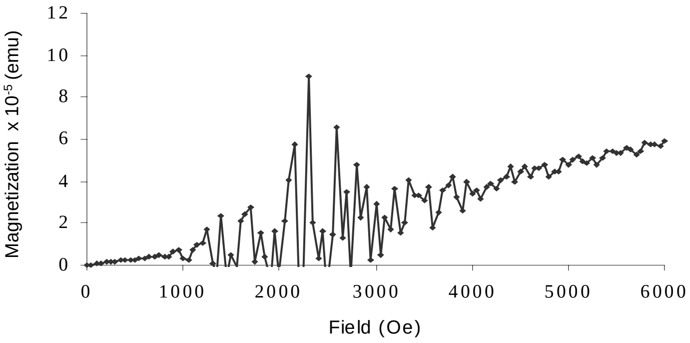
Quantum Design

MPMS Service Note 1014-820

Characterization of Magnet Noise in Superconducting Magnets When Charging the Magnetic Field in Unidirectional Steps

Overview

This service note outlines the effects of magnet noise that may take place when unidirectional incremental charging steps are used during a field sweep. The noise is most typically seen in step scan DC measurements in the region of 1,000 Oe to 4,500 Oe when relatively small charging steps are used and data are collected immediately following a change in field. This noise region has been identified on systems equipped with 1 T, 5 T, 5.5 T, and 7 T superconducting magnets and results from inherent properties of all superconducting magnets. An example of this noise region is shown in **Figure 1**. The data shown in Figure 1 were collected using a field independent paramagnetic sample.



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

Figure 1. Example of data collected in magnet noise region using a field independent paramagnet.

Objective

You may use this service note as a guide to minimize noise due to nonlinear SQUID drift. It is for those who collect data within the field region of 1,000 Oe and 4,500 Oe using relatively small field changes.

Origin of Magnet Noise

The noise shown in **Figure 1** results from flux creep in the superconducting magnet. As flux creep occurs, the magnetic field at the detection coils changes, causing the SQUID voltage to drift. On the time scale of a single measurement scan, "normal" SQUID drift appears in the raw voltage as an offset that is virtually linear (**Figure 2a**). This linear component of the drift can be accounted for (subtracted) when the magnetic moment of the sample is calculated.

The MPMS control system has the ability to compensate for large linear SQUID drifts. However, the SQUID detection system of the MPMS is unable to compensate for nonlinear SQUID drifts (**Figure 2b**). In fact, the strongly nonlinear SQUID drift is ultimately responsible for the noise shown in Figure 1. Examples of strong linear and nonlinear SQUID drifts are shown in Figure 2. Charging the magnet in 50 Oe steps using the No Overshoot Mode collected data for Figure 2. Immediately following each incremental 50 Oe field change, the SQUID voltage (at a constant 0.00125 emu range) was recorded as a function of time. The voltage response for Figure 2a was collected at 50 Oe (before the noise region); the voltage response for Figure 2b was collected at 2,200 Oe (within the noise region).

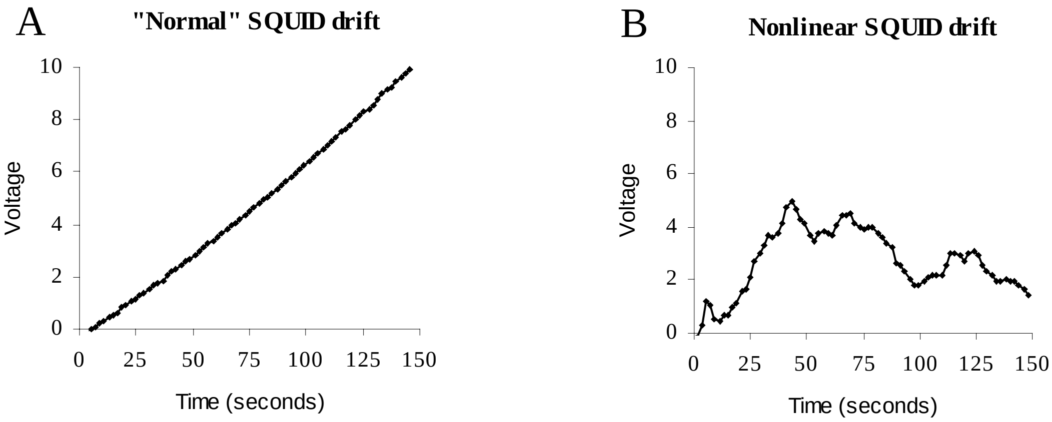


Figure 2. Voltage response curves for (a) nominally linear SQUID drift and (b) strongly nonlinear SQUID drift.

