URBAN MAPPING
UNDERGROUND NAVIGATION
SUBSEA MAPPING
ARCHAEOLOGICAL PROSPECTING
GRAVITY GRADIENT SENSORS
Foreword

GG-TOP, the Gravity Gradient Technologies and Opportunities Programme is the starting point of our vision to open up a new window to the underworld based on gravity sensing. Gravity – the all-penetrating force holding the Universe together – promises an unprecedented and unobstructed view of the underground.

GG-TOP’s comprehensive technology research programme crosses the boundaries between physics, engineering and industry, providing an accelerated pathway to move from blue sky research into innovation. Atom interferometry as disruptive quantum technology has the potential to exceed conventional gravity gradient sensors by several orders of magnitude in sensitivity and allows flexible sensor schemes to suppress terrain, geological and other noise sources. The potential of gravity gradient technology as pursued in GG-TOP is to locate underground features at significant depths with a diameter to depth ratio of <<1, eg, a 100mm object at 1m depth and to speed up conventional gravity surveys by more than 100-fold. Close interactions between physicists with engineers doing real-world field trials in collaboration with industry partners ensures meaningful and practical instrument development.

Applications are at the centre of GG-TOP and industry views guide our sensor developments and modelling focusing on the sources of importance for commercial applications and creating the visual interface most practical in the field.

The success of GG-TOP in relating blue-sky research to meaningful commercial applications is reflected in the growth of the commercial partner base from 14 to over 30 during the last 4 years and the inclusion of its vision into the UK national quantum technology strategy.

Kai Bongs
Principal Investigator
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Civil Engineering Applications
Dr Nicole Metje, Dr Dan Boddice,
Professor Chris Rogers, Dr David Chapman

It is vital for civil engineers to know what hazards lie in the ground, such as pipes, cables and buried mineshafts, but also the condition of the ground, ie, whether there are wet patches, soft ground or hidden sinkholes, prior to construction. This aids engineers when designing new buildings or simply breaking ground, eg, for streetworks thereby reducing their impact (estimated at £5billion/year for the UK alone), reducing the risks due to excavation and associated Health and Safety impacts and saving project costs.

Several different technologies exist to see through the ground, but many rely on transmitting an electromagnetic wave through the ground which is then reflected off a buried pipe or cable with the reflected signal received at the ground surface. However, this approach requires ever greater amounts of transmission power to ‘see deeper’ into the ground, while the ground properties can considerably attenuate signal propagation – this is especially true in saturated soils, such as wet clay, can make it difficult to see anything deeper than around 1–2 metres.

As pipes and cables can be buried up to several metres below the ground surface, an alternative technology such as microgravity needs to be utilised, yet existing sensors are affected by the density of surrounding buildings or features, vibration from traffic and wind, and ocean tides, to name but a few influences. This limits the maximum possible resolution to a target size to depth ratio of around one, so only large drainage and sewer pipes can be detected.

In the GG-TOP sensor, cold atoms are used as ideal test-masses to create a gravity sensor which can measure a gravity gradient rather than an total value. This suppresses several noise sources, and creates a sensor useful in everyday applications. The GG-TOP project identified a range of different noise sources affecting existing microgravity sensors based on a mass and spring principle including:

- Sensor noise (tilt, temperature, linear drift, flicker noise from the electrical components)
- Environmental noise (eg, tides, atmospheric pressure, seismic and wind noise)
- Location effects (eg, latitude, height of sensor, terrain, buildings)

These noise sources have been assessed with respect to their impact on the gradiometer rather than the a single gravity sensor (see Figure and Table below). Most will be suppressed as the gradiometer will take two measurements simultaneously at the same location. Models were developed to distinguish the signal of interest from the other noise sources.

