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Application Note
Calibrating the Magnetic Field for Magneto-Electric Measurements
Rev A

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Introduction:
The Vision Library offers the Magneto-Electric Response Task to measure the magneto-electric coupling coefficient in multiferroic materials and composite magneto-piezoelectric devices. The test stimulates a sample with a small AC magnetic field while measuring its charge generation. Provisions are available to apply a background magnetic bias field to the sample in addition to the AC stimulus. Figure 1 diagrams the test configuration for measuring magneto-electric properties with a Precision tester.

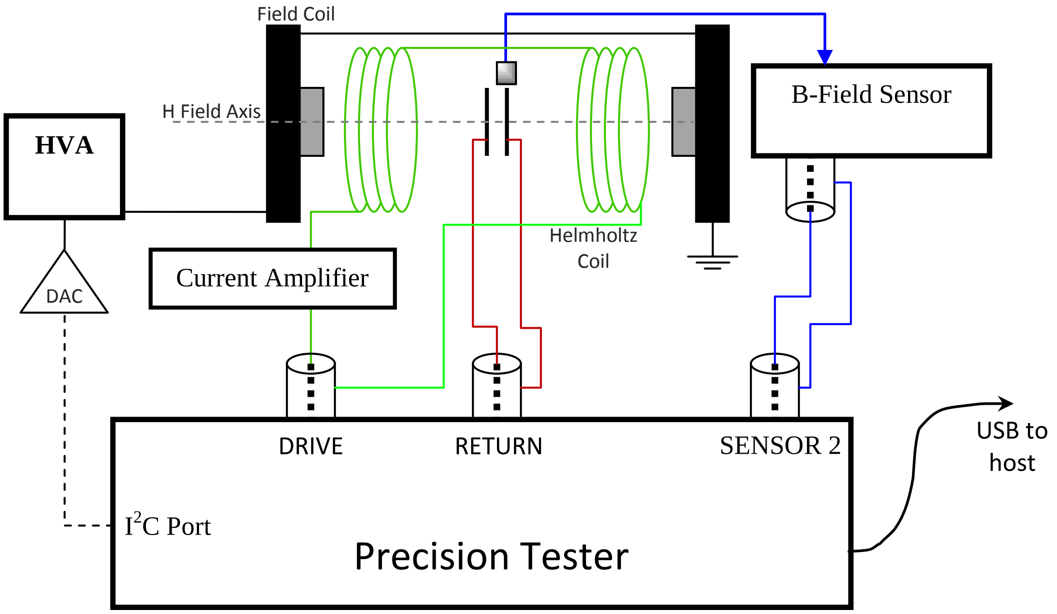


Fig. 1: Measuring magneto-electric response with a bias magnetic field.

As in all testing, the goal is to achieve the maximum accuracy. Here the word “accuracy” is defined to mean minimizing the difference between the measured value and the true value of the parameter being measured. In magneto-electric testing, the two parameters being measured are the magnetic field applied to the sample under test and the charge generated by the sample as a result of the magnetic field. The Precision tester will measure the generated charge with an accuracy of 0.5% or better as long as the tests are executed within the specified performance envelope of that tester. Measuring magnetic field accurately, and cheaply, is more difficult. That is the subject of this application note.

Determining the Magnetic Field during a Test:
Radiant's MR Task has three methods by which it can determine the magnetic field applied to the sample. The first and least accurate is for the Task to estimate the magnetic field given the characteristics of the current amplifier and the Helmholtz coil in Figure 1. The equation estimating the magnetic field is

$$B = V_{Drive} \text{ x I/V Ratio x B/I Ratio x Geometry Coefficient} \qquad \text{Eq(1)}$$

The I/C ratio is the inverse of the Current-to-Voltage function of the current amplifier which converts the DRIVE voltage on its input to a specified current. The B/I ratio is the inverse of the efficiency with which the Helmholtz coil converts current from the amplifier to magnetic field at its center. The Geometry coefficient defaults to unity but allows the user to adjust the B-field calculation if the sample is not placed in the center of the Helmholtz coil. The I/V ratio can be measured in place and/or is published. The B/I ratio is supplied by the manufacturer.

The magnetic field estimation algorithm has several sources of error. The primary source of error is that the algorithm cannot know of changes in the impedance of the Helmholtz coil due to changes in current. These changes create a back EMF that modifies the current from the amplifier according to the equation

$$V = L\, \delta i/\delta t \qquad \text{Eq(2)}$$

The estimation algorithm must be used if there are no sensors available to assist in determining the strength of the magnetic field at each sample point in the test.

The second method for determining the strength of the magnetic field is to place a current sensor in series with the Helmholtz coil and connect the output of the current sensor to the SENSOR1 input of the Precision tester. Since the magnetic field is directly proportional to the current coursing through the Helmholtz coil, calculating the magnetic field from the current flow will be more accurate than the estimation performed by Equation (1). During a test, the tester captures the voltage output of the current sensor at each sample point and converts it to the magnetic field using the following equation.

$$B = \text{SENSOR1 x V/I Ratio x B/I Ratio x Geometry Coefficient} \qquad \text{Eq(3)}$$

The V/I ratio converts the voltage output of the current sensor measured on SENSOR1 to the value of the current flowing through the current sensor. As with Equation (1), the B/I ratio and the Geometry coefficient convert the current to the magnetic field at the location of the sample.

Radiant has designed two current sensors for use with the MR Task. The first sensor, the **RCSi**, uses an instrumentation amplifier to measure the voltage across a very small resistance in series with the coil current. The second, the **RCSh**, uses a Hall Effect sensor. The difference between the two sensors is the non-common mode voltage rejection. In a current sensor, the current being monitored should theoretically flow into and out of the sensor with no impedance between the sensor terminals and the current should not interact with the measurement circuitry. The measurement circuitry *should sit to the side watching the current without interfering with it.* A barrier exists between the current carrying wire and the measurement circuitry. That barrier will have a voltage limit above which the current carrying wire will arc to the measurement circuitry. A current sensor that uses an instrumentation amplifier to measure the current flow will be very sensitive with high resolution and high frequency response but the breakdown voltage of that barrier will be low. A Hall Effect sensor can isolate the measurement circuitry from very high voltages but does not have the resolution of the instrumentation amplifier and may be affected by the very magnetic field it is intended to calculate. The choice between the RCSi and RCSh is determined strictly by the maximum voltage that will appear on the current carrying line being monitored. The RCSi can withstand 200 V while the RCSh can withstand 1500 V.

