

Magnetometry with Broadband Microwave Fields in Nitrogen-Vacancy Centers in Diamond

Arezoo Afshar,^{1,2} Andrew Proppe,^{1,2} Noah Lupu-Gladstein,^{1,2}
Lilian Childress,³ Aaron Z. Goldberg,¹ and Khabat Heshami^{1,2}

¹*National Research Council of Canada, 100 Sussex Drive, Ottawa, Ontario K1N 5A2, Canada*

²*Department of Physics, University of Ottawa, 25 Templeton Street, Ottawa, Ontario, K1N 6N5 Canada*

³*Physics Department, McGill University, 3600 Rue University, Montréal QC H3A 2T8, Canada*

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Nitrogen vacancy (NV) centers in diamond are optically addressable and versatile light-matter interfaces with practical application in magnetic field sensing, offering the ability to operate at room temperature and reach sensitivities below $\text{pT}/\sqrt{\text{Hz}}$. We propose an approach to simultaneously probe all of the magnetically sensitive states using a broadband microwave field and demonstrate that it can be used to measure the external DC magnetic field strength with sensitivities below $1 \text{ nT}/\sqrt{\text{Hz}}$. We develop tools for analyzing the temporal signatures in the transmitted broadband microwaves to estimate the magnetic field, comparing maximum likelihood estimation based on minimizing the Kullback-Leibler divergence to various neural network models, and both methods independently reach practical sensitivities. These results are achieved without optimizing parameters such as the bandwidth, power, and shape of the probing microwave field such that, with further improvements, sensitivities down to $\text{pT}/\sqrt{\text{Hz}}$ can be envisioned. Our results motivate novel implementations of NV-based magnetic sensors with the potential for vectorial magnetic field detection at 1-10 kHz update rates and improved sensitivities without requiring a bias magnetic field.

I. INTRODUCTION

Color centers in diamond provide an attractive light-matter interface for applications in quantum sensing [1] and development of quantum networks [2–5]. Nitrogen vacancy (NV) centers in diamond have become a well-established system for magnetic sensing [6–10] owing to their long spin coherence times [11], optical spin preparation, and a variety of spin detection techniques [12]. The NV center’s general versatility and ability to operate from cryogenic to above room temperature [13] have been key to applications ranging from nanoscale materials imaging [14, 15] to neuroscience [16].

The four vectorial orientations of NV defects and the hyperfine coupling to nearby nuclear spins leave a rich spectrum of resonances in the microwave (MW) domain, whose locations encode information about the vector components of the DC magnetic field. Scanning these spin resonances with a tunable MW field and off-resonant optical readout is the basis of the widely employed optically detected magnetic resonance (ODMR) modality for magnetic field sensing [17, 18]. To more efficiently probe multiple NV orientations, vector magnetometers employ sequential measurements of different resonances [19] or complex multi-frequency lock-in techniques for simultaneous detection of all orientations [20]. While fluorescence detection of the NV spin is most common, other methods such as photoelectric readout [21, 22], spin-to-charge conversion [23, 24], IR absorption [25], or laser-threshold [26] are also possible, in each case detecting the spin populations without directly probing

coherent processes on the spin transitions. In contrast, magnetic sensing based on electromagnetically induced transparency [27] or MW cavity coupling [28–30] exploits the coherent interactions of the NV spins with incident electromagnetic radiation. Aided by low shot noise power in the MW regime, MW cavity-coupling approaches [30] have reached sensitivities rivaling the best fluorescence detection results [31]. However, narrowband high-finesse MW cavities can only probe a single spin transition at a time, impeding vector field sensing applications.

Here, we consider broadband MW probes for NV magnetometry, theoretically examining the transmission of a short-duration MW pulse through an NV ensemble. In particular, the transmitted pulse encodes the full spectrum of NV spin resonances into its temporal response, which can be directly measured by fast MW receivers without the need for frequency-domain spectroscopy. The primary challenge that we broach in this paper is how to accurately and robustly invert such a time-domain signal to extract the magnetic field. While we consider the field magnitude in this initial study, this approach permits sampling all orientations simultaneously, offering a clear path towards high-bandwidth vector magnetometry with shot-noise-unlimited MW detection. Without fully optimizing our protocol, we demonstrate that analyzing the transmitted MW signal in the time domain is sufficient to reach sensitivities that are comparable to those of ODMR. In addition, our approach remains accurate at small magnetic field values without requiring a bias field to spectrally separate resonances, a feature that may further improve practical applica-

tions of these sensors.

The remainder of the paper is structured as follows: We begin by describing our approach, where we use the NV center's electronic and nuclear spin Hamiltonian to find an expected absorption profile in the MW domain, then use the Kramers-Kronig relation to determine the full response function for evaluation of the transmitted MW signal for any given external magnetic field. In Section III, we first use minimization of Kullback-Leibler (KL) divergence curves to find our best estimate of the magnetic field for a given output signal. We also discuss an independent approach based on neural networks to extract external magnetic field strengths from the output MW signal. Finally, in Section IV, we evaluate and discuss the sensitivity of our approach based on these techniques.

II. SCHEME

In this work, we aim to develop a technique for magnetic field sensing that simultaneously addresses multiple transitions between different spin states of NV centers in the ground state manifold using a broadband MW field. This approach could potentially reveal more information from the spectrum and, consequently, provide a more accurate measurement of the magnetic field. As depicted in Fig. 1, all magnetically sensitive states of an NV center in diamond are probed with a broadband MW field. At high NV concentrations, this will result in an absorption signature on the transmitted MW field that will be dependent on the external magnetic field.

Inspired by methods in inhomogeneous absorption engineering for photon echo quantum memories for light [32–34], we expect the output signal to carry information about the position of the absorption peaks and therefore the external magnetic field. For example, a periodic absorption peak separation of δ (as proposed in atomic frequency comb quantum memories [32]) will result in a echos in the time domain that appear at the intervals of $2\pi/\delta$. For this approach to be applicable to any given magnetic field, we need to develop methods to analyze the output MW signal in the time domain. This will be covered later in this section.