In Civil Engineering we aim to bring a range of quantum sensor devices out of the laboratory and in to the real-world. To achieve this, close collaboration with end-users, such as geophysical surveying companies, is essential to understand the practical challenges and limitations of existing technologies, ie, the ‘competitors’, to provide a reality check as the developing quantum technology (QT) has to operate in the harsh environment on site. The SIGMA project is an example of the strong collaboration with...
This project is led by RSK with the aim of understanding current survey practices and quantifying the potential of the next generation of QT-based microgravity geophysical instruments to create a step-change in how the ground is investigated. This work featured two joint measurement campaigns using multiple existing microgravity instruments to quantify the environmental noise (waves, tides, earthquakes, wind) and the variability in instrument noise. It further quantified the field of opportunity compared with existing geophysical sensors showing the range of targets and depths that would make a significant difference if the QT sensor could fill this gap.

**Measurement Campaigns**

Initial measurement campaigns have utilised existing microgravity sensors, mostly the Scintrex CG5. In parallel with practical evaluation of environmental and location effects, different correction algorithms were tested as well as forward modelling to assess the potential of the QT gradiometer. For example, the impact of a ‘cliff’ on the measurements (blue area at the bottom) can be seen below. Once a cliff correction has been carried out, high and low density soil areas close to the cliff can be identified. This is an example of the importance of terrain corrections. Similar corrections are needed for other exogenous sources.

The campaigns demonstrated that the GG-TOP gravity gradiometer has the potential to reveal the extent of the usable underground space in cities, showing natural and man-made features at depths beyond current surface surveying capabilities, as well as the condition of the ground.
GG-TOP Sensor-Gravity Gradiometer

Mr Alexander Niggebaum, Mr Andrew Hinton, Mr Georgios Voulazeris, Dr Michael Holynski

The advent of laser cooling has opened a wide spectrum of applications and research opportunities. One aspect that has moved into focus recently is the use of quantum effects for sensor applications. First, we like to clarify what quantum effects means in this context: a particle showing quantum behaviour is ordinary matter with the only difference that it is heavily isolated from the surrounding and has therefore very limited interaction. If the interaction with the surrounding is suppressed, effects within the particle or a group of particles become visible which would otherwise be shadowed.

So how can this stage be reached? At room temperature gaseous atoms are moving with roughly the speed of sound. Therefore it is very likely that they hit other particles and the afore mentioned shadowing occurs. The first task is therefore to slow them down such that they would only move with cm/s to mm/s and we will see that laser cooling is the tool to achieve this.

Laser cooling uses the absorption and emission spectra of elements to selectively transfer force. Very much like sodium street lamps shine orange because their emission spectrum is in this colour range, rubidium is emitting and also absorbing at 780nm, a dark and barely visible red. This wavelength is conveniently the same used for CD drives and laser systems are therefore readily available, which is one argument for the common choice of rubidium in atom interferometers. Light of this colour therefore is absorbed and emitted by the atoms. However we know that light is quantized so the process can be seen as the emission and absorption of individual photons which is accompanied by a small amount of momentum transfer. If the atoms are in a beam of directed light, they will absorb a photon travelling in the direction of the beam gaining one unit of momentum in the same along this axis. However they are moving freely and therefore emission occurs in a random direction and so does the momentum decrease of one unit. If a lot of these processes happen, over time, the atom will eventually feel a force which is pushing it away from the source of the light. But because the atom has a spectrum, this will only happen at a resonant wavelength.

Changing the colour of the light allows therefore to tune the force on the atoms. The trick with laser cooling is to use the Doppler Effect, the change of frequency when the source moves towards or away from the observer. If the light is slightly red detuned, only atoms moving towards the source will feel a force. Atoms at rest are not resonant and are therefore unaffected. This velocity dependence creates the cooling effect we seek because only atoms which are hot and moving fast, need to be decelerated.

The second stage is to trap the atoms. Although Doppler cooling slows atoms it does not confine them and they eventually move out of reach. Trapping is achieved by modifying the spectrum through an external field exploiting the Zeeman Effect. This creates a position dependent force on top of the velocity dependent one which in combination leads to a cold cloud of atoms. A sketch of such a Magneto-Optical-Trap, or short MOT, is shown below. The atoms are confined in a cross of 6 counter-propagating laser beams and are gathering in the centre of two coils which are run in Anti-Helmholtz configuration, creating a quadrupole field with zero amplitude in the centre. These atoms now are slow enough to show the quantum effects scientists are interested in. The typical unit of measure is temperature which is proportional to the remaining energy. Our cloud now has a temperature of typically tens of µKelvin, which is a billionth of a degree above absolute zero (zero K).

