Name ________________________________ School __________________________________ Date ___________

Lab 21.1 – The Tangent Galvanometer

Purpose

To investigate the magnetic field at the center of a current-carrying loop of wire.
To verify the right-hand rule for the field inside a current loop.
To investigate the vector nature of magnetic fields.
To verify the relationship between the current, the number of turns, and the magnetic field inside a current loop using Earth's field as a reference.
To determine the strength of Earth's magnetic field at the lab's virtual location.
To verify results using NOAA's Geophysical Data Center and Google Earth.

Equipment

Virtual Tangent Galvanometer PENCIL

Theory

You have learned that the magnetic field due to the current at a point in a straight wire takes on a circular shape around the wire. (Figure 1a.) You've further found that by wrapping a length of wire into loops a large part of the field on one side of the wire can be "focused" into the small area inside the loop resulting in an area of stronger magnetic field. (Figures 1b and 1c.)

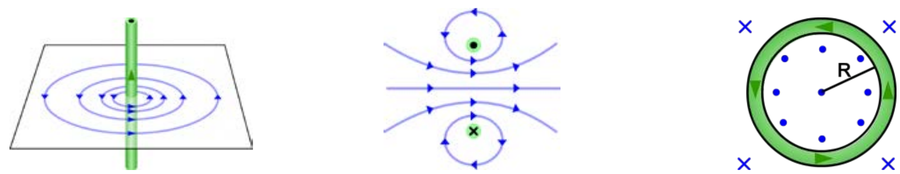

Figure 1 **1a** **1b** **1c**

At the center of the circular loop this field is normal to the loop and has a magnitude of

$$B_{loop} = \frac{\mu_o NI}{2r}$$ **Equation 1**

where μ_o: the permeability of free space = $4\pi \times 10^{-7}$ T· m/A
N: the number of loops
I: the current (Amps)
r: the radius of the loop = .20 m

The term NI gives the total current around the loop since each loop individually contributes a current I to the total current around the loop.

We're going to investigate the field inside a large, circular loop. You can look ahead to Figure 4 or to the actual apparatus to see what it looks like. Figure 2 shows a simplified representation of the overhead view.

Since a compass will always point in the direction of the **net** magnetic field at its location we can use it to indicate the net field at the center of our loop. The net field there depends on the contributions of the loop's field and Earth's. This is actually the horizontal component of Earth's field, $\mathbf{B}_{\mathbf{Earth(h)}}$. Figure 2 is an overhead view of a horizontal plane.

Figure 2 shows the three possibilities – Earth only, loop only, Earth and loop. Since we don't have any way to shield against Earth's magnetic field, we can only produce the fields shown in figure's 2a and 2c.

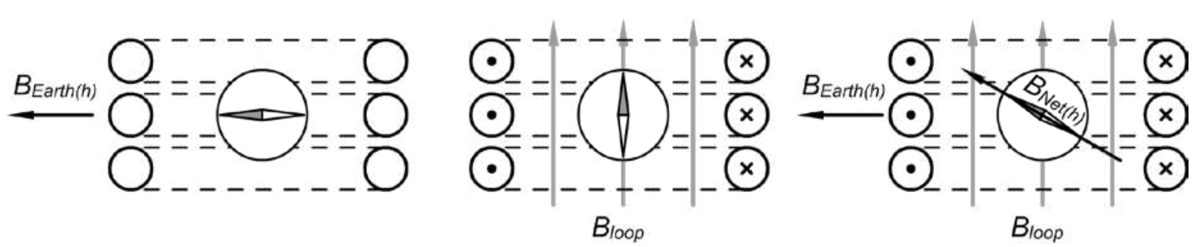

Figure 2 **2a** **2b** **2c**

We can describe Figure 2c by the **vector** equation:

$$\vec{B}_{net(h)} = \vec{B}_{loop} + \vec{B}_{earth(h)} \qquad \textbf{Equation 2}$$

Figure 3 is a vector diagram of Figure 2c. You should be able to see how it is generated from Equation 2.