> WARNING: If the RCSh is used, it must be placed at least one meter from the Helmholtz coil and the field coil for every 50 Gauss of magnetic field the coils generate. It also should be placed so that it will not sit on the magnetic axis of the Helmholtz and field coils in Figure 1.

The final and most accurate method, as well as the most expensive method, for capturing the magnetic field strength during a test is to use a B-field sensor, called a Gaussmeter. A Gaussmeter typically uses a Hall Effect sensor that can be placed directly at the location of the sample. The Hall Effect sensor must be perpendicular to the magnetic field. Any angle between the face of the Hall Effect sensor and the actual magnetic field will reduce the value of the measured field versus the actual field. The voltage output of the Gaussmeter must be connected to SENSOR2 on the Precision tester. The voltage output of the Gaussmeter must be proportional to the magnetic field it senses. The MR Task multiplies that voltage by the conversion ratio of the Gaussmeter to arrive at the magnetic field.

$$B = \text{SENSOR1}\ \mathbf{x}\ \text{B/V Ratio x Geometry Coefficient} \qquad \text{Eq(4)}$$

The B/V ratio is the ratio between the B-field that sensor sees and the voltage output by the Gaussmeter. If the sensor is placed directly at the location of the sample, the Geometry coefficient should be left at unity.

Selecting the B-field Measurement:

The MR Task will always perform the calculation of Equation (1) on every test execution. This occurs because the user enters the desired B-field for the test and the Task must determine the voltage profile to output from DRIVE. If either SENSOR1 or SENSOR2 is enabled during a test, those inputs will be also be captured and the magnetic field calculated from those two inputs. The user may choose in the Plotting Options the source of the X-axis B-field values. Selecting the “Polarization vs. Time” plotting option will display all three of the sources if they are all turned on. The user may also elect to plot “Magnetic Field vs. Time” in order to compare the values from the different sources.

Calibrating the Individual Sensor:

Once inserted into the test fixture, the current sensor and the Gaussmeter must be calibrated for that specific installation. The *Set SENSOR1* and *Set SENSOR2* buttons on the MR Task menu provide the tools for the user to execute the calibration. The window for enabling the use of SENSOR1 or SENSOR2 will display the following equation:

$$[\ \text{SENSOR} - \underset{\text{Offset}}{\boxed{0.00}}\ ]\ \text{x}\ \underset{\text{Scale}}{\boxed{0.00}} = \text{Current in}\ \boxed{\text{Units}} \qquad \text{Eq(5)}$$

The MR Task assumes that calibrated values of the *Scale* for each sensor is provided by the sensor manufacturer and the user should enter that value.

> NOTE: If the *Scale* value must be calibrated in place, please contact Radiant for assistance in establishing a procedure for the calibration.

The *Offset* value must be determined for each situation and each sensor. The reason is that the determination of the final value of the magnetic field will be sensitive to differences on the order of millivolts. Millivolt offsets that change with time are typical for external sensors and can be affected by temperature or changes in the positions of cables or the powered state of nearby equipment.

To capture the offset of the sensor being calibrated, set the sensor to a zero condition. For a current sensor, this means putting a shorting cable across the current-in and current-out terminals of the sensor. Gaussmeters typically have a zeroing function that must be activated. Once the sensor is zeroed, it may still output a small voltage. The user should click on the *Capture Offset* button in the SENSOR window. The tester will make multiple measurements of the specified SENSOR input, average the measurements, and place that averaged value in the *Offset* window.

> NOTE: The default *Offset* value for the RCSi is "0.0" and "2.5" for the RCSh.

The user may manually enter the values into the controls if desired.

> NOTE: The current sensor must have a frequency window of 20 kHz to be able to keep up with a 10 Hz MR Task execution. Typical bench-top ammeters or hand-held CVMs do not have this fast frequency response and should not be used for dynamic measurements. Any Gaussmeter used to directly capture the magnetic field at the sample must also have a 20 kHz frequency response.

Calculating the Maximum Test Frequency:
When sending an AC signal through a magnetic coil, the voltage required to generate the desired magnetic field strength may not exceed the maximum voltage the current amplifier has the capability to generate. The voltage across a magnetic coil arises from two sources:

$$V_{\text{Resistance}} = I \text{ x } R_{\text{Coil}} \qquad \text{Eq(6)}$$

$$V_{\text{Inductance}} = L\ \delta i/\delta t \qquad \text{Eq(2)}$$

"R_{Coil}" is the intrinsic resistance of the coil. "L" is the inductance of the coil. Combining the two effects yields Equation 7.

$$V(I) = I \text{ x } R_{\text{Coil}} + L\ \delta i/\delta t \qquad \text{Eq(7)}$$

The $\delta i/\delta t$ term in Eq (7) establishes that the faster the test, the greater the voltage required to move the same current through the coil to generate the same magnetic waveform. If a sine wave is used to drive the coil and I_{Peak} is defined as the current necessary to create the peak magnetic field in the Helmholtz coil, $\delta i/\delta t$ becomes

$$\delta i/\delta t = I_{\text{Peak}} \text{ x } \omega\cos(\omega t) = I_{\text{Peak}} \text{ x } 2\pi f\cos(\omega t) \qquad \text{Eq(8)}$$

At the peak current where $\cos(\omega t) = 1$, Equation 7 reduces to

$$V(I_{\text{Peak}}) = I_{\text{Peak}}\ [\ R_{\text{Coil}} + 2\pi fL] \qquad \text{Eq(9)}$$

