UK
Quantum Technology Hub
Sensors and Timing


# Reflecting on a decade of quantum sensing and timing

# Reflecting on 10 years of quantum sensing and timing development with industry

When the National Quantum Technology Programme was initiated 10 years ago, the role of sensors and timing in a future quantum economy was uncertain. While a great deal of progress has been made across all aspects of quantum technology since then, the landscape for sensors and timing has been absolutely transformed and now represents a huge opportunity. Why can we make this assertion?

The QT Hub for Sensors and Timing has led the charge in bringing our devices and systems out of the research laboratory and into the real-world environment of end users and the associated supply chain. This has only been possible through the hard work and commitment of the entire Hub team. Working together with our partners from industry, we have produced a range of demonstrators and start-up companies. The Hub has delivered demonstrations in urban environments, healthcare settings, within complex systems such as radar, and on mobile vehicles including trucks, trains, aerial vehicles, and ships at sea.

We are proud that our team has enabled the community to recognise that many QT sensors are ready for exploitation now. The potential advantages and unique capabilities of QT sensors and timing systems to solve economically significant problems for which there is no classical solution have been identified, and confidence that they can be practically realised has been firmly established. So, what needs to be done next?

We are still in the early stages of moving from compelling demonstration to deployment at scale. Substantial further effort is needed to develop fully engineered products and services and to create new business models that will maximise economic value. It is essential that this is supported by a pipeline of research to drive improved performance and miniaturisation. The next phase of government, academic, and industry collaboration is aimed at doing precisely that.

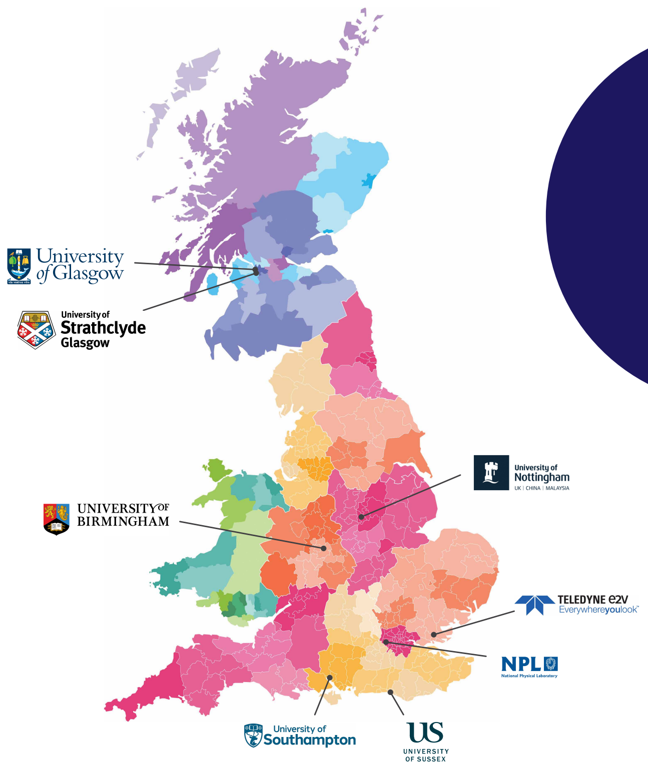
The potential for the UK to reap the economic growth potential of a world-leading quantum industry, in the face of rapidly increasing international competition, is only possible because of the National Quantum Technologies Programme and the outstanding success of the QT Hubs and the wider community. This brochure charts the remarkable journey of the Hub for Sensors and Timing from laboratory concept to field deployment over the past 10 years and clearly shows that we are ready: the time is now.

**Professor Michael Holynski**, Principal Investigator
**Dr Simon Bennett**, Director

We acknowledge and would like to give thanks for the funding received from the Engineering and Physical Sciences Research Council, as part of the UK National Quantum Technologies Programme. We would like to also thank Innovate UK, Dstl, Ministry of Defence, Science and Technologies Facilities Council and the Natural Environment Research Council for funding our wider programme of research.

## UK Quantum Technology Hub in Sensors and Metrology, 2014 – 2019

The first phase of the Hub focused on gravity, magnetometry, rotation, imaging, timing, and underpinning technology.




## UK Quantum Technology Hub Sensors and Timing, 2019 – 2024

The second phase of the Hub focused on geophysics, healthcare, navigation, timing/radar and underpinning technology.


Badges set up for the launch event for the Hub's second phase in December 2019.


Dr Simon Bennett, Director of the UK Quantum Technology Hub Sensors and Timing, speaking at the launch event for the Hub's second phase in December 2019.

**“This new funding will build on the enormous momentum we have already created. Our Birmingham-led Hub for Sensors and Timing will be focusing on applications in geophysics, navigation, brain imaging and precision timing, each of which has the potential to create significant economic and societal benefit.”**

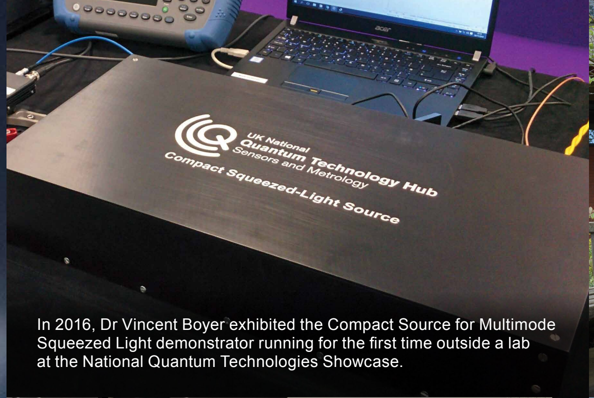
Professor Kai Bongs, former Director and Principal Investigator for the UK Quantum Technology Hub Sensors and Timing, on receiving funding for the second phase of the Hub.

# Quantum technologies in action

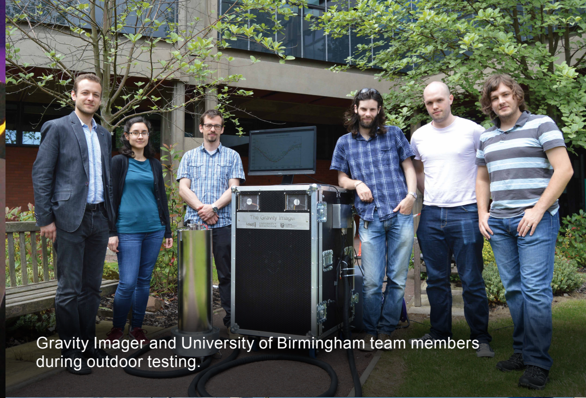
10 years ago, there were just a few small signs of laboratory to field activity. The UK Quantum Technology Hub for Sensing and Metrology (2014-2019) managed to create initial demonstrators, and the UK Quantum Technology Hub Sensors and Timing (2019-2024) has since pioneered quantum sensor technologies in the field. Furthermore, quantum sensing and timing technology has drastically increased in prominence in the national and international landscape, and there is now a real interest in quantum sensor development as there is clear evidence of near term potential impact.

This progress has taken a lot of hard work and perseverance from researchers in delivering underpinning technology, demonstrators and demonstrations. There has been much effort to build understanding of the techno-economical advantages, through analysis of value chains, road mapping, industry co-engagement and co-activity, and growing cross-sector interest. We are thankful for the support and commitment from our funders and government.

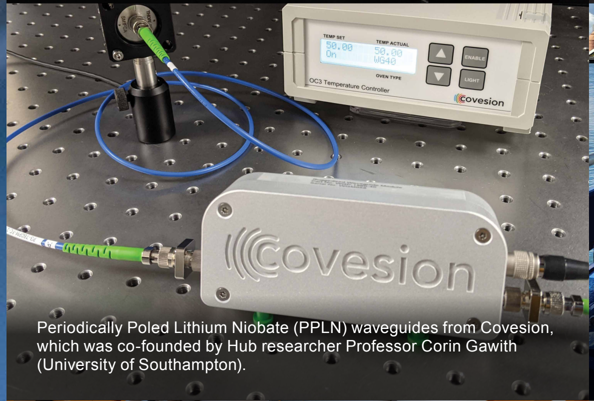
Dr Elena Boto putting MEG wearable scanner onto a child in the lab.



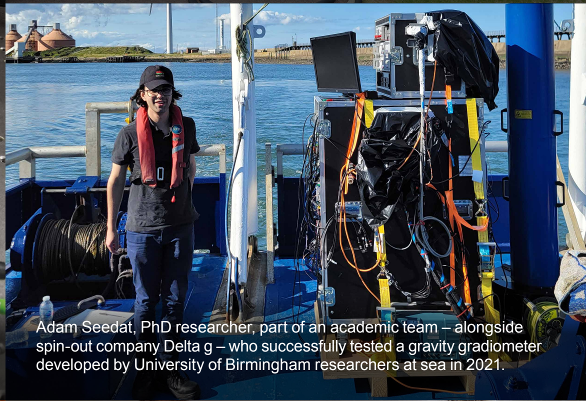

In 2016, Dr Vincent Boyer exhibited the Compact Source for Multimode Squeezed Light demonstrator running for the first time outside a lab at the National Quantum Technologies Showcase.