We begin by describing the spin structure of a negatively charged NV center, which comprises an $\mathbf{S} = 1$ electronic spin and an $\mathbf{I} = 1$ nuclear spin associated with the host ^{14}N nitrogen. The state space is spanned by the states $|m_s, m_I\rangle$, where m_s and m_I are the electronic and nuclear spin Zeeman sublevels, respectively.

The total Hamiltonian for the NV center can thence be broken into three contributions:

$$\hat{H}_{total} = \hat{H}_{el} + \hat{H}_{nuc} + \hat{H}_{el-nuc}. \quad (1)$$

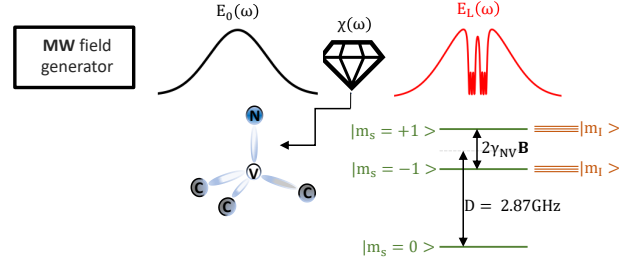


FIG. 1: In this scheme, the MW field generator sends a broadband pulse to the NV ensemble. This can be achieved with a stripline waveguide, allowing evanescent coupling of the MW field to the NV centers or NV ensemble embedded in a MW cavity. As the MW input propagates through the sample, the NV centers partially absorb the signal and consequently modify the signal's intensity. This alteration is depicted in the output signal (red curve). The external magnetic field influences the frequencies at which NV centers absorb the microwave field. This leads to changes in the partially transmitted MW signal, thereby providing information about the underlying magnetic field. Shown below are the atomic and quantum structures of the NV center.

When an external magnetic field $\mathbf{B}$ is applied, due to the Zeeman effect, the degeneracy of the $|m_s = \pm 1\rangle$ levels lifts by up to $2\gamma_e B$ and $\hat{H}_{el}$ becomes:

$$\frac{1}{h}\hat{H}_{el} = D\hat{S}_z^2 + \gamma_e \mathbf{B} \cdot \hat{\mathbf{S}}, \quad (2)$$

where $D = 2.87$ GHz is the temperature-dependent zero field splitting along the NV symmetry axis $\hat{z}$ [35], and γ_e is the gyromagnetic ratio. The ^{14}N nuclear spin Hamiltonian in the presence of an external magnetic field is:

$$\frac{1}{h}\hat{H}_{nuc} = P\hat{I}_z^2 + \gamma_n \mathbf{B} \cdot \hat{\mathbf{I}}. \quad (3)$$

The quadrupole component $P = -4.95$ MHz [36] lowers the energies of the states $|m_I = \pm 1\rangle$ below that of $|m_I = 0\rangle$, and γ_n is the nuclear gyromagnetic ratio. Furthermore, hyperfine interactions generate an additional nuclear-spin-dependent splitting in the ground state manifold through

$$\frac{1}{h}\hat{H}_{el-nuc} = A_{\parallel}S_zI_z + A_{\perp}(S_xI_x + S_yI_y). \quad (4)$$

Here, $A_{\parallel} = 2.16$ MHz [36] and $A_{\perp} = 2.7$ MHz [37] are the magnetic hyperfine parameters parallel and perpendicular to the NV center axis, respectively. Transitions are driven when the NV center is subjected to a MW field resonant with the energy difference between $m_s = 0$ and $m_s = \pm 1$. (Direct $-1 \leftrightarrow +1$ transitions are dipole-forbidden and negligibly weak in the

magnetic dipole approximation.) The electron spin transitions under different magnetic fields are shown in Fig. 2(a). These are assumed to have Lorentzian absorption lines [38].

As described above and shown in Figs. 1 and 2(b), we probe the NV centers within a diamond sample with a broadband MW field. For the sake of simplicity, we consider the shape of the input broadband MW field to be Gaussian:

$$E_0(\omega) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\omega-\omega_0)^2}{2\sigma^2}}, \quad (5)$$

where the central frequency $\omega_0 = 2.87$ GHz matches the zero-field splitting D . When the MW pulse passes through the diamond sample, the response of the NV center spins will be approximately linearly proportional to the perturbation and characterized by dispersion $\chi_1(\omega)$ and absorption $\chi_2(\omega)$. The absorptive component can be found from the Lorentzian-decorated eigenfrequencies of the Hamiltonian. Provided that the absorption spectrum does not change during the pulse, $\chi_1(\omega)$ can be determined from $\chi_2(\omega)$ by Kramers-Kronig relations, yielding the susceptibility

$$\chi(\omega) = \chi_1(\omega) + i\chi_2(\omega). \quad (6)$$

The output signal as a result of the response function for a diamond sample with length z and refractive index n at MW frequencies would be:

$$E(z, \omega) = E_0(\omega) e^{\frac{2\pi}{c} iz(n\omega + \omega_0 \frac{\chi(\omega)}{2})} \quad (7)$$

The absorption profile of the output signal in the frequency domain is shown in Fig. 2 (top panel) for applied magnetic fields of 2, 5, and 15 (G) chosen along a fiducial direction (30° polar and 60° azimuthal angles relative to the crystallographic axis of the 100-oriented diamond). The input signal uniquely responds to each applied magnetic field. As the applied magnetic field strength increases, the absorption lines corresponding to each energy level spread out in the frequency domain. The top plot depicts a typical result from an ODMR measurement, where peaks correspond to absorption lines, while the bottom plot depicts the results from our scheme, where now troughs correspond to absorption. Even with a Gaussian envelope, the NV center absorption frequencies remain clearly visible. In our simulations, we used a Gaussian pulse with a temporal FWHM duration of ~ 5 ns (corresponding to an 85 MHz FWHM bandwidth Gaussian pulse), which is sufficient to cover the full ODMR spectrum. Thus, the broadband illumination method can reproduce an ODMR measurement without requiring a frequency sweep..

