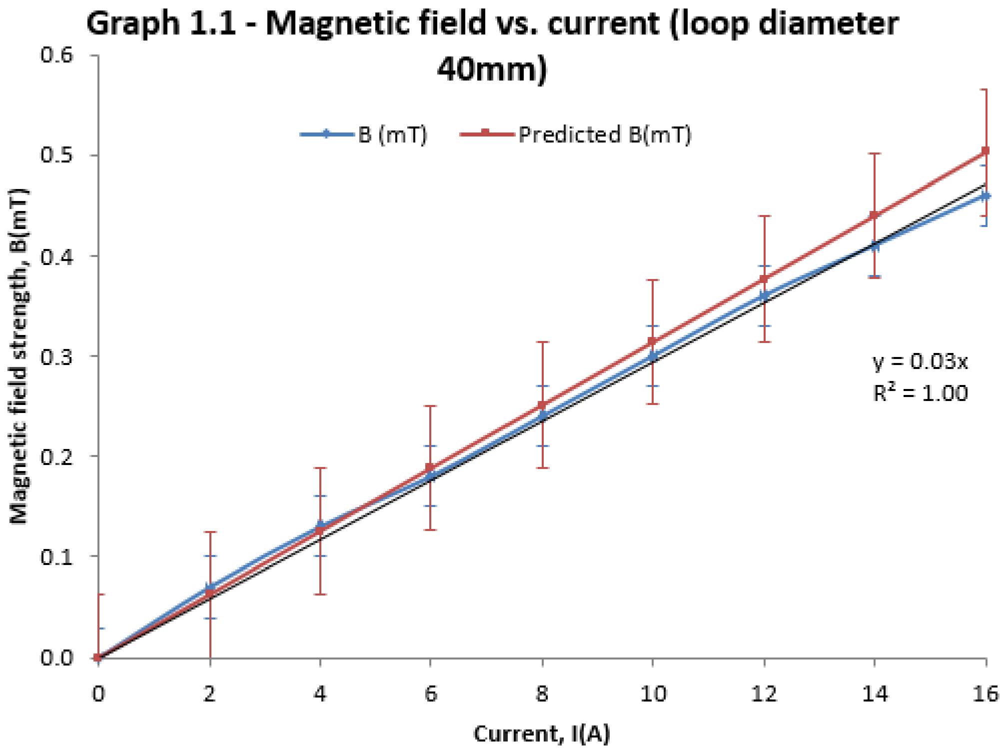

Figure 1:
Shows the magnetic field strength due to a varying current (0-16A) carrying loop of diameter 40mm. This data shows a very high degree of confidence to the fitted line which can be seen from the $R^2 = 1.00$ value. The error bounds from the predicted values encompass all of the data. This shows a linear relationship between axial magnetic field strength and current in a 40mm loop $B = 0.03I$. See 0.5.1 for the error estimation calculations.

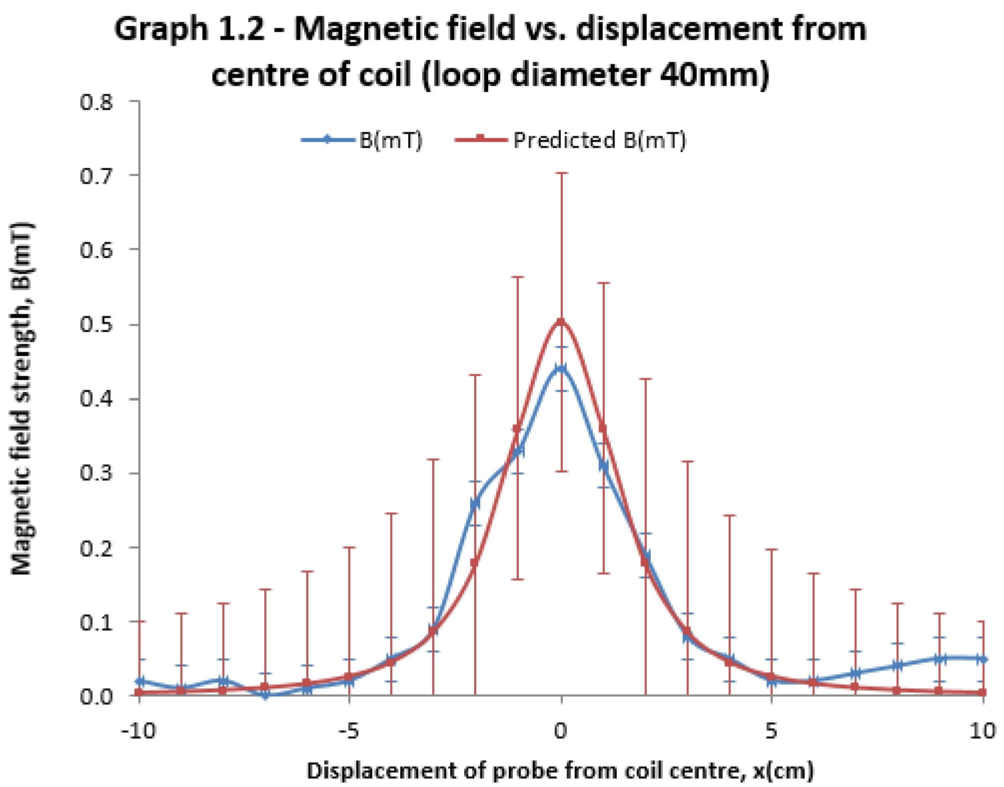

Figure 2:
Shows the magnetic field strength as a function of the displacement from the centre of the coil with a loop diameter 40mm. The error bounds from the predicted values encompass all of the data. Current $=16.00 \pm 0.05A$. This shows a normal distribution shape around the centre of the loop, the magnetic field increases rapidly as it approaches the centre of the loop (factor of ~100), it is relatively an inhomogeneous field. See 0.5.1 for the error estimation calculations.