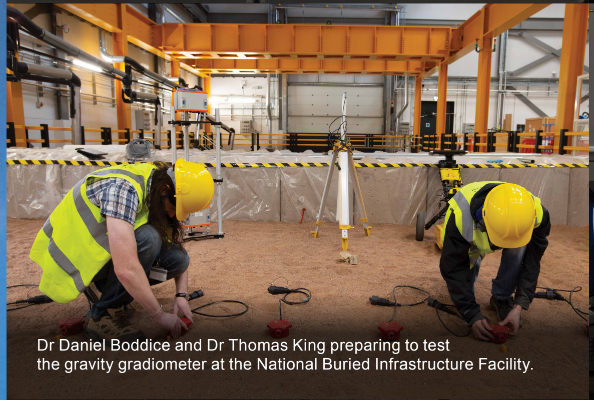
Gravity Imager and University of Birmingham team members during outdoor testing.



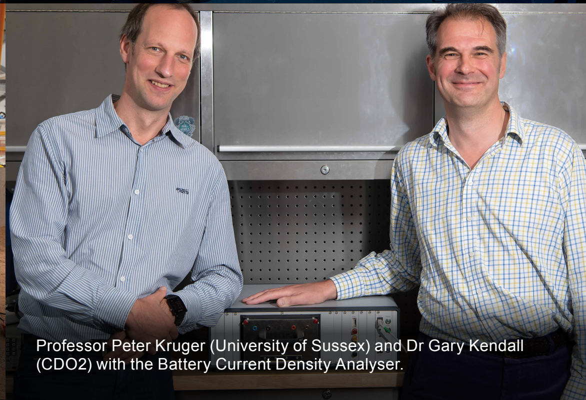

Periodically Poled Lithium Niobate (PPLN) waveguides from Covesion, which was co-founded by Hub researcher Professor Corin Gawith (University of Southampton).



Adam Seedat, PhD researcher, part of an academic team – alongside spin-out company Delta g – who successfully tested a gravity gradiometer developed by University of Birmingham researchers at sea in 2021.

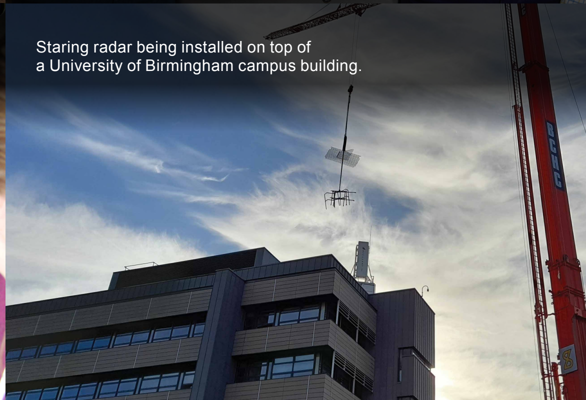


Dr Daniel Boddice and Dr Thomas King preparing to test the gravity gradiometer at the National Buried Infrastructure Facility.



Professor Peter Kruger (University of Sussex) and Dr Gary Kendall (CDO2) with the Battery Current Density Analyser.

Katie Wilkinson, PhD student at the University of Birmingham (right) with the laser and additional control systems used for the Borehole MOT test system.



Staring radar being installed on top of a University of Birmingham campus building.

# Key successes

**17** instruments that work in the lab and have also been tested outside

Over **20** application trials

Over **165** records of invention

**4** patents licensed

**47** people have received Responsible Research and Innovation training

Published **234** papers in Phase 1; **203** in Phase 2

**17** patents submitted from Phase 1; **9** from Phase 2

Generated over **£72M** of industry-focussed projects in Phase 1 and **£67M** in Phase 2

Over both phases, researchers had repeated individual engagement with staff from **119** industry companies

Researchers helped to train **44** students in Phase 1; **66** students in Phase 2

**Three** start-up companies have been set up by Hub researchers since 2014 – Cerca Magnetics Ltd, Delta g and Aquark



## Partnership Resource Funding:

At its heart, the Hub focuses on targeted translation of technology in collaboration with industry. To do this, the Hub engaged with and supported industry by allocating EPSRC's Partnership Resource Funding (PRF) to academics to help companies identify, co-develop and de-risk their own investments in quantum technologies for their applications and markets. So far, **47** projects have been supported by PRF funding.

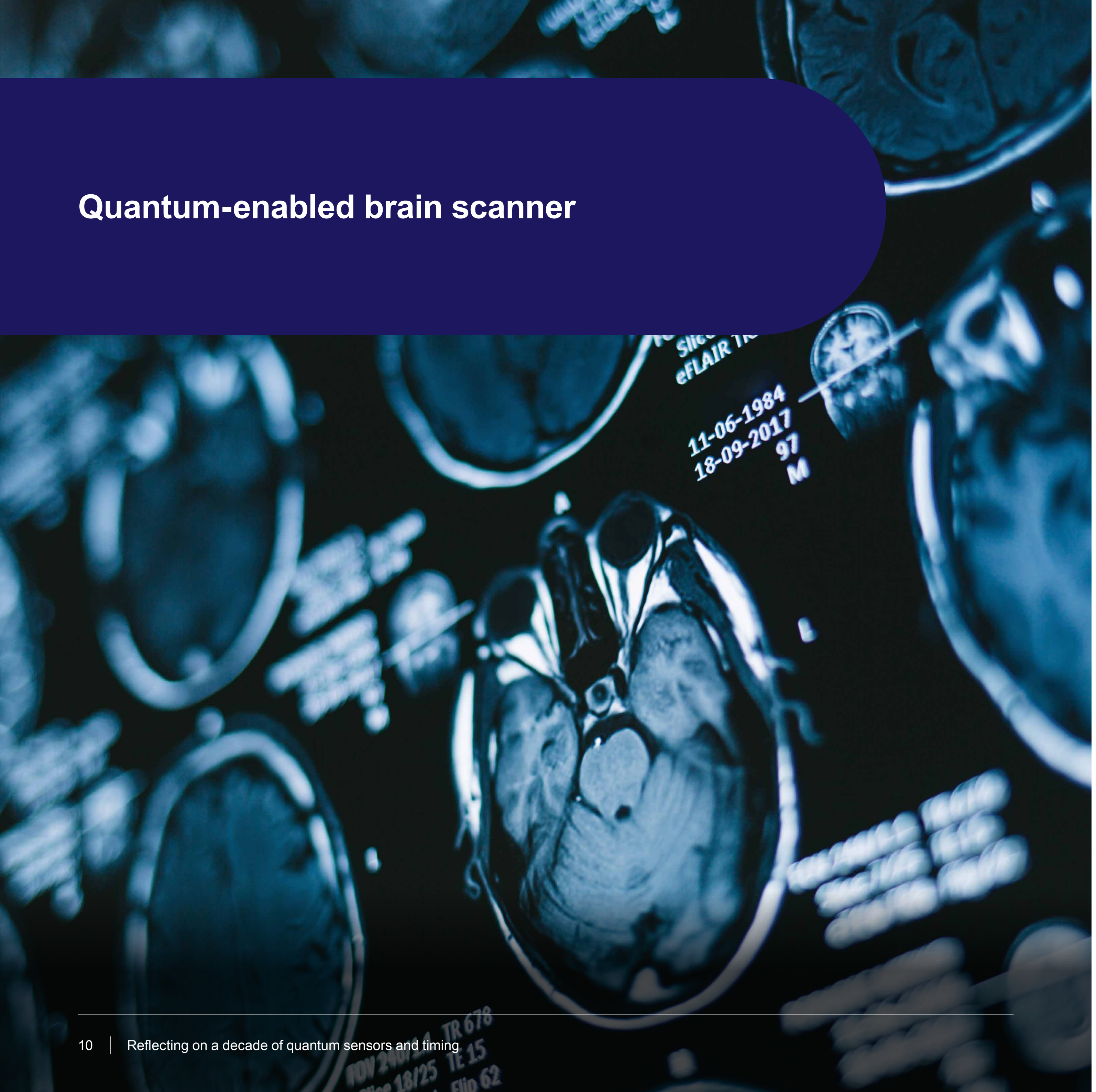
## Targeted translation of quantum sensor innovation:

Geophysics | Healthcare | Navigation | Timing | Underpinning technologies

Complex Systems Innovation

Sensors › System › Regulatory framework › Vehicle

# Quantum-enabled brain scanner



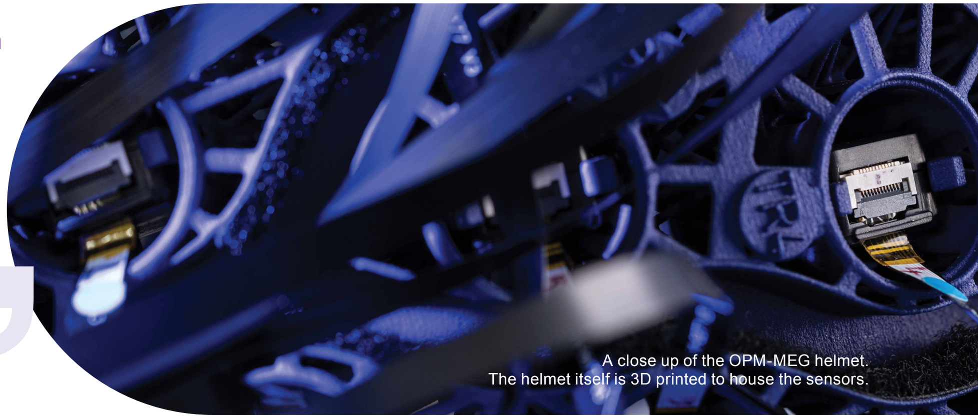

The human brain contains a network of ~100 billion cells, which pass electrical pulses to one another via ~700 trillion connections. This network underpins everything we do, from senses and movement to cognition and attention. Even our personalities.

Understanding the brain, and the many disorders that affect it, is one of the biggest challenges for 21st century science. Scanning techniques like MRI have been game changing, however most technologies generate images of brain structure, whereas in many disorders it is brain function (i.e. what cells do) that is at fault. Consequently, the introduction of scanners that can image brain function, rather than structure, has the potential to revolutionise our understanding of brain health and disease.

Since 2014, Quantum Technology Hub researchers at the University of Nottingham have been developing wearable quantum-enabled brain imaging instrumentation. Their work exploits optically-pumped magnetometers (OPM), a new type of non-cryogenic magnetic field sensor with extreme sensitivity. The team and their academic and industrial collaborators have built imaging systems that measure the tiny magnetic fields generated by current flow through assemblies of neurons. In this way, the recorded data gives a non-invasive record of electrophysiological brain activity. The scanner – termed OPM-MEG – now offers an unprecedented window on the brain function. Moreover, its lightweight wearability (participants can move freely during a scan) and adaptability make it particularly useful for children and patient cohorts who cannot tolerate conventional scanning environments.

**"MEG brings what is not achievable with current technologies. It tells you how the brain functions whilst providing better resolution than traditional modalities. Existing MEG technology is not used in hospitals because it is expensive given its cryogenic form, and its current rigid format is difficult to use on patients."**

Dr Elena Boto, University of Nottingham


A close up of the OPM-MEG helmet. The helmet itself is 3D printed to house the sensors.


In 2021, Cerca successfully installed its OPM-MEG system at Young Epilepsy in Surrey to revolutionise the diagnostic experience for children with epilepsy.

Following six years of research, Cerca Magnetics Ltd – a spin-out company set up by Hub researchers in collaboration with industry partners - was launched in 2020, aiming to commercialise OPM-MEG technology and drive it towards clinical application. Since its launch, Cerca has had considerable success, installing OPM-MEG systems and related technologies at leading academic and research institutions across the globe. This outstanding success is a testament to the impact that the UK National Quantum Programme, and the Hub structure, has had on academia. The OPM-MEG systems now in operation are having impact in basic neuroscience, as well as clinical application in areas including epilepsy, autism, concussion and dementia.

Research in this area has continued at pace. Hub researchers in Strathclyde have built unique OPM sensors; these have not only been used for MEG, but also many other applications from navigation to veterinary science. Researchers in Strathclyde, Sussex and Birmingham have built unique sensors for MEG applications whilst the most recent work in Nottingham has begun to demonstrate how high-density arrays of quantum sensors offer sensitivity advantages beyond what can be achieved with conventional instrumentation.


A quantum sensor. These lego-brick sized devices exploit the quantum properties of Rb atoms to measure magnetic fields.



University of Nottingham researcher Holly Schofield running a visual experiment on a participant.

**"Matt Brookes presented his work on MEG at a Hub event, and he needed shielding for this work. It was clear that these sensors were going to be a step-change, and we worked together to create a magnetically shielded room with a DC field an order of magnitude lower than other commercial competitors, this very low field facilitates acquisition of data from the OPM-MEG system."**

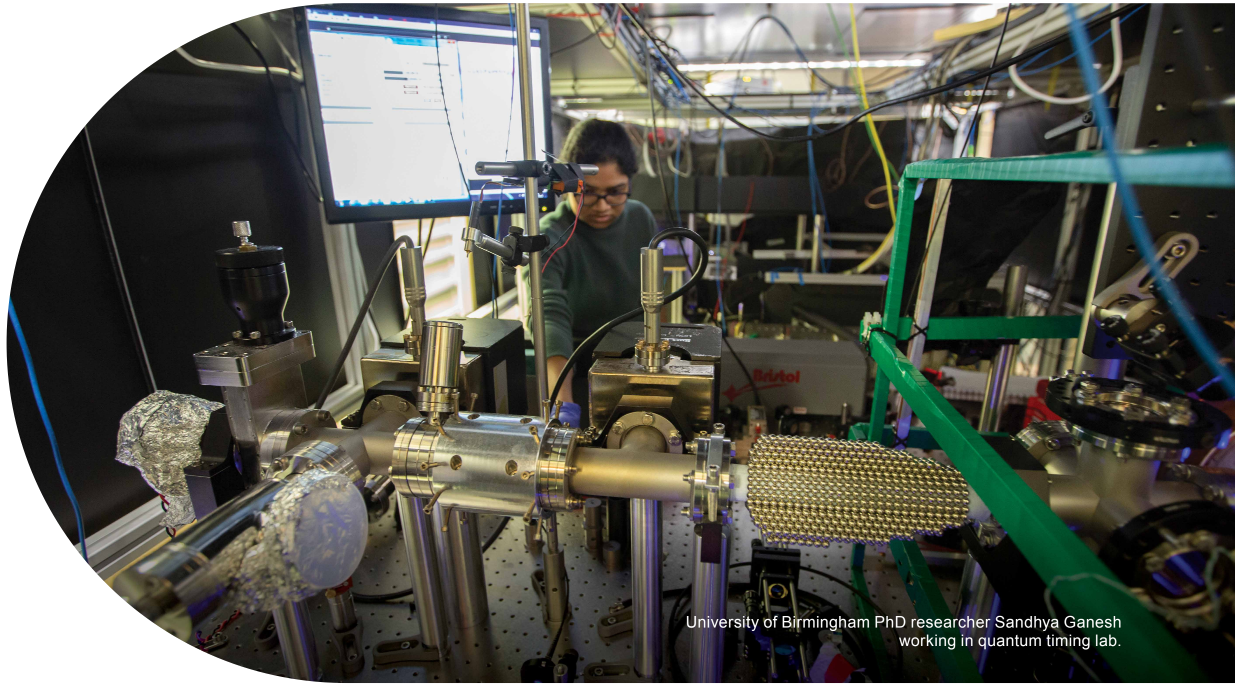
David Woolger, CEO of Magnetic Shields Ltd

# Quantum timing and radar



## Precise timing with quantum clocks

Quantum clocks are widely seen as essential for increasingly precise approaches to areas such as online communications across the world, navigation systems, or global trading in stocks, where fractions of seconds could make a huge economic difference. Atomic clocks based on optical frequencies can be 10,000 times more accurate than their microwave counterparts, opening up the possibility of redefining the standard (SI) unit of measurement.



University of Birmingham PhD researcher Sandhya Ganesh working in quantum timing lab.