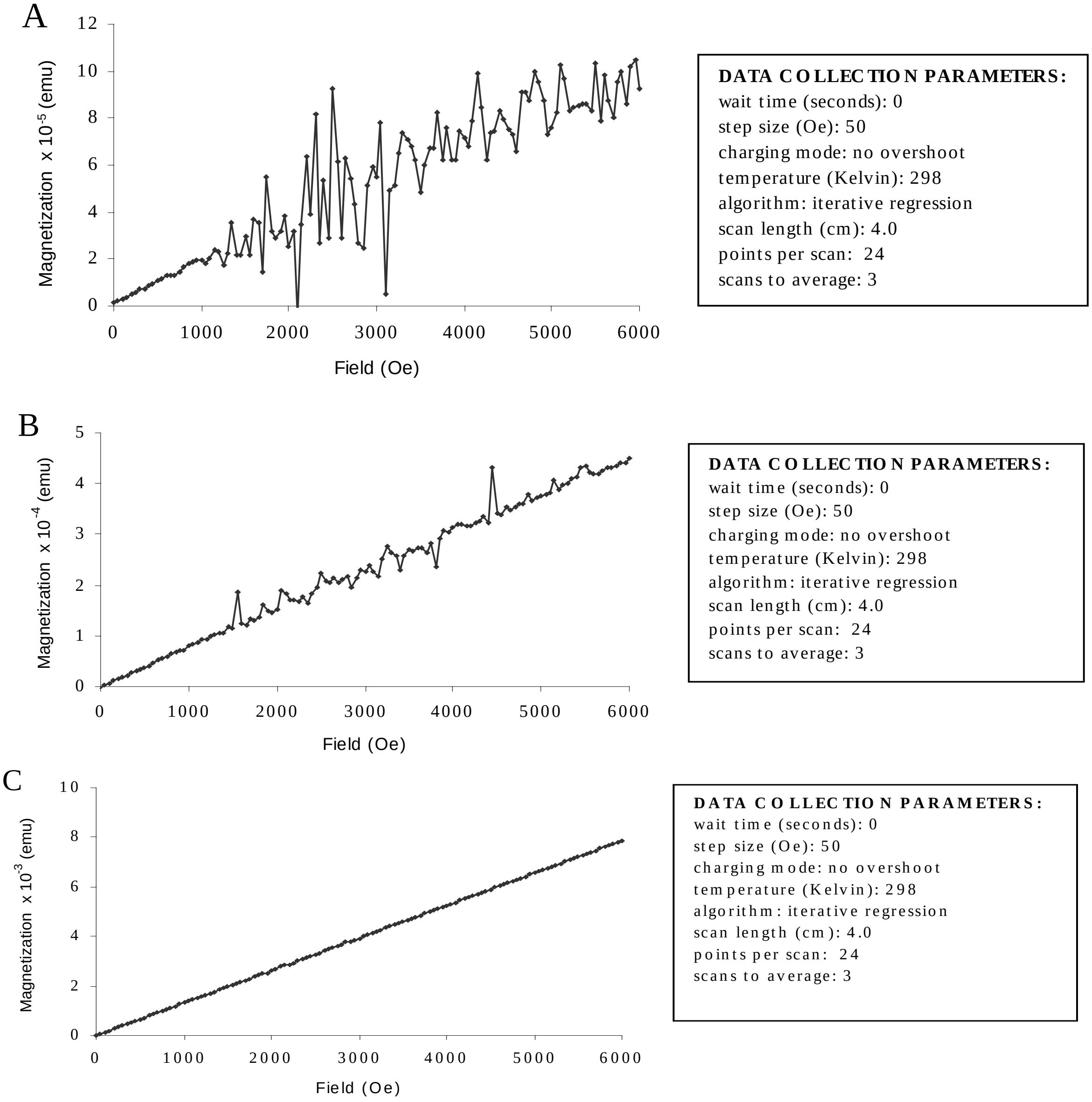
We want to emphasize that, depending on signal intensity and experimental time limitations, the noise (due to nonlinear SQUID drift) in this field region can generally be minimized, if not eliminated, with specific instrumental techniques. The goal of this application note is two-fold: to identify the trouble areas in superconducting magnets by characterizing this noise region and to outline ways that enable users to minimize the effects of magnet noise while collecting data.

The magnitude of the noise is dependent upon several experimental variables including relative signal intensity, magnet charging mode, wait time (time between charging the magnet and taking a measurement), and step size (incremental field changes). Detailed effects of these variables are described in the next section.