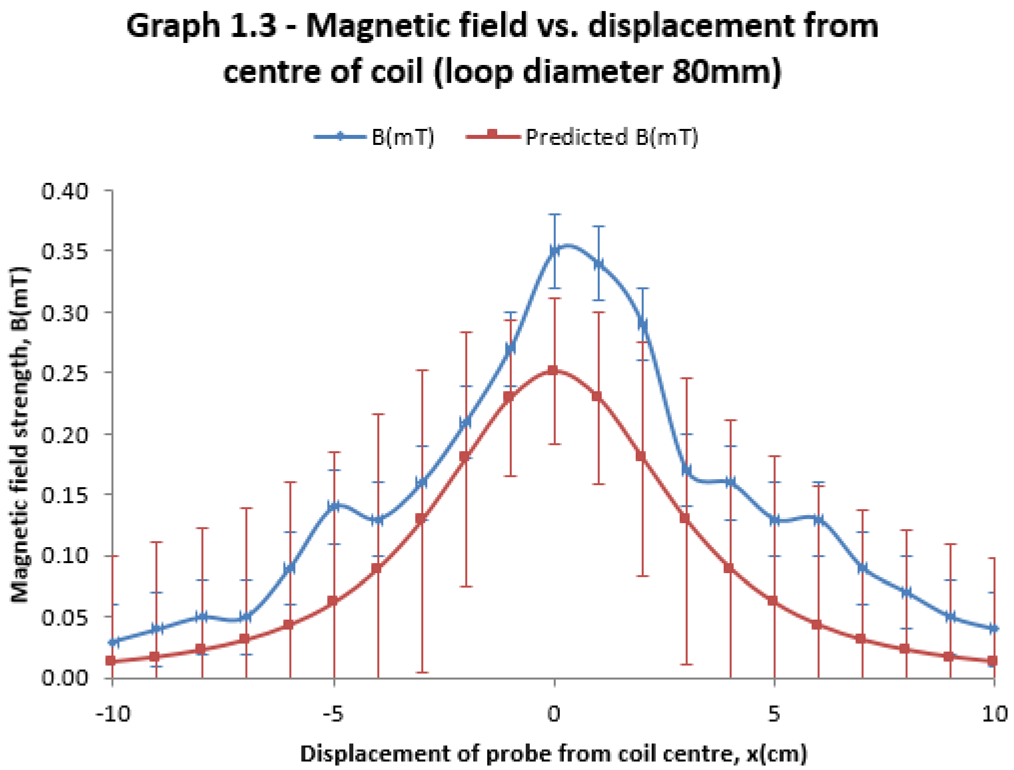

Figure 3:
Shows the magnetic field strength as a function of the displacement from the centre of the coil with a loop diameter 80mm. The error bounds from the predicted values nearly encompass all of the data, the very minor discrepancies are assumed to be due to a random error. Current $=16.00 \pm 0.05A$. This shows a normal distribution shape around the centre of the loop, the magnetic field increases as it approaches the centre of the loop (factor of ~10), it is a somewhat inhomogeneous field. See 0.5.1 for the error estimation calculations.

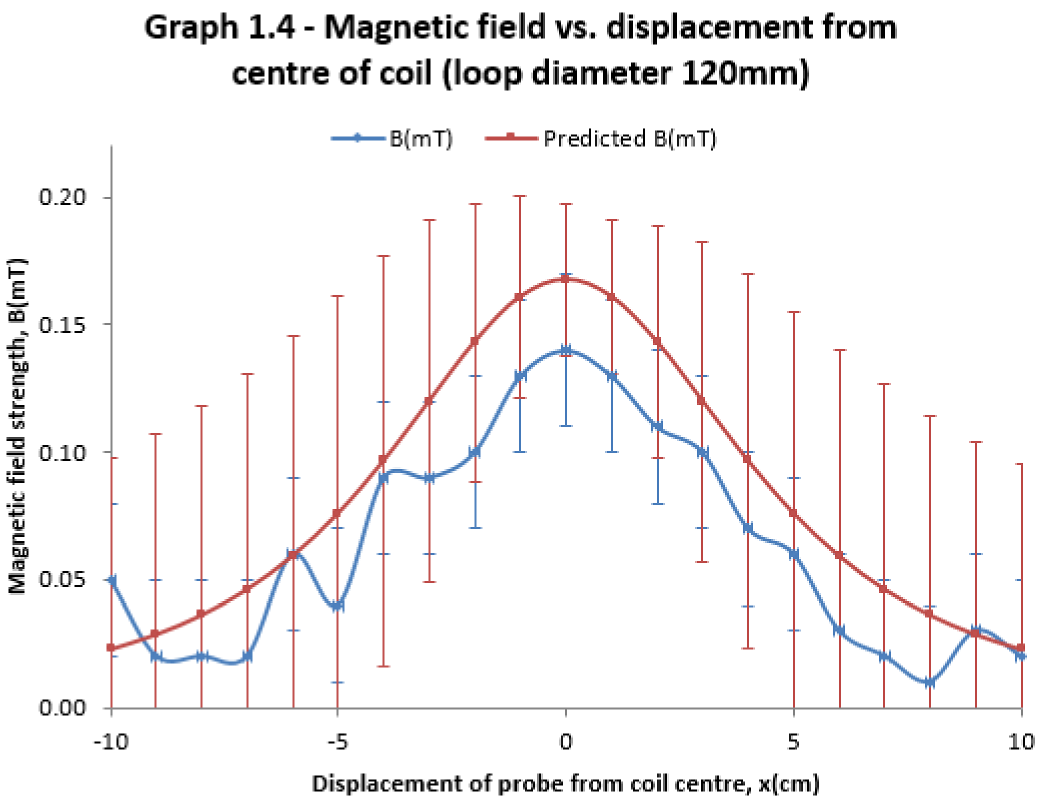

Figure 4:
Shows the magnetic field strength as a function of the displacement from the centre of the coil with a loop diameter 120mm. The error bounds from the predicted values encompass all of the data. Current $=16.00 \pm 0.05A$. This shows a normal distribution shape around the centre of the loop, the magnetic field increases somewhat as it approaches the centre of the loop (factor of ~4), it is relatively an inhomogeneous field. See 0.5.1 for the error estimation calculations.

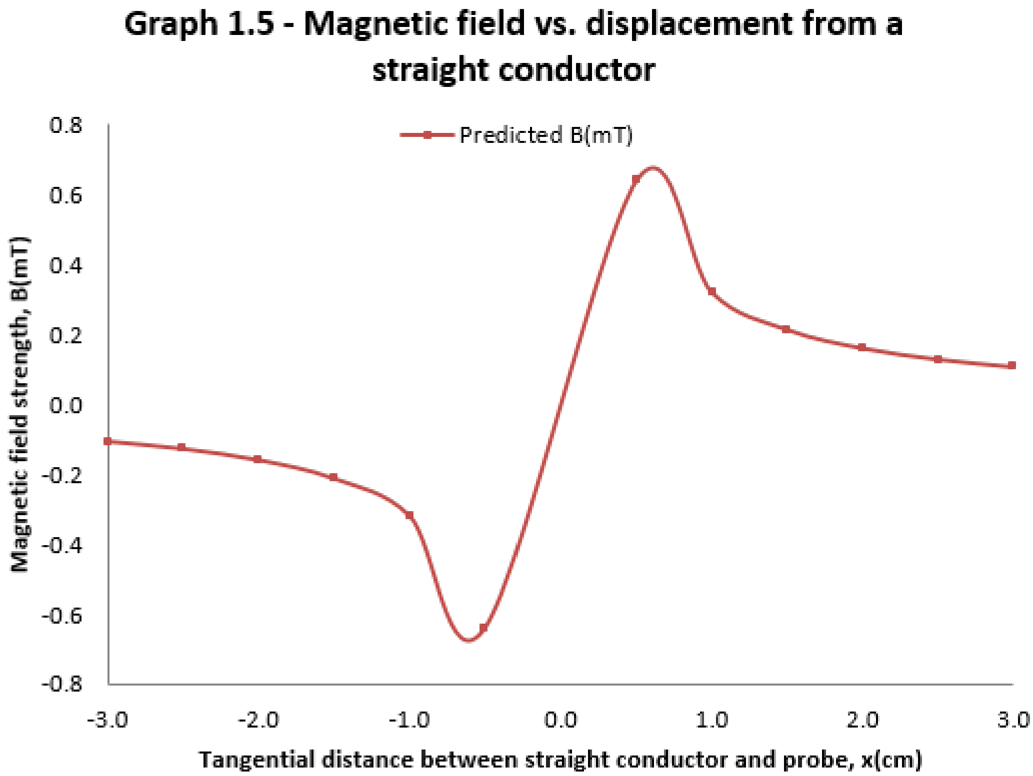

Figure 5:
Shows the predicted magnetic field strength as a function of the displacement from a straight conductor. The measurements have not been plotted because the experimental procedure was not followed correctly and so those results are invalid and useless to plot. Current $=16.00 \pm 0.05A$. While it has not been possible to present valid data for this part, the shape will be discussed. The inversion at 0cm occurs because of the change in direction of the magnetic field. However as the distance (x axis) approaches 0, although the equation predicts that the magnetic field tends towards infinity, it would in reality tend towards a finite value as there is no such thing as a magnetic field of infinite strength. The part of the line between -0.5 to 0.5 cm is not correct for the reason discussed.