The quantum behaviour of atoms at such low temperatures allows the creation of an atom interferometer. In fact atoms can interfere with themselves if cooled to such levels. For comparison: a light interferometer to measure rotation splits a laser beam, directs both arms around an enclosed area and recombines them. One observes changing output intensities at the overlap depending on the rotation speed. This occurs because the path aligned with the rotation direction appears longer than the
opposite, causing the interference pattern to change. The precision depends on the wavelength of the used light. Louis deBroglie found that matter can be associated with an effective wavelength which is typically orders of magnitude smaller than light. An interferometer made from atoms is therefore orders of magnitude more precise than one made from light.

Above is a sketch of a typical atom interferometer geometry. The previously described interaction between light and atoms can be used to create the necessary geometry through light pulses, indicated by red bars on the horizontal time axis. The markings $|e>$ and $|g>$ indicate internal states of the atom, which are used to encode the arms and the phase relation at the output ($|\Psi(\phi)>$). The dashed lines are trajectories of the atoms without gravity. This is important because contrary to light, atoms do have mass and are therefore dragged down by the gravitational pull. We can now use this to our advantage because the geometry of the interferometer does not only change with rotation as in the light example given, but also with the gravitational pull. An atom interferometer is therefore the perfect tool to measure gravity to high precisions. It is in fact precise enough to detect the gravitational field of a person close to the device and therefore other objects such as infrastructure. A wider range of applications is described in this brochure.

The catch is unfortunately that a sensor which can measure to such precisions is also very sensitive to vibrations or other external disturbances. The GG-TOP sensor was therefore designed as a gravity gradiometer. Instead of measuring gravity at a single point as a gravimeter, two atom interferometers are driven at the same time with the same laser pulses and the difference, the gravity gradient, is measured. For example vibration couples into the device and is then visible in the laser pulses. If both clouds and therefore interferometers see the same change but the measured magnitude is the difference of both, the unwanted disturbance cancels out.

The picture below shows the apparatus developed in the program. Atoms are precooled in a two dimensional version of the discussed trap (2D MOT) and used to fast load a three dimensional trap (3D MOT). Once the desired temperature is reached, a cloud is launched vertically into the vacuum tube and while it is still on flight a second one cooled and launched as well. Both of them are accelerated in a way that the apex of their trajectories lies within the areas marked ‘interrogation cubes’. A vertical laser beam along the tube drives the simultaneous interferometers and ensures the noise cancellation. Gravity is read out by probing the atoms with yet another laser beam and monitoring the change in atoms in the two states $|e>$ and $|g>$ mentioned earlier, which is proportional to the local acceleration. This technique has been realised in lab based experiments but the new approach in the GG-TOP programme is to build a mobile sensor.

This is achieved through the use of fibre based components and a compact packing to make the apparatus mobile. The underlying tool is however still the same, atom light interaction is not only used to cool and trap atoms but also create the interferometer geometry which allows the precise measurement of gravitational acceleration.
Noise Sources on Gravity Measurements

Dr Dan Boddice, Dr Yuriy Goncharenko, Dr Nicole Metje, Phil Atkins

The aim of any geophysical survey using gravity instruments is to reduce the data to a map of the localised subsurface density at each measurement point which can then be either interpreted visually or used with an inversion process to identify and derive additional information on the size and depth of the buried features. However, gravity and gravity gradient measurements are strongly affected by noise and gravity signals from sources other than the desired target. These vary temporally and spatially and often exceed the desired signal from the geophysical target. Noise sources on gravity measurements fall into three main categories...