As an example, the Lakeshore MH-6 Helmholtz coil has an inductance of 36 millihenries and a coil resistance of 10 Ω. It can accept a maximum of 2 amps. If it is driven with a Kepco 36-6 current amplifier with a maximum output voltage of 36 volts, the maximum frequency that can be executed by that combination of equipment is

$$36 \text{ volts} = 2 \text{ amps } [\ 10\ \Omega + 2\pi f \times 36 \text{ mH }]$$

$$18\ \Omega = 10\ \Omega + 2\pi f \times 36 \text{ mH}$$

$$8\ \Omega = 2\pi f \times 36 \text{ mH}$$

$$35 \text{ Hz} = f$$

Radiant does not recommend making MR Task measurements at 35 Hz with this equipment. Although it would technically meet the specifications, the Kepco current amplifier would be operating at its maximum power out, introducing phase delay and distortion into its output waveform. That distortion will “soften” any corners in the requested waveform, changing the apparent shape of the measured response. Radiant has arbitrarily established a 10 Hz maximum test limit for the MR Task.

Current Amplifier Resonance with the Helmholtz Coil:

It is possible for the current amplifier to form a resonant circuit with the Helmholtz coil. The result will be an oscillation of the magnetic field at a higher frequency than the test period. The instruction manual for the current amplifier will identify if this could be a problem and suggest solutions. In the case of the Kepco 36-6 current amplifier connected to the Lakeshore MH-6 Helmholtz coil, a resonance does occur. A 100 nF film capacitor placed across the current output terminals of the Kepco stops the oscillation. See the Data Section of this report for a plot of the before and after magnetic field.

Calibration Procedure:

The only absolute calibration reference available for the test configuration is current. Current can be measured with devices traceable to absolute NIST standards. The Gaussmeter cannot be calibrated directly by the user. The calibration value for the coil supplied by the manufacturer must be used. Consequently, the test configuration for determining the calibration of the magnetic field measurement is to put a NIST-calibrated current sensor in-line with the Helmholtz coil and the current sensor that will be used during MR Task execution. See Figure 2. The calibration is executed in DC states by setting a known voltage across the current amplifier and then capturing the values of the three sensors: 1) NIST-calibrated ammeter, 2) RCS, and 3) the Gaussmeter. A special Task named the “Read Sensor – Multi-read” Task has been implemented in Vision to facilitate this calibration procedure. This Multi-read Sensor Task will read both SENSOR1 and SENSOR2 and perform the necessary mathematics to convert the measured signals to current or magnetic field.

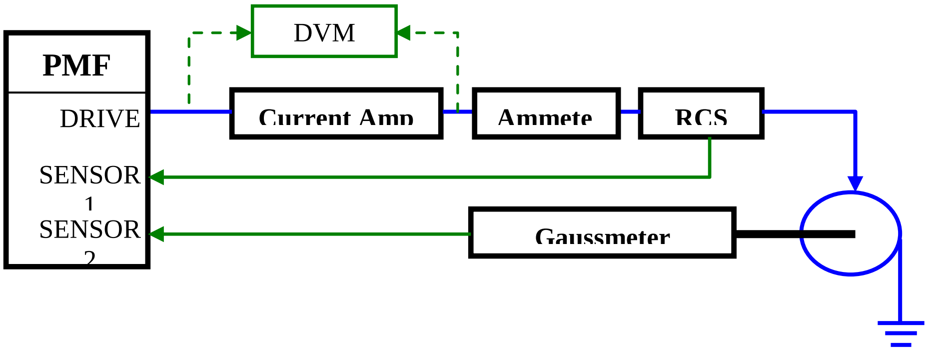
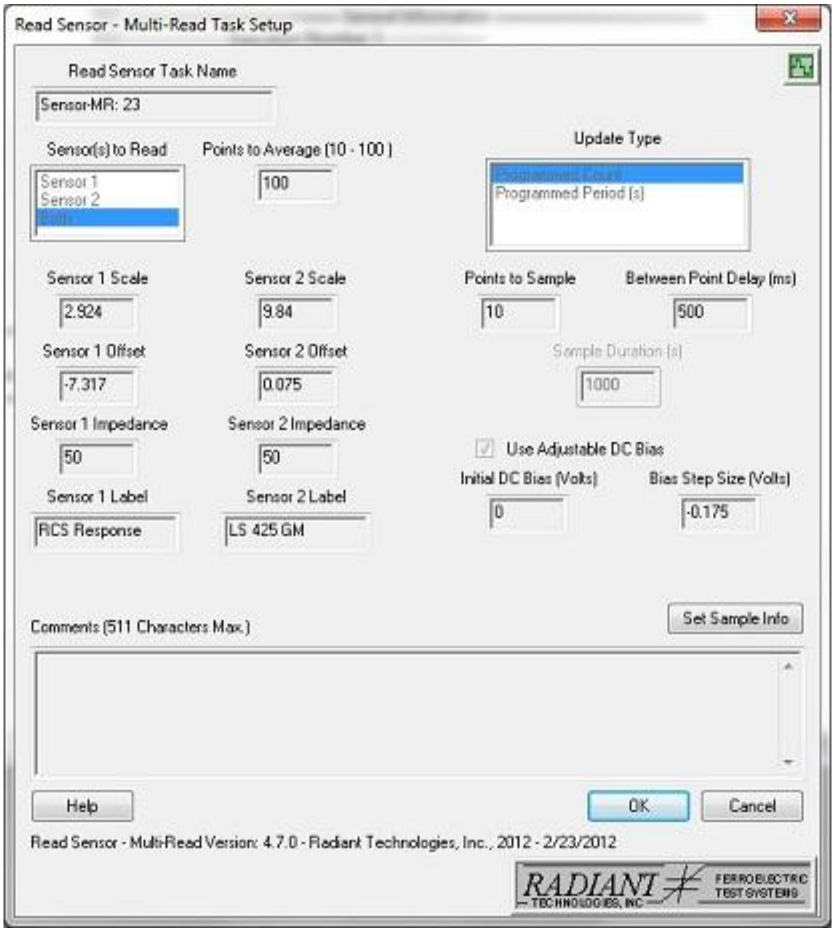


Figure 2: Static Magnetic Field Calibration Configuration

Figure 3 & 4 are pictures of the setup menu and the results page respectively for the Multi-Read Task.



