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## Article

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# Intrinsic Vectorial Gradiometry via Quantum Control of a Spin-based Sensor

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## Abstract

Gradiometry provides a versatile alternative to passive environmental shielding in quasi-static magnetometry, effectively suppressing background noise through differential signal extraction. Nevertheless, traditional implementations rely on multi-sensor architectures restricted to spatial gradients, where subtracting signals from independent detectors involves imperfect suppression of common-mode noise and artifacts, limiting their sensitivity. To overcome these limitations, we introduce a quantum control sequence that enables intrinsic temporal and spatial vectorial gradiometry of magnetic fields using a single quantum sensor. Our method provides direct access to first and higher-order derivatives of the magnetic field and extended applicability via auxiliary nuclear spin memory. We showcase this protocol on an ensemble of nitrogen-vacancy (NV) centers in diamond and combine it with mechanical control to realize high-precision differential sensing. Through detailed numerical simulations, we demonstrate the performance of our scheme in two critical DC magnetometry applications: (i) vector magnetic anomaly detection and (ii) non-invasive gradiometry of neuronal action potentials.

# 1 Introduction

Highly sensitive magnetometers enable a wide range of applications across diverse fields [1–4]. In particular, quasi-static and low-frequency field sensing facilitates geological surveying [5–8], nanoscopic characterization of magnetic materials [9–11] and measurement of biological signals [12–16]. Standard DC magnetometry techniques rely on direct field intensity measurements, making them highly susceptible to magnetic drifts over extended measurement period [9, 17, 18] as well as to strong static background fields, such as the geomagnetic field [19, 20]. These heavily disturb the sensor, degrading its sensitivity, such that shielding from the environment is often introduced to suppress them. However, in certain relevant applications, *e.g.*, detection of magnetic anomalies, the system cannot be isolated from its surroundings.

Gradiometers offer an elegant solution to these issues. By measuring a differential signal, static background fields and magnetic drifts are suppressed. Gradiometry has been demonstrated across a wide range of quantum platforms, including superconducting quantum interference devices (SQUIDs) [5, 21, 22] and optical pumping magnetometers (OPMs) [23, 24]. Typically, these reconstruct the magnetic field gradient by combining the readout from two (or more) spatially separated, independent sensors. However, this common-mode effect rejection is often imperfect, resulting in added noise which is detrimental for the sensitivity of the gradiometer. Furthermore, multi-sensor gradiometers show a worsening in the overall sensitivity compared to single-sensor measurements [25, 26].

Intrinsic gradiometers, on the other hand, provide a more robust alternative. Previous studies based on OPMs have demonstrated intrinsic spatial gradiometry using multi-cell and single-cell atomic ensembles by measuring light polarization after interacting with two independent cells or two regions of a single, large cell, respectively [26, 27]. In the former case, localized environmental fluctuations can degrade performance across sensors, whereas the latter avoids this issue but requires a larger cell volume.

In the case of solid-state spin defects, the standard approach for DC magnetometry is Ramsey interferometry [28]. In the particular case of color centers, DC magnetometry via optically detected magnetic resonance (ODMR) has recently gained interest [29–31]. Such measurements are particularly vulnerable to environmental noise when probing weak signals in complex environments, to the extent that high-precision applications –such as magnetoneurography and magnetomyography– typically require heavy magnetic shielding [19].

Spatial gradiometers using color centers have been implemented using pairs of non-interacting sensors [16, 19, 32, 33], though these configurations are prone to errors arising from imperfect suppression of common-mode effects. Conversely, recent intrinsic spatial gradiometry with a single NV center mounted on an oscillating cantilever tip [9, 10] bypasses multi-sensor noise, but relies on extracting differential readouts at the oscillation extrema. This rigidly locks the spatial gradient baseline to the physical amplitude of the tip motion, which confines the technique to the nanoscale, rendering it challenging to adapt to broader spatial baselines. Furthermore, to the best of our knowledge, no intrinsic gradiometer has been proposed for time domain measurements.

