Characterization of noise sources in a microfabricated single-beam zero-field optically-pumped magnetometer

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S. P. Krzyzewski,^{a)} A. R. Perry, V. Gerginov, and S. Knappe

AFFILIATIONS

University of Colorado Boulder, Boulder, Colorado 80309, USA

^{a)}Sean.Krzyzewski@Colorado.edu

ABSTRACT

We present an experimental noise characterization of a miniature single-beam absorption-based optically-pumped magnetometer with a noise floor of $7 \text{ fT/Hz}^{1/2}$ operating in the spin-exchange relaxation-free regime. We experimentally evaluate noise arising from the laser intensity, laser frequency, laser polarization, cell temperature, and magnetic field coils used for the phase-sensitive detection of the magnetometer signal. We find that noise in the range between DC and 30 Hz is a result of noise sources coupling to the atoms in a manner similar to a magnetic field, while the noise at frequencies above 30 Hz is mainly due to laser intensity noise. Our results place an upper limit on the noise sources for our system that matches well with the noise spectrum of the magnetometer at frequencies above 5 Hz.

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I. INTRODUCTION

Optically-pumped magnetometers have seen a recent rise in popularity due to new optical interrogation schemes, new fabrication methods for vapor cells, miniaturization of components, and inexpensive lasers.¹ Uses for optically-pumped magnetometers include geophysical surveys for archeology,² detection of magnetic anomalies such as unexploded ordnances,³ medical applications such as the recording of magnetic fields from the heart^{4,5} and brain,⁶ petroleum exploration,⁷ quantum communication,⁸ and magnetic field sensing in space.¹ Schwindt *et al.*⁹ constructed the first chip-scale atomic magnetometer based on coherent population trapping. Microfabricated magnetometers have since been further developed, and zero-field versions have been used for high sensitivity applications inside magnetically-shielded environments, namely, magnetocardiography,¹⁰ magnetoencephalography,¹¹ and remotely detected nuclear magnetic resonance.¹² Arrays of optically-pumped magnetometers have been developed for use in medical imaging.^{13,14}

In most optically-pumped magnetometers, the magnetic moment of a gas of alkali atoms is aligned through optical pumping. When a static magnetic field B_0 is applied to the atoms in a direction perpendicular to the optical pumping direction, the magnetic moment precesses about the magnetic field at the Larmor frequency $\omega_L = \gamma B_0$,

where γ is the gyromagnetic moment. Typically, the performance of optically-pumped magnetometers is limited by spin-exchange collisions, where interactions between the alkali atoms lead to a destruction of spin orientation. These limitations can be overcome in the spin-exchange relaxation-free (SERF) regime,^{15,16} reaching magnetic field sensitivities in the attotesla range.¹⁷

Operating magnetometers in the SERF regime has led to compact sensors with sensitivities approaching those of superconducting quantum interference devices. However, noise sources can limit the applicability of the sensors, especially at low frequencies. General noise sources inherent to magnetometers such as spin projection noise and photon shot noise have been previously discussed¹ and are calculated to be below $1 \text{ fT/Hz}^{1/2}$ for our microelectromechanical systems (MEMS) based cell.¹⁸ A number of noise sources inherent to the use of microfabricated cells with SERF sensors have been previously discussed.¹⁹ The study described in Ref. 19 was performed with a microfabricated vapor cell in a perpendicular pump-probe configuration by monitoring the polarization rotation of a far detuned probe beam. While this scheme achieves very good performance,²⁰ it is difficult to implement in a compact sensor design. In this study, we quantify the limiting noise sources in a single-beam absorption-based method.^{20,21}

II. EXPERIMENTAL METHOD

We use microfabricated vapor cells for the system evaluations presented here with the goal of developing manufacturable sensors in small integrated packages. The cells are made by anodically bonding borosilicate glass windows to a silicon wafer with a hole etched through it, a fabrication method previously described in Refs. 22 and 23. The inner cell dimensions are $3 \times 3 \times 3 \text{ mm}^3$. The cell is filled with roughly 1 amagat of N_2 gas and a droplet of ^{87}Rb . The nitrogen broadens the linewidth of the optical D1 line resonance to approximately 18 GHz.²⁴ The cell is placed in a stereolithographically-printed enclosure with glass windows to thermally isolate the vapor cell. Four sides of the enclosure are surrounded by an insulating aerogel-based fabric (Pyrogel 2250 Hydrophobic Flexible Aerogel) to further reduce heat losses. The aerogel was cleaned using compressed air to remove magnetic particulates. An optical fiber delivers roughly 780 mW of light at 1550 nm to the silicon body of the vapor cell that is painted black for the increased absorption of the heating light. The cell is heated to approximately 160 °C for optimal performance. The entire package is mounted onto an acrylic rod and inserted into a magnetically-shielded enclosure.