0.4.2 Measure axial magnetic field of an air solenoid

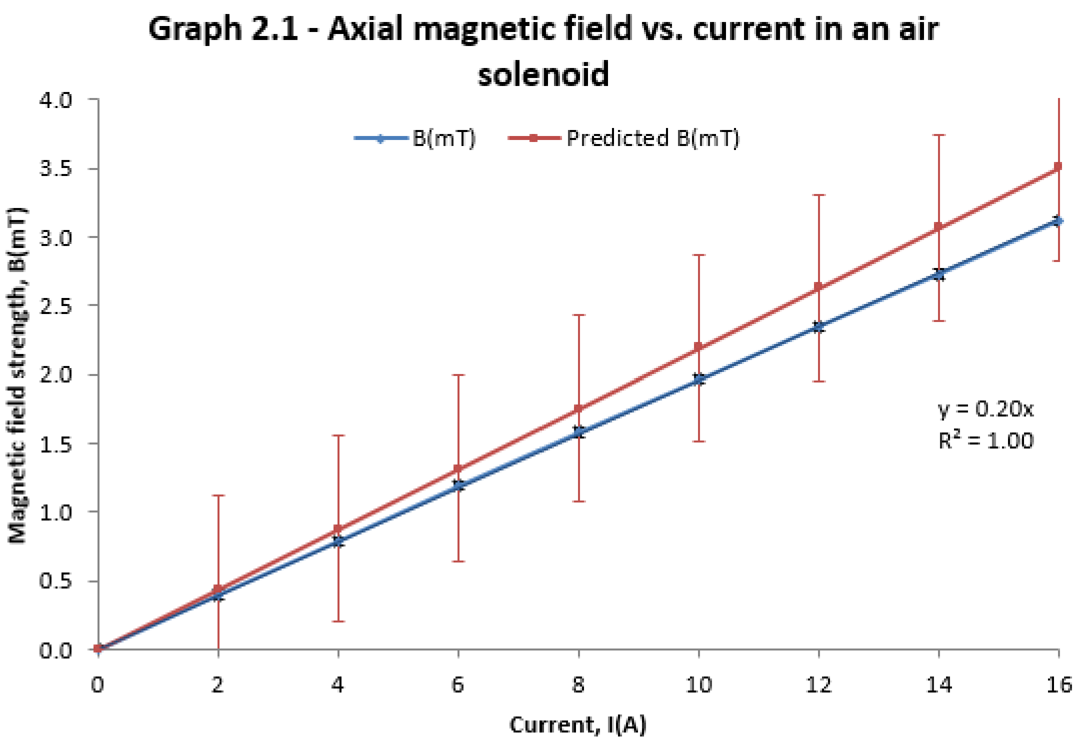

Figure 6:
Shows the axial magnetic field strength as a function of the current in an air solenoid with a length of $15 \pm 2cm$ and the number of turns, N = 30. This data shows a very high degree of confidence to the fitted line which can be seen from the $R^2 = 1.00$ value. The error bounds from the predicted values encompass all of the data. This shows a linear relationship between axial magnetic field strength and current in an air core solenoid, $B = 0.20I$. See 0.5.3 for the error estimation calculations.

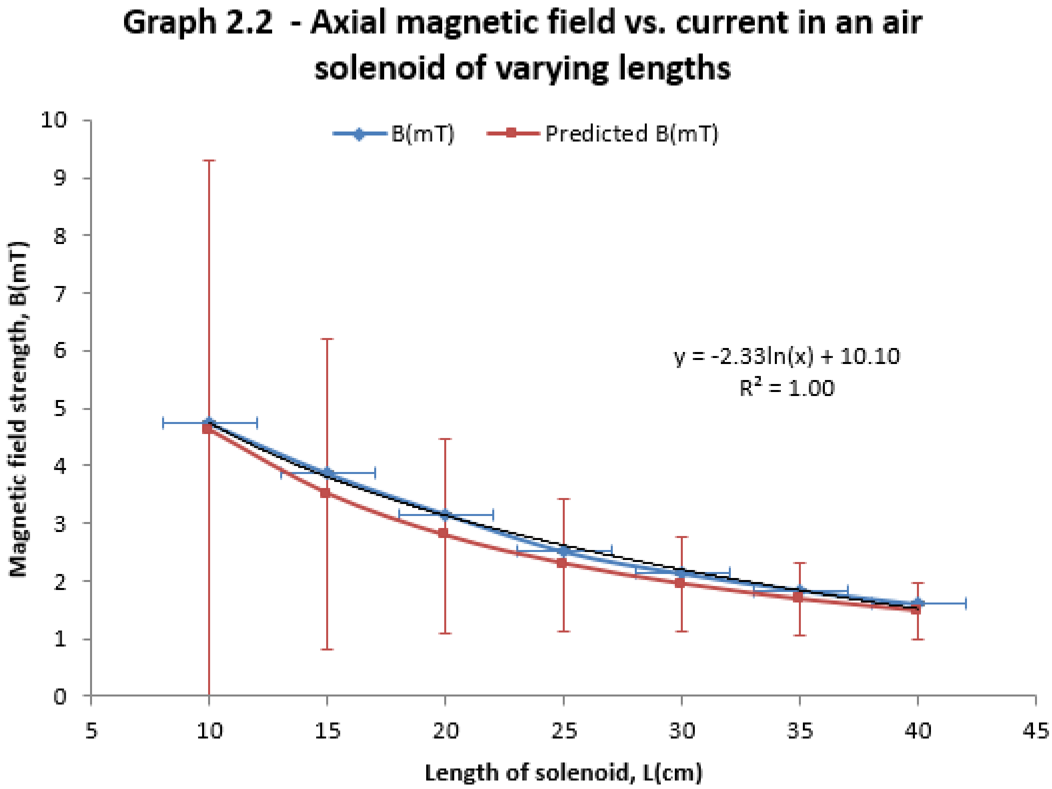

Figure 7:
Shows the axial magnetic field strength as a function of the current in an air solenoid with varying lengths, current $=16.00 \pm 0.05A$ and number of turns, N = 30. The uncertainty of the axial distance was 2cm. This data shows a very high degree of confidence to the fitted line which can be seen from the $R^2 = 1.00$ value. The error bounds from the predicted values encompass all of the data. This shows that the axial magnetic field strength increases at the centre of an air solenoid when the length of the coil decreases with a constant current. See 0.5.3 for the error estimation calculations.