- Instrumental noise stemming from the instrument itself which tends to vary as a function of time. Examples include tilt on the instrument, drift on the sensor and electronic flicker noise from the instrumental electronics.
- Environmental noise stemming from vibrations and signals from the movements of the planets and seas. These typically vary as a function of both time and spatial location. Examples include tidal signals, changes in atmospheric pressure, noise from traffic and microseismic noise from ocean waves.
- Location based noise caused by the position of the instrument due variations in the distance from the centre of the Earth’s mass and signals from nearby objects. These are static as a function of time but vary according the location of the instrument. Examples include latitude noise, height of the sensor and signals from surrounding buildings and terrain.

Knowledge of the scale and effect of these different noise sources is vital for a successful survey as these noise sources must be either eliminated or reduced by good survey practice or using corrective procedures in post-processing. Additionally, knowledge of noise sources can be used to better understand the likely challenges to applying the new sensors to real world problems as the scale of the noise limits the resolution of the survey regardless of the accuracy at which it is measured. One final reason to have a good understanding of noise sources is to quantify the uncertainty associated with each measurement, which is vital in order to make use of Bayesian inversion processes.

One difficulty with assessing the sources of noise on gravity measurements is the difficulty in separating the different sources of noise from each other, which requires the use of multiple instruments with different corrections. Therefore to quantifiy these sources of noise, the GG-TOP and SIGMA projects have conducted a number of measurements using multiple instruments both for long term static measurements, field measurement campaigns and over known targets (Figure 1). Data were analysed using a range of statistical techniques and the results of this testing was a quantification and assessment of the noise and corrections used in microgravity survey (see Table 1).

Figure 2 shows the current limitations on noise reduction associated with practical measurements with current instruments by comparing the theoretical response of two concrete blocks with processed real world...
data collected using the Scintrex CG5. The main current practical limitations on survey accuracy come from the instrument noise and environmental noise from ocean waves, man-made vibrations and the wind.

Knowledge of noise sources is also useful for assessing the potential of the new quantum technology (QT) sensors as practical limitations on performance are limited by their ability to measure the signal from the target instead of simply measuring the sources of noise more accurately. Information generated from the field trials has been fed into the simulation of signals and noise to generate realistic survey outcomes (see Figure 4). Results show that the key advantage of the new QT sensor operating in a gradiometer configuration is that environmental sources of noise that affect single sensor gravimeters will cancel in the subtraction between the two sensors (see Figure 4), whereas a single sensor QT sensor will only be more effective if used to measure for longer measurement times than those currently used in order to average out the effects of microseismic noise. The use of simulations such as these can be used to test the effects of different instrument configurations in terms of sensor height and separation, and measurement strategies in terms of measurement grid separation and measurement time.

Table 1. The scale and methods to correct microgravity noise

<table>
<thead>
<tr>
<th>Noise</th>
<th>Size of error</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt from vertical</td>
<td>0-900 μGal for tilt 0-200 arcseconds in X and Y planes</td>
<td>Corrected by internal sensors</td>
</tr>
<tr>
<td>Temperature on sensor</td>
<td>Varies between instruments 130 μGal/degree mK</td>
<td>Corrected by internal sensors</td>
</tr>
<tr>
<td>Linear creep on sensor springs</td>
<td>&lt;2mGal per day</td>
<td>Linear Drift removal from repeat base stations</td>
</tr>
<tr>
<td>Electronic flicker</td>
<td>Varied between instruments. Up to 12 μGal (SD 2.5 μGal)</td>
<td>None</td>
</tr>
<tr>
<td>Celestial Tides</td>
<td>Up to 280 μGal in a day</td>
<td>Harmonic or Ephemeris models Direct measurement</td>
</tr>
<tr>
<td>Oceanic Tidal Loading</td>
<td>Up to 20μgal per day</td>
<td>Ocean Tide models, Direct measurement</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>0.3 μGal per hPa Typically &lt;3 μGal per day can be up to 7 μGal per day</td>
<td>Correction to sea level pressure using height and recorded pressure</td>
</tr>
<tr>
<td>Seismic noise (ocean waves and earthquakes)</td>
<td>Dependent on periodicity and size of ocean waves. Earthquakes give very large but short disturbances</td>
<td>Reduced by averaging over long period. Earthquakes removed using despiking or filtering</td>
</tr>
<tr>
<td>Man Made Noise (Vibrations)</td>
<td>Dependent on activity</td>
<td>Reduced by averaging over long period. Despiking and filtering</td>
</tr>
<tr>
<td>Wind Noise</td>
<td>Dependent on weather</td>
<td>Windshield (elimination) despiking and filtering (reduction)</td>
</tr>
<tr>
<td>Natural Soil Density Variability</td>
<td>Currently estimating at c. 1μGal but will depend on the type of soil</td>
<td>None</td>
</tr>
<tr>
<td>Latitude</td>
<td>At mid latitudes c. 0.8 μGal per m</td>
<td>International gravity formula</td>
</tr>
<tr>
<td>Height of sensor from centre of earth’s gravity</td>
<td>∼30 μGal per m of elevation</td>
<td>Free Air correction</td>
</tr>
<tr>
<td>Terrain effects</td>
<td>Depends on density and size and proximity of the terrain</td>
<td>Bouguer Correction (slab) and Hammer Correction, DTM model</td>
</tr>
<tr>
<td>Buildings</td>
<td>Depends on size of the building and materials used</td>
<td>Forward models of the building</td>
</tr>
</tbody>
</table>