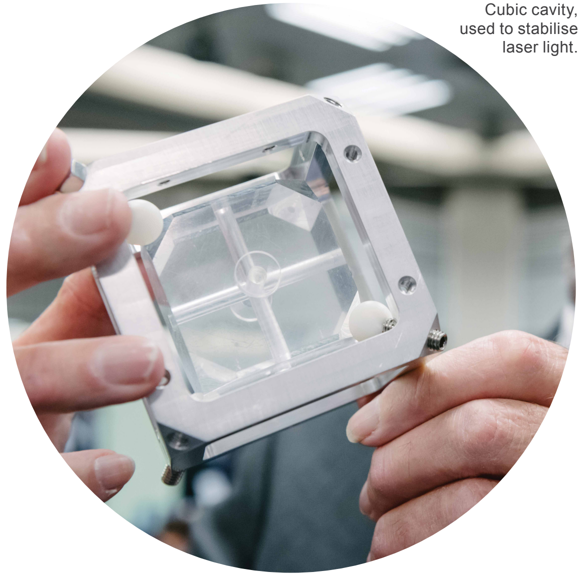
Even more advanced optical clocks could one day make a significant difference both in everyday life and in fundamental science. By allowing longer periods between needing to resynchronise than other kinds of clock, optical clocks offer increased resilience for national timing infrastructure and will unlock future positioning and navigation applications for autonomous vehicles. The unparalleled accuracy of these clocks can also help us investigate beyond standard models of physics and understand some of the most mysterious aspects of the universe, including dark matter and dark energy. Such clocks will also help to address fundamental physics questions such as whether the fundamental constants are really ‘constants’ or if they are varying with time.


Professor Patrick Gill with a cavity for an optical lattice clock at the 2016 National Quantum Technologies Showcase.



**“The stability and precision of optical clocks make them crucial to many future information networks and communications. Once we have a system that is ready for use outside the laboratory, we can use them, for example, on ground navigation networks where all such clocks are connected via optical fibre. Such networks will reduce our dependence on GPS systems, which can sometimes fail.”**

Dr Yogeshwar Kale, Hub researcher



Cubic cavity, used to stabilise laser light.

Since 2014, Hub researchers have been developing highly accurate transportable quantum clock technology for many different application purposes, such as space and navigation. Once the new clocks have become commonplace, they can be used to increase navigation system precision to the scale of centimetres, which would revolutionise the way in which we measure the Earth.

An example of the timing and synchronisation work at the University of Birmingham is the newly established dark fibre link between the National Physical Laboratory (Teddington) and the University of Birmingham campus, developed in phase two of the Hub. This was a ground-breaking achievement, and the first link of its kind set up in the UK.

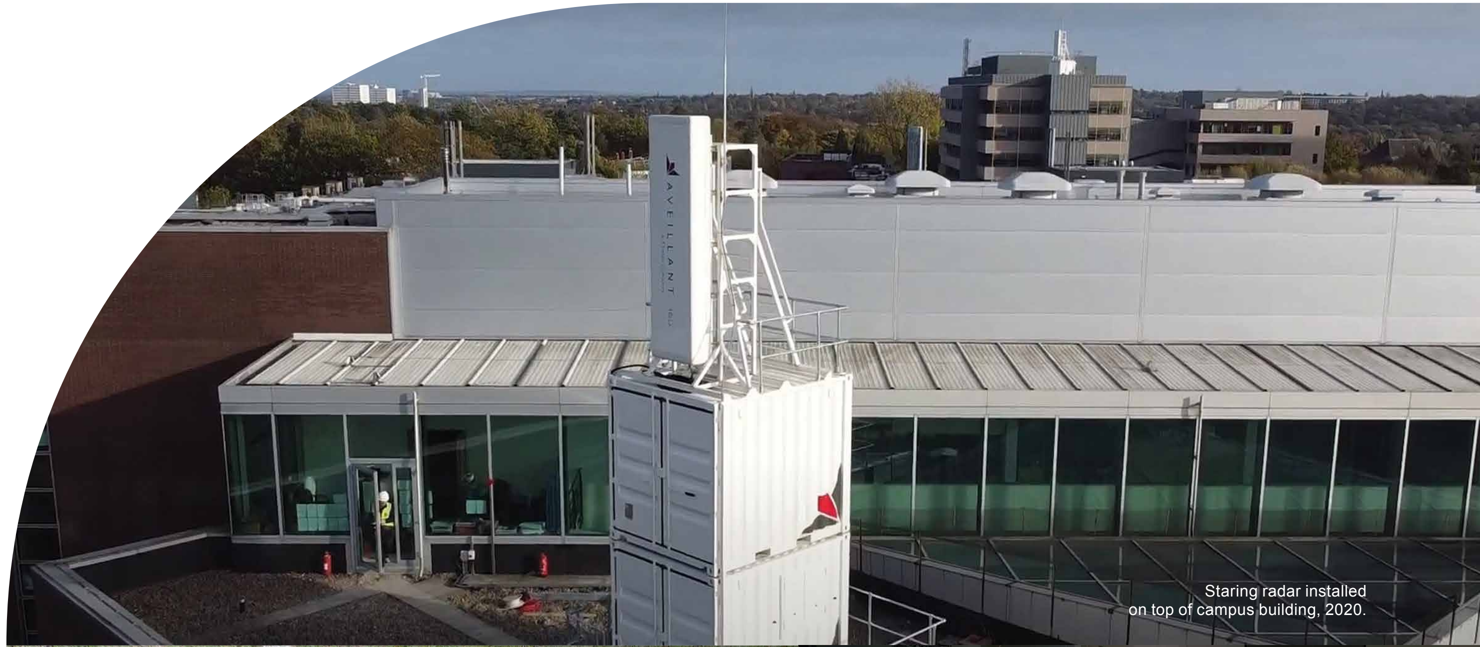
# Quantum-enabled networked radar

Since 2019, UK Quantum Technology Hub Sensors and Timing researchers have been exploring how ultra-precise quantum clocks can transform radar capability for detecting miniature objects. Radar, which detects target objects using electromagnetic radiation, is already being used for a wide variety of real-world applications, from spaceborne Earth Observation to hazard detection in self-driving cars.

Quantum-enabled radar, utilising ultra-stable and highly precise quantum oscillators to discipline a classical radar system, has the potential to significantly improve the capabilities of conventional radar to detect smaller targets such as drones and birds. Identification and detection of these smaller targets is becoming increasingly important in preventing and mitigating crises such as unauthorised drone usage as well as increasing our understanding of future usage of low to medium altitude airspaces, particularly in urban areas.

The second phase of the Quantum Technology Hub saw the development of the ADvanced RAdar Network (ADRAN) on the University of Birmingham campus. This unique facility comprises a network of two commercial-off-the-shelf, all-digital radar systems which can operate using a common, ultra-precise sense of time provided by quantum oscillator inputs. This degree of precision can be a game-changer for networked radar systems to operate in unison, rather than in isolation, and allow the combination of individual radar outputs for a performance improvement that can exceed that of the sum of its parts.

This experimental testbed has thus enabled foundational and practical research on how quantum oscillators can be leveraged for networked radar systems to reach their full potential and will continue to do so for years to come – including exploration into how they can maximise coverage, how they can detect and track smaller objects, further away, and how they can improve radar object identification accuracy, whilst being more resilient to external interference.



Staring radar installed on top of campus building, 2020.

Control radar trials with small drones.

Menlo Microwave Photonic Generator being installed in the radar cabin.

# Quantum sensors for navigation

## Quantum inertial navigation system

The consequences of our Global Navigation Satellite System (GNSS) failing ranges anywhere between inconvenient to catastrophic. It is easy to underestimate how reliant we have become on navigation systems in our daily lives, and we often do not realise how dependent our services and national infrastructure are on GNSS, so much so that it has now become known as the ‘invisible utility’.

Dr Joe Cotter with a team of researchers from Imperial College London aboard trials ship XV Patrick Blackett with the quantum inertial navigation system, which was tested in collaboration with the Royal Navy in 2023.

Hub researchers at Imperial College London have been developing a standalone quantum inertial navigation system which does not rely on satellite signals and is therefore impervious to the external vulnerabilities of GNSS.

Classical microelectromechanical systems (MEMs) can already provide high precision sensors for inertial navigation systems. However, MEMs devices are prone to drift, which limits how long they can provide accurate location information. Quantum inertial sensors overcome the problem of drift by measuring properties of atoms supercooled using lasers. At extremely low temperatures, the ‘quantum’ nature of atoms dominates and they behave like waves, which can be used to encode inertial information. By hybridising MEMs and quantum inertial sensors we can achieve the best of both worlds – drifts are minimised, and measurement speed is maintained.

# Pinpointing the location of a moving train

Since 2019, the Birmingham Centre for Railway Research and Education (BCRRE) at the University of Birmingham, alongside spin-out company Monirail, have worked to improve railway navigation technology in an effort to reduce train delays and improve passenger experience. The project tries to tackle one of the rail sector's biggest challenges: how to pinpoint the accurate location of a moving train. Overcoming this challenge is key to ensuring fewer train delays and increased passenger safety.

