The Performance of the Model 7400 VSM: Sensitivity

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Introduction

Measuring the magnetic properties of thin magnetic films and hetero-structures that comprise current and future generation magnetic recording materials is becoming increasingly difficult owing to the decreasing magnitude of the magnetic moment signal that is to be measured. In addition there are continuing demands for higher and higher field strengths. Many VSM manufacturers specify a "best case" noise/sensitivity and field range without clearly stating the conditions under which such specifications are achievable. In this application note we will discuss these issues and present measurement data on the new Lake Shore Model 7400 VSM which features sensitivity of 1×10^{-7} emu (0.1 µemu). The trade-offs in VSM performance based on noise, field, and sample size are discussed.

The Model 7400 includes three different models based on variable-gap 4-inch, 7-inch and 10-inch electromagnets. These magnets allow for simple reconfiguration of the magnet gap to accommodate varying sample sizes (up to 25 mm), or to achieve maximum field strengths of 1.8, 2.3, and 3.1 T, respectively, for small sample specimens (up to 3 mm). The Model 7400 also features patented[a] technology that leads to stability of 0.05% *per day,* which surpasses the stability of any other commercial VSM.

Noise/Sensitivity

The sensitivity of a VSM depends on a number of factors:

- Electronic sensitivity
- Noise rejection through signal conditioning
- Amplitude and frequency of mechanical drive
- Thermal noise of sensing coils
- Optimized coupling (proximity) of sensing coils to the sample under test
- Vibration isolation of the mechanical head assembly from the electromagnet and VSM sensing coils
- Minimization of environmental mechanical and electrical noise sources that can deleteriously affect VSM sensitivity

The voltage induced in the VSM sensing coils is given by:

$$V_{emf} = mAfS$$

Where:
m = magnetic moment
A = amplitude of vibration
f = frequency of vibration
S = sensitivity function of VSM sense coils

It is clear from this expression that increasing A, f, or S will improve moment sensitivity. S may be increased by either increasing the coupling between the sense coils and the sample under test (i.e., minimize gap spacing), or by increasing the number of windings contained in the sense coils. The former places constraints on the physical size of the sample that may be measured while the latter requires more sophisticated electronics, owing to impedance matching considerations (i.e., between coils and electronics), and capacitive and inductive effects that increase with increased windings.

The Model 7400 VSM may be configured with interchangeable sense coils, one optimized for small samples (740EMSC), and one optimized for large samples (740ESC). To show the effects of sense coil coupling on VSM sensitivity, noise measurements were conducted at various sensing coil gaps for both coil sets. These noise measurements were also conducted at various sampling rates to gauge the effect of signal averaging on VSM noise. These test results are tabulated in Table 1 and Table 2 for the 740EMSC and 740ESC coils, respectively.

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[a] Patent pending: Electromechanical Drive for Magnetometer

Table 1: 740EMSC RMS noise *vs*. gap *vs*. average-time-per-point

Sensing Coil Gap (mm)	10 s/pt[b] (µemu)	1 s/pt[c] (µemu)	0.1 s/pt[d,e] (µemu)
3.5	0.070	0.232	0.439
5	0.129	0.356	0.690
7.5	0.153	0.495	1.020
10	0.259	0.784	1.600
15	0.628	1.896	3.852
20	0.843	2.802	5.617
25	1.427	4.367	8.814

Table 2: 740ESC RMS noise *vs*. gap *vs*. average-time-per-point

Sensing Coil Gap (mm)	10 s/pt[b] (µemu)	1 s/pt[c] (µemu)	0.1 s/pt[d,e] (µemu)
3.5	0.161	0.500	1.250
5	0.203	0.597	1.491
7.5	0.231	0.708	1.825
10	0.302	0.993	2.549
15	0.495	1.721	4.048
20	0.787	2.400	5.727
25	1.349	3.748	8.973

Figure 1 shows typical results of a noise test at 3.5 mm sensing coil gap using the 740EMSC sense coils. This noise test consisted of 60 points at 10 s/pt sampling (i.e., 10 min measurement).