The magnetic shield consists of four layers of mu-metal and an additional inner layer of MnZn ferrite with a calculated noise floor of $2 \text{ fT/Hz}^{1/2}$ at 1 Hz.²⁵ Three orthogonal sets of magnetic field coils are used to shim the magnetic field zero to the location of the atoms.

The experimental setup is shown in Fig. 1. The wavelength of a distributed Bragg reflector (DBR) laser with a linewidth of roughly 1 MHz is tuned to the center of the pressure-broadened ^{87}Rb D1 line. The laser light is delivered from the DBR laser to the experiment via a polarization-maintaining optical fiber. The laser beam is passed through a zero-order half-wave plate, an acousto-optic modulator (AOM), expanded to a $1/e^2$ diameter of 2 mm, and passed through a zero-order half-wave plate and linear polarizer. A tilted glass slide reflects a small fraction of the beam onto a photodiode.

FIG. 1. The experimental setup. Light from a distributed Bragg reflector (DBR) laser is coupled into a fiber (not shown). The output light passes through a half-wave plate (HWP), an acousto-optic modulator (AOM), a second HWP, and a linear polarizer (LP). A part of the light is split off with a glass slide (GS) and detected with a photodiode (PD) to lock the intensity of the light. The rest of the light passes through a second linear polarizer, a quarter-wave plate (QWP), and the Rb vapor cell that is enclosed in a magnetic shield (not shown). The transmitted light is detected with a photodiode and the signal is sent to a lock-in amplifier (LIA). The field coils are modulated by the output of the lock-in amplifier.

The output of the photodiode is used to stabilize the laser intensity through a servo with feedback to the AOM. The beam next passes through a second linear polarizer, a zero-order quarter-wave plate to circularly polarize the beam and is detected with a second photodiode after the vapor cell. The power of the light before and after the cell is 1.6 mW and 100 μW , respectively, for an optical density of roughly 1.2.

Parametric modulation measures the magnetometer signal with lock-in detection.^{21,26} In our parametric modulation, a 100 nT oscillating magnetic field (roughly an order of magnitude larger than the dynamic range of the sensor) transverse to the laser beam is applied at $\omega_m = 1.77 \text{ kHz}$, generated by the lock-in amplifier driving Helmholtz coils in series with a 1.2 k Ω resistor. The signal from the photodiode is phase-sensitively demodulated. The output signal of the lock-in amplifier yields a dispersive lineshape as the transverse magnetic DC field parallel to ω_m is slowly swept through zero by a solenoid coil controlled by a voltage source over a 2 k Ω resistor. This same coil is used to null the background magnetic fields in the sensitive direction ($\hat{z}$). The background field is not actively nulled. We find that the field is stable over the course of the measurements. The lock-in technique suppresses many low-frequency noise components from temperature drifts, air currents, and laser intensity.²⁷ Both of the lock-in amplifier outputs, in- and out-of-phase with respect to the reference signal, are recorded and the amplitude spectral densities (ASD) of the voltage outputs are measured with a spectrum analyzer. The out-of-phase signal corresponds to the magnetometer output, while the in-phase signal is insensitive to fluctuations in the magnetic field and is used to monitor the noise on the light.

A. Noise measurements

In the following discussion, we define a right-handed coordinate system with the direction of the laser beam propagation along $\hat{x}$, and the external magnetic field to be along $\hat{z}$. If the atoms are exposed to a magnetic field transverse to the laser beam, which consists of a DC component $B_0 = \gamma^{-1}\omega_L\hat{z}$ and an oscillating component $B_m = \gamma^{-1}\omega_1\cos(\omega_mt)\hat{z}$, the atomic polarization along the laser beam ($\hat{x}$) can be approximated by^{26,30}