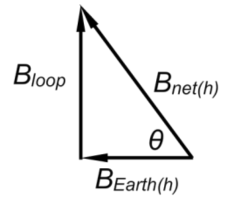

Figure 3

From Figure 3 we can say

$$\tan(\theta) = \frac{B_{loop}}{B_{earth(h)}} \qquad \textbf{Equation 3}$$

Explore the Apparatus

We'll use our virtual lab apparatus to study this interaction between Earth's field and the loop's field. The apparatus is viewed from two perspectives as shown in Figure 4: View 1: **Overhead**, and View 2: **Oblique**.

You'll switch between views using the buttons at the top left edge of the screens. The oblique view shown in Figure 4b provides the best view of the apparatus.

A frame supports a circular coil made of insulated wires. From 1 to 5 loops are possible.

A horizontal platform holds a sheet of polar graph paper used for visualizing angles in the horizontal plane.

In the overhead view shown in Figure 4a, you see two vector arrows. One represents the horizontal component of Earth's magnetic field. The other represents the magnetic field produced by the current-carrying wire loops. It's only visible when the loop current is turned on. Neither vector automatically points in the appropriate direction. Rather these vectors can be rotated as needed by dragging the points of the arrows.

In overhead view, the entire apparatus can be rotated by dragging the Handle. The loop field vector arrow, B_{Loop}, rotates with the apparatus. But you can rotate it relative to the apparatus by dragging its point as previously discussed.

The two views are completely independent. You'll only work with one view while performing a given part of the lab. You'll use the overhead view for part I of the lab and the oblique view in parts II and III.

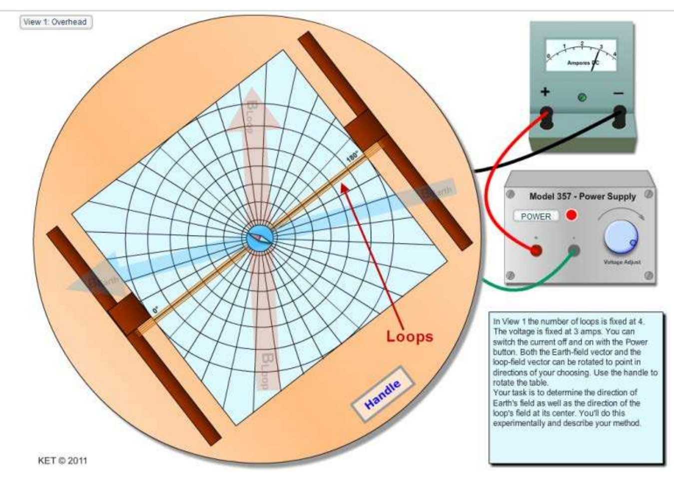

Figure 4a. View 1: Overhead

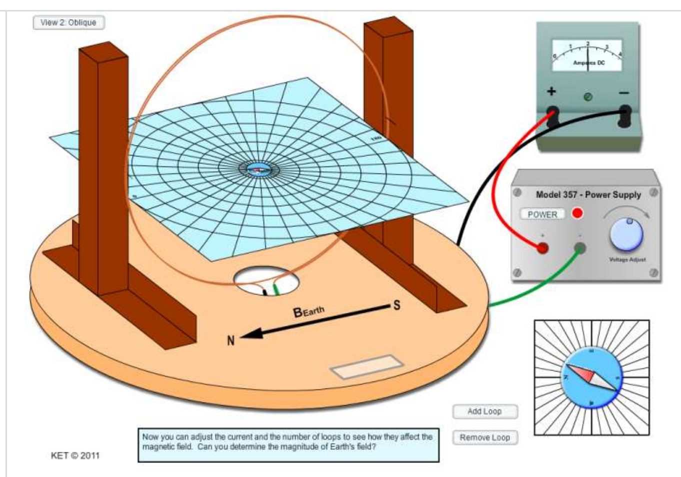

Figure 4b. View 2: Oblique

Take some time to become familiar with each view. Explore the following in the oblique view.

a. Notice how the large compass at the bottom right provides a close-up of the real compass. You'll take compass readings with the large version. The red end of the compass is its north end.

b. Notice how the deflection of the compass is affected by the power switch, the voltage adjust knob, and the number of loops of wire. Be sure to try all three.

c. When the power is on and current flows through the wire, a magnetic field due to the current is produced inside the loop. We expect it to be normal to the plane of the loop. If Earth's magnetic field were nonexistent the compass needle would point in the direction of the loop's field. **However, under the influence of the two magnetic fields, the compass takes the direction of their resultant field, B_{net}.**

d. Note the important relationship between the two fields given in Equation 3. The tangent of θ is directly proportional to B_{loop}. ($B_{Earth(h)}$ is constant.) In this lab we will use the reverse of this, i.e., that B_{loop} is proportional to tan(θ).