Read Sensor Task Name: Sensor-MR: 23

Sensor(s) to Read: Sensor 1 / Sensor 2 / Both

Points to Average (10 - 100): 100

Update Type: Programmed Count / Programmed Period (s)

Sensor 1 Scale: 2.924

Sensor 2 Scale: 9.84

Points to Sample: 10

Between Point Delay (ms): 500

Sensor 1 Offset: -7.317

Sensor 2 Offset: 0.075

Sample Duration (s): 1000

Sensor 1 Impedance: 50

Sensor 2 Impedance: 50

☑ Use Adjustable DC Bias

Initial DC Bias (Volts): 0

Bias Step Size (Volts): -0.175

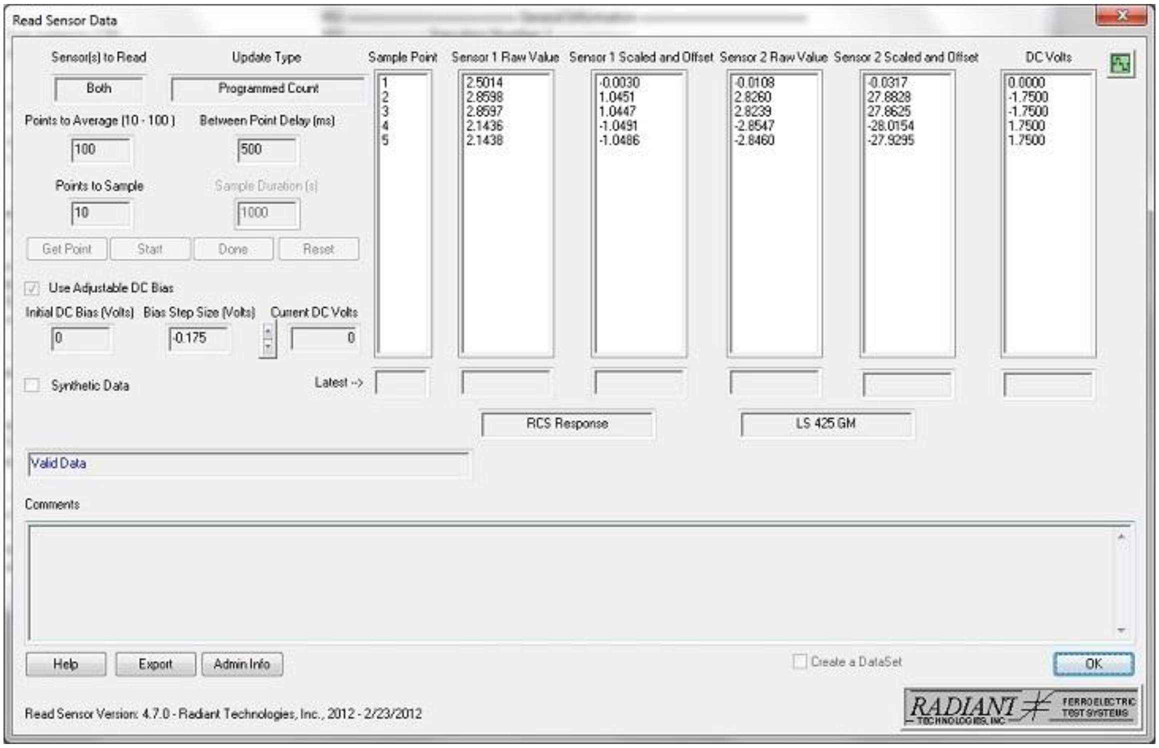
Sensor 1 Label: RCS Response

Sensor 2 Label: LS 425 GM

Comments (511 Characters Max.)

Read Sensor - Multi-Read Version: 4.7.0 - Radiant Technologies, Inc., 2012 - 2/23/2012

Fig. 3: Setup menu for the Read Sensor – Multi-Read Task.



Sensor(s) to Read: Both
Update Type: Programmed Count
Points to Average (10 - 100): 100
Between Point Delay (ms): 500
Points to Sample: 10
Sample Duration (s): 1000
☑ Use Adjustable DC Bias
Initial DC Bias (Volts): 0
Bias Step Size (Volts): -0.175
Current DC Volts: 0
☐ Synthetic Data

Sample Point	Sensor 1 Raw Value	Sensor 1 Scaled and Offset	Sensor 2 Raw Value	Sensor 2 Scaled and Offset	DC Volts
1	2.5014	-0.0030	-0.0108	-0.0317	0.0000
2	2.8598	1.0451	2.8260	27.8828	-1.7500
3	2.8597	1.0447	2.8239	27.8625	-1.7500
4	2.1436	-1.0491	-2.8547	-28.0154	1.7500
5	2.1438	-1.0486	-2.8460	-27.9295	1.7500
Latest -->					

RCS Response
LS 425 GM

Valid Data

Comments

☐ Create a DataSet

Read Sensor Version: 4.7.0 - Radiant Technologies, Inc., 2012 - 2/23/2012

Fig. 4: Results table for the Read Sensor – Multi-Read Task.

In the example of Figures 3 and 4, an RCSh is connected to SENSOR1 while a Lakeshore Model 425 Gaussmeter is connected to SENSOR2. The SENSOR1 *Scale* and *Offset* in Figure 3 are set to report the current seen by the RCSh. The SENSOR2 *Scale* in Figure 4 is set to report the magnetic field generated by the Helmholtz coil as seen by the Gaussmeter. The results of a few measurements are shown in Figure 4. Every time the "Get Point" button is pushed, the voltage set in the Current DC Volts window of Figure 4 is output for 5 seconds. The inputs SENSOR1 and SENSOR2 are measured at the end of the time period. The last line of results in Figure 4 shows that 1.75 volts was output from the tester into the Kepco 36-6 current amplifier. This should result in -1 amp of current through the coil and 26.76 Gauss of magnetic field. The scaled and offset output of SENSOR1 shows -1.0486 amps while the calculation for SENSOR2 shows -27.9295 Gauss.