Dependence of Magnet Noise on Data Collection Parameters

Relative Signal Intensity Dependence

The relative magnitude of the noise in this field region does **not** scale with signal intensity. Samples with weak magnetic signals are affected by the noise more than samples with large magnetic signals. **Figure 3** shows the effects of magnet noise on samples with signal intensities in the 10^{-5} emu, 10^{-4} emu and 10^{-3} emu ranges. Data for **Figures 3a-c** were collected using identical data collection parameters; the data collection parameters for each set of data are reported to the right of each plot. The DC step scan measurements were collected immediately following a field change (no wait time). Figure 3 shows you that the relative intensity of the noise decreases as signal intensity increases. As the signal approaches 10^{-3} emu, the noise is virtually nonexistent.



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

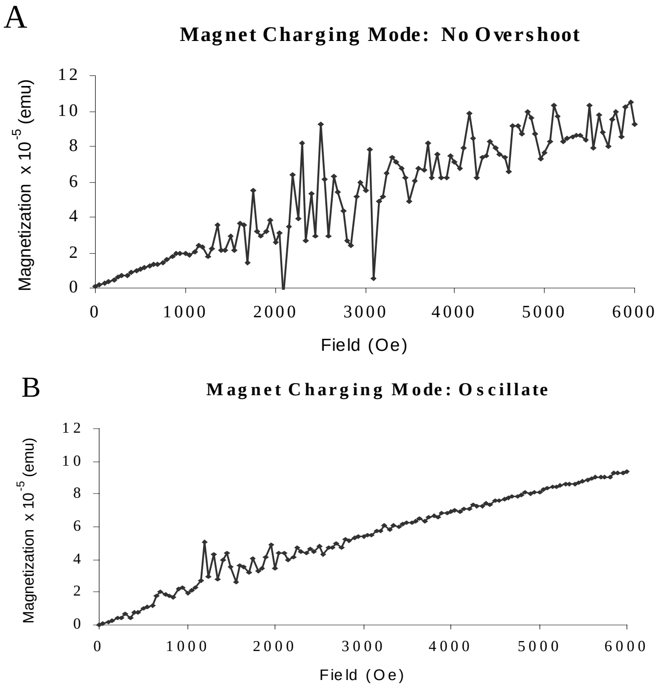
Figure 3. Comparison of relative signal intensity dependence on magnet noise for (a) 10^{-5} emu, (b) 10^{-4} emu, and (c) 10^{-3} emu sgnals.

All data outlined in the remaining portion of this application note were collected using a sample with a relatively small intensity signal (in the 10^{-5} emu range) to maximize the effects of magnet noise. The same field independent paramagnetic sample was used in each of the following experiments.

Magnet Charging Mode Dependence

The two modes available for making field changes in the MPMS are No Overshoot Mode and Oscillate Mode. As outlined in Application Note 1014-208, flux creep is generally minimized in MPMS systems when the magnetic field is set using the Oscillate Mode. The Oscillate Mode forces the magnet to relax during the charging process by cycling it through a series of smaller and smaller hysteresis loops. The No Overshoot Mode approaches the target field without reversing the sign of the field (ideal for samples displaying hysteretic behavior). As a result, the drift in the SQUID detection system immediately following a field change will be much greater when using the No Overshoot Mode.

As shown in **Figure 4**, the relative magnitude of the experimental noise (due to nonlinear SQUID drift) is dependent on the charging mode of the magnet when a measurement is taken immediately following 50 Oe field changes. Magnet noise is accentuated when using the No Overshoot charging mode (**Figure 4a**) in comparison to the Oscillate Mode (**Figure 4b**) when measurements are collected immediately following a field change. This is because the magnet requires more relaxation time following a field charge when using the No Overshoot mode. The data collection parameters for each set of data are reported to the right of each plot.



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: **no overshoot**
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: **oscillate**
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

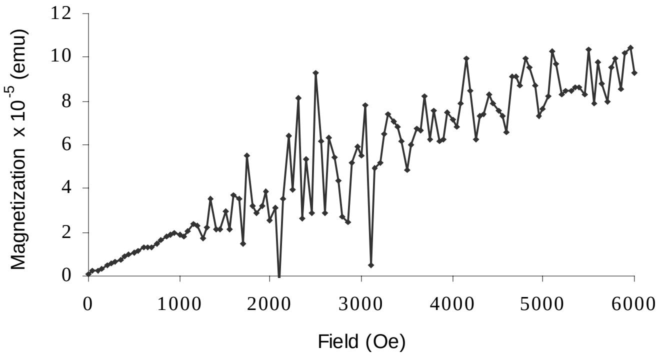
Figure 4. Below is a comparison of two magnet charging modes on magnet noise: (a) No Overshoot Mode and (b) Oscillate Mode.