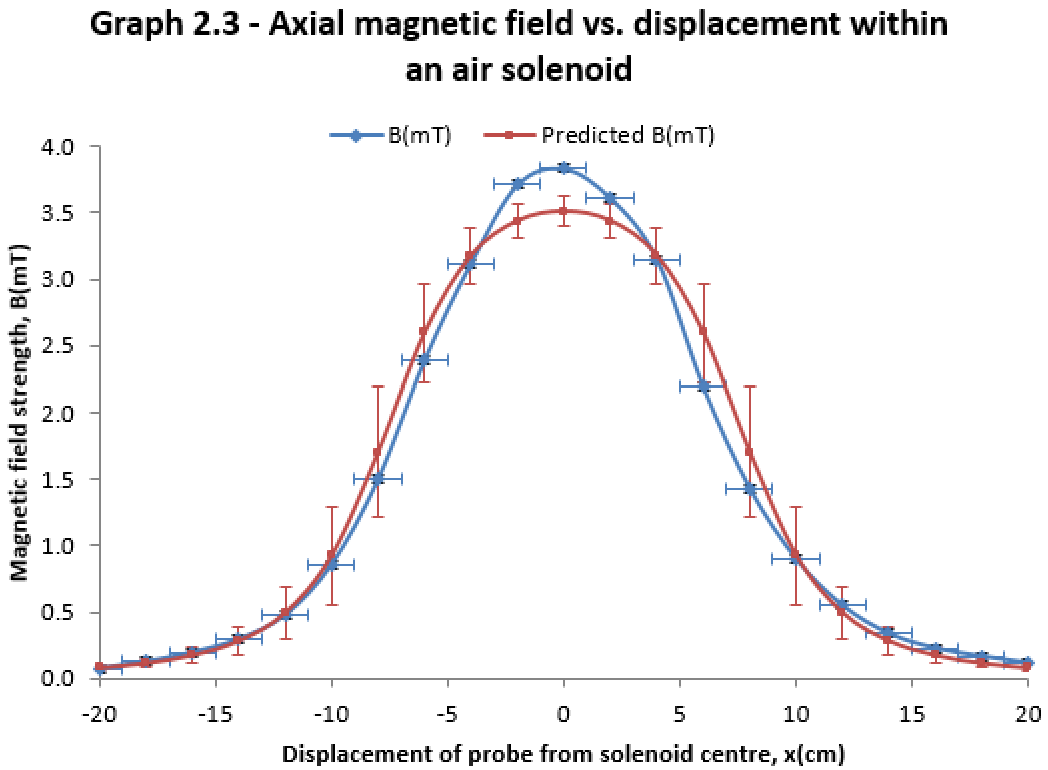

Figure 8:
Shows the axial magnetic field strength as a function of the displacement through it in an air solenoid with length of the coil $= 15 \pm 2cm$, current $=16.00 \pm 0.05A$ and number of turns, N = 30. The uncertainty of the axial distance was 2cm. The error bounds from the predicted values nearly encompass all of the data, the minor discrepancies are assumed to be due to a random error. It is noted in the lab book that from -4 to +4 cm, there was a repeat for those measurements only after an anomaly thought to have been caused by the high temperature of the coil. This may account for middle 3 measurements being higher than predicted. This shows a normal distribution shape around the axial centre of the solenoid, the magnetic field strength reaches a maximum at the centre of the solenoid. See 0.5.3 for the error estimation calculations.

0.4.3 Measure radial and tangential magnetic field of a coil

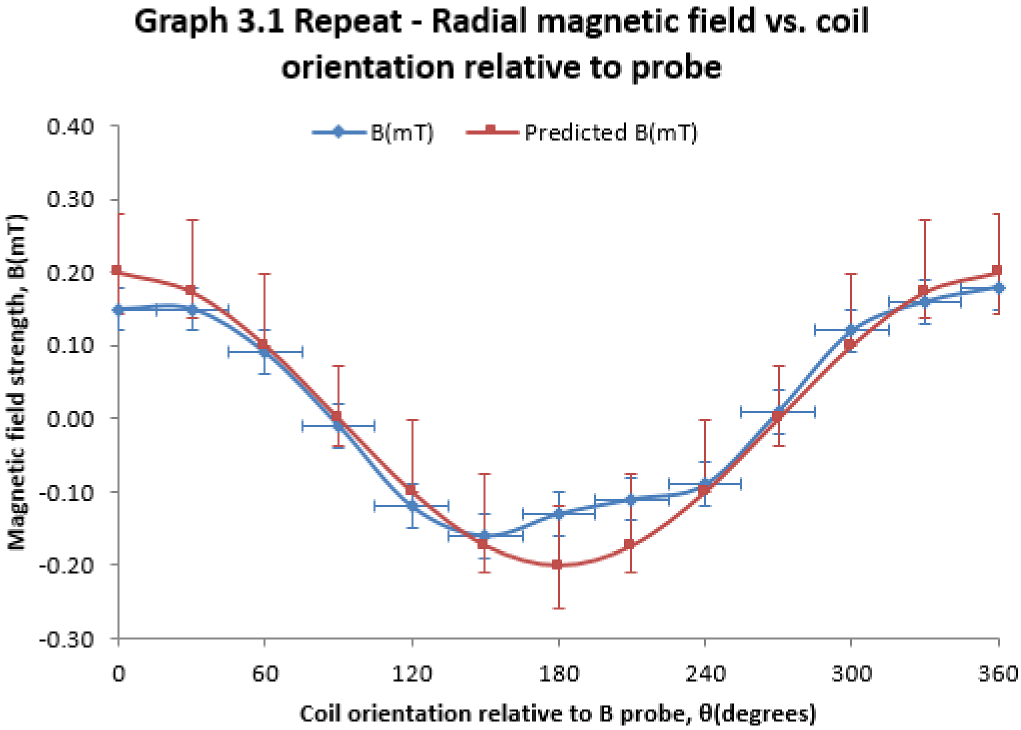

Figure 9:
Shows the radial magnetic field strength as a function of the orientation of the coil relative to the probe. It follows a sinusoidal path and also the expected results. Errors were estimated for the predicted magnetic field by using the minimum and maximum of the variables within the equation used to respectively find the maximum and minimum values of the resultant function. The error bounds from the predicted values encompass all of the data. Current $=1.50 \pm 0.05A$, distance from probe to centre of coil $= 175 \pm 10mm$. This shows that at 90 and 270 degrees, the magnetic field strength is 0 which is related to the definition of magnetic flux $\phi = BA \cdot cos\theta$

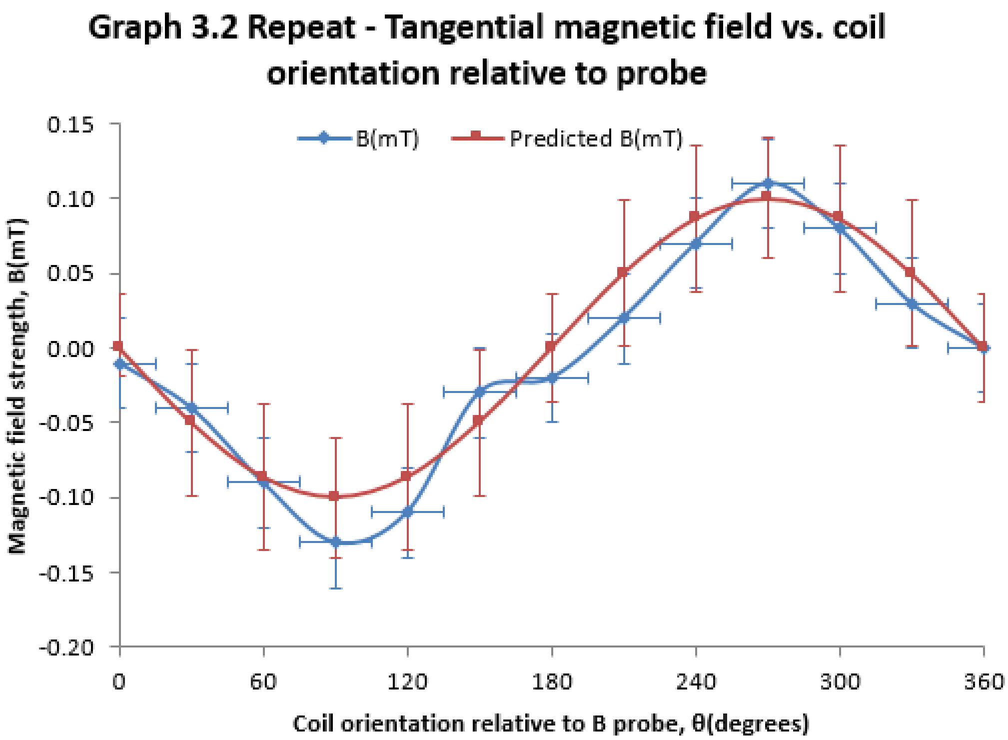

Figure 10:
Shows the tangential magnetic field strength as a function of the orientation of the coil relative to the probe. It follows a sinusoidal path and for all data points, follows the expected results.Errors were estimated for the predicted magnetic field by using the minimum and maximum of the variables within the equation used to respectively find the maximum and minimum values of the resultant function.. Current $=1.50 \pm 0.05A$, distance from probe to centre of coil $= 175 \pm 20mm$. This shows that at 0 and 180 degrees, the magnetic field strength is 0 which is shown in the 'right hand rule' - $F = qvB \cdot sin\theta$ or the vector form $\overrightarrow{F} = q\overrightarrow{v} \wedge \overrightarrow{B}$