$$P_x = P_0 \left(J_0^2 \left(\frac{\omega_1}{\omega_m} \right) \frac{1}{1 + (\omega_L\tau)^2} + J_0 \left(\frac{\omega_1}{\omega_m} \right) J_1 \left(\frac{\omega_1}{\omega_m} \right) \frac{\omega_L\tau}{1 + (\omega_L\tau)^2} \sin(\omega_mt) \right), \quad (1)$$

where $P_0 = \frac{R_{OP}}{R_{OP} + \Gamma_2}$ is the equilibrium spin polarization, R_{OP} the optical pumping rate, and Γ_2 is the spin relaxation rate. J_0 and J_1 are Bessel functions of the first kind, ω_L is the Larmor frequency, and $\tau = (R_{OP} + \Gamma_2)^{-1}$. The first term is responsible for the absorptive Lorentzian lineshape of the magnetic DC signal, while the second causes the dispersive Lorentzian line of the out-of-phase component of the lock-in amplifier signal. There is no term oscillating at $\cos(\omega_mt)$, which corresponds to the in-phase component of the lock-in amplifier. The in-phase component of the lock-in detector is zero around the magnetic zero-field resonance and only depends on the light and electronic noise.³¹

As light passes through the cell, the intensity $I(x)$ is given by³²

$$\frac{dI}{dx} = -n\sigma(\nu)I(x)(1 - s\langle P_x \rangle). \quad (2)$$

Here, n is the density of the alkali vapor, $\sigma(\nu)$ is the absorption coefficient as a function of laser frequency ν , and s is the polarization of the light. There is no analytical solution for the general case (i.e., $s \notin \{-1, 1\}$) in an optically-thick medium.

The optically-thin solution for $s = 1$ can nevertheless give us indications on how each noise source affects the magnetometer when a small modulation is applied to each noise source (i.e., the laser intensity, frequency, or polarization). A small sinusoidal modulation is applied to the laser parameters in Eqs. (1) and (2), and the in-phase (absorption) and out-of-phase (magnetometer) components are derived. For example, when a small light intensity modulation at a frequency ω_k is present, the modulation will be seen through four different mechanisms. First, the intensity of the transmitted light has a component oscillating at ω_k due to the intensity factor on the right-hand side of Eq. (2). Second, the DC term of Eq. (1) also has a modulation assuming the modulation is changing P_0 through $R_{OP} = \sigma I$. Third, the modulation will cause an oscillation at $|\omega_k - \omega_m|$ with the same amplitude in both lock-in amplifier outputs. This signal is the beat note between the optical and magnetic modulation and causes an indirect modulation on the transmitted intensity due to magnetic field induced transmission. This implies that the laser intensity noise close to the modulation frequency will cause equal low-frequency noise on the in- and out-of-phase signals. Finally, with the same argument, the intensity modulation will cause an oscillation at ω_k in the out-of-phase component at low frequency if $B_0(\omega_L)$ is not equal to zero through its effect on P_0 . Thus, laser intensity noise would again cause low-frequency noise in the magnetometer, but the magnetometer noise will be suppressed in the case of high spin-polarizations (i.e., $P_0 \rightarrow 1$) and at $B_0 = 0$.

Experimentally, the contributions of different noise sources to the magnetometer are evaluated to determine the origin of the observed low-frequency magnetometer noise. These noise sources include laser frequency, intensity and polarization, thermal fluctuations, and stray magnetic fields. Each noise source was characterized in the following ways:²⁸ First, a sinusoidal modulation ω_k is applied to the noise parameter while minimizing its effect on other sources (when possible). Next, the noise spectrum of the noise parameter is measured, showing a peak at the sinusoidal modulation ω_k . Third, the response of the magnetometer to this noise is measured by recording the amplitude spectral density (ASD) of the output of the lock-in amplifier. Since the peaks in both spectra are due to the same parameter modulation, a conversion factor can be extracted to convert the noise spectra into magnetic field units. Modulation signals are applied consecutively at multiple amplitudes and frequencies to determine the spectral dependence and linearity of the noise conversion mechanism. By comparing the size of the effect on the out-of-phase (magnetometer) vs the in-phase (absorption) signal, we can determine whether the source primarily affected the light parameters (which would affect both the in-phase and magnetometer signals equally) or influenced the magnetometer output in the same way as a magnetic field.