Wait Time Dependence

Wait time is defined as the amount of time following a field change before the first measurement is collected. It is best to include a wait time (following a field change) to allow the field to relax and eliminate excessive drift in the SQUID detection system of the MPMS. As outlined in Application Note 1014-208, measurements requiring the highest possible sensitivity should be delayed for five to ten minutes following a change in the magnetic field. **Figure 5** shows the effect of including various wait times on the intensity of the noise.

A

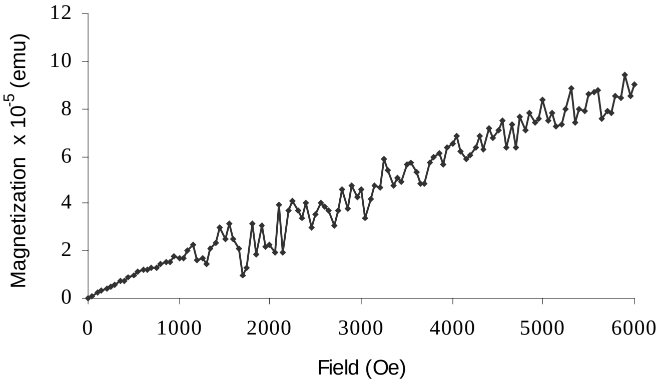
Wait Time: 0 Seconds



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

B

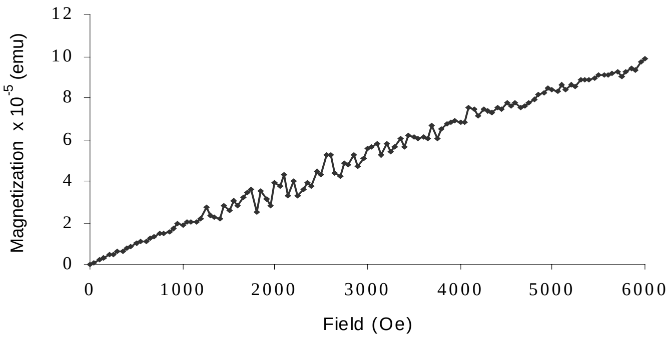
Wait Time: 60 Seconds



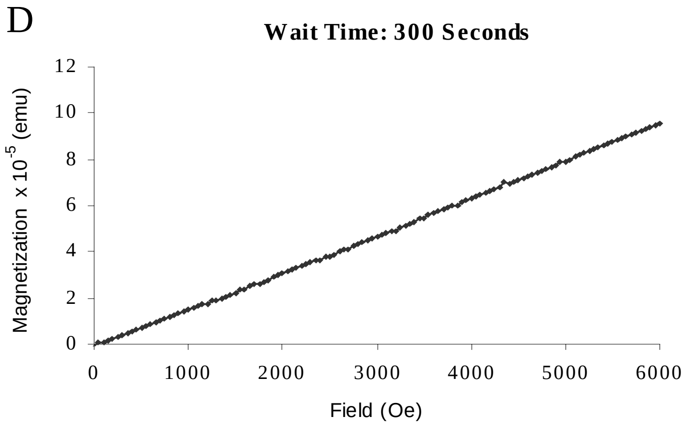
DATA COLLECTION PARAMETERS:
wait time (seconds): 60
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

C

Wait Time: 120 Seconds



DATA COLLECTION PARAMETERS:
wait time (seconds): 120
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3