The microwave absorption coefficient for a waveguide attached to a diamond sample containing NV

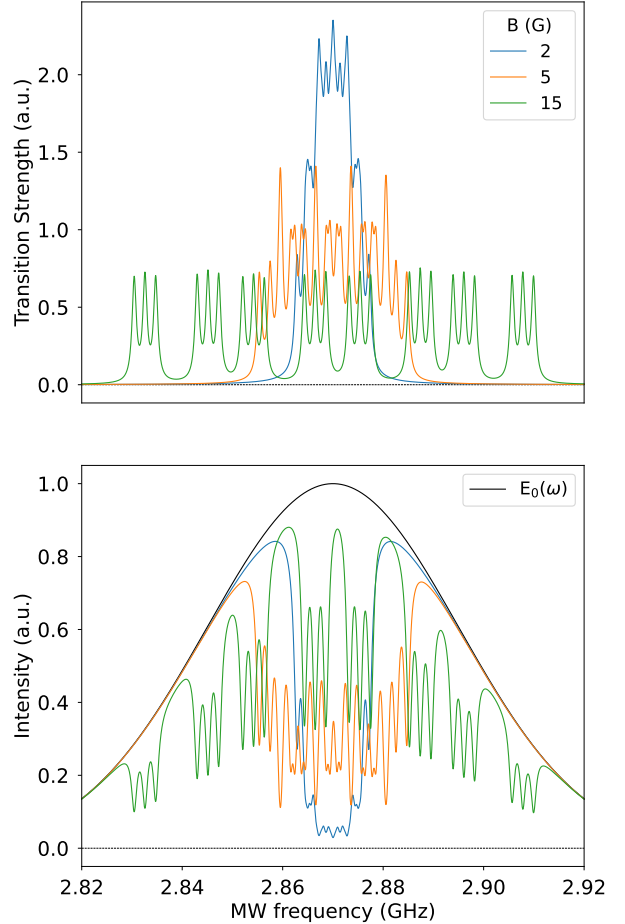


FIG. 2: Top: Expected MW absorption in an ODMR measurement, due to spin transitions from $|m_s = 0\rangle$ to $|m_s = \pm 1\rangle$ in ensemble NV centers, are given by the ground-state-manifold Hamiltonian and combined with Lorentzian lines with 1 MHz linewidth. Magnetic field is oriented along angular coordinates $(\pi/6, \pi/3)$ relative to the diamond. Bottom: Fourier transform of a Gaussian pulse (85 MHz FWHM) transmitted through an ensemble of NV centers in different magnetic fields. In the frequency domain and within linear response theory, the absorption profile from the top graph is imprinted on the MW spectrum.

centers is computed in Appendix A 1. It provides the imaginary part of the magnetic susceptibility $\chi_2(\omega) \approx \chi_0 \omega T_2^*/2$, under the conditions of resonance and sufficiently low MW drive power that power broadening is insignificant. Using the static susceptibility χ_0 , drive frequency ω , and inhomogeneous dephasing time $T_2^* = 1 \mu s$ appropriate to NV centers and realistic waveguide volumes and NV center concentrations of 4.5 ppm, the absorption is anticipated to be 1.28 dB/cm, with roughly 20% of the incident MW power being absorbed per cm of propagation. We use a total absorption of 30% in our simulations to demonstrate the results.

III. DETECTION METHOD AND RESULTS

In practice, a fast detector reads the output signal in the time domain. Here, we use the Fourier transform to calculate the signal in the time domain, $E_z(t)$, from the result of Eq. 7:

$$E(z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(z, \omega) e^{-i\omega t} d\omega. \quad (8)$$

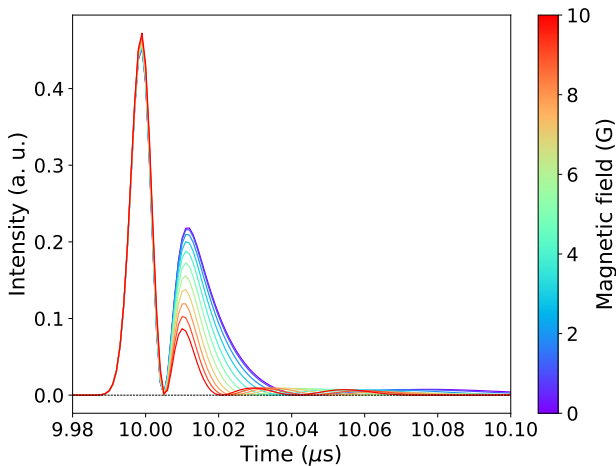


FIG. 3: The time-domain MW transmission through an NV ensemble, $P(t)$, calculated using the same parameters as Fig. 2 for applied magnetic fields ranging from 0 to 10 G. Each magnetic field strength corresponds to a distinct and unique signal behavior, illustrating the variation in the response function as the external magnetic field changes.

Figure 3 shows the signal $P(t) \propto |E(z, t)|^2$ in the time domain for various external magnetic fields B . The signals exhibit different characteristics due to the changes in the response function that occur as the external magnetic field varies. The intensity information alone is sufficient to determine the magnetic field; phase information could be considered in a future study.

A. Noise

To investigate the sensitivity of our proposed approach, we add Gaussian random noise to the output signal. Later in this section and with further discussions on sensitivity in Sec. IV, we show how the signal-to-noise ratio (SNR) affects the absolute error in the predicted magnetic field, where the SNR in dB

is given by $10 \log(\frac{\text{signal power}}{\text{noise power}})$. We will also discuss how one can average output signals from repeated measurements for noise reduction. These considerations are reflected in estimating the total measurement time and sensitivity of our approach. The number of repetitions R required to remove noise from a signal with a high level of noise to a lower level of noise is given by $R = \frac{\sigma_{SNR_1}}{\sigma_{SNR_2}} = 10^{(SNR_2 - SNR_1)/2}$, where σ_{SNR_1} and σ_{SNR_2} are the standard deviations of the Gaussian noise applied to the signal corresponding to higher and lower levels of noise, respectively.

In theory, we can input any amount of noise into our model. To make it realistic, we compute in Appendix A 2 the predicted amount of noise in our modeled system, following Ref. [29]. Johnson-Nyquist noise far exceeds all other fundamental noise sources, such as spin-projection or MW shot noise [29], so we use the predicted Johnson-Nyquist noise to choose the SNR values in our computations. Our estimate of 70 dB indicates that many 10s of dB should be readily attainable in the laboratory.