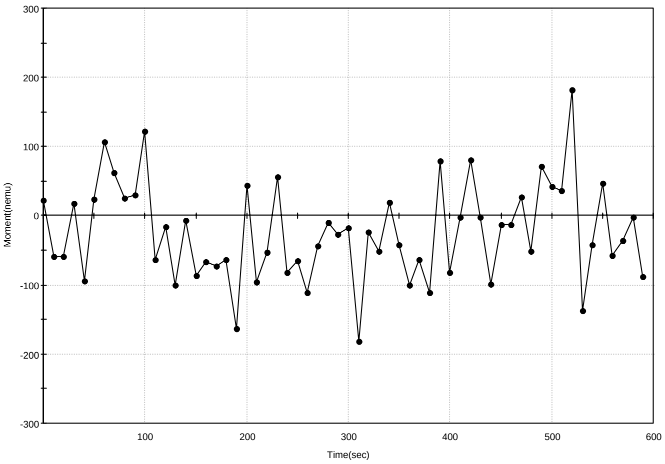

Figure 1: 740EMSC RMS noise test at 3.5 mm sensing coil gap and 10 s/pt sampling – note that the moment (vertical) axis scale is in nemu

Figures 2 and 3 graphically show the results presented in Tables 1 and 2, respectively.

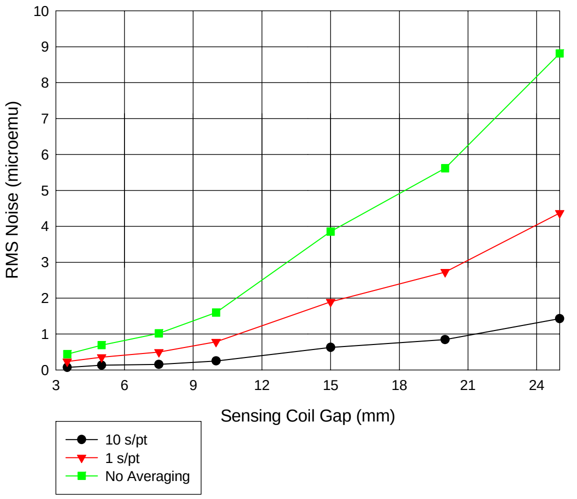

Figure 2: RMS noise *vs.* sensing coil gap and *vs.* sample averaging for 740EMSC sense coils

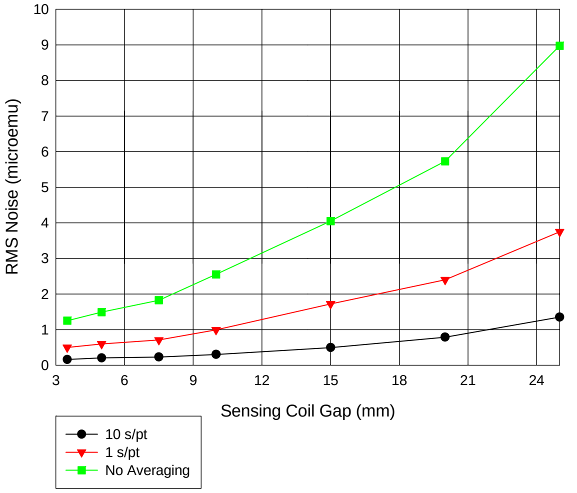

Figure 3: RMS noise *vs.* sensing coil gap and *vs.* sample averaging for 740 ESC sense coils

Figure 4 shows the 740EMSC and 740ESC coil results superposed for sample averaging periods of 10 s/pt and 1 s/pt. Note that the 740EMSC coils produce superior RMS noise characteristics for gaps less than 12 mm, while the 740ESC coils perform marginally better at larger gaps.

At a gap of 3.5 mm the measured RMS noise for the 740EMSC coils is 7×10^{-8} emu at 10 s/pt averaging which approaches the sensitivity achievable using SQUID and force-based magnetometers. Further, even at 1 s/pt the RMS noise is better than 0.25 µemu.

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[b] RMS value based on 10 min measurement consisting of 60 points at 10 s/pt.

[c] RMS value based on 10 min measurement consisting of 600 points at 1 s/pt.

[d] RMS value based on 10 min measurement consisting of 6000 points at 0.1 s/pt.

[e] This is defined as “no averaging” by some manufacturers.

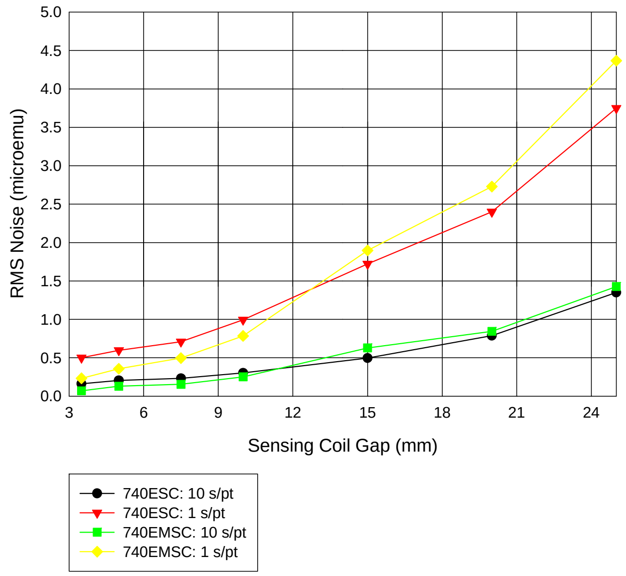

Figure 4: RMS noise *vs.* sensing coil gap and *vs.* sample averaging for 740EMSC and 740ESC sense coils

This means that very fast loop measurements are possible without significant degradation in signal-to-noise ratio (SNR). A hysteresis loop consisting of 180 points at 10 s/pt will take 30 min, while at 1 s/pt only 3 min is required to execute the measurement.

