Institution: University of Birmingham		
Unit of Assessment: UoA 9, Physics		
Title of case study: A UK Quantum Technology Industrial Ecosystem in Quantum Sensors for Gravity and Optical Clocks		
Period when the underpinning research was undertaken: 2010–present		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof. Kai Bongs	Professor	2008–present
Dr Mike Holynski	Senior Lecturer	2016–present
Dr Yeshpal Singh	Senior Lecturer	2016–present
Prof. Nicole Metje	Professor	2010–present
Period when the claimed impact occurred: 2014–2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

The **commercial and economic** impact of the University of Birmingham's Quantum Technology (QT) Hub is significant **innovation within government and industry**. Our ability to measure time and gravity with extreme precision using QT has effected a **strategic shift in public spending priorities** by the MOD agency, Defence Science and Technology Laboratory (Dstl), which has invested over [text removed for publication] of public funding into QT in gravity and timing. We also enabled an **ecosystem of over 70 companies** to engage in QT research. This reach extends to numerous multinational companies including [text removed for publication], informing their **commercial strategic decisions, investment priorities and product pipeline**. The QT Hub leads over 110 projects, valued at approximately £120M and has generated 17 patent applications.

2. Underpinning research

In 2013, the Government announced a £270M investment, over 5 years, in the UK National Quantum Technologies Programme (UKNQTP). This encompasses 4 QT Hubs which support a network of academic and industrial partners. Each of these hubs focuses on a particular aspect of QT, with the University of Birmingham leading the QT Hub in Sensors and Timing from within the Midlands Ultracold Atom Research Centre.

To create an atom interferometer gravity sensor or an atomic clock, atoms need to be measured with extreme precision. This can be done by slowing their movement by reducing their temperature through laser cooling, and then manipulating their quantum behaviour by exposing them to further laser pulses. Our research in this area led to 3 principal key findings [KF] that enabled the commercial impact outlined in section 4.

Firstly, one of the key technical challenges of this cooling technology lies in the laser system, which needs to be absolutely stable in frequency to 1 part per billion, exceeding the state-of-the-art in telecoms by a factor of 1,000. While it is possible to realise such laser systems in well-controlled laboratories, a lack of robustness has been a barrier to wider economic exploitation. Bongs provided a solution to this barrier by **making the laser system sufficiently robust for operation in drop-tower experiments under large temperature fluctuations and accelerations** and packaging them into a smaller format using less power than typical laboratory systems [KF1]. He demonstrated their functionality in **the first realisation of Bose-Einstein condensation and atom interferometry in micro-gravity** [R1, R2].

A second key challenge is to reduce the size, weight and power demand of the atomic equipment to make it useable in the field. Laboratory systems often fill several cubic metres, weigh hundreds of kgs and use kWs of power. In 2015, Bongs and Singh demonstrated **the most compact optical clock atomic package at the time, 10 times smaller and lighter than the state of the art** using **a new atom source and a compact optical/vacuum system** [KF2; R3, R4].

Finally, the atom interferometry activity (Bongs, Holynski) and its applications (Metje, School of Engineering) has focused strongly on the development of gravity-gradient sensors for commercial applications [R5]. The iSense project (EC GA 250072, FET-Open, PI Bongs) and Gravity Gradient - Technologies and Opportunities Programme (EP/I036877/1, PI Bongs) created **the UK's first transportable atom interferometer**. Subsequently, during the MOD-funded Gravity Imager project (DSTLX-1000095040), Birmingham developed this further into the **UK's first cold atom gravity gradiometer** [R5] and demonstrated its use in field environments through creating new approaches in sensor integration and high-performance sub-systems. These includes linear laser beam geometry for both magneto-optical trapping and atom interferometry, very compact vacuum system designs with integrated mirrors, and integrated and robust laser systems based on telecoms fibre technology [KF3; R6].

3. References to the research

[R1] T. v. Zoest, N. Gaaloul, Y. Singh, H. Ahlers, W. Herr, S.T. Seidel, W. Ertmer, E. Rasel, M. Eckart, E. Kajari, S. Arnold, G. Nandi, W.P. Schleich, R. Walser, A. Vogel, K. Sengstock, K. Bongs, W. Lewoczko-Adamczyk, M. Schiemangk, T. Schuldt, A. Peters, T. Könemann, H. Müntinga, C. Lämmerzahl, H. Dittus, T. Steinmetz, T.W. Hänsch, J. Reichel; "Bose-Einstein Condensation in Microgravity", *Science*, 328, 5985 (2010), DOI: 10.1126/science.1189164.

