Quantum sensing for gravitational cartography

Ben Stray*

University of Birmingham

Andrew Lamb*

University of Birmingham

Aisha Kaushik

University of Birmingham

Jamie Vovrosh

University of Birmingham

Anthony Rodgers

University of Birmingham

Jonathan Winch

University of Birmingham

Farzad Hayati

University of Birmingham

Daniel Boddice

University of Birmingham <https://orcid.org/0000-0002-3738-2327>

Artur Stabrawa

University of Birmingham

Alexander Niggebaum

University of Birmingham

Mehdi Langlois

University of Birmingham

Yu-Hung Lien

School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK

<https://orcid.org/0000-0001-6303-1523>

Samuel Lellouch

University of Birmingham

Sanaz Roshanmanesh

University of Birmingham

Kevin Ridley

University of Birmingham

Geoffrey de Villiers

University of Birmingham

Gareth Brown

Defence Science and Technology Laboratory

Trevor Cross

Teledyne e2v

George Tuckwell

RSK

Asaad Faramarzi

University of Birmingham

Nicole Metje

University of Birmingham

Kai Bongs

University of Birmingham <https://orcid.org/0000-0002-7334-1848>

Michael Holynski (✉ M.Holynski@bham.ac.uk)

University of Birmingham <https://orcid.org/0000-0003-0163-5799>

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Abstract

The sensing of gravity has emerged as an important tool in geophysics for applications such as engineering and climate research^{1,2,3} where it provides the capability to probe otherwise inaccessible features under the surface of the Earth. Examples include the monitoring of temporal variations such as those found in aquifers⁴ and geodesy⁵. However, resolving metre scale underground features is rendered impractical by the long measurement times needed for the removal of vibrational noise⁶. Here, we overcome this limitation and open up the field of gravity cartography by realising a practical quantum gravity gradient sensor. Our design suppresses the effects of micro-seismic and laser noise, as well as thermal and magnetic field variations, and instrument tilt. The instrument achieves an uncertainty of 20 E (1 E = 10^{-9} s⁻²) and is used to perform a 0.5 m spatial resolution survey across a 8.5 m long line, detecting a 2 m tunnel with a signal to noise ratio of 8. The tunnel centre is localised using a Bayesian inference method, determining the centre to within ± 0.19 m in the horizontal direction and finding the centre depth as (1.89 -0.59/+2.3) m. The removal of vibrational noise enables improvements in instrument performance to directly translate into reduced measurement time in mapping. This opens new applications such as mapping the water distribution of aquifers and evaluating impacts on the water table⁷, detecting new features in archaeology^{8,9,10,11}, determination of soil properties¹² and water content¹³, and reducing the risk of unforeseen ground conditions in the construction of critical energy, transport and utilities infrastructure¹⁴, providing a new window into the underground.

Main Text

The quantum gravity gradient sensor uses atom interferometry¹⁵, which has been used in laboratory based experiments to provide sensitive measurements of gravity¹⁶, to investigate the equivalence principle¹⁷, the fine-structure constant¹⁸ and Newton's gravitational constant¹⁹, prompting the desire to transition these sensors into practical devices for use in real-world environments²⁰. For example, gravity sensors have been created which can be used on volcanoes and mountain environments^{21,22}, and for measurements by air²³, sea²⁴, and on rockets²⁵. A typical approach in these devices is to employ light pulses to drive two-photon stimulated Raman transitions in atoms and use these to create a superposition of matter waves in different momentum and energy states. The resulting atomic wave packets move along two spatially separated trajectories, before being recombined and interfered. This creates the matter-wave analogue of a Mach-Zehnder interferometer. The phase difference in the resulting interference pattern is proportional to the local gravitational field. However, such devices, as with any gravimeter, are fundamentally limited in their measurement time due to the need to average out micro-seismic vibration²⁶. This presents a major barrier to realising gravity maps with high spatial resolution.

In order to enable gravity cartography, and operation in application-relevant conditions, we implement a novel “hourglass” configuration cold atom gravity gradiometer²⁷. This enables robust coupled differential measurements upon two clouds of atoms, separated by a vertical baseline²⁸. Two counter-orientated single beam magneto-optical traps (MOTs) allow passage of common Raman beams to perform interferometry (Fig. 1a). The measurement axis is aligned to measure the vertical component, G_{zz} , of the (3x3) gravity gradient tensor, which is the largest and most relevant component for gravity cartography. Differential operation suppresses primary noise sources (vibration and micro-seismic), systematic shifts (such as tilt), and changes in the optical path-length between the beams used to drive the Raman transitions²⁹. The commonality of laser intensity noise for the cooling beams of the single-beam MOTs⁶ enables cloud temperature fluctuations to be stable to within a few 100 nK (Fig. 1b, upper), limiting the impact of AC Stark shifts, and reduces cloud centre-of-mass motion by an order of magnitude when compared to conventional 6-beam approaches (see Methods). The resulting baseline stability is 50 ppm (Fig. 1b, lower), which corresponds to a systematic error of less than 0.1 E.