As stated in the purpose we'll use the apparatus to test and/or determine four things.

I. We'll verify that the field at the center of a current loop is normal to the loop and in accordance with our right hand rule for the field at the center of a loop in part I.

II. According to Equation 1 the field at the center of the loop is determined by the number of turns on the loop, N, and the current in the loop, I. Thus the field is determined by the product, NI. We'll test this relationship between B and NI in part II.

III. From our graph we'll determine the experimental horizontal component of Earth's magnetic field, $B_{Earth(h)}$, at the virtual location of the apparatus.

IV. We'll use $B_{Earth(h)}$ and the inclination (dip angle) at the location of the apparatus to find the experimental total value of Earth's field, B_{Earth} at the location of our apparatus and compare it to the actual value.

Procedure

Be sure to turn the power off when you're not making measurements. Well, that's not actually true with virtual equipment, but with real apparatus you'd want to reduce the negative effects of long-term heating of the equipment by taking this precaution. In a future version of this lab we'll probably insert a feature that would help you develop that habit.

Part I. The direction of the magnetic field at the center of a current loop

You'll use the overhead view for this part of the lab. In this view **the number of loops is fixed at 4 and the current is fixed at 3.0 A** when the power is turned on. Begin with the power turned off.

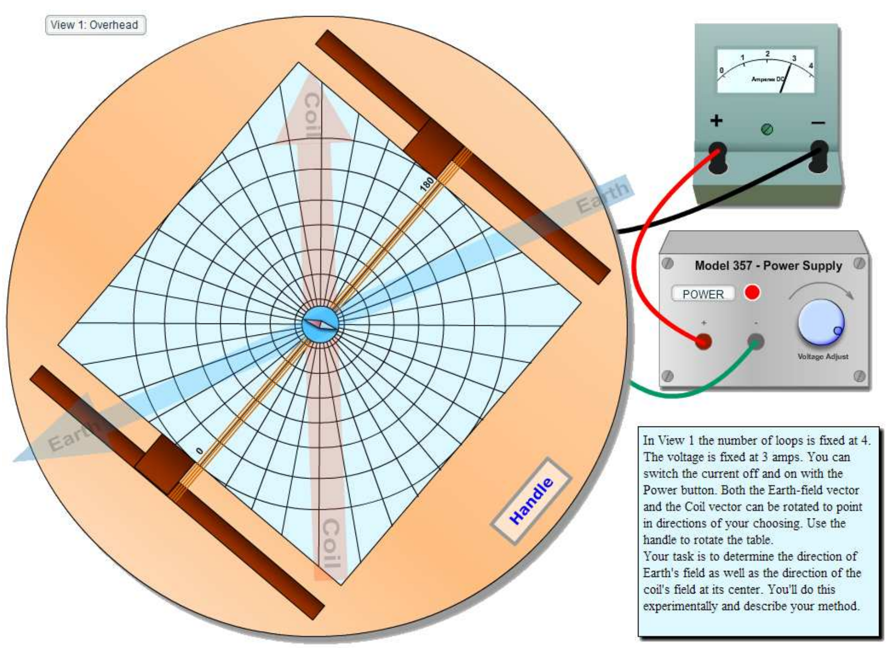

Figure 5

Drag the handle to orient the frame so that the 0° end of the loop is to the north. (This is north at the virtual location of the apparatus. This is probably not your actual location.) Drag the "B_{Earth}" end of the Earth-field vector to point in the magnetic north direction. (Yes, toward the south magnetic pole near Santa's house.) See Figure 6.

As always with these labs, you can zoom in and out as needed to improve your precision.

1. Verify that the **loop's field** at its center is normal to the plane of the loop.
   Your method for achieving this is not at all obvious. You'll need to experiment a bit and develop a plan. You might want to arrange the B_{Loop} vector to point in the direction you think is correct to begin with. Your method should involve switching the current on and off and rotating the apparatus. Remember, there are two magnetic fields present and $B_{Earth(h)}$ will never change.