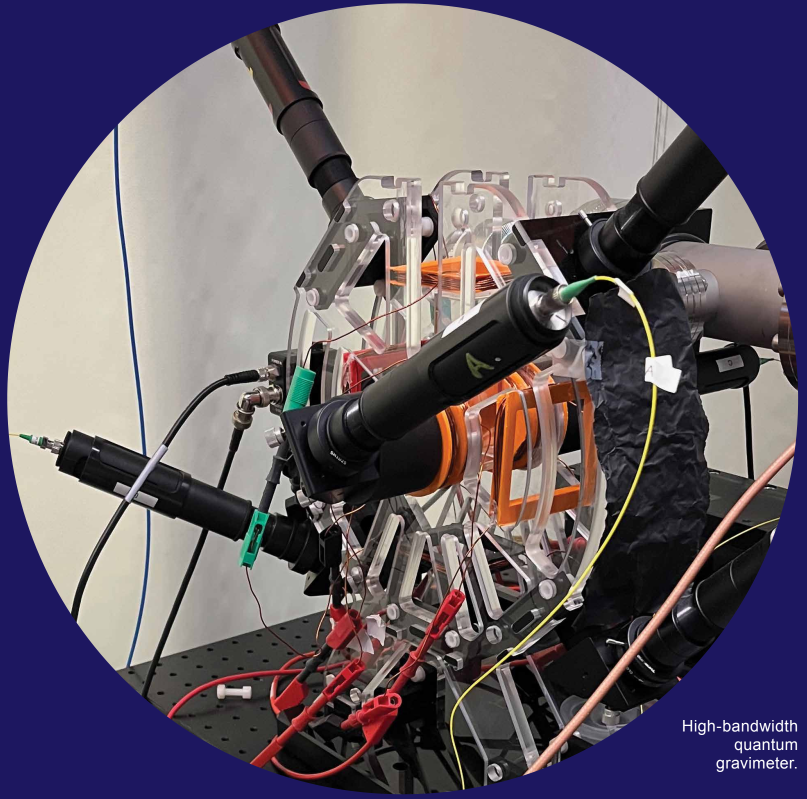
Researchers have been developing a system for quantum-enabled navigation, capable of capturing highly accurate measurements without reliance on Global Navigation Satellite Systems (GNSS), which will help engineers ensure the health of the railway track and passenger ride comfort. Field tests are continuing to take place with sensors installed on a purpose-built stabilisation platform in a train.

Preliminary testing of a mobile stabilisation platform setup at the National College for Advanced Transport & Infrastructure in Birmingham, UK. The platform (rear), control unit (centre) and drive cart (front) were investigated for vibrational characteristics along a section of railway in preparation for the deployment of quantum sensors.

Dr Fedja Orucevic (left), Daniel Nightingale (middle) and Dr Thomas Coussens (right) from the University of Sussex testing their magnetometer with map-matching capabilities on the London Underground, 2024.



## Towards resilient absolute gravity sensing



High-bandwidth quantum gravimeter.

Gravity sensing provides information on nearby local masses and is important for reference to the global geodetic reference frame. Within the Hub, researchers have been active in developing absolute gravimeters, to provide local gravity information for applications including satellite laser ranging. This could play an important role in improving our knowledge of local variations in gravity near satellite ranging stations. This would enable improvements in our knowledge of the position of satellites, feeding into climate models and Earth observation. Furthermore, through exploiting an approach for making high bandwidth measurements, the sensor has relevance to navigation systems as an additional input for correcting accelerometers and potentially as a tool for map-matching.

# Gravity sensing for the underground



## Seeing underground with quantum sensing of gravity gradients

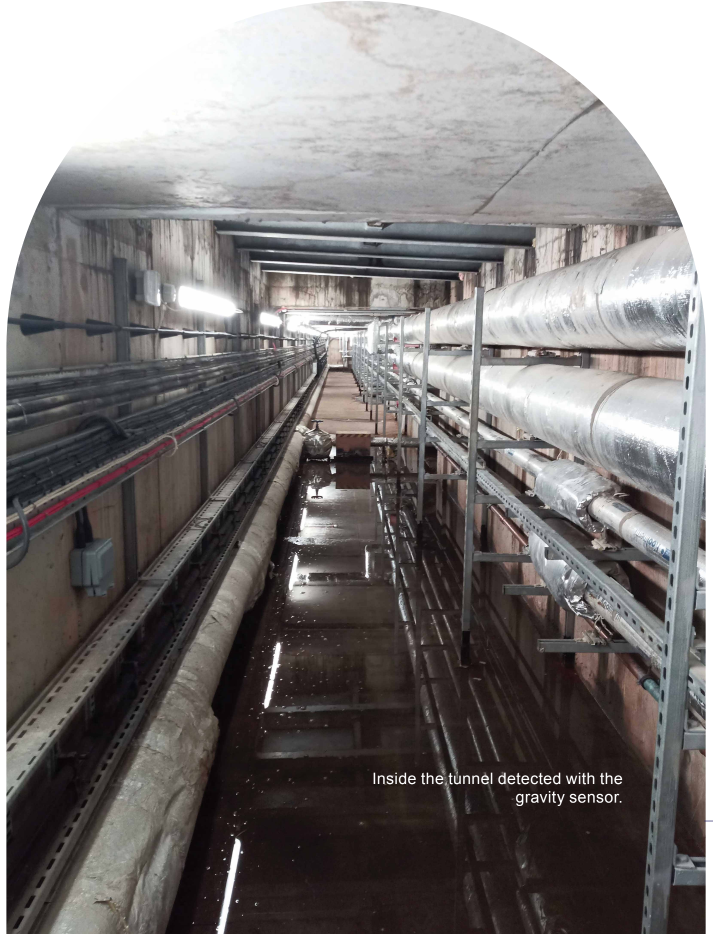
An estimated 4 million road excavations are carried out per year in the UK for utilities maintenance and repairs, which constitute a major source of disruption and delay to surface travel. In 2014-15, the cost of utility street works to the UK economy was estimated to be around £7 billion (Institution of Civil Engineers) and the projected cumulative total cost of utility street works in the UK from 2013 and 2030 is £319 billion (National Joint Utilities Group). In addition, 20-60% of linear and transport infrastructure projects experience delays due to unforeseen ground conditions (Future of the Subsurface, Government Office for Science, June 2024).

To fulfil vast infrastructure, development and repair projects, such as roadworks, these sectors rely on accurate surface-level information to enable the visualisation of underground locations. However, existing cartographic tools are limited, whether this is poor ability to see past only the topmost layers, inconsistent measurements in varying ground conditions, a complete inability to measure in high-vibration environments, or slow measurements resulting in prohibitive time and financial costs of surveys.

Gravity gradiometer being tested by University of Birmingham researchers Dr Ben Stray and Dr Andrew Lamb.



> **"The prospects of sensitive, stable cold-atom based sensors, alongside quantum-enhanced gravity monitoring networks, offers the potential to significantly enhance our ability to look beneath the Earth's surface."**
>
> Dr Paul Wilkinson, British Geological Survey



Inside the tunnel detected with the gravity sensor.

In 2022, Hub researchers reported in Nature that the quantum gravity gradiometer, which was developed under a contract for the Ministry of Defence and in the UKRI-funded Gravity Pioneer project, was used to find a tunnel buried outdoors in real-world conditions one metre below the ground surface. This event marked a long-awaited milestone with potential implications for industry, historical investigation and national security.

This breakthrough and significant technical development led to the creation of a new start-up – Delta g – founded by Professor Michael Holynski, Dr Andrew Lamb and Jonathan Winch in 2023. The company has since secured funding to develop commercial gravity gradiometry solutions based on atom interferometry. Recently, it has undertaken a project to develop a prototype for investigating applications for the Department of Transport.

# Gravity gradiometry at sea for map matching navigation

In 2023, the quantum sensor for gravity gradiometry developed by Hub researchers at the University of Birmingham was successfully tested in trials on a ship in the North Sea in conjunction with university spin-out Delta-g, offering new capabilities for mapping the ocean and resilient long-term navigation.

During these measurements – which were performed while the ship was moving at low speed in the harbour, and later while moving in the open sea – the system was left to operate on the open deck in a strap-down configuration, without inertial stabilisation, and with no control over tilt or temperature and climate. The system was able to perform atom interferometry in variable weather conditions, including direct sunlight, and being placed under a tarpaulin for sudden downpours of rain.

In 2024, in collaboration with the Royal Navy, Hub researchers alongside scientists from Dstl completed a significant field trial on a ship where a gravity gradient sensor was tested for the first time specifically for maritime navigation applications.