**Figure 2.** a) Theoretical response from forward model b) Actual response measured by the instrument

**Figure 3.** The effect of wind noise on gravity readings

**Figure 4.** Simulation of a 1m radius spherical void at a depth of 3.5m below the surface based on 3 x 30 second measurements per point and a grid spacing of 1m.
Development of Quantum Sensing Technology for Subsea Applications

Charles Wang

Quantum cold atom matter wave interferometers are extremely sensitive instruments to measure acceleration, rotation and gravity. If the device is subject to external influence such as acceleration, gravity or magnetism, then a phase shift will perturb the interference fringes, and from this, the external influence can be reconstructed and measured. Their superior scale resolution could make them a powerful tool in the next generation of gravimeters, inertial sensors and magnetometers for subsea environments. Such devices can be used in mapping subsurface structures for oil and minerals and detecting gravitational and EM anomalies due to pipeline erosion and structural failure. The device being developed at Aberdeen is a compact cold atom g-sensor to meet the requirements of subsea deployments. It could provide the basis for a miniaturised sensor suitable for system integration with an underwater vehicle such as AUV and ROV, subject to stringent payload and power constraints.

The new quantum technology is expected to improve measurement sensitivity over existing methods, with significantly reduced power requirements and physical dimensions. It could offer advantages in mobility and real-time sensing, and has no moving parts and no loss of signal due to medium absorption. It would make possible the deployment of precision gravitational and EM sensors in challenging environments such as deep water. It can be applied to pipeline and riser inspection, under seabed survey and prospecting for reservoirs irresolvable with present technology. Being more cost effective, it has the potential to provide non-destructive and non-intrusive alternatives to in-line inspection. It is expected to lead to improvements in system integrity and field exploration.

Potential benefits of this technology would be:

- COMPACT – suitable for deployment on ROVs and AUVs.
- ROBUST AND MOBILE – no moving parts for use in challenging subsea environments.
- REAL-TIME SENSING – operators view results during deployment.
- NO LOSS OF SIGNAL DUE TO ABSORPTION – good signal to noise ratio.
- SENSITIVE – significant improvement over existing technology.
- LOW POWER REQUIREMENTS – suitable for subsea deployment.

Potential applications of this technology include:

- LOCATING OIL
- MAPPING TERRAIN
- LOCATING BLOCKED OR CORRODED OIL PIPES
- NAVIGATION

The quantum sensing technology can be deployed on a Remotely Operated Underwater Vehicle (ROV). In this case, only the atomic trap as sensing unit needs be mounted onto an ROV. The sensor modules would be located on board the deployment vessel with the operator and connected to the ROV via power, optical fibre and communication cables. The Sensor could be mounted onto the front of an ROV and used to measure of the magnetic structure of the pipeline to find faults. A Mu-metal belt, an accessory, is used around the pipe to alleviate the influence of external magnetic field.
To illustrate the deployment of this technology, we use the symbols listed in Fig. 2. See Fig. 3 for the deployment on an ROV.