In this work, we propose a quantum control scheme which enables intrinsic temporal and spatial vectorial gradiometry with a quantum sensor (see Fig. 1) while suppressing background fields and magnetic drifts. Notably, our protocol provides access to first, and higher-order derivatives of the magnetic field and can naturally incorporate a nuclear memory

to achieve extended operational times. The manuscript is structured as follows. In Section 2 we present a detailed description of our protocol. Next, in Section 3, we investigate a method to convert DC magnetic fields into effective AC signal via physical motion of the sensor in order to improve the sensitivity of our protocol. We conduct numerical simulations to showcase our sensing scheme and present the results in Section 4. In particular, our simulations model a diamond sensor containing an ensemble of NV centers, which intrinsically incorporate a nuclear spin memory. Leveraging this, we investigate two important application for DC magnetometry: vectorial magnetic anomaly detection and measurement of magnetic field gradients originating from neuronal action potentials (APs). Our results demonstrate the broad applicability of the protocol for highly sensitive gradiometry. Finally, in Section 5 we discuss and conclude.

## 2 Pulse Sequence for Intrinsic Gradiometry

Our gradiometric sensing scheme comprises an initialization and a readout step, and a measurement sequence, sequentially repeated  $N$  times (see Fig. 1). The latter involves two interrogation stages (I and III) separated by a signal evolution stage (II). Here, all pulses are applied along the same axis (*e.g.*,  $x$ ) except the first, which is applied along an orthogonal direction (*e.g.*,  $y$ ), see blue block in Fig. 1. As long as the phase accumulated by the sensor during the intermediate stage is small, the measured signal will be proportional to the difference between the field values at both interrogation stages. By adding blocks of signal evolution and sensor interrogation stages, one recovers higher order derivatives of the target field. In the following, we describe in detail the theory behind our pulse sequence.

The theoretical description that follows is general for any pair of electron and nuclear spin qubits, which we call the sensor ( $e$ ) and the ancilla ( $a$ ) or memory, and are both initialized

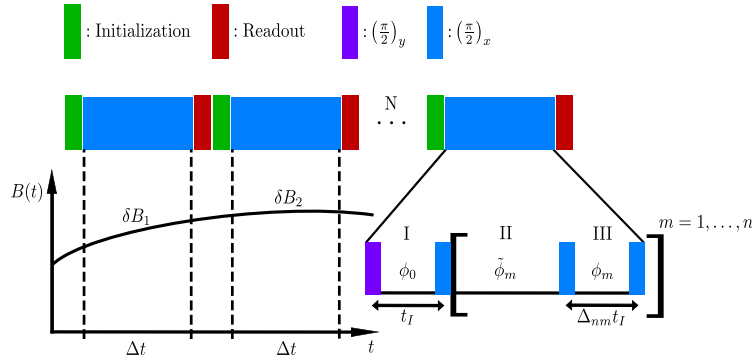


**Fig. 1** Gradiometric sensing scheme. Our protocol comprises an initialization and a readout step, and a measurement sequence (in green, red and blue, respectively), sequentially repeated  $N$  times. Our sequence allows to measure the magnetic field difference between two points separated by a time  $\Delta t$ . Considering that the magnetic field  $B(t)$  changes slowly within a single sequence, each measurement will be proportional to the field difference within the sequence,  $\delta B_i = B(t_i + \Delta t) - B(t_i)$ , such that, after  $N$  repetitions, the full gradient of the field can be recovered. Here,  $t_i$  sets the start of  $i$ -th measurement. Each of these sequences consists of two interrogation stages (I and III) wherein the value of the field remains unchanged, and a signal evolution stage (II) wherein the field changes its value. Repetition of stages II and III within each sequence allows access to  $n$  order derivative of the field. Here, the duration of stage III in the  $m$ -th block (relative to stage I) is given by the combinatorial number  $\Delta_{nm} = \binom{n}{m}$ .

in the  $|0\rangle$  state, such that  $\rho_e = \rho_a = \frac{\mathbb{1} + \sigma_z}{2}$ . The signal to be detected  $b(t)$  is weak and slowly varying, hidden behind a static background field  $B$ . For the sake of simplicity in the presentation, we consider the time dependent signal  $b(t)$  to remain static during stages I and III, but not during stage II, although this need not always be the case. Repetition of the sequence enables the discretization of the field, as shown in Fig. 1, such that it takes values  $b_I^i = b(t_i)$  and  $b_{III}^i = b(t_i + \Delta t)$  during stages I and III in the  $i$ -th repetition, respectively, where  $t_i$  sets the start of the  $i$ -th sequence and  $\Delta t = t_{II}$  is the duration of stage II. Then, the  $i$ -th measurement will be proportional to the field difference in that sequence, *i.e.*,  $\delta b_i = b(t_i + \Delta t) - b(t_i)$ , from where the discretized temporal gradient of the total field  $B(t) = B + b(t)$  can be found,  $\left. \frac{dB(t)}{dt} \right|_{t_i} \approx \frac{\delta b_i}{\Delta t}$ . The temporal behavior described directly models relevant practical scenarios detailed in subsequent sections.