Once the static accuracy of the system has been determined, the dynamic accuracy is then compared between the RCS and the Gaussmeter by executing the MR Task. The ammeter used as a calibration standard most likely will not be able to keep up with the execution of a 1 Hz or 10 Hz sine wave and should be ignored for the AC calibration.

Example Calibration:
The results below are the calibration results achieved at Radiant Technologies using a

1) KEPCO 36-6 current amplifier,
2) HP ammeter,
3) Fluke voltmeter,
4) RCSh,
5) Lakeshore Model 425 Gaussmeter with HMFT-3E03-VR Hall Effect probe, and
6) Lakeshore MH-6 Helmholtz coil.

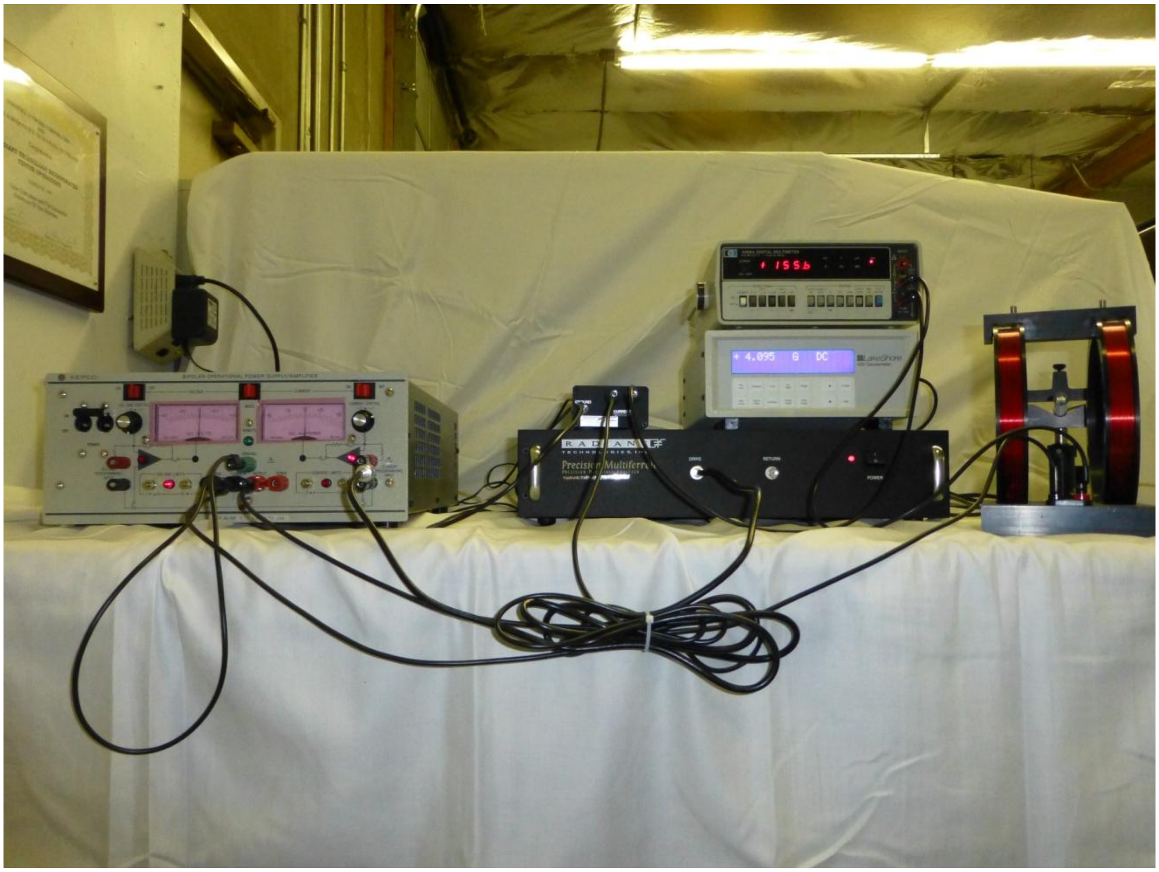


Fig.5: Photograph of test configuration.

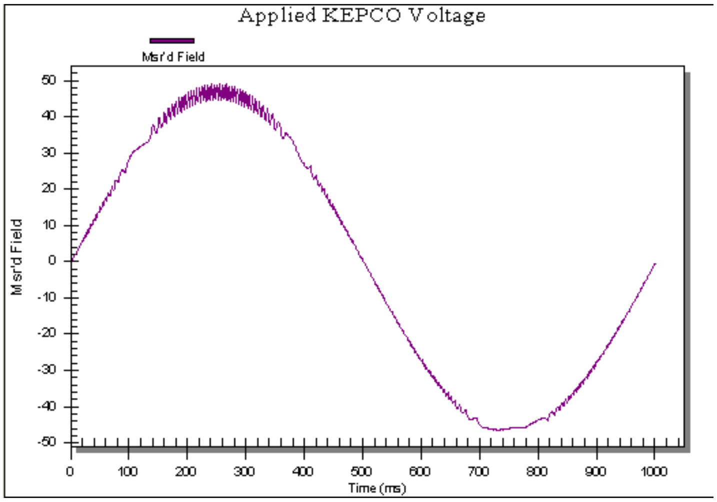
RCSh vs. NIST-Calibrated Ammeter - DC:
The graph below compares the current measurement reported by the RCSh compared to Radiant's NIST-traceable Fluke 8840A ammeter.