The quantum sensing technology can be deployed on an Autonomous Underwater Vehicle (AUV). Mounted internally to the AUV, are the same the atomic trap as sensing unit and sensor modules and power source that can be used on an ROV. On an AUV the system is completely detached from the deployment vessel a part from wireless communication with the operator. See Fig. 4.

This sensor can be used for mapping subsurface structures, as well as detecting gravitational and electromagnetic anomalies due to erosion and mineral, oil and gas deposits. The new sensing technology should make possible the deployment of precision sensors in challenging environments such as deep subsea to provide a nondestructive and non-intrusion alternative to structure and formation surveying using current technologies such as seismic technology.

References
Bayesian Inference

Anthony Rodgers

For many of the practical civil engineering applications of a field robust quantum instrument, an inference algorithm is needed to analyse gravity measurements and produce an intuitive output of the information contained within.

Due to the ambiguity problem inherent in potential field measurements, surface gravity measurements could be produced by an infinite set of underground density distributions. To overcome this problem an inference technique is needed that can incorporate a-priori information from other sources to help limit the set of solutions to those that are physically plausible.

Bayesian inference provides a means of updating our a-priori information with information contained within gravity data. Using Markov chain Monte Carlo (MCMC) algorithms to efficiently explore the model space, the algorithm outputs models that fit the data with high probability. From these many models, a picture of the underground can be built that incorporates all uncertainty present in the measurement process. With such a robust treatment of uncertainty, end users are able to make decisions based on the level of confidence indicated by the inference algorithm outputs.

As a demonstration of the capabilities of the inference algorithm, synthetic data for a target pipeline was generated for both the current portable gravimeter technology (Scintrex CG-5) and for a future atom interferometer gradiometer (AI). Corresponding Gaussian measurement uncertainties were added to the data, with a standard deviation of $3 \times 10^{-8}$ ms$^{-2}$ (3 microGals) for the CG-5 and $6 \times 10^{-9}$ s$^{-2}$ (6 Eotvos) for the AI. A measurement spacing of 1 m was used for both data sets.

Here, the pipeline is not infinite but has a ‘dog leg’. Such anomalies are complex in the sense that they cannot be easily forward modelled by a single object. In order to infer model parameters of such a data set, the Bayesian inference algorithm needs the ability to explore models that differ in the number of parameters needed to describe them, i.e., the model dimension. To do this reversible jump-MCMC (RJ-MCMC) is used, which allows the measurement data to determine how complex the model should be. Bayesian inference has an inbuilt ‘Occam’s...
Razor”, meaning that the simplest model which has the fewest number of parameters will be preferred to more complex models.

The synthetic data for each instrument was input into the Bayesian inference algorithm with the same a-priori information. A typical output from the RJMCMC algorithm is shown below. Histograms like these can be plotted for each unknown parameter, showing succinctly the distribution mean (solid green line), the 95% Bayesian credibility interval (dashed green lines) and the correct parameter value (solid red line). Is is clear from the plots that the AI measurements provide a closer fit to the synthetic data than the CG-5 measurements. This is due to a combination of the higher signal to noise ratio of the AI measurements and the increased positional information inherent in a gravity gradient signal.

Although the histogram output gives a sense of the uncertainty on each unknown parameter individually, it does not give an intuitive spatial uncertainty for an end user to make decisions regarding excavation. To achieve this, 100 random draws are made from the RJMCMC accepted models and each cylinder is plot with one percent transparency. Such a graph gives an idea of the areas where there is likely to be an object (dark) and areas less likely to contain an object (light). The actual object position is outlined in red. This map easily translates the outputs of the RJMCMC algorithm to the practical needs of an end user.
Computer-aided design of high-precision cold-atom sensors

Dr Daniel Brown, Dr Rebecca Palmer, Professor Andreas Freise

Atom interferometry can measure gravity with potentially very high precision. However, reaching this precision in practice requires a careful design that relies on understanding the sensor performance in great detail.