Our protocol allows for the construction of this discretized gradient as follows: during the  $i$ -th measurement block in Fig. 1, the sensor first accumulates a phase  $\phi_0 \propto B + b_I^i$ , where  $b_I^i = b(t_i)$  is the value of the signal  $b(t)$  during stage I. Next, in stage II, free evolution of the sensor during signal variation results in accumulation of a phase  $\tilde{\phi}_1$ . Lastly, the sensor acquires a phase  $\phi_1 \propto B + b_{III}^i$ , where  $b_{III}^i = b(t_i + \Delta t)$ , is the value of the signal during stage III. Upon measurement of the spin state of the sensor, we find the expectation value of the third Pauli matrix  $\sigma_z$  to be

$$\langle \sigma_z \rangle = \cos \phi_0 \sin \phi_1 - \cos \tilde{\phi}_1 \sin \phi_0 \cos \phi_1 \approx \sin(\phi_1 - \phi_0). \quad (1)$$

It follows from Eq. (1) that the static environmental noise  $B$  is completely removed, and because the field difference between stages I and III is expected to be small, the expectation value becomes linear in the accumulated phases, such that we can write  $\langle \sigma_z \rangle \approx \phi_1 - \phi_0 \propto b_{III}^i - b_I^i = \delta b_i$ . As described above, by performing  $N$  of such measurements, one can find the discretized temporal gradient of the total field  $B(t)$ . For the condition in Eq. (1) to be fulfilled, the duration of stage II needs to be smaller than the sensor dephasing time  $T_2^*$ . However, because this stage is not used for measurement, dynamical decoupling (DD) techniques can be applied such that this limitation is extended to the coherence time  $T_2$ .

Interestingly, our sequence can be generalized for measuring the  $n$ -th order derivative. Here, the block comprising stages II and III is repeated  $n$  times and we allow a variable duration of stage III in the  $m$ -th repetition (see Fig. 1). Then, the state of the sensor at the end of the  $m$ -th block reads:

$$\rho_e^{(m)} = \frac{\mathbb{1}}{2} + \frac{1}{2}(a_m \sigma_x + b_m \sigma_y + c_m \sigma_z), \quad (2)$$

where the coefficients  $a_m$ ,  $b_m$  and  $c_m$  are given recursively by

$$\begin{aligned} a_m &= \cos \phi_m \cos \tilde{\phi}_m a_{m-1} - \cos \phi_m \sin \tilde{\phi}_m b_{m-1} + \sin \phi_m c_{m-1}, \\ b_m &= -\sin \tilde{\phi}_m a_{m-1} - \cos \tilde{\phi}_m b_{m-1}, \\ c_m &= \sin \phi_m \cos \tilde{\phi}_m a_{m-1} - \sin \phi_m \sin \tilde{\phi}_m b_{m-1} - \cos \phi_m c_{m-1}, \end{aligned} \quad (3)$$

with  $a_0 = \cos \phi_0$ ,  $b_0 = 0$  and  $c_0 = \sin \phi_0$ . Remarkably, we find that  $\langle \sigma_z \rangle^{(n)} = c_n$ , which assuming small  $\tilde{\phi}_m$  reads (see Section 2 in the Supplementary Information for more details):

$$\langle \sigma_z \rangle^{(n)} \approx (-1)^n \sin \left[ \sum_{m=0}^n (-1)^m \phi_m \right]. \quad (4)$$

Note that Eq. (4) is the generalization of Eq. (1) to derivatives of any order  $n$ .