B. Prediction models

We employ two approaches to determine the magnetic field strength applied to the NV ensemble from the time-domain transmitted MW signal. First, we describe an approach based on the Kullback-Leibler (KL) divergence, where one can compare a measured output signal with a reference to find the best estimate of the underlying magnetic field. The second approach is based on neural networks, where we train our model with many examples of output signals for various magnetic field values.

As seen below, we normalize the output intensity and treat it as a photon-arrival-time probability distribution to benefit from the KL divergence formalism. Though we expect to deal with high intensity MW fields, this approach is justified as even under noisy conditions we average over repeated experiments to reach a low-noise approximation of the signal before proceeding with the KL divergence approach. On the other hand, the estimation approach based on neural networks does not rely on any underlying assumptions about the signal that is fed into the model. Both of these approaches reach practical levels of sensitivity, with some neural network models performing better than others, all of which we will discuss below.

1. Kullback-Leibler divergence

The KL divergence, also known as relative entropy, quantifies the information loss incurred when using an estimated probability distribution $Q(x)$ to approximate the observed data probability distribution $P(x)$ within the same sample space X , where $x \in X$ are the

possible measurement outcomes. The KL divergence is mathematically defined as follows:

$$D_{\text{KL}}(P\|Q) = \sum_{x \in X} P(x) \log \left(\frac{P(x)}{Q(x)} \right). \quad (9)$$

In our simulation, the distributions P and Q are defined as:

$$P(t) = \frac{I(t)}{\sum_t I(t)} \quad \text{and} \quad Q(t|B) = \frac{J(t|B)}{\sum_t J(t|B)}. \quad (10)$$

Here, $I(t) = |E(z, t)|^2$ represents the observed temporal distribution, and $J(t|B)$ is the expected temporal distribution of the output signal for a given magnetic field B . Since, in the present study, even $I(t)$ comes from numerical simulations, both distributions are calculated in the time domain using Eqs. 7 and 8, but in a physical experiment, $I(t)$ would be measured directly. This is why in our simulations we add noise to $I(t)$ but not to $J(t|B)$. In the calculation of KL divergence, the magnetic field B is varied for Q , while it remains fixed for $P(t)$, and a lower value of D_{KL} between the two distributions indicates that they are more similar. By minimizing the divergence, we arrive at an estimator for the magnetic field:

$$\tilde{B} = \arg \min_{B_{\text{model}}} D_{\text{KL}}[P(t)\|Q(t|B_{\text{model}})]. \quad (11)$$

Since the distributions P and Q are interpreted as the likelihoods with which photons arrive at each time step, the value of $\tilde{B}$ is equivalent to the maximum-likelihood estimator for the magnetic field strength.

Figure 4 illustrates the behavior of the KL divergence (D_{KL}) as a function of the modeled magnetic field B_{model} , which as aforementioned, only leads to variation in the probability distribution $Q(t|B_{\text{model}})$. In contrast, the reference probability distribution $P(t)$ remained fixed because it depends on a fixed magnetic field B_{true} with a single instance of small noise (SNR 100 dB) added to the intensity trace. The plot shows the KL divergence values for different values of B_{true} , with each curve representing a distinct magnetic field condition.

As depicted, the KL divergence reaches its minimum at specific magnetic field strengths, indicating the optimal similarity between the reference distribution $P(t)$ and the predicted distribution $Q(t|B_{\text{model}})$. These minima indicate the points at which the model distribution best approximates the true underlying distribution and the value of B_{model} at that minimum becomes the estimate $\tilde{B}$, with the narrowness of the curves and their unique minima highlighting the effectiveness of using KL divergence to identify the most representative magnetic field. Furthermore, the analysis was performed with a high level of precision, with the granularity of the predicted magnetic field

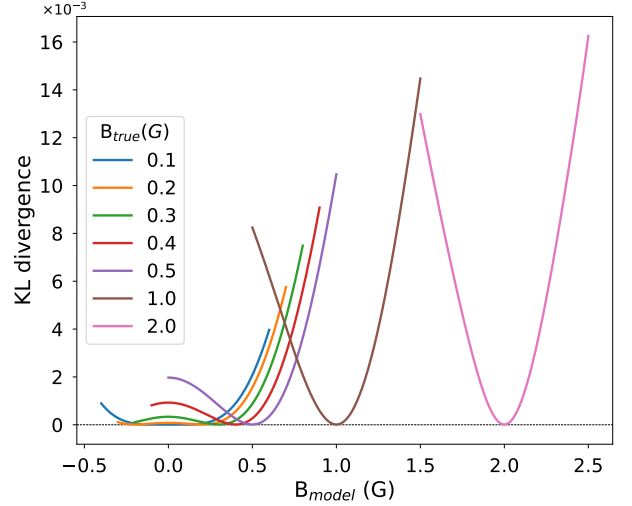


FIG. 4: The KL divergence (D_{KL}) is computed across a range of magnetic field values applied to the probability distribution $Q(t|B_{\text{model}})$ while keeping the probability distribution $P(t)$ constant. The resulting curve reaches its minimum at the magnetic field strength where $P(t)$ and $Q(t|B_{\text{model}})$ exhibit the highest similarity. It should be noted that the granularity of the magnetic field, B_{model} , in the analysis is set at 10^{-5} G; all other parameters are the same as in Fig. 2.

(B_{model}) set at 10^{-5} . This fine granularity ensures that the computed KL divergence accurately captures variations across the range of magnetic fields tested, allowing for precise identification of the optimal similarity points.

It is also worth mentioning that both distributions P and Q are considered to have collected the signal over a $\Delta t = 4 \mu\text{s}$ time window. We tried different values of Δt and found no marked difference in sensitivity per unit time for Δt down to $1 \mu\text{s}$, so long as the time around $10 \mu\text{s}$ after the incident pulse (see Fig 3) was included in the window. Then, for choosing the optimal start to this time window, we use a measure inspired by the Fisher information as explained in Appendix A 3 to decide as to how long after the incident pulse one should measure the output signal in order to gain the most information about the underlying magnetic field. The results show that there is a $1 \mu\text{s}$ time window where the output intensity is most sensitive to changes in the external magnetic field so, to be safe, we measure between 8 and $12 \mu\text{s}$. This informs our subsequent choices about the measurement time per trial and eventually the total measurement time used to calculate the overall sensitivity of this approach.