Explain the plan you'll use along with your logic. Use a pencil so that you can edit it.

2. You should have noticed one slight problem. There seem to be two different orientations of the loop that work. That is, there are two orientations that result in no change in the needle's direction when the current is turned on and off. But only one of them can match our right hand rule. If you didn't discover this, go back and find it.

What are the two orientations that work? What do these two results suggest about the possible directions for the loop's field?

3. Hopefully you've found that the plane of the loops must be perpendicular to Earth's field for the needle to remain still. But how can the net field, B_{net}, be the same in two different cases? It's not. It's just in the same direction – north.

See if you can illustrate how this happens. Below you see a vector representing Earth's field. Draw two more vectors in the boxes below it representing the loop's field, one for each of the two cases discussed above. Be careful to choose a reasonable (same) length for these two vectors. Label them B_{loop1} and B_{loop2}. Should they be shorter or longer than $B_{Earth(h)}$? The B vectors shown in the lab apparatus are actually of correct scale.

Now show the graphical vector addition of $B_{Earth(h)}$ with each of the two B_{loops}. Be sure and show their sum, B_{net} for each case. Your drawings should show graphically how the B can be in the same direction in each case.

$\vec{B}_{\text{net}} = \vec{B}_{\text{Earth(h)}} + \vec{B}_{\text{loop1}}$:	

$\vec{B}_{\text{net}} = \vec{B}_{\text{Earth(h)}} + \vec{B}_{\text{loop2}}$:	

4. So what's the real answer? Which way does the loop's field pass through the loop? Set up the apparatus as in Figure 6.

East

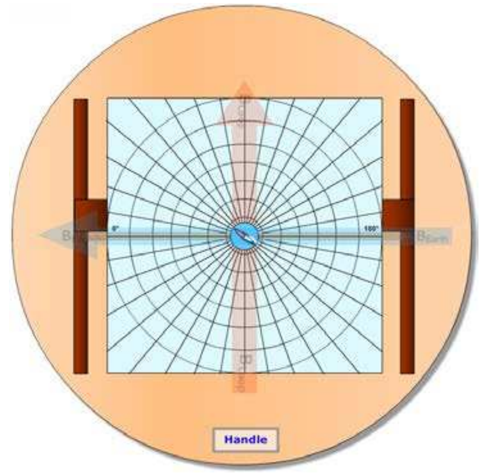

Figure 6 **West**

We now know that Earth's field is fixed – to the left (North). Note that the East and West directions have been added to the figure. We've confirmed that the loop's field is perpendicular to the loop – up (east) or down (west). We also know that, for the orientation in Figure 6, when the current is flowing, the compass always points in the direction of B_{net} which we can see is at about 37° north of west. But in which direction does the loops' field actually point? Is it to the east or the west?

Is the direction of the loop's field to the east or west? Explain how you know from the compass' orientation in Figure 6.

What about the direction of the current in the loop? Is the current flowing into the screen at 180° (the South end) or 0° (the North end)? Explain using your right hand rule for the field at the center of a current loop.

Part II. Confirm two of the relationships given by Equation 1 using Earth's field as a reference.

$$B_{loop} = \frac{\mu_o N I}{2r} \qquad \textbf{Equation 1}$$

$$\tan(\theta) = \frac{B_{loop}}{B_{Earth(h)}} \qquad \textbf{Equation 3}$$

We would like to confirm that $\mathbf{B_{loop} \propto N}$ **and I**. To do this we would need to hold I constant and then measure B_{loop} for different values of N, and similarly to show that $B_{loop} \propto I$.

We can't measure B_{loop} directly but we do know from Equation 3 that $B_{loop} = B_{Earth(h)} \tan(\theta)$. So combining Equations 1 and 2 we have

$$B_{Eart(h)} \tan(\theta) = \frac{\mu_o N I}{2r} \qquad \textbf{Equation 4}$$

Since $B_{Earth(h)}$, μ_o, and r are constants, we have

$$\tan(\theta) \propto NI \qquad \textbf{Equation 5}$$

So if Equation 1 is correct, $\tan(\theta)$ should be directly proportional to N and to I. Thus we can confirm Equation 1 by plotting $\tan(\theta)$ vs. N, for a constant current, I. And likewise we can plot $\tan(\theta)$ vs. I, for a constant number of turns, N. Straight lines for each plot would confirm the relationship.