To achieve the form of the  $n$ -th discretized derivative, the duration of the  $m$ -th stage III is set to  $t_{III,m}^{(n)} = \Delta_{nm} t_I$ , where  $\Delta_{nm} = \binom{n}{m}$  is the combinatorial number. Again, we see that the background field  $B$  is suppressed and then, because the total phase accumulated is expected to be small, Eq. (4) is rewritten as  $\langle \sigma_z \rangle^{(n)} \approx \sum_{m=0}^n (-1)^{n+m} \phi_m \propto (-1)^n b_I^i + \sum_{m=1}^n (-1)^{n+m} \Delta_{nm} b_{III,m}^i = \delta b_i^{(n)}$ , where  $b_I^i$  and  $b_{III,m}^i$  are the values of the signal  $b(t)$  during stage I and the  $m$ -th stage III, respectively. As before, by performing  $N$  of such measurements, the discretized  $n$ -th order time derivative of the total field  $B(t)$  can be obtained:  $\left. \frac{d^{(n)} B(t)}{dt^n} \right|_{t_i} \approx \frac{\delta b_i^{(n)}}{\Delta t^n}$ , with the superscript  $i$  referring to the  $i$ -th measurement. As an example, consider the second order protocol; here, we find  $\langle \sigma_z \rangle^{(2)} \propto b_I^i - 2b_{III,1}^i + b_{III,2}^i = \delta b_i^{(2)}$ , such that  $\left. \frac{d^{(2)} B(t)}{dt^2} \right|_{t_i} \approx \frac{b_I^i - 2b_{III,1}^i + b_{III,2}^i}{t_{II}^2}$  is the discretized second order derivative of the field  $B(t)$ .

As discussed above, the duration of stage II cannot be longer than the sensor coherence time for the approximations in Eqs. (1) and (4) to remain valid. To surpass this limitation, stage II can be transferred to the state of the memory. By applying SWAP gates at the beginning and end of stage II, the state of the sensor can be encoded in and then recovered from the memory (see Fig. 2a). An efficient construction of the SWAP gates consists in applying double

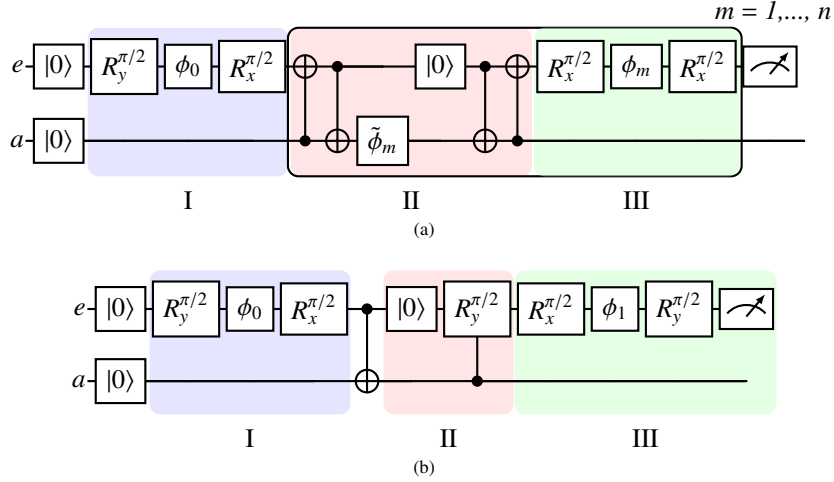


**Fig. 2** Circuit diagram of the memory assisted pulse sequence for intrinsic temporal gradiometry. (a) General sequence for measuring the  $n$ -th order derivative of the field. SWAP gates may be used during stage II for encoding/recovering the sensor ( $e$ ) state in/from a nuclear ancillary qubit ( $a$ ) such that the protocol is limited by the nuclear dephasing time  $T_2^a$ . (b) Modified protocol for  $T_1^a$ -limited magnetometry. Here, only the population information is encoded in the nuclear memory during stage II.

CNOT gates as follows:  $C_a\text{NOT}_e - C_e\text{NOT}_a$  gates to encode the state and  $C_e\text{NOT}_a - C_a\text{NOT}_e$  to recover it. Such storage is beneficial because the gyromagnetic ratio of a nuclear ancilla is much smaller than that of the electron,  $\gamma_a/\gamma_e \sim 10^{-3}$ , such that the adverse phase accumulated by the memory during stage II will be much smaller than if it was accumulated by the sensor. Thus, the protocol is now limited by the larger nuclear dephasing time  $T_2^a \sim T_1^e$ , enabling longer durations of stage II and thus improves the applicability of the protocol.

