Welcome to QuantIC’s first annual report. The past year has flown by at the speed of light for us. Since the announcement of the UK National Quantum Technologies Programme, our Hub has hit the ground running, from setting up a core central team to establishing a new approach to working with industry and the way academic research is translated into innovative technologies for the market. Collaboration is at the centre of everything we are doing and has been a key component in our achievements.

QuantIC’s technological innovation focuses on quantum enhanced imaging. While pioneering new innovative technologies is great, it is only through industrial collaboration that we discover how they can make an impact in the market. This year, we have engaged with over 60 companies, and this has resulted in 9 new joint projects where our researchers and industrial engineers will come together to explore the potential of our new innovative technology.

The QuantIC Innovation Space is now complete and the new laboratory and hot-desking office facility will allow companies to co-locate with our researchers to refine demonstrator systems and advance their technology readiness level to full prototypes.

Collaboration has also been essential in reaching a variety of stakeholders. QuantIC led and worked together with the other Quantum Technology Hubs on the inaugural UK National Quantum Technology Showcase held in November at the Royal Society. The event was well attended by key industry players and government officials, and has set the template for future events.

Taking a longer term strategic view of building the next generation of quantum engineers, we also joined forces with the Scottish Schools Education Research Centre (SSERC) to increase the take up of quantum physics in secondary schools by running workshops for physics teachers to help build their confidence in the subject matter and we are excited to be working with the Glasgow Science Centre on developing a permanent exhibit on quantum technologies.

There are more examples within the pages of our annual report to highlight our achievements so far, and I hope that this report will spark a possible opportunity to work with us and realise the next generation of quantum technology.
It seems a long time ago when one of my (now) co-investigators came to my office and suggested that I had what it would take to lead one of the UK’s quantum Hubs. Being blind to flattery I decided they were right and so the journey began. It took six months to put our bid together, throughout which I could not have been better supported by a more committed team ranging from human resources to finance and most importantly our college business development manager Sara - now our Hub manager.

Come interview, EPSRC knew we were serious when I turned up wearing not only a suit but a tie too – indeed, apparently I spent a whole hour answering questions, during which I am told I did not fidget once. The interview went well, so well in fact that Steve and I missed our plane home! And so after a slight delay for a vote, the Hub came to be and QuantIC was born.

This last year has been a learning experience for me, working alongside Steve and together with a fantastic central team, as our Hub PI alongside my own research. I thought I knew the physics, I thought I knew the technology but what I did not know is what a talented and truly committed team of investigators I was going to find myself working with. Truly it has been a privilege to get to know not only the work we do but all of the people that make QuantIC the success we are becoming.

It struck me as I stood up on behalf of us all to present our Hub in the Royal Society at the first annual QT Showcase that never have I been more proud to be part of something as I am now. I hope that, upon reading this, the first of our annual reports, you can all feel some of that pride too – thank you all for the journey so far.

Professor Miles Padgett
QuantIC’s Principal Investigator
QuantIC is one of four Quantum Technology Hubs established as part of the £270m government investment in the UK National Quantum Technology Programme to accelerate the translation of quantum science into economic and societal impact for the benefit of the UK. The vision of the UK National Quantum Technology Programme is the creation of a cohesive quantum technology community where government, academia and industry collaborate to secure a leadership position for the UK in the emerging quantum technology market.

The partners of the UK National Quantum Technology Programme are:
- The Engineering and Physical Sciences Research Council
- Innovate UK
- The Department for Business Innovation and Skills
- The National Physical Laboratory
- Government Communications Headquarters
- The Defence Science and Technology Laboratory
- The Knowledge Transfer Network

The National Network of Quantum Technology Hubs is the core investment of the UK National Quantum Technology Programme. Through a competitive call for proposals, four Hubs were awarded a total of £120m to undertake technology research and to fund associated capital equipment. Each of the Hubs focuses around a particular suite of emerging quantum technologies:
- QuantIC – UK QT Hub in Quantum Enhanced Imaging
- NQIT - UK QT Hub in Networked Quantum Information
- The UK QT Hub in Quantum Sensors and Metrology
- The UK QT Hub in Quantum Secure Communication

For more information on the UK National Quantum Technology Programme please see: http://uknqt.epsrc.ac.uk/
QuantIC is the UK centre of excellence for research, development and innovation in quantum enhanced imaging. Over the next five to ten years, quantum enhanced imaging technologies will deliver economic and societal benefits in areas such as security, medical imaging, scientific instrumentation, oil and gas, energy and defence.

Our vision, shaped in collaboration with over 30 industry partners, is to pioneer a family of multidimensional cameras operating across a range of wavelengths, time-scales and length-scales, creating a new industrial landscape for imaging systems and their applications in the UK. QuantIC’s approach to user engagement and innovation includes a strategy aimed at exploring with industry the potential for quantum technologies to improve products and processes in the imaging sector.