0.4.4 Measure axial magnetic field of a pair of Helmholtz coils

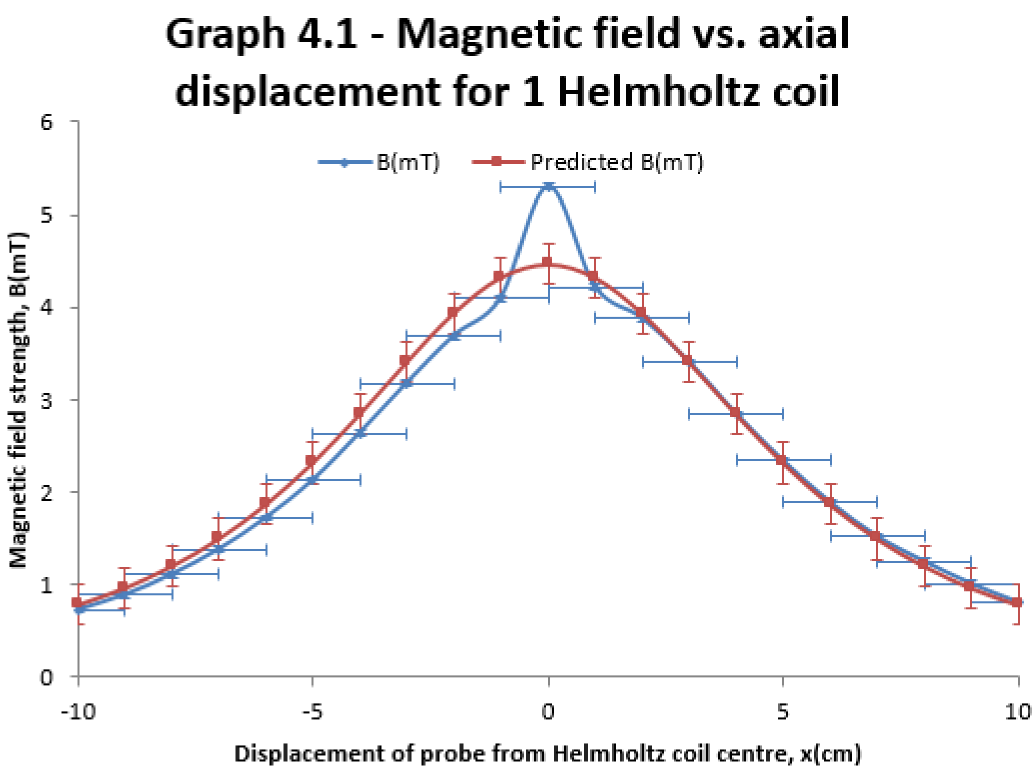

Figure 11:
Shows the magnetic field strength against the displacement from the centre of one Helmholtz coil along the axis perpendicular to the coil. It is not known why there is an unexpected spike for the 0cm measurement, it is assumed to be due to a random error. Almost all of the measurements appear to be within the error bounds of the predicted values. Current $=16.00 \pm 0.05A$. This shows a normal distribution shape around the axial centre of the Helmholtz coil. See 0.5.1 for the error estimation calculations.

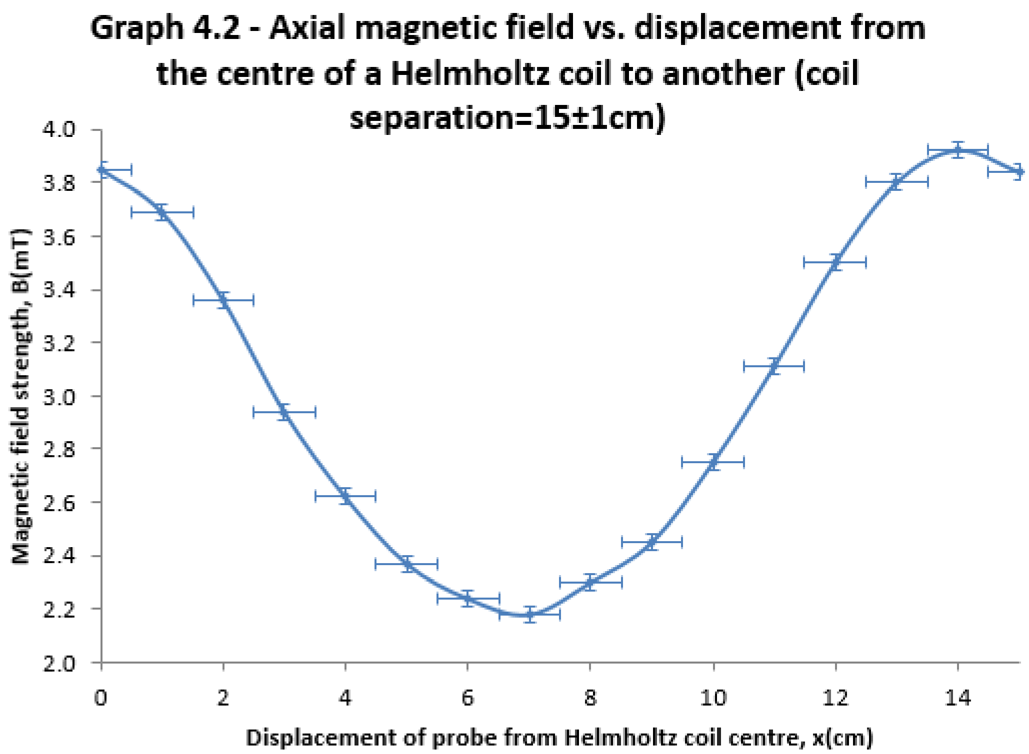

Figure 12:
Shows the axial magnetic field against the displacement from the centre of one Helmholtz coil out of a pair of Helmholtz coils where the coil separation is $15 \pm 1cm$. There is no central homogeneous magnetic field region at this separation distance. Current $=16.00 \pm 0.05A$