A final modification to the first order gradiometry protocol can be made such that stage II is limited by the nuclear relaxation time  $T_1^a$ , which is at least one order of magnitude longer than the dephasing time  $T_2^a$ . Instead of the first SWAP gate, a  $C_e\text{NOT}_a$  gate is applied before stage II, such that only the information about the sensor qubit populations is transferred to the nuclear memory. Thus, no phase is accumulated during this stage. The sensor is reinitialized to the  $|0\rangle$  state and then a  $C_a\text{ROT}_e(\pi/2)$  gate along the  $y$ -axis is applied to recover the state from the memory (see Fig. 2b). Measuring the sensor state, we find

$$\langle\sigma_z\rangle = -\frac{1}{2} \{ \cos\phi_1 - \sin\phi_0 \cos\phi_1 + \sin\phi_1 + \sin\phi_0 \sin\phi_1 \}. \quad (5)$$

Here, as long as  $\phi_0$  and  $\phi_1$  are small enough as to neglect the term  $\sin\phi_0 \sin\phi_1$ , we may write  $\langle\sigma_z\rangle \approx -1/2 \{1 + (\phi_1 - \phi_0)\}$ .

Although this modified sequence does not allow measurement of higher order derivatives, it can be used for measuring deviations with respect to a reference signal. In this case, the state of the memory is unaffected by the CROT operation, such that the information about the first accumulated phase  $\phi_0$  remains in the nuclear state. Thus, subsequent measurements after repetition of stages II and III will be proportional to the difference between  $\phi_0$  and some phase  $\phi_1$  accumulated due to the field at a later time. This can be used for signal referencing, *e.g.*, to monitor magnetic drifts with respect to some initial magnetic field.

In all previous cases, the interrogation stages I and III, Ramsey sequences, are limited by the short dephasing time  $T_2^*$  of the sensor. However, the conversion of a DC field into an eAC signal via fast mechanical control [17, 34–36], ancillary qubits [37] or flux modulation [38], enables the application of dynamical decoupling techniques which lead to sensor interrogation times limited by the much longer coherence time  $T_2$ . In this work, we investigate the DC to AC conversion via fast mechanical oscillation of the sensor by placing it on the tip of a vibrating cantilever (see Fig. 3).

### 3 DC to AC Conversion

We consider an NV-based sensor, where the NV axis (oriented along the  $z$  direction in the NV reference frame,  $z_{NV}$ ) forms an angle  $\theta_0$  with the  $z$  axis in the laboratory reference frame (see Fig. 3). The sensor is mounted on the tip of a cantilever which oscillates with frequency  $\nu$  and amplitude  $\alpha$ , such that the angle between the  $z$  and  $z_{NV}$  axes becomes time dependent,  $\theta_{NV}(t) = \theta_0 + \alpha \sin \nu t$ . Hence, the magnetic field detected by the sensor at time  $t_i$ ,  $\mathbf{B}(t_i) = (B_x, B_y, B_z)$ , acquires a time dependence in its reference frame,  $\mathbf{B}^{NV}(t) = R_{\hat{k}}(\theta_{NV}(t))\mathbf{B}$ , where  $R_{\hat{k}}(\theta_{NV}(t))$  is a rotation matrix which models the oscillation of the NV sensor and  $\hat{k} = (k_x, k_y, k_z)$  is a unit vector perpendicular to the plane of vibration. For the particular case shown in Fig. 3, where

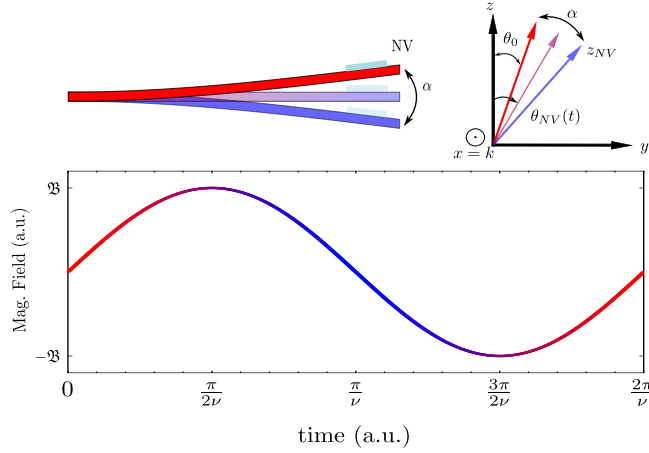


**Fig. 3** Schematic of DC to AC conversion method. (Top left) An NV-based sensor is placed on the tip of an vibrating cantilever, where the oscillation amplitude is  $\alpha$ . (Top right) The orientation of the sensor coordinate system changes with respect to the laboratory frame following the oscillatory motion of the cantilever. (Bottom) Imprinted eAC signal over a full oscillation of the cantilever. The amplitude of this signal is proportional to the intensity of the DC field,  $\mathfrak{B} = \alpha \cos \theta_0 B_y$ , and its frequency to the cantilever vibration frequency,  $\nu$ .