RCSh Gauss	Fluke Meter Gauss	Difference	Percent Difference
0.186	-0.161	0.347	186.304
-2.807	-2.783	-0.024	0.859
-5.616	-5.566	-0.050	0.893
-8.422	-8.376	-0.046	0.543
-11.244	-11.186	-0.058	0.519
-14.041	-13.969	-0.072	0.512
-16.859	-16.752	-0.107	0.635
-19.667	-19.588	-0.079	0.402
-22.466	-22.371	-0.095	0.422
-25.273	-25.154	-0.118	0.468
-28.072	-27.937	-0.134	0.478
-30.877	-30.747	-0.130	0.420
-33.688	-33.530	-0.157	0.467
-36.500	-36.340	-0.160	0.437
-39.311	-39.123	-0.187	0.477
-42.123	-41.933	-0.191	0.452
-44.925	-44.716	-0.209	0.466
-47.724	-47.526	-0.198	0.416
-50.557	-50.336	-0.222	0.438
-0.007	0.000	-0.007	100.000
2.793	2.783	0.009	0.340
5.600	5.566	0.034	0.604
8.400	8.376	0.024	0.284
11.223	11.186	0.037	0.333
14.029	13.969	0.060	0.427
16.843	16.779	0.064	0.381
19.646	19.562	0.084	0.428
22.443	22.345	0.099	0.440
25.250	25.128	0.122	0.484
28.064	27.937	0.127	0.452
30.876	30.747	0.129	0.418
33.687	33.530	0.157	0.466
36.492	36.340	0.152	0.417
39.305	39.123	0.182	0.464
42.098	41.933	0.165	0.392
44.910	44.716	0.194	0.432
47.708	47.499	0.209	0.438
50.540	50.336	0.205	0.405

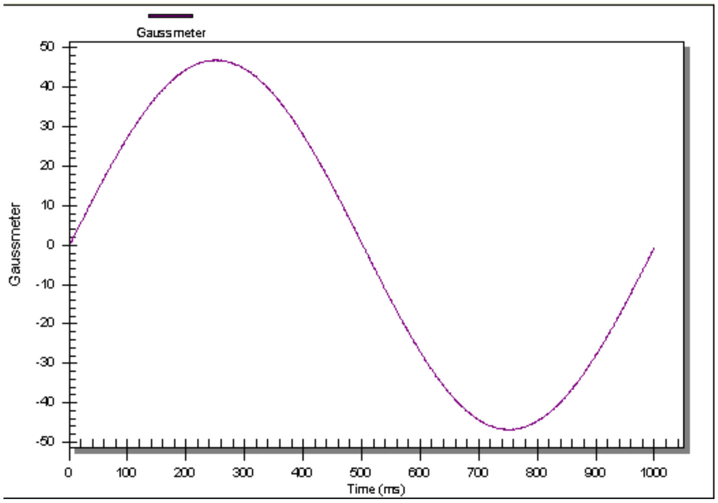
Fig.6: RCSh vs. Calibrated Ammeter

Kepco 36-6 Resonance with the Model 425 Gaussmeter - AC:

The Kepco 36-6 has a resonance with the Lakeshore MH-6 Helmholtz coil. Per the instructions for the Kepco amplifier, a 100 nF capacitor placed on the output terminals of the amplifier eliminated the resonance. The graph below shows the magnetic field measured by the Lakeshore Model 425 Gaussmeter and its Hall Effect probe with the resonance and after compensation by the capacitive load



Measured 1000 ms Field – Uncompensated



Measured 1000 ms Field – Compensated

Fig. 7: Coil resonance before and after compensation

Model 425 Gaussmeter vs. NIST-Calibrated Ammeter - DC:

In the graph below, the current through the MH-6 Helmholtz coil measured by Radiant’s NIST-traceable Fluke 8840A ammeter is multiplied by the Lakeshore-supplied IB ratio (26.76 Gauss/Amp) to estimate the coil’s magnetic field and compare it to the output of the Lakeshore Model 425 Gaussmeter with its HMFT-3E03-VR Hall Effect probe.

Model 425 Gauss	Fluke Meter Gauss	Difference	Percent Difference
-0.552	-0.161	0.347	-62.817
-3.519	-2.783	-0.024	0.685
-6.296	-5.566	-0.050	0.797
-9.062	-8.376	-0.046	0.504
-11.860	-11.186	-0.058	0.492
-14.638	-13.969	-0.072	0.491
-17.405	-16.752	-0.107	0.615
-20.166	-19.588	-0.079	0.392
-22.970	-22.371	-0.095	0.412
-25.752	-25.154	-0.118	0.459
-28.513	-27.937	-0.134	0.471
-31.304	-30.747	-0.130	0.414
-34.079	-33.530	-0.157	0.462
-36.862	-36.340	-0.160	0.433
-39.614	-39.123	-0.187	0.473
-42.405	-41.933	-0.191	0.449
-45.187	-44.716	-0.209	0.463
-47.962	-47.526	-0.198	0.414
-50.739	-50.336	-0.222	0.437
-0.739	0.000	-0.007	0.941
2.036	2.783	0.009	0.466
4.813	5.566	0.034	0.703
7.560	8.376	0.024	0.315
10.348	11.186	0.037	0.361
13.165	13.969	0.060	0.455
15.926	16.779	0.064	0.403
18.700	19.562	0.084	0.450
21.477	22.345	0.099	0.460
24.252	25.128	0.122	0.504
27.053	27.937	0.127	0.469
29.821	30.747	0.129	0.433
32.604	33.530	0.157	0.481
35.370	36.340	0.152	0.430
38.160	39.123	0.182	0.478
40.938	41.933	0.165	0.403
43.700	44.716	0.194	0.444
46.493	47.499	0.209	0.449
49.268	50.336	0.205	0.416

Fig. 8: Gaussmeter vs. Helmholtz coil current

RCSh vs. Model 425 Gaussmeter – AC:
The AC test was executed using the MR Task. The dynamic magnetic field values measured by SENSOR1 (RCSh) and SENSOR2 (Gaussmeter) were exported directly from the Magnetic Field vs. Time plot option in Vision.