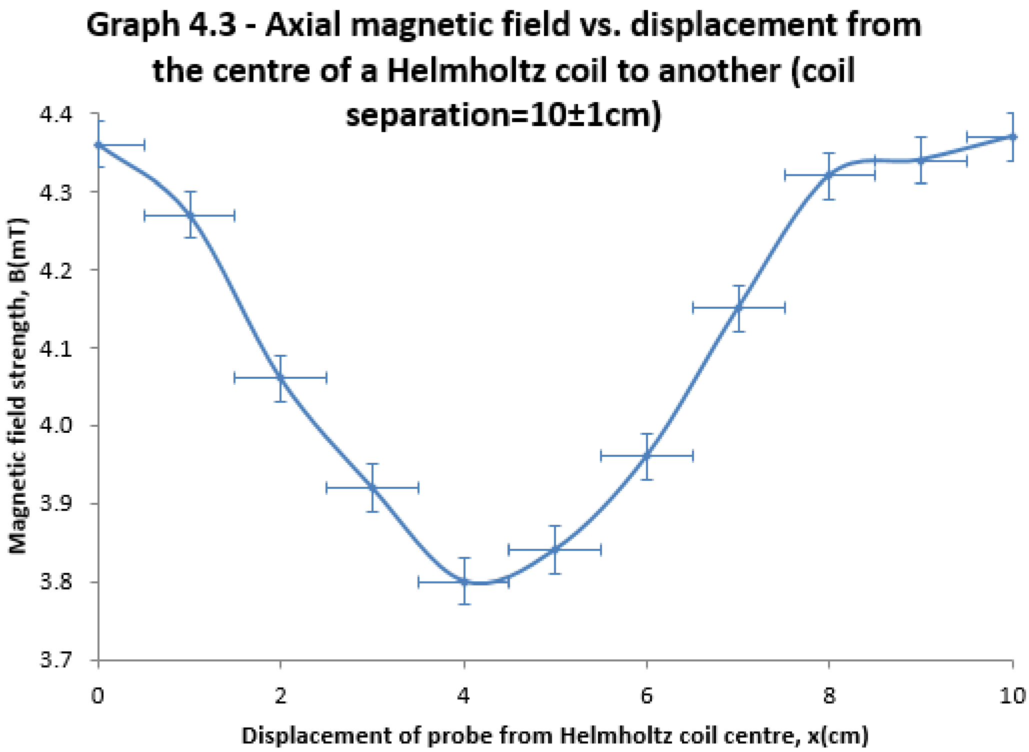

Figure 13:
Shows the axial magnetic field against the displacement from the centre of one Helmholtz coil out of a pair of Helmholtz coils where the coil separation is $10 \pm 1cm$. There is no central homogeneous magnetic field region at this separation distance. Current $= 16.00 \pm 0.05A$

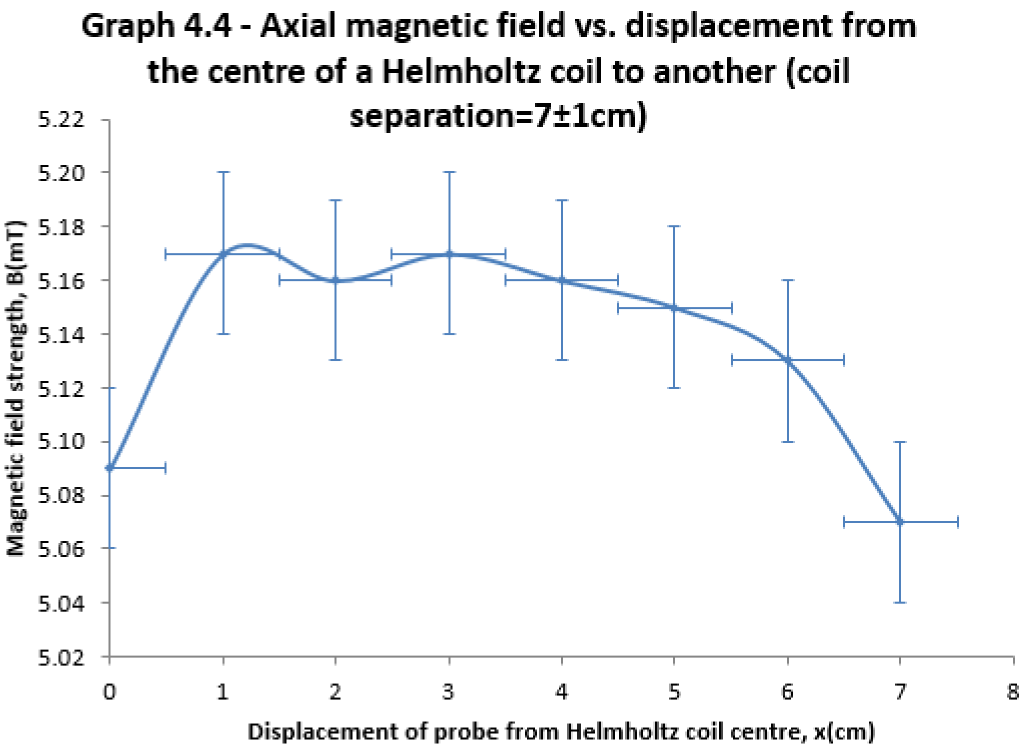

Figure 14:
Shows the axial magnetic field against the displacement from the centre of one Helmholtz coil out of a pair of Helmholtz coils where the coil separation is $7 \pm 1cm$. There is a central near homogenous magnetic field region between 1-5cm where the magnetic field could be constant between 5.14-5.16mT. Current $= 16.00 \pm 0.05A$

Graphs 4.2 to 4.4 show the convergence from an inhomogeneous field to a near homogeneous field ($B = 5.15 \pm 0.01mT$) over approximately a 5cm distance (1-6cm displacement from Graph 4.4). The optimal distance to create a homogeneous magnetic field at the centre region of the Helmholtz coils is equal to the radius of the Helmholtz coils (which should be of equal size). In this case, that optimal radius for a homogenous field is 6.75cm (13.5cm/2) and is very close to the situation in Graph 4.4.

0.5 Error calculations

This section follows the document on propagating errors from the document 'Uncertainty' (Author: Paul Cornwall?) by using the partial derivative method. Not all parts will be included for the sake of space, most notably the actual differentiation of the various functions.

The general case followed for the following error calculations is as follows:

$$\Delta A^2 = \sum_{i=1} \left| \frac{\delta f(x_i)}{\delta x_i} \right|^2 \times \Delta x_i$$

0.5.1 Uncertainty for $B = \frac{\mu_0}{4\pi} \cdot I \cdot \frac{2\pi R^2}{(R^2+x^2)^{\frac{3}{2}}}$

This section (0.5.1) applies to Graphs 1.1-1.4 and 4.1

$$\Delta B^2 = \left| \frac{\delta B}{\delta I} \right|^2 \cdot \Delta I^2 + \left| \frac{\delta B}{\delta R} \right|^2 \cdot \Delta R^2 + \left| \frac{\delta B}{\delta x} \right|^2 \cdot \Delta x^2$$

$$= \left| \frac{2\pi R^2}{10^7 \cdot (R^2+x^2)^{\frac{3}{2}}} \right|^2 \cdot \Delta I^2 + \left| \frac{2\pi IR\left(2x^2 - R^2\right)}{10^7 \cdot (R^2+x^2)^{\frac{5}{2}}} \right|^2 \cdot \Delta R^2 + \left| \frac{-3 \times 2\pi IR^2 x}{10^7 \cdot (R^2+x^2)^{\frac{5}{2}}} \right|^2 \cdot \Delta x^2$$

$$\Delta B^2 = \frac{4\pi^2 R^4}{10^{14} \cdot (R^2+x^2)^3} \cdot \Delta I^2 + \frac{4\pi^2 I^2 R^2 \left(2x^2 - R^2\right)^2}{10^{14} \cdot (R^2+x^2)^5} \cdot \Delta R^2 + \frac{9 \times 4\pi^2 I^2 R^4 x^2}{10^{14} \cdot (R^2+x^2)^5} \cdot \Delta x^2$$

$$B^2 = I^2 \times 10^{-14} \times 4\pi^2 R^4 \cdot \left(R^2+x^2\right)^{-3}$$

ΔB^2 divided by B^2 , the square root is taken

$$\frac{\Delta B^2}{B^2} = \left(\frac{4\pi^2 R^4}{10^{14} \cdot (R^2+x^2)^3} \cdot \Delta I^2 + \frac{4\pi^2 I^2 R^2 \left(2x^2 - R^2\right)^2}{10^{14} \cdot (R^2+x^2)^5} \cdot \Delta R^2 + \frac{9 \times 4\pi^2 I^2 R^4 x^2}{10^{14} \cdot (R^2+x^2)^5} \cdot \Delta x^2 \right) \div \left(I^2 \times 10^{-14} \times 4\pi^2 R^4 \cdot \left(R^2+x^2\right)^{-3} \right)$$