$\hat{k} = \hat{x}$ , the projection of the time dependent field along the NV axis reads

$$B_z^{NV}(t) \approx \alpha \sin \nu t \cos \theta_0 B_y = \mathfrak{B} \sin \nu t, \quad (6)$$

where  $\mathfrak{B}$  is the effective amplitude of the sensed magnetic field and a small oscillation amplitude is assumed. See Section 3 in the Supplementary Information for a more detailed description.

When combining this oscillatory motion of the sensor with our gradiometry protocol, a dynamical decoupling pulse sequence with an interpulse separation  $\tau = 1/(4\nu)$  is applied during stages I and III to capture the imprinted eAC signal. This allows longer durations of the interrogations stages.

## 4 Results

In this section, we apply our protocol to two distinct scenarios. First, we discuss the detection of magnetic anomalies and, second, we consider the measurement of magnetic fields originated from neuronal action potentials (APs). For details on the modelling of these systems, see the Supplementary Information Sections 4 and 5. We choose our sensor to be an ensemble of NV centers in diamond comprising  $N_{NV} = 10^{11}$  active spins [12, 39]. Our simulations include photon shot noise modeled as a Gaussian with zero mean and standard deviation  $\sigma_R = 1/(C \sqrt{n_{av} N_{NV}})$  [40], such that a fluorescence contrast  $C = 10\%$  and an average number of photons received per spin  $n_{av} = 0.022$  are assumed, and  $10^3$  ‘experimental’ repetitions are realized.

## 4.1 Magnetic Anomaly Detetction

When placed in a magnetic field, a ferromagnetic object magnetizes, giving rise to a secondary field which opposes the first. In geological applications, the magnetizing field is the geomagnetic field ( $B_{gm} \sim \mu\text{T}$ ), while the secondary is called magnetic anomaly ( $B_a \sim \text{nT}$ ), which is typically originated from underground ferromagnetic sources. The detection and characterization of magnetic anomalies is relevant to distinct applications in geophysical research [5–8].

Often, magnetic anomalies show spatial variations on a shorter scale than the geomagnetic field, such that the latter can be considered static across the anomaly. By displacing the sensor at a constant speed  $v$ , the magnetic anomaly acquires a time dependence (in the frame of the sensor) which fits within the methodology of our protocol. We consider our source of magnetic anomaly to be a ferromagnetic sphere of radius  $R = 16$  cm and a geomagnetic field of intensity  $B = 45.85\mu\text{T}$ , colatitude  $\vartheta = 105.63^\circ$  and longitude  $\varphi = 320.72^\circ$  (see Section 4 in the Supplementary Information for details on the modelling of the magnetic anomaly).

Figure 4 shows the numerical results obtained for an NV ensemble which vibrates at a frequency  $\nu/(2\pi) = 1$  MHz, and is displaced at a constant speed  $v = 20$  m/s and height  $h = 1$  m following a straight trajectory over the spheric source. The inset in Fig. 4 shows the intensity of the magnetic anomaly as a function of the distance to the source, which is located at the center of the trajectory (*i.e.*, at  $r_x = 0$ ). The evolution during stage II occurs in the state of the nitrogen nucleus, such that the duration of this stage is  $t_{II} = 4$  ms. A CPMG dynamical decoupling sequence with an interpulse separation  $\tau = 1/(4\nu)$  is applied to the sensor during stages I and III to capture a phase due to the effective AC signal, which reads

$$\phi = \frac{2N_p\alpha|\gamma_e|B_i}{\nu}, \quad (7)$$

where  $\gamma_e = -28.024\text{GHz/T}$  is the electron gyromagnetic ratio,  $N_p = 16$  is the number of pulses in the CPMG sequence and  $B_i$  is some component of the total field in the laboratory reference frame. If this is taken such that  $\theta_0 = 0$  (*i.e.*, the NV is aligned with the  $z$ -axis in the laboratory frame) and  $\hat{k} = \hat{x}$  ( $\hat{k} = \hat{y}$ ), then  $B_i = B_y$  ( $B_i = -B_x$ ). If, however,  $\theta_0 = \pi/2$  and  $\hat{k}$  lies in the  $xy$  plane, then  $B_i = -B_z$ . Therefore, by considering these three different geometric configurations of the system, vector gradiometry is enabled (see Section 3 in the Supplementary Information for more details).