Sample Size: Noise *vs.* Field Strength

In some circumstances it may be preferable to measure samples with larger physical dimensions as they produce larger moment signals and are easier to handle. This however must be balanced against the increased noise, and the reduced field strengths at larger gaps. Consider a hypothetical example – three film samples with identical thickness *t* but with different areas. Table 3 shows that the signal-to-noise-ratio improves as the sample area increases.

Table 3: Sample area *vs.* Signal to Noise Ratio

Sample Area (mm^2)	3 × 3 = 9	6 × 6 = 36	10 × 10 = 100
M$_S$ (μemu)	10	40	111
RMS Noise (μemu)	0.07[f]	0.15[g]	0.28[h]
SNR[i]	28.5	53.3	79.3

This, however, must be balanced against the field strengths required to fully saturate any given material, e.g., high anisotropy materials.

The Model 7400 includes three different models based on variable-gap 4-inch, 7-inch and 10-inch electromagnets. Maximum field strengths versus magnet gap and versus maximum sample size are tabulated in Table 4 for each configuration.

Table 4: Field Strength *vs.* Magnet Gap

Magnet Gap (mm)	16	23	38
Maximum Sample Size (mm)	3	10	25
4-inch EM (51 mm)[j]	1.8 T	1.45 T	1.0 T
7-inch EM (76 mm)[j]	2.3 T	2.1 T	1.65 T
10-inch EM 50 mm)[j]	3.1 T	2.85 T	2.15 T

Typical Measurement Results for Low Moment Samples

As an illustration of the performance capabilities of the Model 7400, typical low moment measurement results are presented below for three different thin film samples.

Figures 5, 6, and 7 show M(H) loop data at a sensing coil gap of 3.5 mm for a thin film sample with saturation moment of only 12.5 μemu. These loops were recorded at sampling times of 10 s/pt, 5 s/pt, and 1 s/pt, corresponding to total loop measurement times of 35 min, 17 min, and 3.5 min, respectively. These are measured results with no corrections (i.e., linear or background corrections) applied to the data. The peak-to-peak noise in Figures 5 and 7 is better than 1 μemu and 3 μemu, respectively, and is completely consistent with the RMS noise values tabulated in Table 1 at a sensing coil gap of 3.5 mm at 10 s/pt and 1 s/pt sampling, respectively.

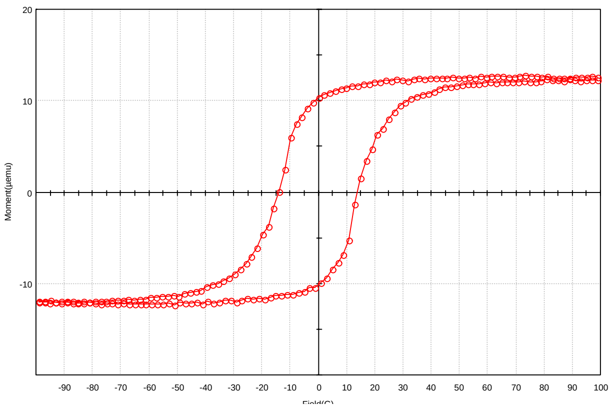

Figure 5: M(H) at 10 s/pt sampling

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[f] Assumes 3.5 mm sensing coil gap at 10 s/pt sampling

[g] Assumes 7 mm sensing coil gap at 10 s/pt sampling

[h] Assumes 11 mm sensing coil gap at 10 s/pt sampling

[i] SNR defined here as M_S/(5 x RMS)