2. Neural network

We also investigated the use of deep learning neural network models to estimate the value of B from the

time traces. We generated a dataset of 20000 time traces with SNRs of 20, 50, or 100 dB. 80% of the dataset was used for training, 10% for validation, and 10% for testing. We examined several network architectures to perform this regression task, including:

1. Multilayer perceptrons (MLP) with skip connections,
2. 1D convolutional networks,
3. Long short-term memory (LSTM) layers,
4. Gated recurrent unit (GRU) layers,
5. A latent neural ordinary differential equation (NODE) model.

Details about model training (hyperparameter tuning, optimizers, learning rates and schedulers) are given in Appendix A 4. All models (besides the MLP) made use of either a single linear layer or an MLP to project the hidden state of the LSTM, GRU, or NODE layers to a single output, corresponding to the predicted magnetic field, akin to $\tilde{B}$ but using the deep-learning as an estimator. Notably, all variations of our convolutional models failed to learn from the data, and consistently predicted the mean of the dataset labels (i.e. a value of 0.5 for the normalized B range of 0.0 to 1.0). We observed this for other hybrid models where any convolutional layers were present, e.g. downsampling with convolutional layers before or after recurrent layers.

Table I shows the performance of the different models, taken as the mean absolute error (in units of nT) for a batch of 500 traces from the test set. The best performance is attained using the NODE model, with an accuracy of 46.4 nT, followed by the GRU, LSTM, and MLP models, respectively. Table II compares the performance of the NODE models for time windows of 0.2 μ s and 4 μ s and for SNRs of 20, 50, and 100 dB. For SNRs of 20 and 50 dB, the NODE model has better performance with the longer 4 μ s time window, but at 100 dB, the errors are very similar for the 0.2 and 4.0 μ s time windows (45.9 nT and 46.4 nT, respectively), and so the overall sensitivity and accuracy can be increased.

TABLE I: Mean absolute error of predicted B (in units of nT) for different models, using inputs with an SNR of 100 dB and a time window of 4 μ s, for 500 randomly chosen true magnetic fields from 0 to 10 G.

Model	Absolute error (nT)
MLP	6.85×10^3
LSTM	9.51×10^2
GRU	5.84×10^2
NODE	4.64×10^1

TABLE II: Comparison of error values at different SNR levels and time intervals based on the NODE model.

SNR (dB)	Abs. err. 0.2 μ s int. (nT)	Abs. err. 4 μ s int. (nT)
20	1.32×10^4	6.75×10^3
50	6.42×10^2	3.33×10^2
100	4.59×10^1	4.64×10^1

IV. SENSITIVITY

The sensitivity of NV centers in diamond to magnetic fields is a critical element of magnetometry. This sensitivity informs the minimum magnetic field that an NV ensemble can detect within a fixed time for a given approach. Typically, sensitivity is influenced by factors such as coherence time (here we take $T_2^* = 1 \mu$ s) and photon collection efficiency. Our method, which does not rely on optical readout, complicates conventional sensitivity calculations due to factors such as SNR levels that depend on the intensity of the MW input, density of the NV centers to avoid saturated absorption, and MW waveguide or cavity design and characteristics. Here, we study mag-

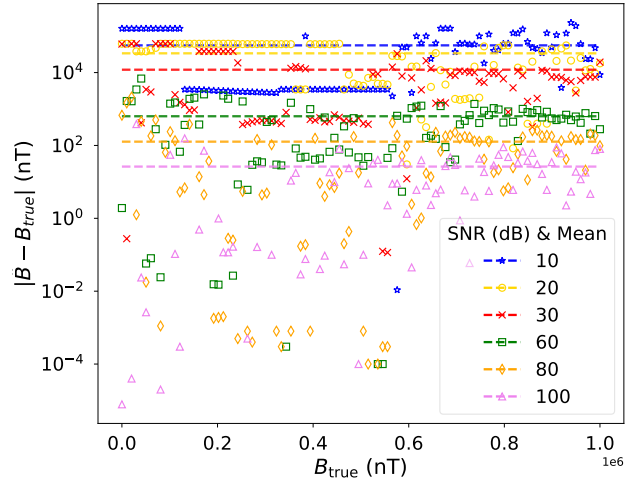


FIG. 5: Absolute magnetic field estimation error, $\delta B = |\tilde{B} - B_{\text{true}}|$, as a function of the true magnetic field B_{true} for various signal-to-noise ratios (SNR) in dB. The vertical axis is displayed on a logarithmic scale to highlight variations across several orders of magnitude. Scatter markers represent individual data points for each SNR, while the dashed horizontal lines indicate the mean δB for the corresponding SNR. The results show a strong decrease in δB with increasing SNR.

netic field sensitivity, as well as its accuracy, by evaluating the quality of the magnetic field extraction using

KL divergence calculations for a signal with low noise (high SNR).

The ultimate bound on the sensitivity achievable with this method is given by the curvature of the KL divergences versus true magnetic field and the number of photons per second. Those curvatures are on the orders of 10^{-3} to 10^{-1} G^{-2} for true magnetic fields ranging from 0.05 to 2.0 G which, with our rates of 5×10^{13} photons per $5 \mu\text{s}$ pulse, could achieve shot-noise-limited sensitivities ranging from $10 \text{ fT}/\sqrt{\text{Hz}}$ to $1 \text{ pT}/\sqrt{\text{Hz}}$. A real experiment will be limited by factors other than this shot noise and so we study the effects of realistic SNR values stemming from Johnson-Nyquist noise.

Beginning with an example, we compare in Fig. 5 the magnetic field predicted by the KL divergence, denoted as $\tilde{B}$, and the actual magnetic field, B_{true} , for different SNRs. SNR is quantified as the ratio of the maximum signal of the output to the Gaussian noise width. The accuracy of the calculated prediction $\tilde{B}$ improves with higher SNR values.