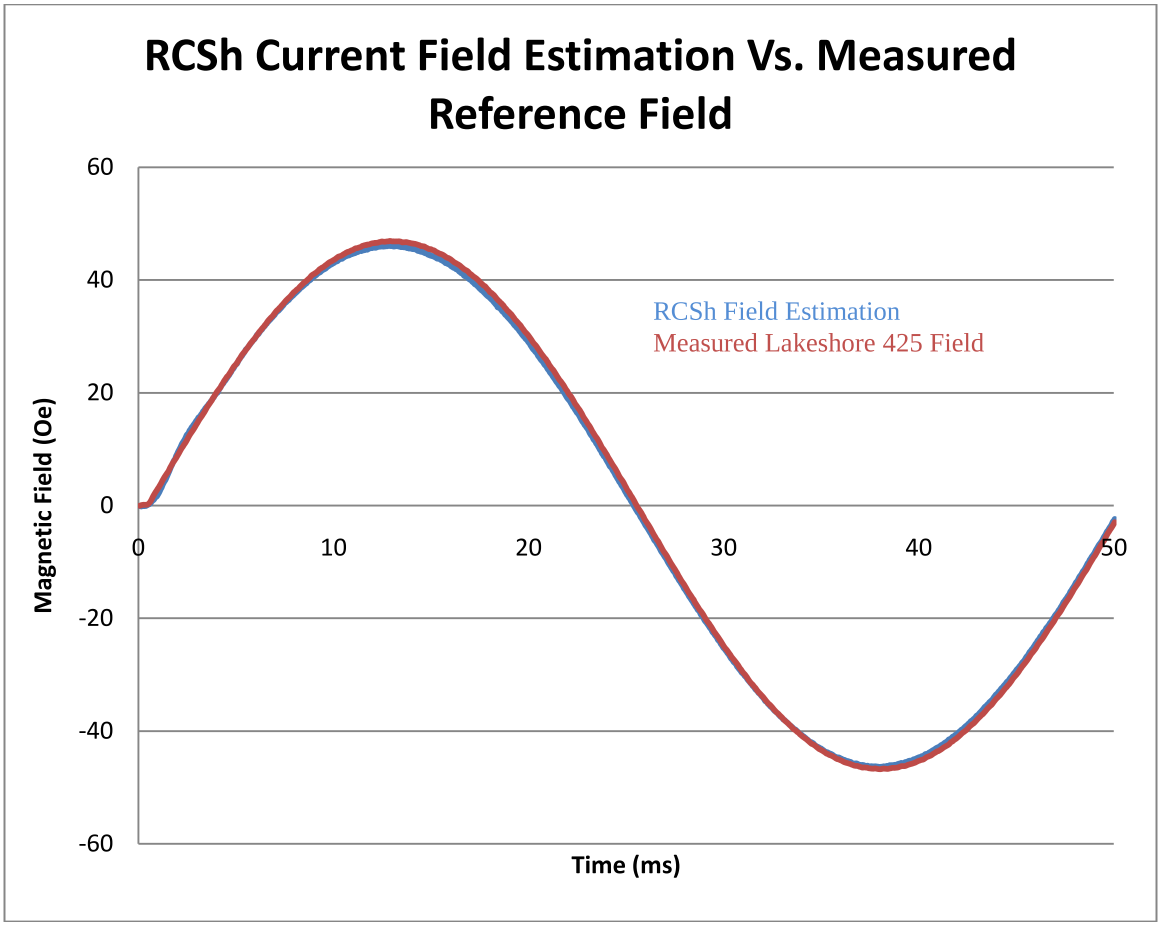


Fig. 9: Comparison of RCSh estimation and Gaussmeter measurement during 20 Hz sine wave.

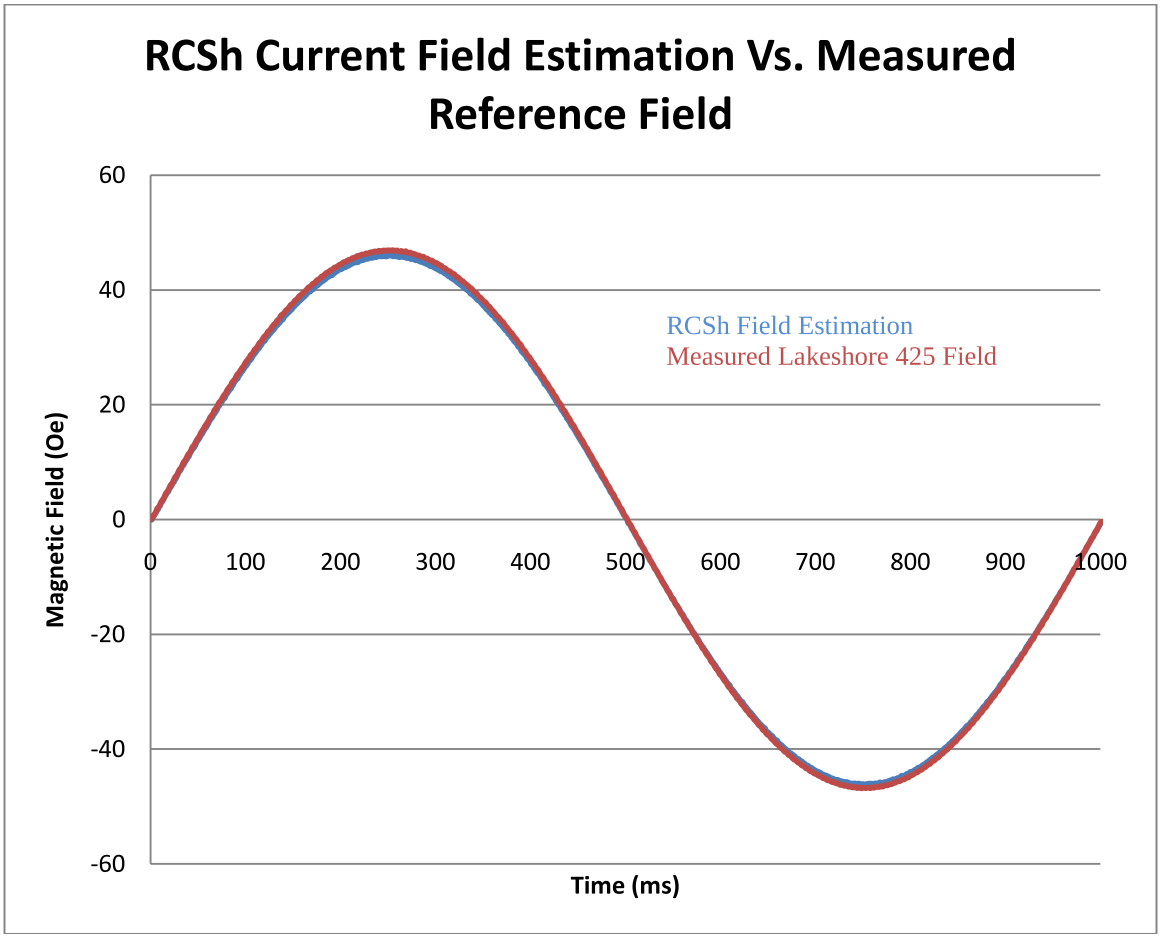


Fig. 10: Comparison of RCSh estimation and Gaussmeter measurement during 1 Hz sine wave.