The sensors developed by the GG-TOP project will push the boundary of state of the art technology. To achieve this we need to reduce the intrinsic noise of the sensors themselves. This ‘sensor noise’ is a combination of all kinds effects that can potentially distort the output signal. The picture below illustrates the complexity of the sensor, showing the instrument on the left and the paths of the atom clouds over time; the ultimate performance can only be achieved if all the many mechanical and optical parts follow stringent requirements.

Experience with other high precision devices has shown that numerical computer models are an important tool for understanding and reducing sensor noise already during the design phase. We have 20 years of experience building and using such tools for gravitational-wave detectors, large laser interferometers that currently are the most sensitive length measurement devices ever built.

Based on our experience we are now developing a new computer model of the GG-TOP atom interferometer to help with the design and commissioning:

**Design optimization:** Sensor design includes many trade-offs between different sources of noise (a design change may reduce one noise type but increase another), or between other criteria such as size and cost. In a complex design it is often impossible to find the optimal solution analytically. Numerical models instead offer more flexibility especially to model noise due to material imperfections.

**Testing and commissioning:** After the instrument is built, its actual noise level can be measured, and compared to the level predicted to determine whether the instrument is working properly. A detailed noise budget that specifies the noise properties such as frequency dependence can be used to identify the likely source of any performance deficit, to guide the repair of the system or a re-design of an improved version.

**Types of noises**

Atom interferometer sensors are complex devices with hundreds of intrinsic noise to investigate. Some dominant sources are:

**Atom shot noise:** Quantum interference is an inherently random process: the phase we are trying to measure is encoded in the probability of atomic states. The thermal motion of the atoms can result in a reduced contrast defect, increasing the shot noise level.

**Rotations** of the device introduce a velocity-dependent acceleration, producing a spurious signal. Rotations can be introduced into the detector due to the rotation of the Earth or rotational vibrations of the platform and need to be reduced through auxiliary systems.

**Wavefront distortions** of the various laser beam, produced by imperfect optical components and diffraction at apertures, introduce a spatial distortion in the phase stored in the atom clouds.

**Optimising detection beam size**

Using our model we have already determined a number of design decisions. For example, by tuning the beam size of the read out laser it is possible to select certain parts of the cloud and, in certain conditions, to reduce the amount of noise in the measurement. Using our numerical model of the detector we are able to determine the optimum beam size given a set of experimental parameters, as shown in the figure. The figure below shows a typical model output, in this case the noise budget as a function of the size of the laser beam. Many more such budgets must be created and eventually combined to create a full model of the full sensor system.
Understanding Stone Henge – Archaeological Prospecting

Professor Vince Gaffney, Dr Philip Murgatroyd, Eamonn Baldwin, Anthony Rodgers, Dr Dan Boddice, Dr Yuriy Goncharenko

GG-TOP has worked in partnership with the Stonehenge Hidden Landscapes Project to generate comparative data against which to test gravity sensing’s capacity to search for archaeological features. Archaeology uses a variety of different types of geophysics, including magnetometry, Ground Penetrating Radar (GPR) and electrical resistivity but gravity sensing is very infrequently used due to its poor sensitivity and slow rate of data capture. The addition of a viable gravity-based sensing technique would add another tool to the archaeologists toolkit and therefore allow a fuller picture of the archaeological features under the ground.

The Stonehenge Hidden Landscapes Project (SHLP) is a joint project by the Universities of Bradford, Birmingham, St Andrews and Ghent and the Ludwig Boltzmann Institute for Archaeological Prospection in Vienna. The study area measures around 4km x 2km around the Stonehenge UNESCO World Heritage Site and encompasses a huge variety of monuments, from Bronze Age round barrows to one of the Royal Flying Corps first air bases and the area of the Stonehenge Free Festival in the late 1970s and early 80s. Due to the use of a variety of different geophysical techniques the SHLP has captured over 1000 hectares of geophysical data. 3D laser scanning, motorized magnetometry, Electromagnetic Induction, electrical resistivity and GPR were all used to provide 2D and 3D data sets within a 3D landscape. This not only enabled the discovery of many new monuments within the area around Stonehenge but also provides a wealth of comparative data against which to test gravity sensors.