Figure 5 concerns a single instance of the random noise for each SNR value. To evaluate the overall sensitivity and accuracy of our method, we repeat this process for 50 instances of the random noise and observe that the calculated predictions are consistently close to the true values. For SNR values ranging from 90 to 120 dB, we used the KL-minimization technique to predict the magnetic field value when the true value was 0.5 G, then plotted histograms of the predictions in Fig. 6. As the SNR increases from 90 to 120 dB, the histograms narrow. The uncertainties in the esti-

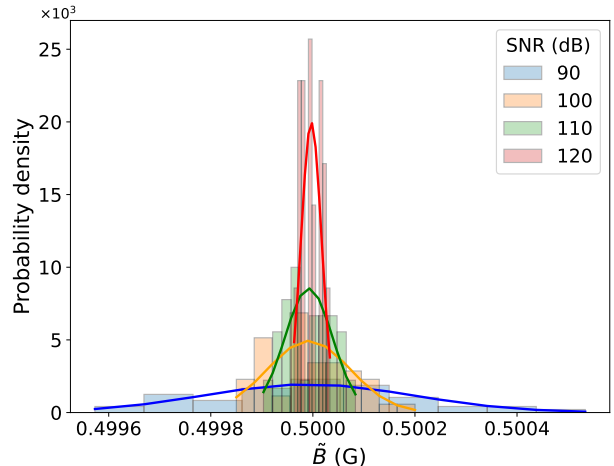


FIG. 6: Histogram of $\tilde{B}$ values with Gaussian fits for an ensemble of NV centers, measured under a real magnetic field of 0.5 G at SNRs of 90 dB, 100 dB, 110 dB, and 120 dB. Each histogram reflects the distribution and precision of $\tilde{B}$ estimations at increasing levels of signal clarity.

mated magnetic fields, denoted σ_B , correspond to the standard deviations of Gaussian distributions fitted to the histograms of predicted magnetic field values and are also illustrated in Fig. 6.

The values of the mean predicted magnetic field $\tilde{B}_{\text{mean}}$ and uncertainty σ_B at an SNR of 100 dB are presented in Table III. This analysis covers a range of true magnetic fields from 0.1 G to 2 G. The KL divergence sensitivity is computed using 100,000 data points sampled across this magnetic field range. For these parameters, the accuracy and sensitivity are demonstrated by biases $\Delta B = |B_{\text{true}} - \tilde{B}_{\text{mean}}|$ and uncertainties σ_B on the orders of 1 and 10 nT, respectively.

Additionally, we consider the total time required to obtain a signal at a noise level of 100 dB from signals at noise levels of 20 dB, 30 dB, and 70 dB. The total experimental time is given by the measurement ($4 \mu\text{s}$) and reset ($1 \mu\text{s}$) times, which together account for the $5 \mu\text{s}$ intervals between measurements. The data are then presented in Table III in terms of precision per unit time.

These inform a fully realistic evaluation of our method. Using measured properties of diamond samples and their interactions with waveguide-coupled light outlined in Appendix A 2, the dominant fundamental source of noise is Johnson-Nyquist noise of the detectors, with effects such as shot noise being relatively negligible. Over the course of a single experimental duty cycle, Johnson-Nyquist noise can lead to an SNR of approximately 75 dB (as discussed in A 2), a process that can be repeated until the SNR improves

TABLE III: Comparison of the true magnetic field (B_{true}) and the average estimated magnetic field ($\bar{B}_{\text{mean}}$, obtained by minimizing the Kullback–Leibler (KL) divergence for randomized SNR = 100 dB, across various magnetic field strengths in the range of 0.1 to 2 G. The average bias $\Delta B = |B_{\text{true}} - \bar{B}_{\text{mean}}|$ quantifies the accuracy of the estimation and is around 10^{-5} G for each true field value. The uncertainty σ_B represents the standard deviation in the estimated magnetic field after averaging over multiple measurements and is calculated from a Gaussian fit to the predicted field distribution.

B_{true} (G)	ΔB (nT)	σ_B (nT)	$\sigma_B \times \sqrt{\text{time}}$ (nT/ $\sqrt{\text{Hz}}$)		
			SNR: 20 30 70 (dB)		
0.1	1	64(6)	14	8.7	0.87
0.2	4	32(3)	7.1	4.0	0.40
0.3	1	21(2)	4.6	2.6	0.26
0.4	4	14(1)	3.1	1.7	0.17
0.5	5	13(1)	2.9	1.6	0.16
0.6	2	14(1)	3.1	1.7	0.17
0.7	1	12(1)	2.8	1.6	0.16
0.8	2	9.2(9)	2.1	1.2	0.12
0.9	1	9.3(9)	2.1	1.2	0.12
1.0	2	10(1)	2.1	1.2	0.12
2.0	1	10(1)	2.2	1.2	0.12

statistically to 100 dB after 158 μs . Despite this, we limit our results in Table III to SNR of 70dB that is more in line with MW source noise and limitations from sampling of the output signal; see below for a discussion on avenues for improvement.

The KL method thus provides achievable sensitivities on the order of $10^{-1}\text{nT}/\sqrt{\text{Hz}}$ and achievable accuracies well below 10 nT (i.e., we see no systematic error associated with the KL minimization routine down to 1 nT) for measuring magnetic fields ranging from 0.1 to 2 G with 6.3 kHz update rates, with further improvement possible by refining the pulse shape and other operational parameters.

Our sensitivity calculations above remained limited to SNR of 70 dB and without any further optimization on other operational parameters such as pulse shape. The limit of 70 dB primarily arises from realistic technical noise in MW sources and detectors. Given that our MW signal intensity assumptions are orders of magnitude below saturation and line broadening limits, improvements in MW sources will lead to significant improvements in the SNR and the pre-

dicted sensitivities. This is especially true because the shot noise remains below 1 pT/ $\sqrt{\text{Hz}}$. In addition, optimal pulse shaping would allow further improvements in the sensitivity. With these considerations, sensitivities down to 10 pT/ $\sqrt{\text{Hz}}$ may become achievable with our proposed method.

V. CONCLUSION

We proposed a new approach to probe NV centers in diamond for magnetic field sensing using broadband MW pulses. We demonstrated that the time-domain transmitted MW field does carry information about the absorption and dispersion due the electronic and hyperfine states of NV centers which, consequently, allow us to develop a measure for the external magnetic field affecting these states. We utilized the minimization of the KL divergence to obtain a maximum likelihood estimate of the underlying magnetic field, yielding sensitivities that are below 1 nT/ $\sqrt{\text{Hz}}$; down to the ~ 1 nT levels we investigated, the analysis introduced no detectable systematic error. We also showed that neural network models can be trained to develop a direct prediction of the magnetic field with absolute errors on the order of 10 nT. Our approach can be further improved by optimizing the MW probe pulse shape and bandwidth. We expect our approach to be extendable to vectorial magnetic detection. One key aspect of our proposed approach to highlight is that, unlike ODMR, we do not require a bias magnetic field, as our approach remains reliable down to magnetic fields of 0.1 G. Even though we require optical addressing of the NV ensemble for initial preparation and resetting after each measurement, we believe not requiring optical detection will help adoption of this approach for practical devices.