Simplification stages have been taken giving the final uncertainty

$$\Delta B = B\sqrt{\frac{\Delta I^2}{I^2} + \frac{\left(2x^2 - R^2\right)^2 \Delta R^2}{\left(R^2+x^2\right)^2 R^2} + \frac{9x^2 \Delta x^2}{R^2 \left(R^2+x^2\right)^2}}$$

0.5.2 Uncertainty for $B = \frac{\mu_0}{4\pi} \cdot I \cdot \frac{2\pi}{r}$

This section (0.5.2) would apply to Graph 1.5 but has not actually been calculated due to the lack of valid results to compare them against.

$$\Delta B^2 = \left| \frac{\delta B}{\delta I} \right|^2 \cdot \Delta I^2 + \left| \frac{\delta B}{\delta r} \right|^2 \cdot \Delta r^2$$

$$= \left| \frac{2 \times 10^{-7}}{r} \right|^2 \cdot \Delta I^2 + \left| \frac{-2 \times 10^{-7}}{r} \right|^2 \cdot \Delta r^2$$

$$\Delta B^2 = \frac{4 \times 10^{-14}}{r^2} \cdot \Delta I^2 + \frac{4 \times 10^{-14}}{r^2} \cdot \Delta r^2$$

$$B^2 = 4 \times 10^{-14} \cdot \frac{I^2}{r^2}$$

ΔB^2 divided by B^2 , the square root is taken followed by simplification stages giving the final uncertainty

$$\Delta B = B\sqrt{\frac{\Delta I^2}{I^2} + \frac{\Delta r^2}{r^2 I^2}}$$

0.5.3 Uncertainty for $B = \frac{\mu_0}{4\pi} \cdot I \cdot \frac{N}{2L} \cdot \left(\frac{x+\frac{L}{2}}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} - \frac{x-\frac{L}{2}}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} \right)$

This section (0.5.3) applies to Graphs 2.1-2.3.

For the sake of simplification, the following substitution is made

$$b_1 = \left(\frac{x+\frac{L}{2}}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} - \frac{x-\frac{L}{2}}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} \right)$$

So that

$$B = \frac{\mu_0}{4\pi} \cdot I \cdot \frac{N}{2L} \cdot b_1$$

$$\Delta B^2 = \left|\frac{\delta B}{\delta I}\right|^2 \cdot \Delta I^2 + \left|\frac{\delta B}{\delta x}\right|^2 \cdot \Delta x^2 + \left|\frac{\delta B}{\delta R}\right|^2 \cdot \Delta R^2 + \left|\frac{\delta B}{\delta L}\right|^2 \cdot \Delta L^2$$

$$\frac{\delta B}{\delta I} = \frac{N\mu_0}{2L} \cdot b_1$$

$$\left|\frac{\delta B}{\delta I}\right|^2 = \frac{N^2\mu_0^2}{4L^2} \cdot b_1^2$$

$$\frac{\delta B}{\delta x} = \frac{NI\mu_0}{2L} \cdot \left(\frac{\left(x-\frac{L}{2}\right)^2}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} - \frac{1}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} + \frac{1}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} - \frac{\left(x+\frac{L}{2}\right)^2}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} \right)$$

$$b_2 = \left(\frac{\left(x-\frac{L}{2}\right)^2}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} - \frac{1}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} + \frac{1}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{1}{2}}} - \frac{\left(x+\frac{L}{2}\right)^2}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} \right)$$

$$\left|\frac{\delta B}{\delta x}\right|^2 = \frac{N^2I^2\mu_0^2}{4L^2} \cdot b_2^2$$

$$\frac{\delta B}{\delta R} = \frac{NI\mu_0}{2L} \cdot \left(\frac{R\left(x-\frac{L}{2}\right)}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} - \frac{R\left(x+\frac{L}{2}\right)}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} \right)$$

$$b_3 = \left(\frac{R\left(x-\frac{L}{2}\right)}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} - \frac{R\left(x+\frac{L}{2}\right)}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)^{\frac{3}{2}}} \right)$$

$$\left|\frac{\delta B}{\delta R}\right|^2 = \frac{N^2I^2\mu_0^2}{4L^2} \cdot b_3^2$$

$$\frac{\delta B}{\delta L} = \frac{NI\mu_0}{2L} \cdot \left(\frac{(L-2x)^2}{\left(L^2-4Lx+4\left(R^2+x^2\right)\right)^{\frac{3}{2}}} + \frac{1}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)\frac{1}{4}} + \frac{1}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)\frac{1}{4}} - \frac{\left(x+\frac{L}{2}\right)^2}{2\left(\left(x+\frac{L}{2}\right)^2+R^2\right)\frac{3}{2}} \right) - \frac{NI\mu_0}{2L} \cdot b_1$$

$$b_4 = \left(\frac{(L-2x)^2}{\left(L^2-4Lx+4\left(R^2+x^2\right)\right)^{\frac{3}{2}}} + \frac{1}{\left(\left(x-\frac{L}{2}\right)^2+R^2\right)\frac{1}{4}} + \frac{1}{\left(\left(x+\frac{L}{2}\right)^2+R^2\right)\frac{1}{4}} - \frac{\left(x+\frac{L}{2}\right)^2}{2\left(\left(x+\frac{L}{2}\right)^2+R^2\right)\frac{3}{2}} \right)$$

$$\left|\frac{\delta B}{\delta L}\right|^2 = \frac{N^2I^2\mu_0^2}{4L^2} \cdot \left(b_4^2 - b_1^2\right)$$

$$\Delta B^2 = \frac{N^2\mu_0^2}{4L^2}\cdot b_1^2\cdot \Delta I^2 + \frac{N^2I^2\mu_0^2}{4L^2}\cdot b_2^2\cdot \Delta x^2 + \frac{N^2I^2\mu_0^2}{4L^2}\cdot b_3^2\cdot \Delta R^2 + \frac{N^2I^2\mu_0^2}{4L^2}\cdot (b_4^2 - b_1^2)\cdot \Delta L^2$$

$$B^2 = \frac{N^2I^2\mu_0^2}{4L^2}\cdot b_1^2$$

ΔB^2 divided by B^2 gives

$$\frac{\Delta B^2}{B^2} = \left(\frac{\Delta I^2}{I^2} + \frac{b_2^2\cdot\Delta x^2}{b_1^2} + \frac{b_3^2\cdot\Delta R^2}{b_1^2} + \frac{b_4^2\cdot\Delta L^2}{b_1^2} - \frac{\Delta L^2}{L^2}\right)$$

Gives the final equation for the uncertainty estimation

$$\Delta B = B\sqrt{\frac{\Delta I^2}{I^2} + \frac{b_2^2\cdot\Delta x^2}{b_1^2} + \frac{b_3^2\cdot\Delta R^2}{b_1^2} + \frac{b_4^2\cdot\Delta L^2}{b_1^2} - \frac{\Delta L^2}{L^2}}$$

0.6 Conclusion

There is a global potential systematic error which has been attempted to be corrected for, which is a combination of the Earth's magnetic field along with all other sources of background magnetic field. These sources include power cables going along near where the experiment was situated. The 'zeroing' of the teslameter was the attempt to correct for this background noise, this is not quite enough to compensate for the background noise because the background noise is not constant.