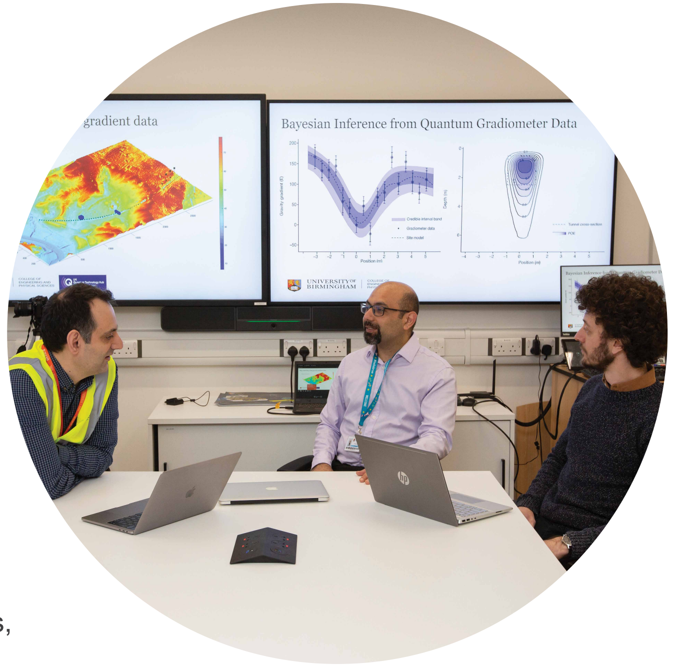
The field trial, which commenced in January in a separate trip, sought to explore the effects of ship vibration, motion, and acceleration on the sensor. After mounting the gravity sensor in a shipping container aboard the vessel in a strapdown configuration, the team set off for Norway where various experiments were carried out under the Northern Lights to measure and assess the behaviour of atoms in an inertial environment, and to study the effect of motion and magnetic fields.

The team successfully demonstrated robustness of the sensor over two weeks at sea, including in a variety of sea states.

Trials of the sensor in the North Sea, 2023.



# Advanced techniques for quantum sensor data processing




Professor Asaad Faramarzi, Dr Farough Rahimzadeh and Dr Anthony Rodgers processing and visualising quantum sensor data.

Hub researchers at the University of Birmingham developed advanced numerical algorithms, combining machine learning techniques such as genetic algorithms, Bayesian inference, and adaptive meshing, to process gravity gradient data from quantum sensors for geophysical sensing and map-matching navigation. In geophysical sensing, these methods overcame gravity inversion challenges, enabling the identification of underground features and accurate subsurface density estimations.

For map-matching navigation, researchers developed computational procedures that integrated polygon matching with evolutionary computing, significantly enhancing positioning accuracy in GPS-denied environments. This optimisation process showed potential to reduce errors in initial inertial navigation estimates and improve navigation in complex terrains. These unified approaches demonstrate the versatility of quantum gravity sensors in geophysical analysis and navigation, with future applications in archaeology, environmental monitoring, on-terrain, marine, and aviation systems using cold atom gradiometry.

# A small revolution in gravity imaging

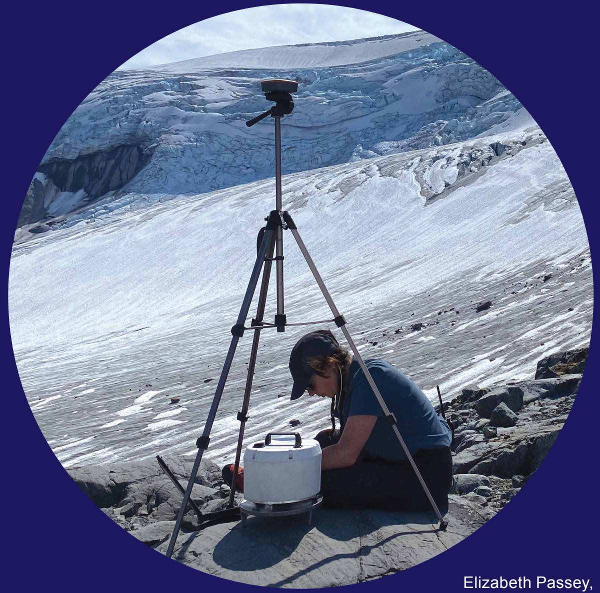
The Wee-g, a microelectromechanical system (MEMS) gravimeter developed by University of Glasgow researchers, uses a sensing element based on the same technologies used to make sensors in smartphones, and has proven to be a small but powerful gravimeter. While the MEMS technology in phones uses relatively stiff and insensitive springs to maintain the orientation of the screen relative to the Earth, Wee-g employs a silicon spring ten times thinner than a human hair. This allows Wee-g's 12mm-square sensor to detect very small changes in gravity.

Wee-g being tested by Dr Thomas King from the University of Birmingham in the National Buried Infrastructure Facility, 2021.

In the second phase of the Quantum Technology Hub, the Wee-g – a radically tiny gravimeter – was tested in the Garibaldi Volcanic Belt in British Columbia. Multiple field campaigns – both helicopter and truck-based – were undertaken to fully understand Wee-g's performance during spatial surveys in extreme environments. This testing marked the first time a full-scale survey has been conducted with a MEMS gravimeter and is a crucial step towards Wee-g becoming a fully field deployable sensor. This project itself was funded by Mitacs Globalink exchange project and was based at Simon Fraser University in Vancouver.

University of Glasgow researchers also travelled to the National Institute of Geophysics and Volcanology (INGV) in Catania, Sicily to deploy multiple Wee-g gravimeters on Europe's most active volcano, Mt Etna, in July. The gravimeters were deployed at different altitudes ranging from 1730m to 3000m above sea-level. These field trials have provided valuable data to characterise Wee-g's behaviour and performance when subjected to large temperature gradients, turbulent travel and substantial changes in elevation between measurement points.

The Wee-g has been developed and tested over many years as part of the Hub's work, and has been greatly supported by the Newton-g project, led by the Istituto Nazionale di Geofisica e Vulcanologia. The Wee-g has also been tested by the British Geological Survey and the University of Birmingham's National Buried Infrastructure Facility.



Elizabeth Passey, PhD researcher at the University of Glasgow, testing Wee-g on Mt Garibaldi volcanic complex (BC, Canada) in 2022.

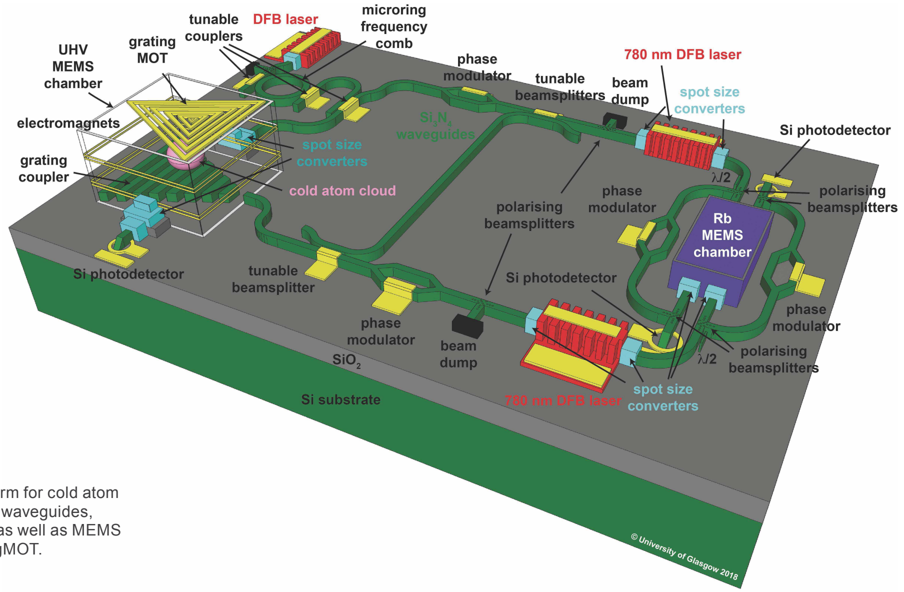
# Miniaturising quantum sensor technology

A determining factor for the impact and scale of adoption of quantum technology is the ability to miniaturise, ruggedize and ultimately mass manufacture systems. This process will inevitably involve the heterogeneous integration of atomic, photonic and electronic systems. Specifically, the atomic systems at the core of the technology would typically require AlGaAs-based lasers. Hub researchers are driving innovation integrating these with low-loss (e.g. SiN) waveguides, frequency and amplitude modulators, beam expanders and ultimately the cell containing the atomic species. For cold atom and optical atomic clock applications, there are additional challenges associated with beam configurations and the conversion from optical to microwave frequency.

Researchers have pursued game-changing size, weight, power and cost (SWaP-C) reductions in the underpinning platform technologies, supporting the entire quantum technologies community.

For example, compact laser systems, compact frequency combs and chip-scale cold atom sources would underpin the miniaturisation of all atomic quantum sensors across the UK national programme and provide a competitive advantage to UK industry in the global quantum sensor race. Researchers have made specific steps towards these aims.