1. Laser intensity noise

Laser intensity noise can couple into the magnetometer in several different ways: a direct change of the transmitted light power, a change in the pumping rate of the atomic polarization manifested as a change in absorption, and as a “fictitious magnetic field” that shifts the energy levels of the atoms in a way similar to a real magnetic field, known as a light shift or AC Stark shift.^{1,29,30} We expect the contribution from a fictitious magnetic field to be negligible for an on-resonant well-collimated beam that is actively power stabilized. Although the frequency is not locked, the frequency drift and laser linewidth (MHz) is small as compared to the optical linewidth (18 GHz) over the course of data taking. The homogeneous laser beam causes the same light shift for all atoms since it depends on the laser intensity. Finally, actively stabilizing the laser power with the AOM will suppress the residual light shifts. These factors lead to a relatively constant fictitious field offset that would be nulled.

The effect of laser intensity noise was introduced by applying a small sinusoidal modulation to the AOM that leads to a small intensity modulation to the laser light. Modulation frequencies at ω_k were chosen either between 5 and 100 Hz (low frequency) or ± 100 Hz around the 1.77 kHz lock-in amplifier reference frequency (high frequency). The effect was measured either with a pick-off beam before the cell (low frequency) or directly on the light after the cell (high frequency). The low-frequency intensity noise is measured before the cell to isolate it from other low-frequency effects that influence the transmitted intensity such as wavelength or polarization. The high-frequency measurement was performed without the magnetic field modulation at ω_m ; therefore, the measurement depends upon the intensity fluctuations and also includes photon shot noise. We assume minimal noise from frequency and polarization near ω_m which is discussed later. The low-frequency intensity modulation leads to a relatively small peak in the photodiode ASD at ω_k . The peak converts into a negligible magnetometer noise below $1 \text{ fT/Hz}^{1/2}$.

For high-frequency intensity noise, a modulation at $\omega_k = 1.72 \text{ kHz}$, for example, was applied to the AOM. The ASD of the transmitted light falling onto the photodiode after the cell was demodulated at the lock-in reference frequency of $\omega_m = 1.77 \text{ kHz}$ and a peak is shown at the beat frequency of 50 Hz. The spectra 100 Hz above and below the modulation frequency are added in quadrature to convert the result to a single-sided spectrum. Assuming the peak at $|\omega_k - \omega_m|$ in the lock-in output signal is due to the intensity modulation at ω_k , the ratio of the peak amplitudes in the photodiode signal after the cell with no modulation at ω_m vs the lock-in amplifier output spectra when ran as a magnetometer generates a conversion factor for laser intensity noise around ω_m . It is found that intensity noise close to ω_m translates nearly equally into low-frequency noise on both lock-in amplifier outputs. Figure 2 shows an example of the down-converted intensity modulation near 1.77 kHz that has been converted into magnetic field noise and the magnetometer signal. The effect of both low- and high-frequency laser intensity noise of the in- and out-of-phase can be seen in Figs. 3 and 4.

2. Laser frequency noise

Frequency noise of the laser can couple into the magnetometer through changes in the pumping rate, FM-AM conversion on

FIG. 2. High-frequency intensity data comparison. The amplitude spectral density around the modulation frequency ω_m of the out-of-phase lock-in signal (blue) and the expected magnetic field noise from laser intensity fluctuations (red).

the slope of the pressure-broadened resonance line, and light shifts. The laser frequency noise is roughly 1 MHz at low frequency and drops to approximately 100 kHz near the modulation frequency ω_m . The laser frequency noise near the modulation frequency will lead to an AM-FM conversion that will couple into the lock-in amplifier as a signal. We assume that the 100 kHz noise at high frequency leads to a negligible AM-FM conversion due to the four orders of magnitude difference between the noise and the atomic linewidth (18 GHz). Low-frequency frequency noise will couple into the magnetometer through changes in optical pumping and a

FIG. 3. Noise contributions to the magnetometer signal from different sources. Low-frequency noise (1–10 Hz) in the magnetometer is mainly due to high-frequency intensity noise and current noise on the field coils, while the main contribution from 10 to 100 Hz is the high-frequency intensity noise coupling into the lock-in amplifier. The signals will add together in quadrature to provide the final estimate of the signal. The data have been smoothed to reduce large spikes from electronic signals such as 60 Hz.