We apply our gradiometry protocol to measure first and second order variations of the field,  $d^1B$  and  $d^2B$  (in blue and red, respectively), and show that in both cases the static geomagnetic field is suppressed. Note that the  $n$ -th order variation of the field is given by  $d^{(n)}B = \frac{\nu}{2N_p\alpha|\gamma_e|}\langle\sigma_z\rangle^{(n)}$ . We show results for the three cartesian components of the field, showcasing the applicability of our protocol for vector gradiometry.

## 4.2 Magnetophysiology from neuron action potentials

For biosensing applications, magnetophysiology has gained huge interest in recent years [13, 16, 19, 41, 42]. While electrophysiology is easier to perform due to the stronger electric signals, magnetic biosignals are less affected by biological tissue and also carry directional information about the field [41]. Highly sensitive quantum sensors open the door to magnetic biosensing, with many applications in life sciences, such as magnetocardiography [14–16]

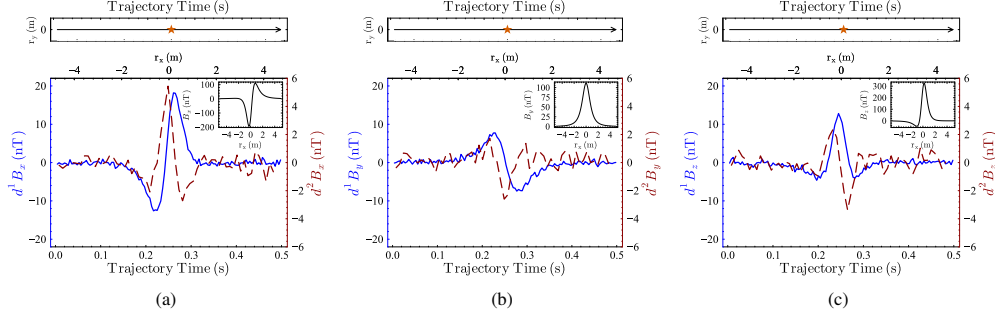


**Fig. 4** Numerical simulation of vectorial gradiometry for magnetic anomaly detection. The sensor vibrates at a frequency  $\nu/(2\pi) = 1$  MHz and is displaced at a constant speed  $v = 20$  m/s and height  $h = 1$  m over the source of the magnetic anomaly (marked with a star), which is located at the center of the trajectory (shown in the top panel). The source of the anomaly is a ferromagnetic sphere of radius  $R = 16$  cm, which is magnetized by a geomagnetic field of intensity  $B = 45.84 \mu\text{T}$ , colatitude  $\theta = 105.63^\circ$  and longitude  $\varphi = 320.72^\circ$ . The intensity of the anomaly field as a function of the sensor position is shown in the inset. Nonetheless, the geomagnetic field is also included in the simulations. Our protocol is applied to measure first ( $d^1 B$ ) and second ( $d^2 B$ ) order temporal variations (solid and dashed lines, respectively), of all three cartesian coordinates of the field  $B_x$ ,  $B_y$  and  $B_z$  (panels (a), (b) and (c), respectively), with stage II occurring in the memory state and having a duration  $t_{II} = 4$  ms. The geomagnetic field is suppressed in the measurement output. Photon shot noise is accounted for in our simulations, such that the measurement contrast is taken to be  $C = 10\%$ , the average number of photon collected per NV center is  $n_{av} = 0.022$ , the number of NVs in the ensemble is  $N_{NV} = 10^{11}$  and the number of repetitions is  $10^3$ . The total duration of the ‘experiment’ is  $t = 8.33$  min.

and magnetoencephalography [12, 20, 33]. In particular, monitoring neuronal activity from single cells is relevant for early detection of neurodegenerative diseases. However, magnetic biosensing requires shielding from the environment, which is expensive and often weak, resulting in an imperfect suppression of background fields.