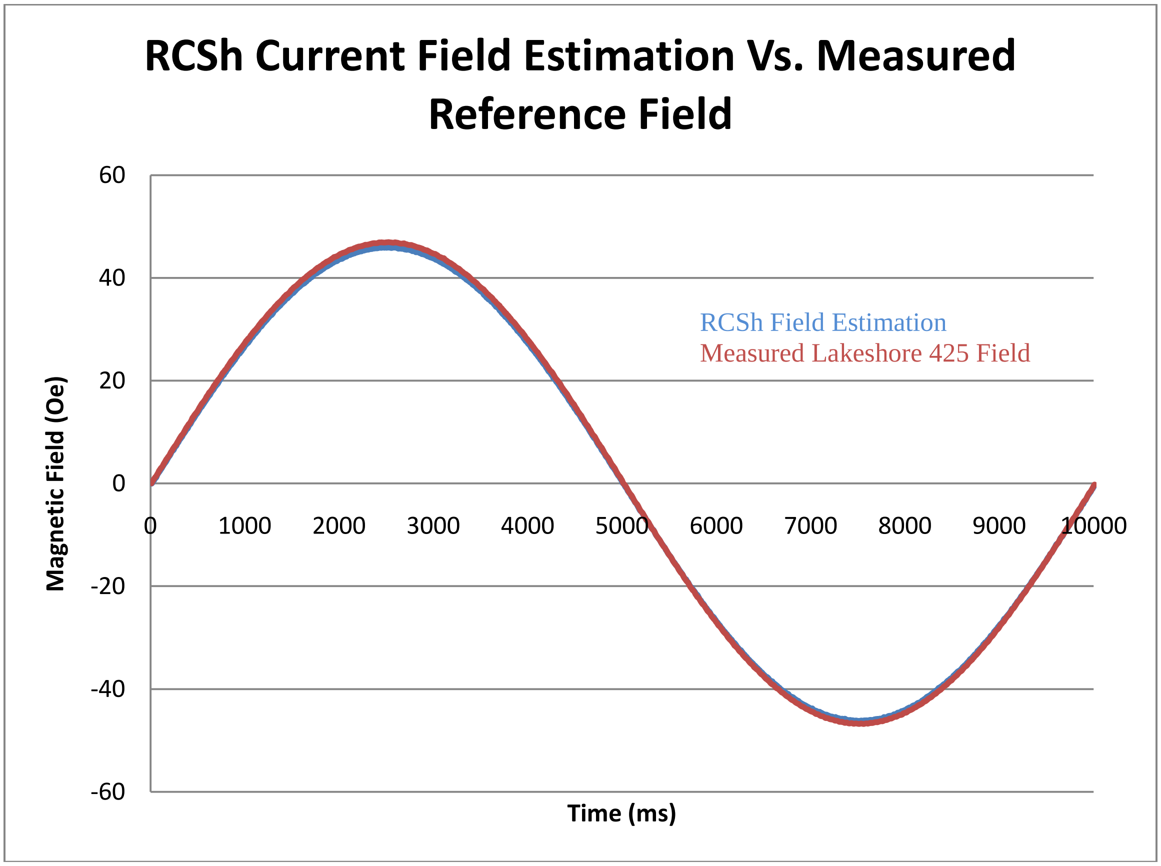


Fig. 11: Comparison of RCSh estimation and Gaussmeter measurement during 0.1 Hz sine wave.

Analysis:
Using the NIST-traceable Fluke 8840A ammeter and the B/I ratio of the MH-6 Helmholtz coil as the center reference, the RCSh DC values were within 0.86 % of the reference and the Model 425 Gaussmeter were within 0.94 % of the reference at DC Bias. For the 1 Hz AC measurement, subtracting the RCSh estimation from the Gaussmeter measurements yields a maximum differential of 1.14 (Oe) at 46.8 Oe, a 2.44 % variance between the two. Note that the response of the Model 425 (or any) Gaussmeter is highly dependent on the test wand positioning and orientation. The Model 425 Gaussmeter has a DC specification from Lakeshore of ±0. 2%, however in order to incorporate subtle errors in wand positioning, RTI is assuming a Lakeshore accuracy of ±1.0 %. In a periodic signal, a constant variation will yield a variable percentage error over the signal period, with a much higher percentage error at lower signals. Furthermore, comparing the RCSh sinusoidal signal to the Model 425 Gaussmeter is not a comparison to a firm reference standard, but to a standard with variable error. Using these measured values and measured and assumed limits, an accuracy of between ±1.5 % and ±2.5 ± is assumed for the RCSh at 1.0 Hz. Note that the ±45 Oe signal is very near the lower limit of RCSh measurements. The RCHi is expected to produce much more accurate results at lower signal strength.

Conclusion:

There is a reasonable expectation that the Lakeshore Model 425 Gaussmeter with the HMFT-3E03-VR Hall Effect probe does meet its specified ±0.2% accuracy during a 1 Hz MR Task execution. This expectation only holds *as long as the hall Effect probe is perpendicular to the applied magnetic field.* The user can expect ±2.5% minimum accuracy in the magnetic field values using a Radiant Current sensor in-line with the Helmholtz coil.