[j] Pole cap diameter

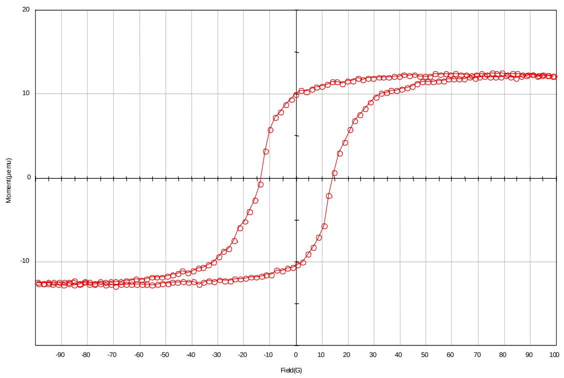

Figure 6: M(H) at 5 s/pt sampling

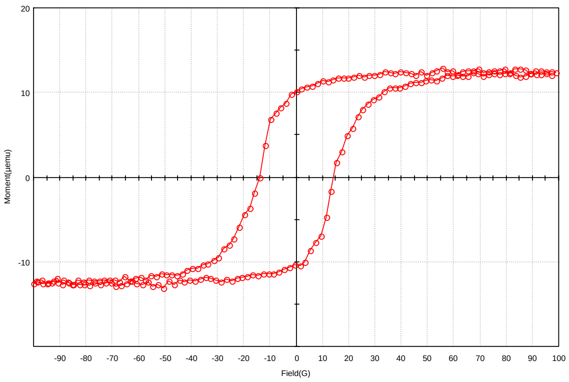

Figure 7: M(H) at 1 s/pt sampling

Figure 8 shows M(H) loop results for a CoPt thin film sample with saturation moment of only 11 μemu. These data were recorded at a 3.5 mm sensing coil gap at 10 s/pt sampling, and the results have been corrected for signal contributions arising from the VSM sample holder, i.e., M = M(sample + holder) – M(holder). The peak-to-peak scatter in these results is somewhat higher than the scatter in figure 5 (i.e., at the same sampling rate) because the noise in the processed data goes as the square root of the sum of the squares of the RMS noise in each data set, i.e., M(sample + holder) and M(holder).

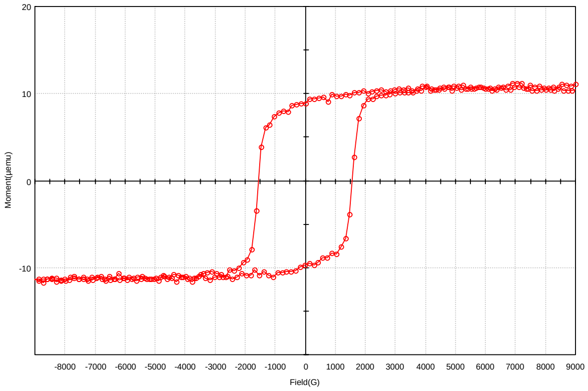

Figure 8: M = M(sample + holder) – M(holder) for a CoPt thin film

Figure 9 shows M(H) loop results for a patterned NiFe (permalloy) film sample with saturation moment of only 7 μemu. These data were recorded at a 5 mm sensing coil gap at 10 s/pt sampling, and the data that is shown is the raw data without any manipulation or background correction applied. The peak-to-peak noise in this measurement is less than 1 μemu.

These results show the excellent sensitivity that is achievable with Lake Shore Model 7400 VSM systems.

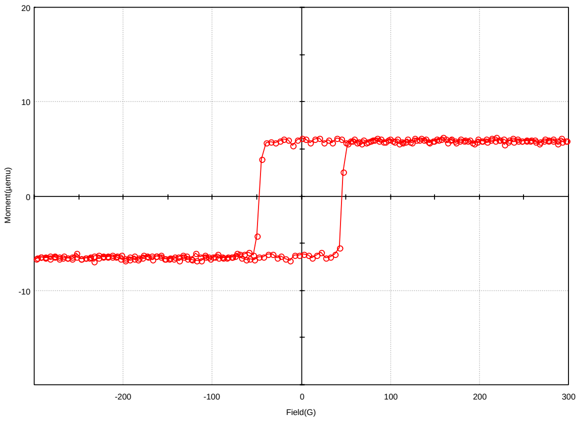

Figure 9: M(H) at 10 s/pt for a patterned NiFe film

Summary

Many VSM manufacturers cite noise/sensitivity and field range specifications without qualifying the conditions under which such specifications are achievable. In this note we have presented noise/sensitivity and field range data of the Model 7400 VSM as a function of sensing coil gap, sample averaging and sample size. The utility of the Model 7400 VSM for measurement of low moment magnetic materials has been demonstrated with the presentation of measurement results for low moment thin films. The Model 7400 features:

1. Better than 0.1 μemu sensitivity at 10 s/pt sampling and 16 mm air gap
2. Better than 0.4 μemu and 0.75 μemu at 1 s/pt and 0.1 s/pt, respectively, allowing faster data acquisition cycles without significant sacrifices in signal-to-noise
3. Variable-gap magnets provide for maximization of either sample size or applied field strength