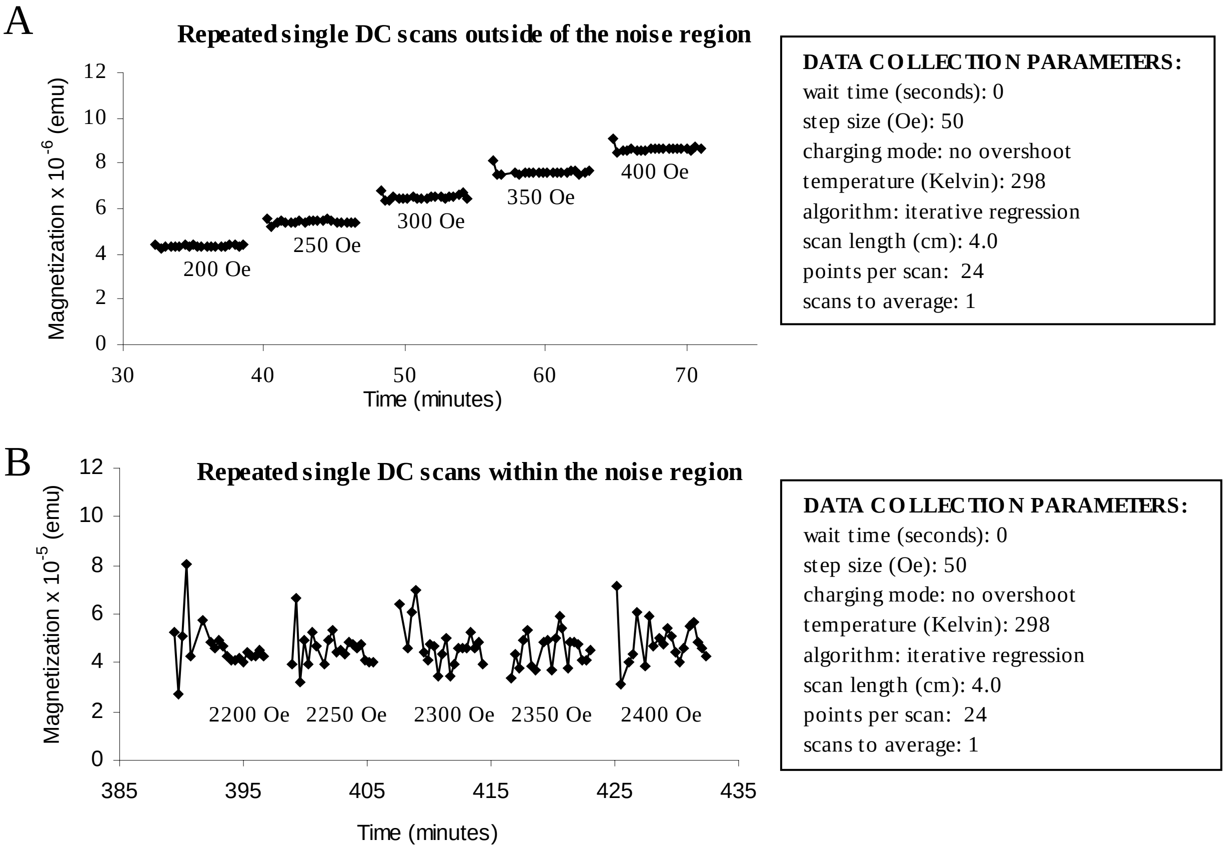
DATA COLLECTION PARAMETERS:
wait time (seconds): 300
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

Figure 5. Comparison of wait time dependence on magnitude of magnet noise:
(a) zero wait time, (b) 60-second wait time, (c) 120-second wait time, and (d) 300-second wait time.

The data shown in Figure 5a were collected immediately following a field change; the data shown in Figures 5b-d had 60-second, 120-second, and 300-second wait times, respectively. It is important to note that the No Overshoot charging mode (the magnet charging mode most susceptible to field drift following a field change) was used to collect the data shown in these plots.

A 60-second wait time results in an extreme minimization of noise in this region (relative to zero wait time). When comparing the 120-second wait time in Figure 5c with a 60-second wait time in Figure 5b, a less dramatic but still significant effect is seen in the reduction of noise. A 300-second wait time in Figure 5d virtually eliminates the effects of noise.

The addition of a wait time after the magnet is charged and before the measurement is taken allows the field to relax and ultimately results in a reduction in both the linear and nonlinear drift of the SQUID detection system. **Figure 6** shows the results of 20 repeated single DC scans measurements for data outside of the noise region (**Figure 6a**) and within the noise region (**Figure 6b**). Before the noise region (Figure 6a), where the SQUID drift is predominantly linear and can be subtracted from the raw voltage readings consistently, the single DC scans are reproducible almost immediately following a field change. In contrast, nonlinear SQUID drift (an inconsistent baseline) results in scatter in the apparent magnetization (Figure 6b) when repeated measurements are collected within the noise region.