The hourglass configuration provides several practical benefits (see Methods). Avoiding the need for off-axis beams creates a robust and compact optical delivery arrangement, allowing months of operation in the field with no need to correct alignment. The configuration also provides a radially compact form factor, enabling compact magnetic shielding with 25 dB attenuation that suppresses effects due to external magnetic fields, preventing these from affecting the atom cloud generation. The beam configuration, in combination with a robust all-fibre laser system, enables independent control of the counter-propagating Raman beams, facilitating reversal of the light pulse directions³¹. Interleaving measurements in each direction suppresses several systematic effects, including reducing those due to residual magnetic fields to below measurement precision. Furthermore, phase shifts and contrast loss from parasitic Raman transitions³² are prevented through independent delivery of the Raman beams for each direction, without the need for a phase lock.

To measure the gravity gradient (see Methods), each MOT is loaded for 1 to 1.5 seconds with ^{87}Rb atoms before sub-Doppler cooling is used to reduce the cloud temperatures to the micro-Kelvin regime. The clouds are then dropped and simultaneously subjected to an atom interferometry sequence. The output of each interferometer is measured using fluorescence to detect the ratio of the populations of the two relevant atomic ground states, with approximately 10^5 atoms participating in each atom interferometer, for a typical measurement rate of 0.7 Hz. A Lissajous plot of the upper versus lower atom interferometer outputs is then used to extract the differential phase, from which the gravity gradient is determined (Fig 2, inset)³³. The calibration of the sensor was verified under laboratory conditions by modulating the position of known test masses near to the sensor to vary G_{zz} (Fig. 1c). This resulted in a measured change of (205 ± 13.1) E, compared to a modelled signal of 202 E.

Similarly, the sensitivity and stability of the instrument were evaluated in an outdoor environment. The Allan deviation³⁴ of the phase data (Fig. 2) showed an average short-term sensitivity of $(466 \pm 8) \text{ E}/\sqrt{\text{Hz}}$ and an uncertainty of 20 E within 10 minutes of measurement.

To demonstrate the potential for gravity cartography, a 0.5 m spatial resolution survey was performed along an 8.5 m survey line on a road surface above a tunnel (see Methods). A site model using an air/soil contrast infinite cuboid void, and taking into account local buildings and terrain, produced an estimated peak signal of 150 E. The parameters for the model were informed using auxiliary data from on-site measurements such as topography scanning and ground penetrating radar. The measurement data in Fig. 3a shows a gravity gradient anomaly consistent with this site model and the expected location and size of the tunnel (Fig. 3b).

For use in practical applications, it will be important to interpret the data in an accessible way that produces information upon which a user can make decisions or act. For this purpose, we have developed a Bayesian inference method to make quantitative predictions of the depth and spatial extent of the anomaly. This was applied to the gradiometer data with a data-generated model of a buried cuboid³⁵ assumed a priori. The prior distribution of the cuboid density contrast is taken to be Gaussian, with a mean of -1.80 g/cm^3 , to represent a void in surrounding soil, and standard deviation of 0.10 g/cm^3 . The inference process produces distributions for the position, depth and cross-sectional area of the tunnel using the probability of excavation (POE) metric³⁶ (Fig. 3c). The observed spread of the POE is expected, due to measurement uncertainty and the ambiguity that exists between model parameters specifying depth, area, and density, typical of inference from potential field data³⁷. A signal to noise ratio of 8 for the detection is estimated from the data, finding the deduced horizontal position of the tunnel centre at $(0.19 \pm 0.19) \text{ m}$ along the survey line and a depth to the centre of $(1.89 - 0.59/+2.3) \text{ m}$ (see Methods).

Furthermore, by assuming a priori knowledge of the tunnel geometry, the focus of the inference was switched to infer the soil density (Fig. 3d). This results in a near Gaussian posterior distribution for the density parameter, with a mean of -1.80 g/cm^3 and standard deviation of 0.15 g/cm^3 .

The uncertainty demonstrated by the prototype instrument during static operation surpasses the reported performance of commercial gravimeters for survey applications by a factor of $1.5\text{--}4$ ^{38,39}. In this first demonstration of sub-metre resolution mapping with quantum gravity sensors, the repeatability of the

prototype during the survey was similar to commercial gravimeters and limited by systematic effects (see Methods), such as due to the Coriolis effect, which can be addressed through further engineering. Furthermore, the sensor could be moved from one spatial position to another within 75 seconds, including alignment to the vertical to within 1 millidegree. If addressing these aspects, such as through operation on a rail or vehicle, the current instrument performance would in principle allow detection of the tunnel, or similar anomaly, with a 10-point line scan and a signal to noise ratio of 3 within 15 minutes of total measurement time.

