Electromagnetic induction imaging with a scanning radio-frequency atomic magnetometer

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We demonstrate electromagnetic induction imaging with an unshielded, portable radio-frequency atomic magnetometer scanning over the target object. This configuration satisfies standard requirements in typical applications, from security screening to medical imaging. The ability to scan the magnetometer over the object relies on the miniaturization of the sensor head, the inherent safe nature of the technique, due to the lack of ionising radiation, while its technical simplicity makes it easily deployable, thus ideal for rapid assessment of brain injuries. EMI relies on the induction of eddy currents in the target by a low-frequency magnetic field, and the measurements of the resulting secondary magnetic field. Conventional set-ups are based on pick-up coils for the readout of the secondary field. However, this approach is limited by the poor sensitivity of coils at low frequency, which has hindered the development of applications of EMI. The combination of EMI with ultra-sensitive atomic magnetometers (AMs)1,2 has unlocked the potential of the technique, opening up a wealth of applications, from medical imaging3–10, to security and surveillance11–13, and industrial monitoring.

All experimental demonstrations to date11–23 of electromagnetic induction imaging with atomic magnetometers (EMI-AM) rely on the displacement of the target object with respect to the fixed AM. Such arrangements are at odds with the requirements of imaging for many applications, where the ability to scan the sensor over the object is often needed. This is due to the technical difficulties associated with scanning AMs. First, recent realisations of EMI-AM rely on radio-frequency atomic magnetometers (RF-AM)22–25 which typically require two laser beams at different frequency and a radio-frequency source, hence are more difficult to miniaturise than, for example, coherent population trapping14,15 or free-induction decay26 magnetometers. An interesting route could be the adoption of technically simpler RF-AMs based on nonlinear magneto-optical rotation (NMOR)27, although EMI with NMOR based RF-AMs has not been extensively explored28. Second, operation of an atomic magnetometer at extreme sensitivity requires a controlled environment. Typically systems employ several layers of μ-metal shielding to suppress magnetic noise. This limits the scope of practical applications to targets within the shields. There have been many recent efforts to demonstrate the operation of AMs in unshielded environments29–33. Of direct interest to the present work, RF-AMs have been shown to retain their extreme sensitivity in unshielded environments33. This is usually achieved by compensating stray magnetic fields at the position of the AM. However, this results in an RF-AM that is optimized to a fixed position. Hence, until now, the EMI-AM procedure is simplified by keeping the AM fixed while moving the target.

In this Letter we demonstrate EMI with an unshielded, portable RF-AM scanning over a fixed target object, thus satisfying the requirements for real-world applications. Our reported demonstration relies on two innovations. First, a compact RF-AM is realised, with the sensor head including the required lasers sources, the RF source as well as the magnetic field coils for the active compensation of stray magnetic field. Second, we note that the active compensation system used for stray magnetic fields cannot exactly cancel the magnetic environment. Thus a procedure is implemented to reduce the detrimental effects of the residual spatial variations in the magnetic environment experienced by the sensor head while scanning over the object.

Our sensor head follows the standard arrangement of an RF-AM, as sketched in Figure 1. An atomic vapour is spin-polarized by optical pumping via a σ+ laser beam in the presence of an applied bias magnetic field collinear to the laser beam. A perpendicular AC magnetic field (Bpp) excites spin-coherences and produces a transverse atomic polarization. A linearly polarized probe laser beam is transmitted through the vapour, perpendicular to the pump beam. The atomic Larmor precession is mapped on the rotation of the probe plane of polarization which is measured by a polarimeter. The output is then interrogated by a lock-in amplifier (LIA) and a spectrum analyzer.

The implementation of the sensor head is shown in Figure 2. A support in nylon, 3D printed via selective laser sintering (SLS), holds all the optical and electronic parts in place, with a cover printed in the same material enclosing the sensor. A cubic glass cell of 25 mm side contains Rb vapour and 20 Torr of N2 which acts as a buffer gas. Initial tests were carried out with a gently heated isotopically enriched 87Rb vapour. However, a room temperature naturally occurring isotopic mixture of Rb was found to be sufficient for high-quality imaging.
The system is designed to produce a maximum magnetic field of $1.4 \times 10^{-4}$ T at 250 mA along each orthogonal axis within the cell volume. This value is large enough to cancel any ambient magnetic fields and provide a bias field in the desired operating range - up to 100 kHz - regardless of the orientation of the sensor head.

The sensor head also includes a miniaturized balanced polarimeter. It contains a focusing lens (as in the figure description), a polarizing beam splitter (PBS), a mirror and two photodiodes integrated on a printed circuit board (PCB) with the circuit for differential amplification. The total volume of the polarimeter is $29.7 \text{ cm}^3$. The dimensions and weight of the fully assembled head are $110 \times 110 \times 145 \text{ mm}^3$ and 1.49 kg.

The performance of the atomic magnetometer is evaluated by determining its sensitivity. For this, a 17 nT calibration field $B_{RF}$ is applied. The RF field is scanned around resonance, and the polarimeter output is demodulated by a lock-in amplifier. The measured atomic magnetic resonance is displayed in Figure 3 (a), with the in-phase and out-of-phase lock-in amplifier outputs reported as a function of the detuning from resonance. The half-width at half-maximum (HWHM) of the atomic magnetic resonance is 460 Hz. Figure 3 (b) shows the power spectrum of the polarimeter signal when the same field used in Figure 3 (a) is applied, with the reported baseline noise level obtained with the RF switched off. A signal to noise ratio (SNR) of 915 is extracted from the
presented data we derive\(^5\) an AC sensitivity $\delta B = B_{gr} / \text{SNR}$ of 19 pT/$\sqrt{\text{Hz}}$ and a DC sensitivity $\delta B = (h/\mu_B g)(\text{fT}/\text{SNR})$, where $h$ is Planck’s constant, $\mu_B$ is the Bohr magneton, $g$ is the Landé g-factor, $\Gamma$ is the full-width-at-half-maximum of the atomic magnetic resonance, of 22 pT/$\sqrt{\text{Hz}}$.