Glasgow continue to develop a suite of components targeting photonic integrated circuits. DFB lasers targeting Rb atomic transitions are being fabricated, packaged and characterised in Glasgow. These will find applications in atomic clocks and quantum sensors. In particular a device operating at 778 nm, with sub-4 kHz linewidth and integrated mode expander for fibre launch has been demonstrated in collaboration with Strathclyde as a potential source for a compact optical clock.




Heterogeneously integrated platform for cold atom clock application including lasers, waveguides, modulators and beam expanders as well as MEMS components for vapour cells and gMOT.

Another important aspect of Strathclyde's work is the development of MEMS atomic vapour cells for clocks, cold atoms and magnetometers and the now commercialised work on microfabricated gratings for laser cooling of atoms (with KNT) as well as the bespoke miniaturised vacuum systems (with CPI-TMD) enabling routine portable cold atom applications (gMOT). The utility of these approaches has recently been validated by the demonstration of an integrated cold atom microwave cavity clock.

Further work at Strathclyde involves the development of visible (red) VECSEL laser technology. Benefiting from their excellent beam quality, power scaling, efficient intra-cavity nonlinear conversion, ultra-narrow fundamental linewidth and low SWaP-C, VECSELs provide a unique light source for QT applications including optical atomic clocks. In particular a green-diode pumped, monolithic cavity AlGaInP-based VECSEL system at 689 nm has been shown to have a free-running performance with sub-kHz linewidth.

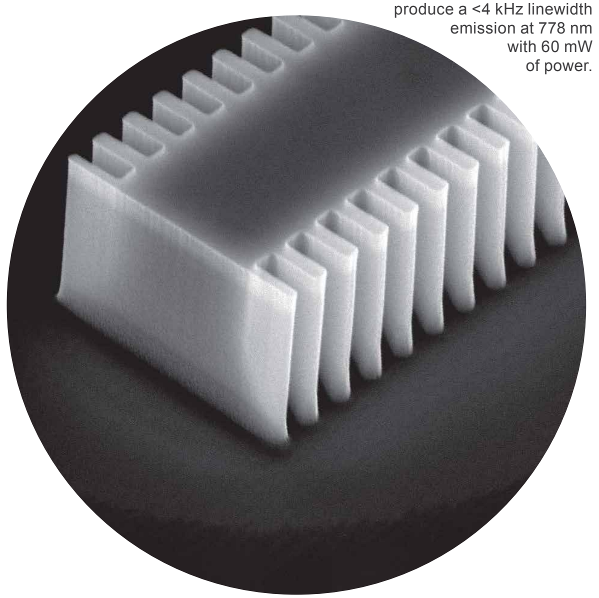
Both Southampton and Glasgow are developing waveguide and microring resonator technology for chip-scale frequency combs with devices from both partners tested at NPL. The Southampton tantala waveguides have demonstrated a loss on straight sections of 1 dB/cm with and have achieved the target Q-factors on microrings of 250 µm radius of approximately 2 x $10^5$. The Glasgow silicon nitride microring results showed an achievement of Q = 1.4M ((1.38±0.04) x $10^6$) with waveguide losses below 0.2 dB/cm at 780 nm.

Field-packaged digital alkali-spin maser optical magnetometer developed at the University of Strathclyde.

**“We were brought on board to develop lasers with novel performance outside of what is available from conventional laser technology, targeting the challenging requirements of the strontium clock set-up at the University of Birmingham. We developed lasers based on semiconductor disk technology that not only met the power requirements at the specific wavelengths in the blue and red, but also met the very narrow linewidth and stability requirements, with a much smaller footprint. We took these lasers down to the labs in Birmingham and demonstrated cooling of strontium atoms with a VECSEL for the first time.”**

Professor Jennifer E. Hastie,
University of Strathclyde

A SEM image of the Distributed Feedback Bragg (DFB) grating etching into the diode laser material to produce a <4 kHz linewidth emission at 778 nm with 60 mW of power.



Compact VECSEL technology being developed at Strathclyde for applications in optical atomic clocks.

# Public engagement

The Quantum Technology Hub Sensors and Timing, in collaboration with the other QT Hubs, has played a definitive role in shaping Quantum City, the public engagement initiative set up in 2018 to explore and understand public views on quantum technologies. Since its launch, Hub researchers and students have participated in many Quantum City-hosted events including New Scientist Live, Cheltenham Science Festival and Pint of Science. The Hub has also helped to put together the newly-launched Quantum City website (www.quantumcity.org.uk), a public-facing website aiming to explain NQTP's work in simple terms. The Hub understands the need for Responsible Research and Innovation (RRI). This involves acknowledging that technology development can appear to have ambiguous purposes and can raise questions and dilemmas, and creating frameworks to explore these aspects. For example, in 2017 the Hub participated in a public consultation and information activity led by Kantar Public. The outcomes and approach of this activity continue to inform our work.

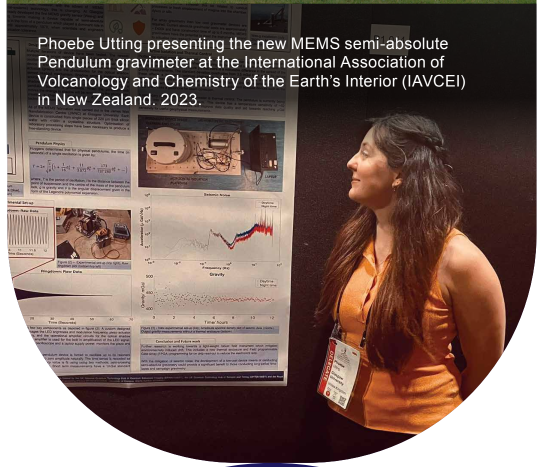
Carlos Nino Sandoval, Jonathan Winch, Sofia Alonso Perez and Dr Isabel Gale at the 2022 New Scientist Live event in London, taking part in the Quantum City exhibit.

Dr Ben Stray, Dr Georgina Croft and Dr Luuk Earl participating in Pint of Science, Birmingham, in 2018.

International Summer School for Quantum Technologies in 2023.



Summer school hosted with Dstl, 2015.



Phoebe Utting presenting the new MEMS semi-absolute Pendulum gravimeter at the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) in New Zealand. 2023.

**"RRI has underpinned the Hub's development of quantum sensing for real-world applications including healthcare. Early on, I participated in EPSRC's public dialogue on Quantum Technologies, where positive comments from the public on emerging quantum brain imaging were hugely energising."**

Professor Mark Fromhold,
University of Nottingham

# Skills

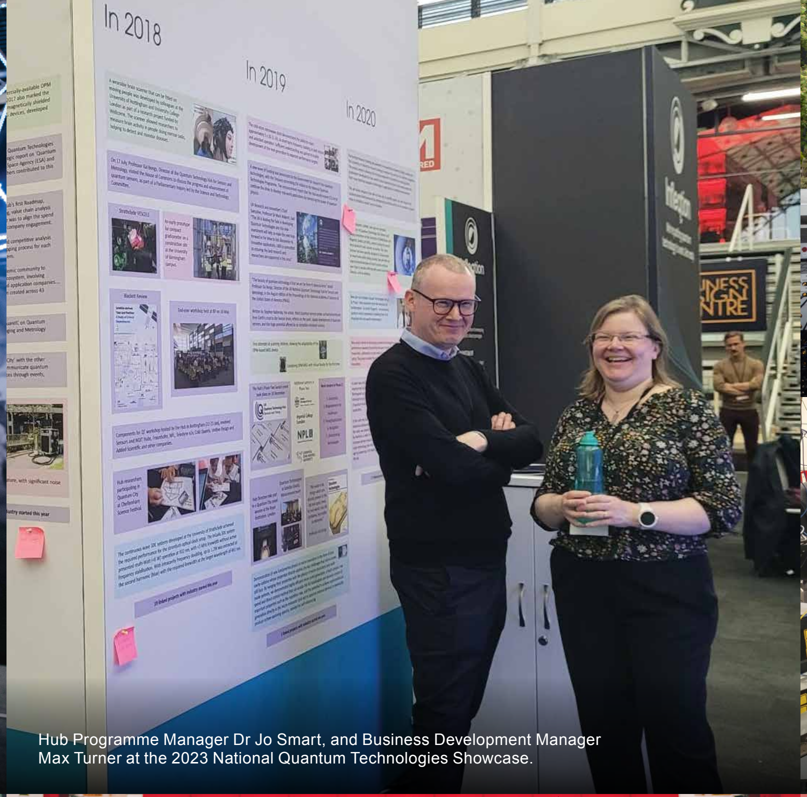
The Hub has aimed to attract, nurture and train people from the widest possible pool of candidates and to retain these trained people within the UK.