The detection of the tunnel allows the assessment of the instrument performance for a range of potential applications. Fig. 4a shows a range of typical signal sizes for a variety of application areas in comparison to the sensor uncertainty, with features in the range above the sensor uncertainty being detectable with the current instrument. In civil engineering applications, this performance could provide a reduction in the uncertainty of ground conditions and be used to inspect brown field sites, to search for tunnels and large or near-surface utilities, and to detect erosion features before they become sinkholes. This performance is also relevant to archaeological applications, for example enabling the detection of tombs or hidden chambers and investigating how previous civilisations used underground infrastructure. Furthermore, the sensor could be of particular use in the mapping of aquifers, in order to better understand and optimise the use of water and its impact on the environment. It could also be used to measure density distributions within the ground. Based upon the inferred standard deviation, the soil density extraction method is currently sensitive to 10% level changes in the mean, meaning that in principle this could distinguish between soil that is either dry or saturated, or used to investigate localised soil compaction, e.g. in precision agriculture. Typical anticipated signals for these applications, with the 20 E noise our sensor achieves within a 10 min measurement time, are illustrated in Fig. 4b.

The removal of vibration noise means, in contrast to gravimeters, that future improvements in instrument sensitivity can be directly translated into reductions in measurement time or improved uncertainty. Implementation of further scientific enhancements to the sensor, including, for example, the use of large momentum beam splitters^{40,41}, has the potential to provide a further 10-100 fold improvement in instrument sensitivity, allowing faster mapping or detection of smaller and deeper features. It is expected that such performance will be achieved in practical instruments within the next 5-10 years.

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39 This comparison is made through comparing the extracted uncertainty for a single gravimeter of the gradiometer, 1.4 ng for the 20 E gradiometer uncertainty (which includes suppression of correlated noise through differential measurement), to the reported value for the gravimeter.

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Declarations

Statement of contributions

The design and development of the sensor was performed by BS, AL, AK, JV, AR, JW, FH, KB, MH with inputs from AS, AN, KR, GdV, ML, YHL, SL, and inputs on design for field use from DB, NM, TC, GT, GB. The characterization and calibration measurements were provided by BS, JV, JW, FH, KR, MH. The survey site modeling was performed by DB, AL, AR, KR, FH with inputs from NM and GT. The survey design and measurements were contributed by JV, DB, JW, FH, KR, SR, BS, AL, MH with input on the survey design and process from NM, KB, GT, AF. Data processing was provided by JW, KR, JV and AR, with AR providing the Bayesian inference. MH and KB conceived and coordinated the experiment. MH, BS, AL, KB, JV, AR wrote the manuscript. All authors contributed to the review and improvement of the manuscript. *The authors Ben Stray and Andrew Lamb, were equal contributors.

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Figures

Figure 1

a) Hourglass gradiometer using two counter-orientated single beam magneto-optical traps, realised using mirror assemblies (blue). The initial atom clouds (green) are dropped before being subjected to light pulses separated by time T to realise the atom interferometers (purple clouds). The beam delivery is shown in red, with the beams transiting through the mirror assembly indicated by the smaller arrow. Each interferometer is operated simultaneously, with a vertical baseline separation of 1 m. b) Temporal variation of atom cloud temperatures from each trapping region, measured using time of flight, and baseline drift, determined from time of arrival, with the sigma range represented by the shaded region. c) Calibration measurement of gravity gradient variation caused by movement of a test mass between two positions (black – mass close, grey – mass displaced) from the sensor (blue tube), with the modelled projection of the change in gravity gradient signal, ΔG_{zz} , shown in red.

Figure 2

Allan deviation with overlapping averages of the instrument output during outdoor operation. Inset - typical Lissajous figure of the output signal of the upper and lower interferometers, which is used to extract the gradiometric phase.

Figure 3

a) Gravity gradient data with standard error (black scatter) and total inferred uncertainty when including model uncertainty (blue scatter, see Methods), 1-sigma (dark blue shading) and 2-sigma (light blue shading) confidence interval bands, and site model (dashed); b) Scale schematic of the site showing the dimensions and position of the tunnel and leading contributions to the gravity signal. The origin for coordinates (red dot) is defined in the vertical direction by the lowest point on the survey line, and in the horizontal direction by the expected location of the centre of the tunnel; c) Probability of excavation (blue contours) inferred from the gravity-gradiometer data, and expected tunnel position (dashed); d) Estimation of soil density by shifting the focus of the inference process to use assumed knowledge of the tunnel geometry and inference of the gradiometer data, showing the 68% highest density interval (HDI).

Figure 4

a) Contour plot for typical gravity gradient signal sizes in various applications, contours in Eötvös for density contrasts of 1.8 g/cm³. The parameters of the detected feature (red dot) and the sensor uncertainty (solid line) are shown. Features in the region above the solid line are detectable with current uncertainty. b) A perspective of future gravity cartography being used with 0.5 m spatial resolution over a region, at an uncertainty level of 20 E. Expected signal sizes for a range of applications are shown.

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