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 1

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 1

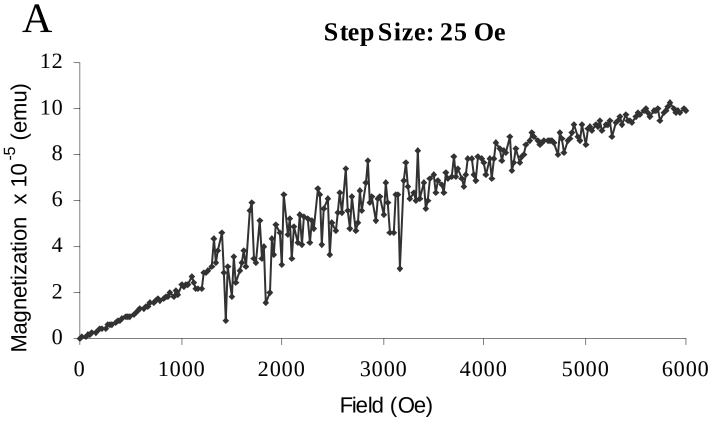
Figure 6. Comparison of 20 repeated single DC scans (a) outside of the noise region and (b) inside of the noise region.

Step size dependence

The step size is defined by the increment in which the field is charged during a field sweep. When there is no wait time between magnet charging and data collection, smaller field increments result in relatively larger nonlinear SQUID drifts. As a result, the apparent noise in this region is more intense when small increments are used. **Figure 7** shows the effects of increasing the step size on the relative magnitude of noise.

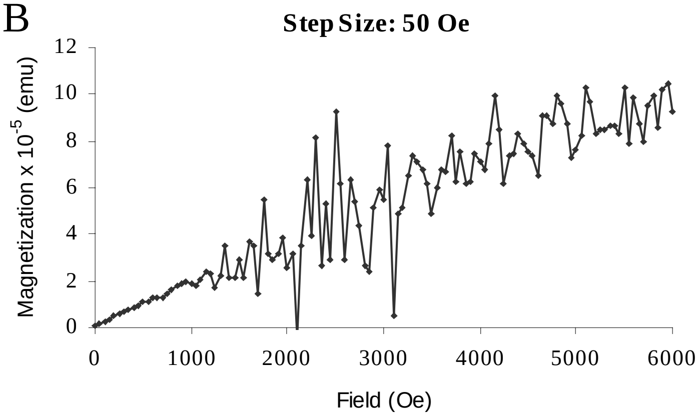
The plots shown in Figure 7 were all collected immediately after the magnet was charged (zero wait time). The data collection parameters for each set of data are reported to the right of each plot. Figure 7 clearly shows that increasing the step size during a field sweep results in a decrease in magnet noise (when the noise is due to nonlinear SQUID drift).

A



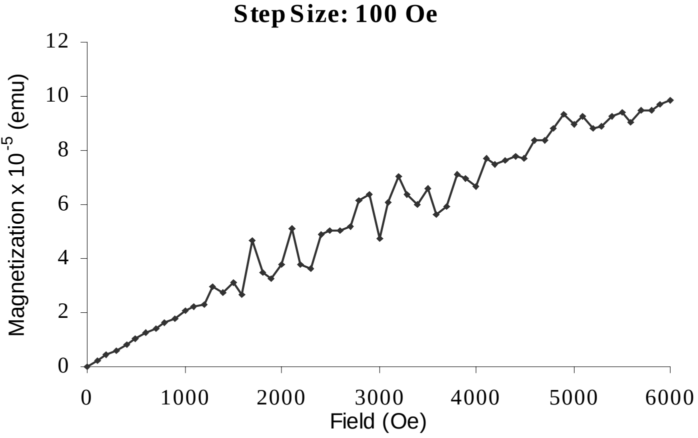
DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 25
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