Here, we study the magnetic field associated with an electrical impulse in a neuron axon. Modelling the axon as a cylinder, Biot-Savart law gives the corresponding magnetic field,  $B(t) = s \frac{d\Phi}{dt}$ , where  $\Phi$  is the intracellular voltage due to the movement of ions in the neuron, which gives rise to the electrical impulse, and  $s$  is a proportionality constant that depends on geometrical and physiological quantities (see Section 5 in the Supplementary Information for more details about the model). Following Ref. [12], where the authors study magnetic fields from neuronal APs in a giant axon from a marine fanworm, we take  $s = 7.6 \text{ pT}/(\text{Vs}^{-1})$ .

The sensor setup is considered the same as in the previous example, although in this case the sensor is not moving, and the evolution in stage II occurs in the sensor state and has a duration  $t_{II} = 32 \mu\text{s}$ . The magnetic field originated from the neuron AP is modeled to replicate the experimental measurement of Ref. [12] and is depicted in Fig. 5 (upper panel). The lower panel in the figure shows the differential signal obtained from our gradiometry protocol. Our results show that a differential measurement of magnetic fields originated from neuron action potentials could be performed, thus not requiring magnetic shielding from the environment. Remarkably, because our protocol can be applied for vectorial magnetometry, we could recover the directional information of the magnetic field, which is one of the main advantages of magnetophysiology over electrophysiology [41].

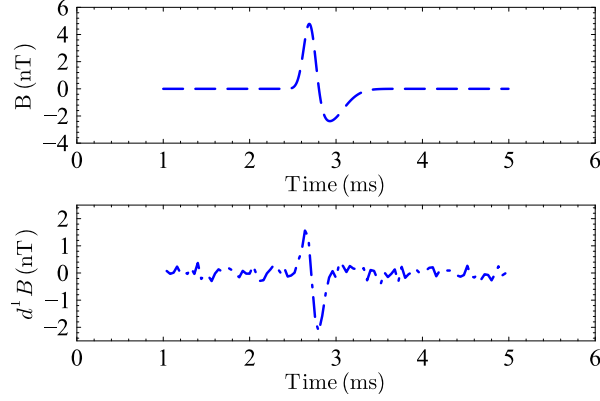


**Fig. 5** (Upper panel) Expected magnetic field from a neuron AP in a giant axon from a marine worm. (Lower panel) Differential signal measured from our gradiometry protocol. Stage II occurs in the sensor state and has a duration of  $32 \mu\text{s}$ . Photon shot noise is accounted for in our simulation, such that the measurement contrast is  $C = 10\%$ , the average number of photons received per NV center is  $n_{av} = 0.022$ , the number of NVs in the ensemble is  $N_{NV} = 10^{11}$  and the number of repetitions is  $10^3$ . Note that the  $x$ -axis corresponds to a single run, such that the total duration of the ‘experiment’ is  $t = 4\text{s}$ .

## 5 Discussion

It is important to note that, if the differential signal is taken between two points with a small temporal or spatial separation between them, the difference between the field values may be close to zero, such that the signal amplitude is heavily reduced, or even suppressed. In order to enlarge this difference, it is possible to extend the duration of the displacement stage, which is limited by the dephasing time of the sensor,  $T_2^*$ . However, because the phase accumulated during this stage has to be small, dynamical decoupling pulse sequences may be applied such that the stage is limited by the sensor coherence time  $T_2$ . Nonetheless, care must be taken in choosing the number of pulses, as an odd multiple causes the phases in Eq.(1) to add rather than subtract, thereby compounding the effect of any background field.

Additionally, the design of the sequence allows for the inclusion of driving fields which suppress unfavorable dipolar interactions between spins [43, 44], further increasing the coherence time of the sensor without damaging the functionality of the protocol. Moreover, as demonstrated in the previous sections, the coherence time can be even further extended to the nuclear  $T_2$ .

Lastly, for the particular case where the target field shows a spatial dependence, physical motion of the sensor enables vectorial gradiometry of the field along the direction of movement. Thus, by changing the direction of motion of the sensor, tensor gradiometry can be performed, which results in a more robust characterization of the field, as it is less orientation dependent.

**Supplementary information.** Supplementary sections are available for this article.

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## Declarations

The data supporting this study are not publicly available. The data are available from the authors upon reasonable request.

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