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Appendix A: Supplementary Materials

1. Microwave Absorption Coefficient

To estimate the microwave (MW) absorption by NV^- centers in diamond at the resonance frequency corresponding to spin transitions (in the absence of an external magnetic field), we follow the approach outlined in [39]. The MW absorption coefficient is given by:

$$\alpha \simeq 27.3 \cdot \frac{\sqrt{\epsilon_R}}{\lambda_0} \cdot \chi_2, \quad (\text{A1})$$

where $\epsilon_R \simeq 5.7$ is the relative permittivity of diamond at microwave/EPR frequencies, λ_0 is the free-space wavelength of the MW field, and χ_2 is the imaginary part of the magnetic susceptibility.

The imaginary part of the susceptibility for a two-level spin system, such as the NV center, is given by [29]:

$$\chi_2(\omega_d) = \frac{1}{2} \chi_0 \cdot \frac{\omega_s T_2^*}{1 + (\omega_d - \omega_s)^2 T_2^{*2} + \left(\frac{\gamma B_1}{2}\right)^2 T_1 T_2^*}, \quad (\text{A2})$$

where ω_d is the drive angular frequency and ω_s is the spin resonance frequency. Here, χ_0 is the static susceptibility, T_2^* is the transverse relaxation time (spin dephasing), T_1 is the longitudinal relaxation time (spin-lattice relaxation), γ is the gyromagnetic ratio, and B_1 is the amplitude of the applied MW magnetic field. The denominator includes contributions from detuning $(\omega_d - \omega_s)$ and power broadening due to the MW drive field B_1 , reflecting how susceptibility varies with frequency and MW power.

Under the on-resonance condition ($\omega_d = \omega_s$) and assuming low MW drive power such that $\gamma B_1 \approx 0$, equation (A2) simplifies to:

$$\chi_2(\omega_s) \approx \frac{1}{2} \chi_0 \omega_s T_2^*. \quad (\text{A3})$$

The static magnetic susceptibility χ_0 describes the linear response of a spin ensemble to a weak static magnetic field and is given by:

$$\chi_0 = \frac{\mu_0 (g \mu_B)^2}{\hbar \omega_s} \cdot \frac{N_0 - N_{+1}}{V}, \quad (\text{A4})$$

where μ_0 is the vacuum permeability, g is the Landé g-factor, μ_B is the Bohr magneton, and V is the volume of the diamond. The terms N_0 and N_{+1} represent the spin populations in the $|m_s = 0\rangle$ and $|m_s = +1\rangle$ states, respectively. Their difference corresponds to the number of polarized spins contributing to MW absorption. Although the volume V appears in the expression for static susceptibility (equation (A4)), it cancels out when the spin polarization is expressed in terms of a volumetric density (e.g., spins per m^3). In our calculation, we directly use the polarized spin density, which already accounts for the NV concentration, charge state occupancy, spin polarization fraction, and the intrinsic atomic density of diamond. However, the physical dimensions of the waveguide are important as they define the mode volume and the total number of accessible NVs, which would set the limit on the signal intensity based on the saturation threshold. A range of waveguide parameters would work with a mode volume of approximately 25 mm^3 (total number of NVs approximately 1×10^{16}).

In the ideal scenario, several favorable conditions are met to maximize MW absorption in NV-doped diamond. These include full polarization of all NV centers in the $|m_s = 0\rangle$ state, 100% occupancy of the negatively charged NV^- state, MW driving in resonance ($\omega_d = \omega_s$), and negligible power broadening ($\gamma B_1 \rightarrow 0$). Furthermore, a high density of NVs and a long coherence time T_2^* enhance absorption, while

optimal spatial overlap between the MW mode and the NV volume ensures efficient energy transfer. Under such ideal conditions, MW absorption can reach 2 dB/cm per ppm of fully polarized NV^- centers, calculated from the theory in [29].

For comparison, a more realistic scenario involves commercially available diamonds such as the E6 B14, which is widely used in many magnetometry experiments. This diamond typically contains an NV concentration of approximately 4.5 ppm, or about 1 ppm per crystallographic orientation. In practice, only about 70% of the NV centers are in the negatively charged NV^- state, and of those, roughly 80% are spin-polarized into the $|m_s = 0\rangle$ state under optical pumping. When accounting for these realistic charge and spin polarization fractions, the effective polarized NV density is reduced to approximately 0.56 ppm. As a result, a more practical estimate for MW absorption is around 1.28 dB/cm, representing a reasonable estimate under typical experimental conditions. This level of absorption corresponds to approximately 20% of the incident MW power that is absorbed per centimeter of propagation through the material.

2. Johnson-Nyquist Noise and Signal-to-Noise Considerations

Johnson-Nyquist noise, also known as thermal noise, arises from the random thermal motion of charge carriers (typically electrons) in a resistor. It is present in the microwave detector even in the absence of any applied voltage or current and represents a fundamental noise floor in electronic systems. The voltage generated on a resistor R over a bandwidth Δf at temperature T is given by the following:

$$V_{\text{JN}} = \sqrt{4k_B T R \Delta f}. \quad (\text{A5})$$

where k_B is the Boltzmann constant. For a system at room temperature ($T = 300$ K), with a termination resistance of $R = 50 \Omega$ as the MW couples to the detector and a field bandwidth of broadband MW of $\Delta f = 85 \times 10^6$ Hz, the Johnson noise voltage is calculated as:

$$V_{\text{JN}} \approx 8.4 \mu\text{V}.$$

This value defines the thermal noise voltage floor of the system and typically dominates other noise sources [29]. To evaluate the impact of this noise on signal quality, the signal-to-noise ratio (SNR) can be expressed in decibels (dB) as:

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \left(\frac{P_s}{P_n} \right), \quad (\text{A6})$$

where P_s and P_n are the signal and noise powers, respectively, each calculated using $P = V^2/R$. Assuming an applied microwave field with voltage amplitude $V_s = 0.05$ V, as reported in [29], the corresponding signal-to-noise ratio with respect to thermal noise is:

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \left(\frac{(0.05)^2}{(8.4 \times 10^{-6})^2} \right) \approx 75.5 \text{ dB}.$$

This high SNR indicates that under these conditions, the signal is well above the thermal noise floor, enabling high-fidelity detection in the system.