You'll use the oblique view this time.

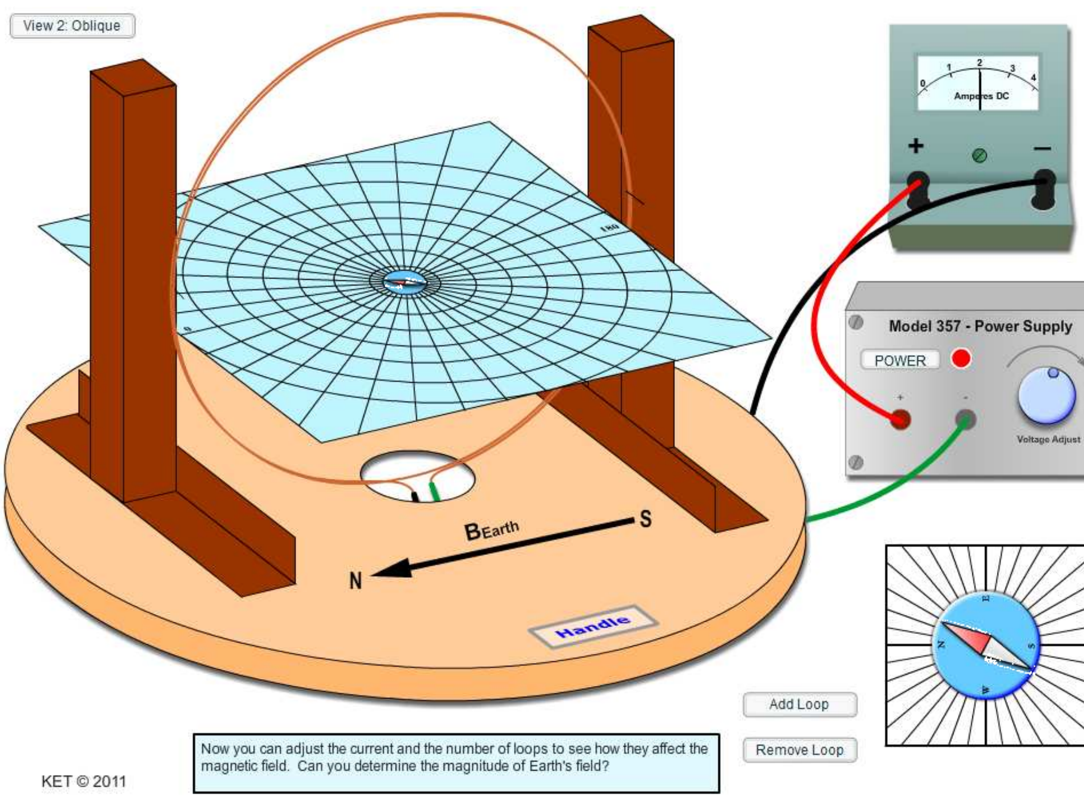

Figure 7

You'll need to read the compass as accurately as possible. Zooming in is very useful. Just right-click (Ctrl-click on a Mac) on the apparatus and select "Zoom In" from the menu. You can then drag the apparatus around as needed.

1. To test the effect of N on B_{loop}, measure the angle of deflection (with respect to north) of the compass for 1 – 5 loops. Use a current of 3 A.
2. Record your results in Table 1.

Table 1 θ, and tan(θ) vs. N I = 3 A			
Trial	N (loops)	θ (degrees)	tan(θ)
1	0	0	0
2	1		
3	2		
4	3		
5	4		
6	5		

3. Test your results by plotting a graph of tan(θ) vs. N. Include your graph with your final report.

4. Does your graph indicate that tan(θ) is directly proportion to N? How? (Two criteria are required.)

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5. To test the effect of the current on B_{loop}, measure the angle of deflection for currents of 0 to 3.5 A in .5-A increments. Use 5 loops for this part.