FIG. 4. Various noise sources examined that affect the in-phase signal. Most sources are below $1 \text{ fT/Hz}^{1/2}$ except for the high-frequency intensity noise. The signals will add together in quadrature to provide the final estimate of the signal. The data have been smoothed to reduce large spikes from electronic signals such as 60 Hz.

light shift. Since the laser wavelength variations in the range below 10 Hz could be substantial, we investigate its effect on the magnetometer by varying the laser injection current with a slow ($\omega_k = 2 - 25 \text{ Hz}$) sinusoidal modulation. Because this modulation changes both laser intensity and laser frequency, the corresponding intensity modulation is countered by locking the intensity of the laser via the AOM and using an autobalanced receiver for detection instead of a single photodiode. The laser frequency noise is measured by passing the beam through a Rb vapor cell that contains no buffer gas and tuning the laser wavelength to the side of a steep absorption profile on the D1 line. Frequency noise is converted into amplitude noise on the steep frequency discriminator slope. We compare the peak in the laser frequency spectrum at ω_k to the same size modulation in the magnetometer. We find that fluctuations of the laser wavelength contribute to the magnetometer at very low frequencies, but are negligible at frequencies above 2 Hz with less than $1 \text{ fT/Hz}^{1/2}$. Since both lock-in components are affected similarly, we conclude that fictitious fields are negligible in our configuration with a well-collimated beam on resonance.

3. Laser polarization noise

Polarization noise in the magnetometer can be caused either by polarization fluctuations close to the lock-in reference frequency or directly at low frequency. In the first case, we expect the noise to have a similar transfer function in both lock-in amplifier components similar to the low-frequency intensity fluctuations. In the latter case, the noise should appear mostly in the magnetically sensitive component if the background field is not adequately zeroed. We do not expect high-frequency polarization fluctuations in the system, only slow polarization drift due to effects such as temperature fluctuations.

To assess the contribution of polarization noise in our sensor, a Pockels cell is inserted before the quarter waveplate and modulates the polarization of the laser between circular and slightly

elliptical. To measure the polarization noise of the laser, the beam is redirected before the quarter waveplate, sent through a Pockels cell and through a polarizer at 45° , converting the polarization fluctuations of the laser into intensity fluctuations. The ASD of the photodiode intensity after the polarizer is compared to the magnetometer and in-phase ASD with the same modulation on the Pockels cell at multiple frequencies to convert the polarization noise spectra, as described before. The polarization noise appears to be a significant contributor at low frequency. This partially accounts for the $1/\sqrt{f}$ noise that is seen in the magnetometer spectrum. However, unlike the laser intensity and frequency noise, the polarization noise seems to affect the magnetometer signal more strongly than the in-phase component. We are unsure of the largest contributor to the polarization noise but suspect it is a combination of strain on optics, changes in the angle of incidence to waveplates, and temperature drifts. To minimize the effects, all optics were enclosed in a box to reduce thermal fluctuations of the optics and air flow, high extinction polarizers and zero-order waveplates were used, and background fields were zeroed to a high degree as with the other measurements that showed noise levels below $1 \text{ fT/Hz}^{1/2}$. We are also investigating if this is an effect of the anodically-bonded borosilicate glass windows on the MEMS cell.

4. Cell temperature fluctuations

Thermal fluctuations of the vapor cell alter the atomic density, affecting the spin-temperature distribution and the optical density. We limit our investigation to low-frequency fluctuations due to the relatively long time constant of thermal effects. We assume that changes in the spin-temperature distribution are small for high polarization.

The temperature of the vapor cell is stabilized by feeding the DC output signal of the photodiode after the cell into a servo that controls a fast variable optical attenuator (VOA) in the fiber that delivers the heating light to the vapor cell. The heat laser intensity is modulated between 0.5 Hz and 20 Hz (assuming thermal fluctuations are within this range) and the effects are measured in the transmitted pump beam intensity. Since the power of the pump laser is stabilized, fluctuations in the ASD of the photodiode output after the vapor cell are indicative of variations in the optical density of the vapor cell. The measurements of temperature fluctuation show a minimal effect on the magnetometer or in-phase noise (see Figs. 3 and 4). Although slow drifts in the temperature over time will change the overall sensitivity, short-term changes are negligible.