3. The Classical Fisher Information

Choosing an appropriate time window to estimate the magnetic field is crucial. A well-sized and positioned window extracts most of the information from the signal without unnecessarily constraining the repetition rate of the experiment and limits the computational resources needed to store and analyze the data. Figure 3 in the main text shows that most of the variation in the signal occurs around 10 μs after the applied magnetic field, which serves as the starting point for our analysis.

We employ a heuristic based on Fisher information to explore a which times in the temporal signal contribute most to an estimate of the magnetic field. The Fisher information $F(\theta)$ describes how helpful a measurement is to estimate small changes in an unknown parameter θ . A measurement that yields an outcome i with probability $p_i(\theta)$ has

$$F(\theta) = \sum_i \frac{1}{p_i(\theta)} \left(\frac{\partial p_i(\theta)}{\partial \theta} \right)^2. \quad (\text{A7})$$

Intuitively, the Fisher information sums up how strongly each outcome probability varies with small changes in θ , with rare events receiving more weight.

Inspired by Equation A7, we use the expression

$$\frac{1}{J(t|B)} \left(\frac{J(t|B + \Delta B) - J(t|B)}{\Delta B} \right)^2 \quad (\text{A8})$$

to quantify how helpful sampling the signal at time t is for estimating small variations in the magnetic field about a particular value B . $J(t|B)$ is the expected intensity at time t given the magnetic field is B and $\Delta B = 0.05$ G is the step size between simulated magnetic fields. Summing the expression over all magnetic field strengths in the study, we obtain the heuristic

$$h(t) = \sum_B \frac{1}{J(t|B)} \left(\frac{J(t|B + \Delta B) - J(t|B)}{\Delta B} \right)^2, \quad (\text{A9})$$

which describes how sensitive the signal is to small changes in the magnetic field on average given each

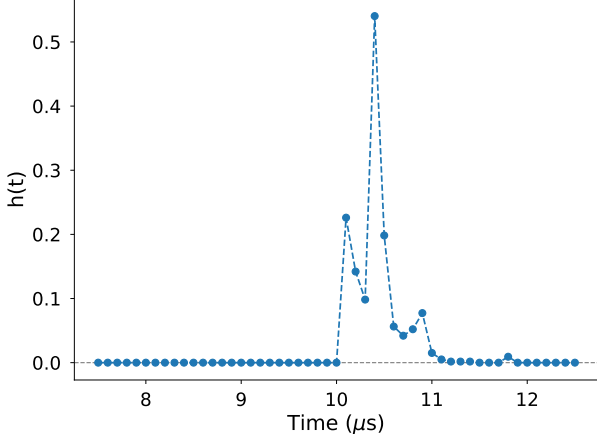


FIG. S1: The function $h(t)$ was calculated from time-domain signal profiles acquired while sweeping the magnetic field from 0 up to 5 G. For each field value, the signal intensity at specific time points was extracted, and $h(t)$ was obtained by summing these intensities over all magnetic fields at each time point. In this construction, $h(t)$ reflects how the temporal response evolves with applied magnetic field. It does not provide meaningful information for times shorter than about 10 μs or longer than about 11 μs ; only the interval between 10–11 μs should be regarded as reliable.

magnetic field strength in the range is equally likely. Figure S1 shows $h(t)$.

Most of the variation of the signal indeed occurs between 10 and 11 μs . Since this is simply a heuristic and small deviations are still occurring outside of this window, we propose that the experiment collects light on either side of this signal for a total duration of 4 μs . Further refinement of the method that considers shorter total measurement time could increase the total sensitivity by a factor of around two if one only inspects the main 1 μs interval or by even more if one finds an optimal tradeoff between even shorter time intervals and information loss.

4. Neural Network Model and Training Details

The MLP model consisted of 4 linear layers with a hidden size of 1024, a leaky ReLU activation between each layer, and a sigmoid activation for the final output. Skip connections were added by summing the input and output of each linear layer.

The 1D convolutional networks were comprised of 1D ResNet-type blocks, where each block consisted of layers in the following order: 1D convolution, 1D

batch normalization, activation, 1D convolution, 1D batch normalization, and a final activation. The kernel size of the convolutional layers was 3, and the stride was 2 for the first layer and 1 for the second. The input to the block is added to the output of the second batch normalization layer, and combined before the last activation. The output of the last ResNet block is flattened and passed through a linear layer which predicts a single output. We varied the depth of these 1D ResNets from 3 – 6, and in all cases the model failed to learn.

The LSTM (GRU) models consisted of a 3 layer bidirectional LSTM (GRU) with a hidden size of 128, followed by a leaky ReLU activation, and finally by a linear layer to predict the scalar output.

The NODE model uses a single layer to project the input time traces into a latent space that serves as the initial state of the NODE layer. The NODE uses an MLP to parameterize the vector field, and is propagated over an arbitrary timespan of 0 to 1. The final timestep of the NODE layer is then passed through another MLP decoder to obtain a single scalar value for the prediction of B .

All models were trained using the PyTorch learning rate scheduler ‘Reduce Learning Rate on Plateau’ (RLROP), with a patience of 50 epochs, a reduction factor of 0.5, and a minimum learning rate of 10^{-10} . Notably, we observed that some models required high initial learning rates (10^{-2}) to achieve any learning, or else they would predict the mean of the labels. Tuning the patience parameter was crucial for achieving the lowest possible error. We made use of the Adam optimizer for all models and a weight decay of 10^{-5} for regularization (although we observed no overfitting).

We tuned hyperparameters for activation functions, hidden layer sizes, and number of layers for the MLPs used as the vector field and decoder, initial learning rate, and RLROP patience using the Weights & Biases package.