6. Record your results in Table 2.

Table 2 θ, and tan(θ) vs I N = 5			
Trial	I (A)	θ (degrees)	tan(θ)
1	0	0	0
2	.5		
3	1.0		
4	1.5		
5	2.0		
6	2.5		
7	3.0		
8	3.5		

7. Test your results by plotting a graph of tan(θ) vs. I Include your graph with your final report.

8. Does your graph indicate that tan(θ) is directly proportion to I? How? (Two criteria are required.)

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Part III. Determine the horizontal component of Earth's magnetic field at the location of the virtual lab apparatus.

We now know that B_{loop} is directly proportional to NI. We'll now test the complete equation by using it to calculate B_{Earth} at the location of our apparatus. We can then compare it to the known value at that location. We'll do that as follows.

a) Using a point from your tan(θ) vs. I graph, calculate B_{loop} for the current at that point on the graph.

b) Compute $B_{Earth(h)}$ using Equation 3.

c) Calculate B_{Earth} from $B_{Earth(h)}$ from trigonometry.

d) Compare your calculate B_{Earth} vs. the known value.

1. Using a convenient point **on your line of best fit** from near the middle of your current (I) graph, determine the loop's magnetic field, B_{loop}, using Equation 1. Record I and tan(θ) for your chosen point along with your calculations below. Note that r = .20 m for our loops.

r = .20 m N = 5 I = ____________________ A tan(θ) = ____________

B_{loop} = ________________ T

2. Using Equation 3 and your value of tan(θ), from your chosen point on your current graph, calculate the horizontal component of Earth's magnetic field, $B_{Earth(h)}$ at the location of your apparatus. Show your calculations below.

Experimental $B_{Earth(h)}$ = _______________ T

Part IV. From the actual location of the apparatus, find the actual value for $B_{Earth(h)}$ at that location and compare it to our experimental value.

We now have our experimental value for the horizontal component of Earth's magnetic field at the location of our apparatus. How will we compare that to the actual value? In the northern hemisphere (where the apparatus is hiding) the field dips down into Earth, so the horizontal component is just a fraction of the total field, B_{Earth}. Figure 8 shows what that looks like. The **angle of inclination, or dip angle, θ_{dip}** is the angle between the horizontal component which we've been working with and the total field, B_{Earth}, as shown in Figure 8.

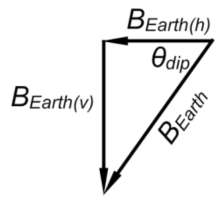

Figure 8

If we knew B_{Earth} and the dip angle at the location of our apparatus we could compute the actual value of $B_{Earth(h)}$.

I can now inform you that the apparatus for this experiment is located in Hamilton, Bermuda. You can find B_{Earth} and the dip angle at that location using some Internet resources. Here's how.

1. Using Google Earth or some similar tool, determine the latitude and longitude of Hamilton, Bermuda. Record these values in degrees, minutes, and seconds.

   Lattitude: _____ ° _____ ' _____ " North (of the equator)

   Longitude: _____ ° _____ ' _____ " West (of Greenwich)

2. Navigate to the NOAA Geophysics Data Center at **www.ngdc.noaa.gov/geomagmodels/struts/calcPointIGRF.** Before you proceed, enter your Zip code and click "Get Location." You'll see your latitude and longitude. Then click "Compute Magnetic Field Values" near the bottom of the page. You'll see a set of numbers for your location. The last one, the total intensity is what we call B_{Earth}. It's in nanoTeslas.

   That's pretty cool, but we need to check out the field in Bermuda.

   Enter Hamilton, Bermuda's latitude and longitude. Be sure to check North and West

   Use this format for degrees minutes and seconds: 22 33 44
   The spaces in between will separate the numbers appropriately.

   Note the elevation. Cool!

   Click "**Compute Magnetic Field Values**" near the bottom of the page

3. Record the values for B_{Earth} which is referred to as the total intensity. Note that it is given in nT. You'll need to convert that to Tesla using scientific notation.

   Total Intensity (B_{Earth}) ____________ T

4. Record the Inclination (dip angle) _________________ °

5. From these two values and Figure 8, you can determine the accepted value of $B_{Earth(h)}$ at the location of the apparatus. You can figure this one out on your own.
   Show your calculations below.

B_{Earth} = ____________ T (from above)

$B_{Earth(h)}$ = __________ T

1. Calculate the % error between the known value and your experimental value.