**Here are some examples of training opportunities provided in the past ten years:**

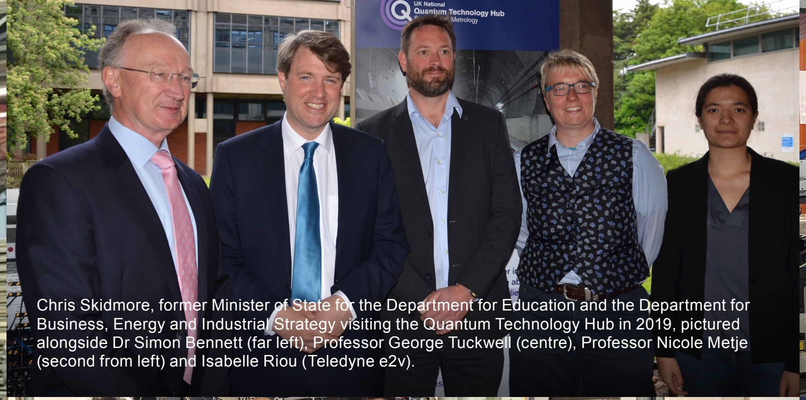
- Sponsored and participated in National Student Space Conference in 2021.
- The International Summer School in Quantum Technologies (ISSQT) was led by Miles Padgett of QuantIC, built by members of all four Hubs, and hosted in Birmingham in August 2023.
- 110 PhD students have benefited from the QT Hub environment.
- Provided training events on intellectual property, entrepreneurship, responsible research and innovation, and trusted research, led by experts at the Universities of Birmingham, Liverpool John Moores and Bangor.
- PRF funding has been used to foster new science and technology concepts across the entire national quantum sensors and timing landscape.
- Researchers have been supported to:
  - give first conference presentation, invited talk or international invited talk;
  - win first (PRF) funding in their own name;
  - participate in research away from their university lab;
  - develop as future leaders through taking on their first lead investigator roles;
  - take up a secondment, industry placement or voluntary role in an institute, get their first post-doctoral role, move into QT industry or become permanent academic staff.

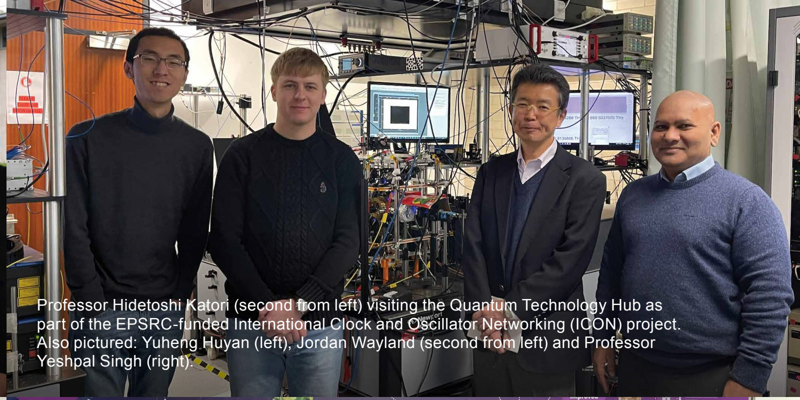
# A few of our events and visits

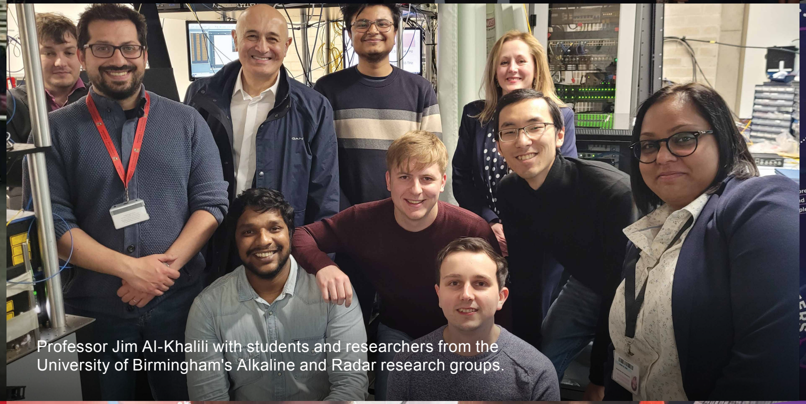

Professor Matthew Brookes, University of Nottingham, at the 2018 National Quantum Technologies Showcase.



Hub Programme Manager Dr Jo Smart, and Business Development Manager Max Turner at the 2023 National Quantum Technologies Showcase.


Chris Skidmore, former Minister of State for the Department for Education and the Department for Business, Energy and Industrial Strategy visiting the Quantum Technology Hub in 2019, pictured alongside Dr Simon Bennett (far left), Professor George Tuckwell (centre), Professor Nicole Metje (second from left) and Isabelle Riou (Teledyne e2v).

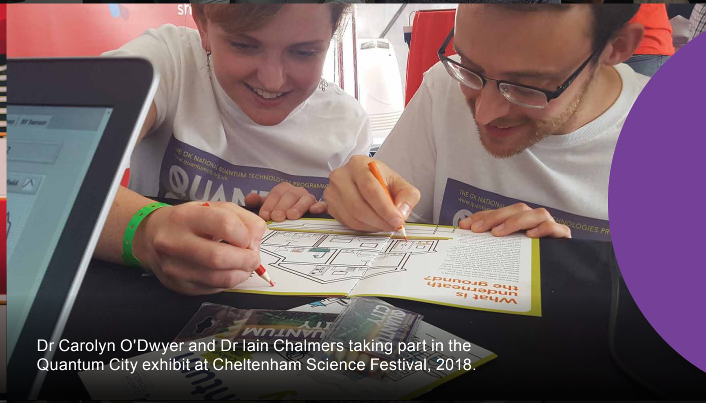

Professor Hidetoshi Katori (second from left) visiting the Quantum Technology Hub as part of the EPSRC-funded International Clock and Oscillator Networking (ICON) project. Also pictured: Yuheng Huyan (left), Jordan Wayland (second from left) and Professor Yeshpal Singh (right).


Professor Jim Al-Khalili with students and researchers from the University of Birmingham's Alkaline and Radar research groups.


Professor Kai Bongs, pictured in back row, third from left, with visitors from the Department of International Trade, 2022.

Professor Michael Holynski presenting at the 3rd annual Commercialising Quantum Global event hosted by Economist Impact in 2024.

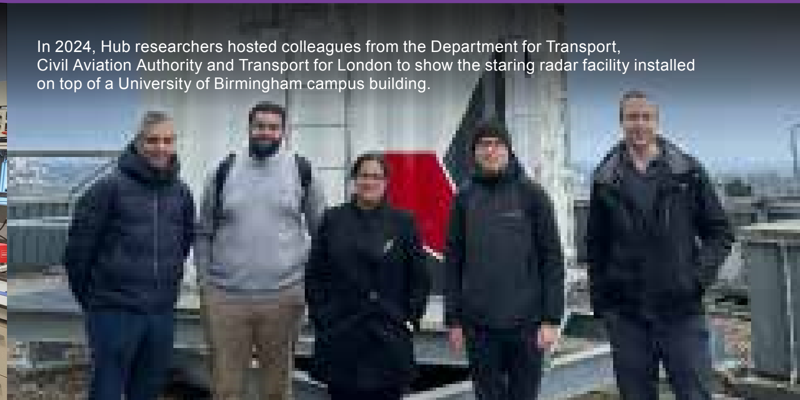

Expert panel discussion on "The Shape of Things to Come: Life in the Quantum Age" as part of the 2018 York Festival of Ideas, with (pictured from left to right): Professor Tim Spiller (University of York), Dr Jo Smart (University of Birmingham), Professor Steve Beaumont (University of Glasgow), Kate Ravilious (journalist and host), Professor Winfried Hensinger (University of Sussex).


Dr Carolyn O'Dwyer and Dr Iain Chalmers taking part in the Quantum City exhibit at Cheltenham Science Festival, 2018.


Professor Mark Fromhold (centre) participating in a panel session at the 3rd annual Commercialising Quantum Global event hosted by Economist Impact.


Professor Kai Bongs, former Director of the QT Hub, speaking at the Quantum Technologies in Satellite Gravity Measurement workshop, 2019.


Professor Mike Holynski, Principal Investigator for the Hub, introducing the quantum sensing labs to Professor Jim Al-Khalili.


In 2024, Hub researchers hosted colleagues from the Department for Transport, Civil Aviation Authority and Transport for London to show the staring radar facility installed on top of a University of Birmingham campus building.

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