Section 1 (0.4.1) shows the relationship between magnetic fields and current in current carrying loops including loops. This revealed a linear relationship between field strength and current in a loop $B = 0.03I$, varying homogeneous axial magnetic fields with different loop sizes and finally how a magnetic field varies by displacement from a straight conductor radially (inversely as it approaches the conductor and then inverting polarity).

Section 2 (0.4.2) shows the measurement of axial magnetic fields within a air solenoids and how that changes with varying current at the centre (linearly $B = 0.20I$), how the field changes with different lengths of solenoids (according to the graph, by the natural logarithm) and how it changes axially within the solenoid (normal distribution).

Section 3 (0.4.3) shows how the radial and tangential magnetic fields from a coil vary relative angle to the probe. The radial field varies by a cosine rule and the tangential field by a sine rule.

Section 4 (0.4.4) investigates axial magnetic fields with Helmholtz coils. Initially, the axial magnetic field distribution is shown for one Helmholtz coil which shows the same shape of a normal distribution as in Graph 2.3 as expected. The rest of the section shows the increasingly homogeneous magnetic field as the separation distance of the coils approaches the radius of the Helmholtz coils. When this radius is reached, it is expected to be the most homogeneous possible magnetic field. At a coil separation of $7 \pm 1cm$ it was found that there was a central region of between 1-5cm (~70% of the separation distance) where it would be possible to have a homogeneous field with a strength of $B = 5.15 \pm 0.01mT$.

0.7 Reference

Laboratory script for Biot-Savart's experiment PH500 - Version 1.1, 01/10/07 - University of Kent

0.8 Appendix

1.1	I(A)	0	2	4	6	8	10	12	14	16
	B(mT)	0	0.07	0.13	0.18	0.24	0.30	0.36	0.41	0.46

Magnetic field due to varying current (0-16A) in a loop (40mm diameter)

1.2	x(cm)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	...
	B(mT)	0.02	0.01	0.02	0.00	0.01	0.02	0.05	0.09	0.26	0.33	0.44	0.31	0.19	0.08	0.05	...

...	x(cm)	5	6	7	8	9	10
...	B(mT)	0.02	0.02	0.03	0.04	0.05	0.05

Magnetic field as a function of axial distance ($I = 16.00 \pm 0.05A$) in a loop (40mm diameter)

1.3	x(cm)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	...
	B(mT)	0.03	0.04	0.05	0.05	0.09	0.14	0.13	0.16	0.21	0.27	0.35	0.34	0.29	0.17	0.16	...

...	x(cm)	5	6	7	8	9	10
...	B(mT)	0.13	0.13	0.09	0.07	0.05	0.04

Magnetic field as a function of axial distance ($I = 16.00 \pm 0.05A$) in a loop (80mm diameter)

1.4	x(cm)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	...
	B(mT)	0.05	0.02	0.02	0.02	0.06	0.04	0.09	0.09	0.10	0.13	0.14	0.13	0.11	0.10	0.07	...

...	x(cm)	5	6	7	8	9	10
...	B(mT)	0.06	0.03	0.02	0.01	0.03	0.02

Magnetic field as a function of axial distance ($I = 16.00 \pm 0.05A$) in a loop (120mm diameter)

1.5	x(cm)	-3	-2.5	-2	-1.5	-1	-0.5	0.5	1	1.5	2	2.5	3
	B(mT)	0.08	0.05	0.04	0	0.02	-0.04	-0.05	-0.06	-0.08	-0.08	-0.07	-0.08

Magnetic field as a function of tangential distance ($I = 16.00 \pm 0.05A$) from a straight conductor

2.1	I(A)	0	2	4	6	8	10	12	14	16
	B(mT)	0	0.40	0.79	1.19	1.58	1.96	2.35	2.73	3.12

Axial magnetic field within an air solenoid as a function of current (N=30 and length of solenoid, $L = 15 \pm 2cm$)

2.2	L(cm)	10	15	20	25	30	35	40
	B(mT)	4.74	3.87	3.16	2.51	2.13	1.84	1.61

Axial magnetic field within an air solenoid as a function of length of solenoid, L (N=30 $I = 16.00 \pm 0.05A$)

2.3	x(cm)	-20	-18	-16	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	...
	B(mT)	0.08	0.13	0.20	0.30	0.48	0.86	1.50	2.39	3.12	3.71	3.83	3.61	3.15	2.19	1.43	...

...	x(cm)	10	12	14	16	18	20
...	B(mT)	0.90	0.55	0.34	0.23	0.17	0.12

Axial magnetic field within an air solenoid as a function of axial distance relative to the centre of the solenoid (N=30 $I = 16.00 \pm 0.05A$ $L = 15 \pm 2cm$)

3.1	Angle(^{0})	0	30	60	90	120	150	180	210	240	270	300	330	360
	B(mT)	0.15	0.14	0.12	-0.05	-0.18	-0.23	-0.23	-0.21	-0.18	-0.02	0.10	0.13	0.15

Radial magnetic field as a function of angle ($I = 1.50 \pm 0.05A$)

3.2	Angle(^{0})	0	30	60	90	120	150	180	210	240	270	300	330	360
	B(mT)	-0.06	-0.13	-0.15	-0.15	-0.10	-0.03	0	0.04	0.10	0.12	0.06	0.01	-0.02

Tangential magnetic field as a function of angle ($I = 1.50 \pm 0.05A$)

4.1	x(cm)	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	...
	B(mT)	0.73	0.89	1.11	1.38	1.72	2.13	2.64	3.18	3.69	4.10	5.30	4.22	3.88	3.41	2.85	...

...	x(cm)	5	6	7	8	9	10
...	B(mT)	2.34	1.89	1.52	1.25	1.01	0.81

Axial magnetic field as a function of axial displacement relative to the centre of 1 Helmholtz coil with only 1 Helmholtz coil ($I = 1.50 \pm 0.05A$)

4.2	x(cm)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	B(mT)	3.85	3.69	3.36	2.94	2.62	2.37	2.24	2.18	2.30	2.45	2.75	3.11	3.50	3.80	3.92	3.84

Axial magnetic field as a function of axial displacement relative to the centre of 1 Helmholtz coil using 2 Helmholtz coils ($I = 16.00 \pm 0.05A$ coil separation distance $= 15 \pm 1cm$)

4.3	x(cm)	0	1	2	3	4	5	6	7	8	9	10
	B(mT)	4.36	4.27	4.06	3.92	3.80	3.84	3.96	4.15	4.32	4.34	4.37

Axial magnetic field as a function of axial displacement relative to the centre of 1 Helmholtz coil using 2 Helmholtz coils ($I = 16.00 \pm 0.05A$ coil separation distance $= 10 \pm 1cm$)

4.4	x(cm)	0	1	2	3	4	5	6	7
	B(mT)	5.09	5.17	5.16	5.17	5.16	5.15	5.13	5.07

Axial magnetic field as a function of axial displacement relative to the centre of 1 Helmholtz coil using 2 Helmholtz coils ($I = 16.00 \pm 0.05A$ coil separation distance $= 7 \pm 1cm$)