![Image](image-url)

**FIG. 3.** (a) A typical atomic magnetic resonance from our system, in unshielded environment and with active stabilisation, with the in-phase (blue circles) and out-of-phase (red squares) signals obtained via demodulation of the polarimeter signal with a lock-in amplifier. The resonance shape was consistent over weeks, proving the high temporal stability of the instrument. (b) Power spectrum of magnetometer signal, giving a signal to noise ratio of 915. (c) PID correction signal of the bias field stabilisation in two different configurations: one operating in the ambient magnetic field (yellow) and the other (black) in the presence of an applied 30 Hz oscillating magnetic field, indicated by an arrow. Data are for a gently heated ($\approx 40^\circ$ C) isotopically enriched $^{87}$Rb vapour and 20 Torr of N$_2$.

The active magnetic field compensation acts along the three directions, as any uncompensated ambient field would shift the magnetometer out of resonance. The most critical stabilization is along the bias field. We verified the effective operation of the feedback loop by applying a 30 Hz oscillating magnetic field and observing the PID correction signal. The appearance of an additional resonance, as shown in Figure 3(c), shows that the PID reacts to the 30 Hz field and acts to cancel it.

Imaging is performed by scanning the magnetometer over a target object held at a fixed position. The sensor head is mounted on a computer-controlled motorized XY stage. Target objects can be placed on a plastic sheet above the scanning magnetometer. Sensor-object distances in the range of 2-12 mm were considered, with similar results. All the results reported here correspond to a sensor-object distance of 2 mm.

A first investigation was devoted to the study of the magnetic environment and specifically to its spatial dependence. An 11 x 11 pixel scan is taken in a 200 x 200 mm plane without any target object. At each position, the RF was scanned and the resonance frequency determined. Two different sets of measurements were taken, the first one without active stabilisation, which was then activated for the subsequent measurements. Results of this background mapping are presented in Figure 4. Figure 4(a) illustrates the background with the feedback loop left open. A 25.6 kHz variation in resonance frequency is seen across the image. For this measurement the output of the PID was manually adjusted to the value corresponding to the PID output at the centre of the image with feedback closed. Figure 4(b) shows the effect of active compensation, as obtained by closing the three feedback loops: the variation in resonance frequency is reduced to 3.2 kHz. The residual inhomogeneity of the magnetic field is due to the unavoidable displacement between fluxgate and sensing volume of the AM, which does not allow for a perfect compensation of the stray magnetic fields at the AM centre. This is particularly affected by any field gradients. The detrimental effect of the spatial variation of the magnetic background is also highlighted in Figure 4(c,d), where the magnetic resonances at opposite edges (position 0,0 mm and 200,200 mm) of the images are measured without/with active compensation in operation. Active stabilization not only reduces the variation in resonance frequency across the image, but also increases the resonance amplitude\(^5\). A consistent background is thus crucial for imaging of conductive objects. While active compensation is essential, we will show in the following that additional procedures are required to obtain high-quality imaging with a scanning atomic magnetometer.

EMI was performed by scanning the magnetometer over the target sample. For each position, the rf frequency is scanned around resonance, with the four outputs of the lock-in amplifier, the in-phase response ($X$), the quadrature response ($Y$), the amplitude of the response ($R$), and its phase lag ($\Phi$), collected during the scan. The time required for a scan is dominated by the acquisition and processing time of the LIA, and by the time required by the XY stage to update the sensor position. For the presented data, a resonance sweep consists of 51 measurements, with a 0.25 s acquisition time per point. An additional 0.9 s between resonance sweeps is taken by the XY stage to move the sensor to the new position. We note that a significant faster scanning can be obtained by only acquiring the polarimeter output traces while scanning, and processing them on a computer. The active compensation of the magnetic field is not sufficient to reduce the level of the spatial variation of the magnetic environment. This is visible in Figure 5(a), where an image of a copper square is produced by plotting the value of $F$ at the same frequency for all pixels. Lines across the image are due to the resonance frequency changing at different positions, as seen in the background scan shown in Figure 4. High-quality imaging was obtained by adopting the following procedure, consisting of two elements. First, the resonance was tracked in the imaging; for each position the magnetic resonance was fitted, and the total signal height
The improvement in imaging performance reduces the sensitivity to phase noise as measured in the configuration with a fixed RF-AM. This significantly reduces the error in the determination of the resonance amplitude. The improvement in imaging performance is visible in Figure 5(b). Second, the image is produced by introducing a detuning from resonance, and specifically taking the measurement for Y at +800 Hz detuning from resonance, and without (c) [with (d)] active compensation of the ambient magnetic field. The amplitude of the resonance is normalised to the maximum amplitude recorded in the image with active feedback. Data are for naturally occurring $^{85,87}$Rb vapour and 20 Torr of $^3$N$_2$ at room temperature.

(1) at resonance was used, as opposed to at a set frequency. The approach presented in this work is suitable for real-world applications, where the ability of scanning the sensor over the target object is typically a requirement. The technique does not require any background subtraction, thus further validating its applicability to a variety of screening scenarios, from security to industrial monitoring and biomedicine.

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The data that support the findings of this study are available.
from the corresponding author upon reasonable request.

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