B

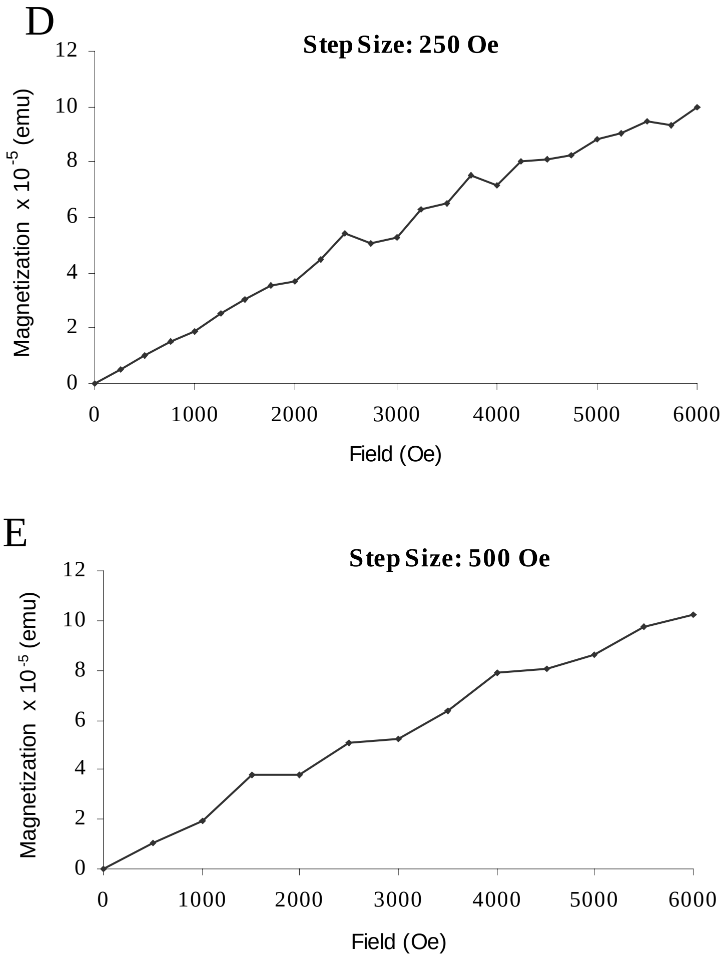


DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

C



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 100
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3



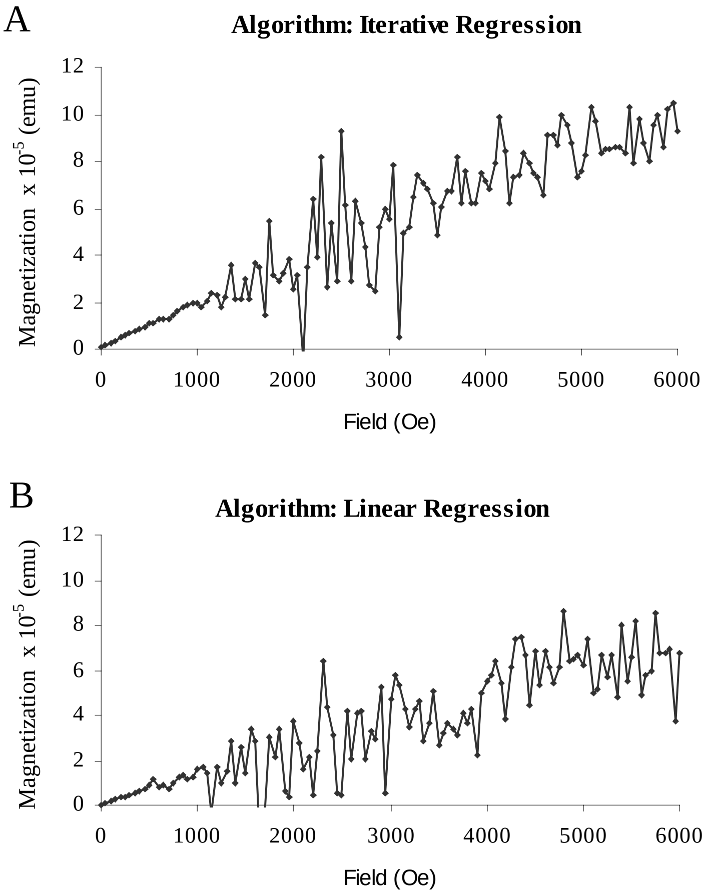
DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 250
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 500
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

Figure7. Plot of step size dependence of magnet noise for (a) 25 Oe steps, (b) 50 Oe steps, (c) 100 Oe steps, (d) 250 Oe steps, and (e) 500 Oe steps.

Measurement and Algorithm Independence

The relative magnitude of the noise has been found to be **independent** of algorithm (linear regression vs. iterative regression). You can find detailed descriptions of the measurement algorithms in Application Note 1014-203, which is available on the Quantum Design web site under "User Resources" (User Name: intl, Password: src72i) followed by "Technical Bulletins/Service Notes" at http://www.quandsn.com. You can also find these measurement algorithm descriptions in Section 3.4 of the MPMS Reference Manual. **Figure 8** displays the independence of algorithm on magnet noise intensity; the data collection parameters for each set of data are reported to the right of each plot.