[R2] H. Müntinga, H. Ahlers, M. Krutzik, A. Wenzlawski, S. Arnold, D. Becker, K. Bongs, H. Dittus, H. Duncker, N. Gaaloul, C. Gherasim, E. Giese, C. Grzeschik, T.W. Hänsch, O. Hellmig, W. Herr, S. Herrmann, E. Kajari, S. Kleinert, C. Lämmerzahl, W. Lewoczko-Adamczyk, J. Malcolm, N. Meyer, R. Nolte, A. Peters, M. Popp, J. Reichel, A. Roura, J. Rudolph, M. Schiemangk, M. Schneider, S.T. Seidel, K. Sengstock, V. Tamma, T. Valenzuela, A. Vogel, R. Walser, T. Wendrich, P. Windpassinger, W. Zeller, T. van Zoest, W. Ertmer, W.P. Schleich, E.M. Rasel; "Interferometry with Bose-Einstein Condensates in Microgravity", *Physical Review Letters* 110, 093602 (2013), DOI: 10.1103/PhysRevLett.110.093602.

[R3] K. Bongs, Y. Singh, L. Smith, W. He, O. Kock, D. Świerad, J. Hughes, S. Schiller, S. Alighanbari, S. Origlia, S. Vogt, U. Sterr, C. Lisdat, R. Le Targat, J. Lodewyck, D. Holleville, B. Venon, S. Bize, G.P. Barwood, P. Gill, I.R. Hill, Y.B. Ovchinnikov, N. Poli, G.M. Tino, J. Stuhler, W. Kaenders; "Development of a strontium optical lattice clock for the SOC mission on the ISS", *Comptes Rendus Physique* (2015), DOI: 10.1016/j.crhy.2015.03.009.

[R4] US Patent No. 10342113; Cold Atom Source, K. Bongs, Y. Singh, O. Kock; granted 02.07.2018.

[R5] GB1721010.5; Gravity Gradiometer, M. Holynski, K. Bongs, A. Lamb, G. De Villiers; Patent Application 15.12.2017.

[R6] A. Hinton, M. Perea-Ortiz, J. Winch, J. Briggs, S. Freer, D. Moustoukas, S. Powell-Gill, C. Squire, A. Lamb, C. Rammeloo, B. Stray, G. Voulazeris, L. Zhu, A. Kaushik, Y.-H. Lien, A. Niggebaum, A. Rodgers, A. Stabrawa, D. Boddice, S.R. Plant, G.W. Tuckwell, K. Bongs, N. Metje, M. Holynski; "A portable magneto-optical trap with prospects for atom interferometry in civil engineering"; *Philosophical Transactions of the Royal Society*. A 375 20160238 (2017), DOI: 10.1098/rsta.2016.0238.

4. Details of the impact

The impact derived from the QT Hub in Sensors and Timing is on **commerce and the economy**, specifically **influencing national public funding priorities** and **commercial strategic decisions, investment and product pipeline** in quantum technology and **securing its future** in the UK. The QT Hub has established an industrial ecosystem in second generation QT, principally in ultra-precise clocks and gravity sensors. The ecosystem consists of component suppliers, system integrators and end-users, with application in numerous sectors from defence and healthcare to civil engineering. The Hub has over 110 projects, valued at approximately £120M, and 17 patent applications [E1].

Influence on national research strategy, the agenda of Dstl and public funding

We led the MOD executive agency Dstl to include applications in next generation sensing technologies in its research strategy through our work on compact and robust ultra-cold atoms systems [KF1, KF2] and through knowledge transfer as a result of KF3. In particular, gravity sensors [KF3] provided new deployable capabilities for the MOD and ultra-precise clocks [KF1, KF2] allowed access to secure time, which underpins all national and economic security. Both also contribute to novel resilient navigation and mapping systems, which are key priorities for the MOD. Dstl confirmed that "Before [Birmingham's] work, we had not been able to identify how to engineer systems which will provide the capabilities critically required in the future" [E2].