5. Current noise

We directly measure the levels of magnetic noise due to current noise on the transverse field coils. The sensitive axis of the magnetometer is defined by the direction of the parametric field modulation. The amount of current that is typically used during the experiment passes through the Helmholtz or solenoid coils and the ASD of the voltage across the coil and resistor circuit is measured via a spectrum analyzer. The voltage noise is converted into magnetic field noise using the known resistance of the circuit and the calibration constant of the coils. For the modulation on the Helmholtz coils, the signal is passed through a 1 kHz low-pass filter and amplified by a low-noise voltage amplifier before the

spectrum analyzer. The low-pass filter is necessary to prevent the modulation from overloading the amplifier. An amplifier is used to move the noise measurement far from the noise floor of the spectrum analyzer. The 1 kHz low-pass filter reduces the low-frequency signal by 3%. The measured ASD was scaled to account for this adjustment. Noise on the Helmholtz and solenoid coils directly affect the magnetometer signal, but not the in-phase component. As seen in Fig. 3, the noise on the modulation coils is significant at low frequencies and levels off to roughly $5 \text{ fT/Hz}^{1/2}$ at higher frequencies. The noise on the solenoid coils, used to apply DC magnetic field offsets in the x-direction, levels off at approximately $1 \text{ fT/Hz}^{1/2}$ for the applied DC nulling field.

Sources of magnetic noise due to current within materials near the cell have been estimated theoretically,^{25,33} and we find, like our previous analysis,¹⁹ that the noise from the silicon body of the cell and the ferrite shield are negligible.

6. Electronic and phase noise

We measure the electronic noise of the system as well as the phase noise of the lock-in amplifier. The electronic noise was measured by blocking the laser beam and measuring the ASD of the output of the lock-in amplifier. This measurement includes the electronic noise of the lock-in amplifier, the spectrum analyzer, and the photodiode/transimpedance amplifier, including the dark current. The electronic noise was flat at $2 \text{ fT/Hz}^{1/2}$ across the measurement. We measure the phase noise of the lock-in amplifier by sending the output of the lock-in amplifier that drives the Helmholtz coils to the input of the lock-in amplifier. The amplitude of the modulation was approximately the intensity modulation seen on the photodiode output that is typically fed into the lock-in amplifier. The ASD was converted into magnetic field units by dividing by the magnetometer response. The measured ASD shows

FIG. 5. Field equivalent noise spectrum of the magnetometer (blue) and the in-phase signal of the lock-in amplifier (red). The noise in both lock-in components is similar at frequencies above 80 Hz: roughly $7 \text{ fT/Hz}^{1/2}$. The dashed lines were computed by adding all expected noise contributions in the out-of-phase (black) and in-phase (orange) signals of the lock-in output in quadrature.

a $1/\sqrt{f}$ noise with an amplitude of $10 \text{ fT/Hz}^{1/2}$ at 0.5 Hz and $3 \text{ fT/Hz}^{1/2}$ at 10 Hz in the out-of-phase component, while the in-phase component was flat at $0.5 \text{ fT/Hz}^{1/2}$.

III. CONCLUSION

A typical magnetometer sensitivity signal is shown in Fig. 5. The 3 dB bandwidth of the magnetometer is approximately 200 Hz. At low frequencies, the magnetometer signal shows excess noise not present in the in-phase component of the lock-in. Beyond 30 Hz, the magnetometer noise has a nearly flat frequency dependence at $7 \text{ fT/Hz}^{1/2}$. The expected magnetometer and quadrature noise are calculated by adding each of the noise sources at difference frequencies in quadrature.

The computed high-frequency intensity fluctuations set a practical limit of the magnetometer sensitivity above 10 Hz. This level of performance was only reached when the laser intensity was locked via the AOM. Without locking the intensity, the noise of the magnetometer increased to roughly $15\text{--}20 \text{ fT/Hz}^{1/2}$ at 100 Hz .²³ To reduce the noise floor of deployable magnetometers that cannot afford an AOM within their size, weight, and power budget, the intensity noise could either be reduced by a gradiometer configuration²³ or a low intensity noise laser such as a VCSEL. Low-frequency noise is dominated by the current noise on the driving or field nulling coils (which can be solved with lower noise current drivers), wavelength fluctuations, high-frequency intensity noise, and polarization noise. Polarization noise is the only noncurrent based source that does not affect each lock-in component equally in this study. We are still investigating the source of the polarization noise. While many contributions to the magnetometer noise have been identified, there is still additional magnetic field noise below 1 Hz not identified yet. Nevertheless, the close agreement between the measured and expected noise of both the magnetometer and in-phase signal indicates a reasonable method for determining different sources of noise in a single-beam magnetometer.

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