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: linear regression
scan length (cm): 4.0
points per scan: 24
scans to average: 3

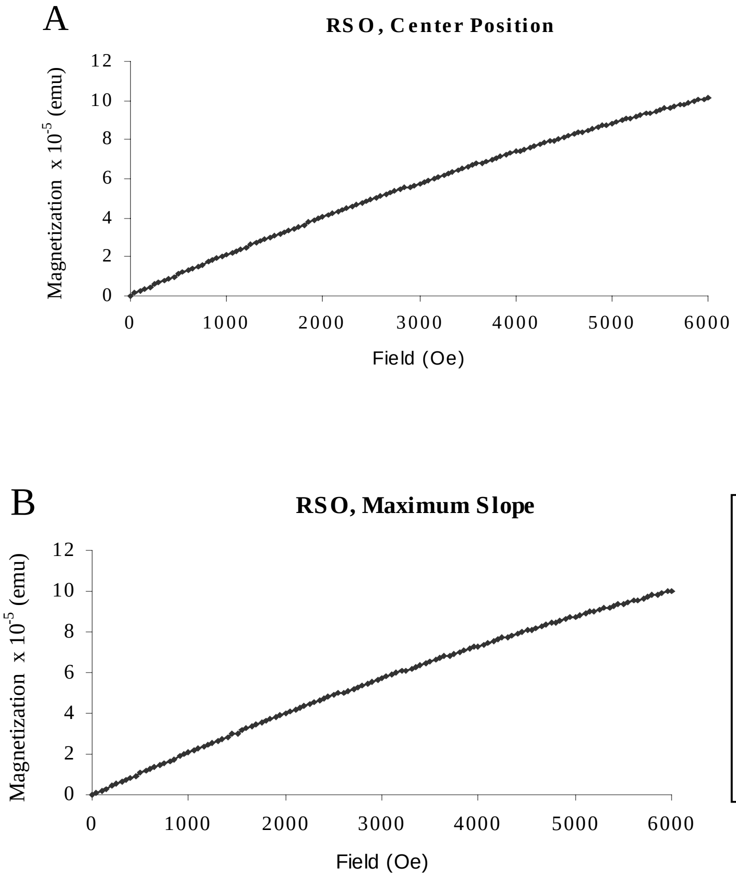
Figure 8. Plot of magnet noise region using (a) iterative regression and (b) linear regression algorithms.

Using the Reciprocating Sample Option (RSO)

The Reciprocating Sample Option (RSO) provides an alternative means of extracting DC magnetization. There are several advantages to using the RSO, including rapid data acquisition times and high sensitivity. More specifically, a Digital Signal Processor (DSP) incorporated in the RSO allows for much more rapid data collection than the standard step scan method. The DSP also decreases the contribution of low frequency noise during data collection, resulting in maximum sensitivity.

Rapid data acquisition provided by the RSO allows you to collect much more data in a given amount of time relative to the step scan technique. As a result, noise can be “averaged out” more easily using the RSO. More importantly, because each individual RSO measurement is collected in a fraction of the time required for a step scan measurement, the resulting signal is less susceptible to the effects of nonlinear SQUID drift that are addressed in this application note. A combination of signal averaging and minimized exposure to field variations make the RSO a reasonable and very practical way of eliminating magnet noise due to nonlinear SQUID drift.

Figures 9a and **9b** show the results of using the RSO to collect data in the magnet noise region using two RSO measurement techniques, center position and maximum slope (see the MPMS Reciprocating Sample Option section in the MPMS Options Manual for detailed descriptions of these measurement types). Data collection parameters for each set of data are reported to the right of each plot. Note that the data shown below were collected using a small step size (50 Oe), zero wait time, and No Overshoot charging mode; magnet noise was maximized when using these data collection parameters with step scan magnetization (see Figure 1).



DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: iterative regression
amplitude (cm): 3.0
frequency (Hz): 1.0
cycles: 15
measurements per cycle: 3

DATA COLLECTION PARAMETERS:
wait time (seconds): 0
step size (Oe): 50
charging mode: no overshoot
temperature (Kelvin): 298
algorithm: linear regression
amplitude (cm): 1.0
frequency (Hz): 4.0
cycles: 15
measurements per cycle: 3

Figure 9. Plot of data collection using the RSO option (a) center and (b) maximum slope.

Summary

The most reliable way of minimizing the effects of magnet noise due to nonlinear SQUID drift is to use the RSO for data collection. If you must use step scan DC magnetization, a wait time (effectively a pause between magnet charging and data collection) should be included in the sequence (see Figure 5). Because the magnitude of the magnet noise is **not** proportional to signal intensity (see Figure 3), samples with smaller signals may require substantially longer wait times than samples with relatively large signals. Similarly, an increase in step size (incremental change in field) or charging the magnet in oscillate mode will result in noise minimization (see Figures 4 and 7). Remember that optimum data collection parameters may vary from sample to sample.