Our work led to a **change in Dstl's funding strategy** and the largest academic R&D investment since its creation in 2001 [E2], thus impacting the development of new technologies. In 2014, Dstl invested [text removed for publication] for QT in Bongs' research to develop 2 demonstrators (a transportable gravity imaging system and an optical lattice atomic clock). Moreover, Birmingham's research [KF3] directly contributed to gravity sensors being included in the key Dstl UK QT Landscape document (2014), ensuring that sustained investment in QT has become an industry priority [E3]. Dstl's Senior Research Fellow in Quantum Technologies stated that "Dstl greatly admires [Birmingham's] outstanding success in delivering a major part of the UK National Quantum Technology Programme (UKNQTP) [. . .] Within MOD Centre, [Birmingham's] success in developing new technologies for Dstl and the UKNQTP has attracted notice at the highest levels in Defence Science and Technology (DST, which sets strategy for future MOD investment in technology), the Front Line Commands (FLCs) and UK Strategic Command and Defence Equipment & Support" [E2].

In turn, this collaboration led Dstl to commence building **internal capability to carry out R&D** for militarily deployable sensing systems. The importance of our contribution to this capacity building is evidenced by the recruitment, in 2020, of 2 permanent members of staff to Dstl from the Birmingham team whose **specialist roles draw on our research** to enable **technology translation**. Dstl confirms the pivotal role of Birmingham's researchers, stating that "The continued collaboration will accelerate knowledge and technology translation from [Birmingham's] team into Dstl and increase Dstl's and the MOD's understanding of the potential of these emerging 'quantum 2.0' technologies" [E2].

Influence on strategic decisions, investment and product pipeline in QT

We created the confidence for **companies to invest and change their research strategies**, through our demonstration of small, light, low-power, and yet robust, quantum sensors and ultra-precise clocks [KF2, KF3]. This was further catalysed by the significant and agenda-setting investment by Dstl. There was no commercial activity in QT sensors and clocks before our findings, but **over 30 companies have now invested £25M, including £7M towards 31 Innovate UK-funded projects** (with a total value £26M), working collaboratively with the QT hub to create new commercial products [E4]. Highlights include:

- Significant industrial investment exceeding [text removed for publication] from international companies, including
  [text removed for publication];
- [text removed for publication] new products, including a sequencer for quantum sensors, quantum sensor vacuum systems, the development of additively manufactured magnetic shields, a miniature atomic clock, a quantum gravimeter and a gravity gradiometer;
- 3 international companies ([text removed for publication]) setting up offices in the West Midlands and contributing to the local economy;
- [text removed for publication] [E5].

From the vast number of industrial collaborations with Birmingham, 4 examples are provided to illustrate the significance of commercialising quantum technology.

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Stimulating the development of the QT sector and securing its future

Our leadership in QT has materially contributed to the success of the QT sector as a whole, setting the agenda for government and industry. In 2019, the Treasury announced £94M of government funding to extend the QT Hubs, thus providing increased security and expansion of QT commercialisation. This would not have been possible without the significant contribution of the 4 national QT Hubs and Bongs and the other Hub directors providing evidence before the House of Commons Science and Technology Select Committee [E12]. This work has demonstrated the development potential of the QT sector and the viable application of QT research in critical national and economic security [E13].

5. Sources to corroborate the impact

[E1] UKNQT Hubs [accessed 14.10.2020]

[E2] Testimony from Senior Fellow (Quantum Technologies), Dstl (28.2.2020)

[E3] Dstl, UK QT Landscape Report, 2014 [accessed 14.10.2020]

[E4] Innovate UK funded projects since 2004 [accessed 14.10.2020]

[E5] Survey response from the following collaborators: a) Fraunhofer UK Research Ltd, [text removed for publication]

[text removed for publication]

[E9] UNNQT, "Quantum technologies" [accessed 14.10.2014]

[text removed for publication]

[E12] House of Commons Science and Technology Committee, Quantum technologies Twelfth Report of Session 2017–19 [accessed 14.10.2020].

[E13] Quantum technologies: Government Response to the Committee's Twelfth Report [accessed 14.10.2020].