Industrial representation is at the core of our management structure. The Market Opportunities Panel, comprising 18 industrial partners, directs the strategic investment of the £4m Partnership Resource Fund (PRF). The PRF has been designed as a flexible and responsive tool to support the translation of QuantIC’s research outcomes into industrial applications and commercial opportunities. In addition to feasibility studies and technology development projects, QuantIC’s PRF also supports the secondment of staff to aid knowledge exchange between academia and industry. A snapshot of our user engagement activities to date and a selection of case studies of funded PRF projects are reported in the Innovation section of this annual report.

The Hub is led by Professor Steve Beaumont, QuantIC’s Director, and Professor Miles Padgett, QuantIC’s Principal Investigator and Scientific Lead. The day to day operation of the Hub is supported by a dedicated central team comprising a Programme Manager, a Business Development Manager, a Communication and Public Engagement Officer and an Administrative Assistant to ensure smooth operation of the Hub and to appropriately resource our outreach and industrial engagement activities. Brief biographies of QuantIC’s management and the central team are provided in the Project Governance section of this document.

QuantIC’s technical programme is delivered through four interlinked work packages (WPs). The first three work packages cover system development, focusing on quantum imaging with correlation (WP1), timing (WP2) and squeezing (WP3), whilst WP4 focuses on the development of components such as sources and detectors. Imaging with correlation (WP1) exploits the quantum-inspired correlation between image and source to realise single-pixel cameras. Single pixel cameras are much cheaper than multimillion pixel array, particularly in the infrared region of the spectrum where traditional cameras are expensive or even impossible to obtain. Imaging in the infrared has innumerable applications for example it can allow firefighters to see through smoke and engineers to image gas leaks. Extension to quantum-correlated sources will allow trans-wavelength sensitivities where samples illuminated in the infrared will be imaged with visible detectors with
QuantIC: enabling tomorrow’s imaging systems

sub-shot noise performance. For example, a biological sample can be illuminated with very low light levels in the infrared and the image or spectroscopy information can be collected using a high-sensitivity detector in the visible, which is more cost effective than a high-performance infrared camera.

Imaging with timing (WP2) exploits the time correlation between source and detected return to provide range-gated and 3D imaging functionality. This is extended using entangled pair sources adding further discriminators for high background and covert scenarios. These camera systems will be able not only to detect an image, but also to establish how far away each pixel in the image is. This range information is obtained by measuring how long it takes for light to bounce off the object and come back to the camera. Depending on the application, ranging can work at distances from metres to miles and can form the basis of collision-avoidance systems or the 3D profiling of historic sites.

Quantum imaging with squeezing (WP3) exploits the number and phase correlations inherent in parametric light to provide ultra-low noise/power transmission imaging, fluorescent gain imaging and phase sensing (for biological and gravitation field imaging). In simple terms, light is made of photons that are measured in packets. It is a law of nature that if we measure 100 units over a certain time, in the next time interval we might measure anything from 90 to 110. This is the noise level inherent in classical physics, but quantum physics can overcome this limit. By squeezing the number of packets such that their flow is constant from one time interval to the next, sources can be developed that can allow more accurate measurements within cameras and other sensors, giving a performance level that no classical system can match.

All the three systems work packages will build on a set of underpinning component technologies in WP4, where we will develop world-leading quantum and classical correlated source technologies, single-photon sensitive imaging, timing arrays and electronic time-position readout technologies. Our objective is to deliver state of the art technology for detectors, sources and optical and electronics design, semiconductor technology, micro- and nano-fabrication, nanophotonics, component assembly and device characterisation and analysis. Important to our mission is also engagement with potential users of technology, stakeholders in the National Quantum Technology Network and government as well as the general public to encourage understanding of quantum technology. QuantIC is working closely with the Glasgow Science Centre to deliver a purpose-built permanent exhibition on quantum technology and to engage the public in a debate around responsible research innovation in this emerging area.
Miles Padgett FRSE, FRSE is QuantIC’s Principal Investigator and WP1 leader. He holds the Kelvin Chair of Natural Philosophy at the University of Glasgow and is one of the world’s most highly-cited researchers in the field of optics (Google≈21,000 citations, h-index 73). His group concentrates on the practicality of systems delivery and his inventions have led directly to commercial products for IBM, Siemens, Shell and most recently Boulder Nonlinear Systems. He holds an ERC Advanced Investigator Grant (TWISTS).

Stephen Barnett FRSE, FRSE is Professor of Quantum Theory at the University of Glasgow. He is a pioneer of quantum information, publishing his earliest work on the subject in the 1980s. He has worked closely with experimentalists and technologists, including those at BT Labs and also NTT in Japan, where he was a visiting professor in the 1990s. He held, until recently, a Royal Society/Wolfson Merit Award and in 2013 was awarded the Institute of Physics (IoP) Dirac Medal and Prize.

Adrian Bowman FRSE is Head of the School of Mathematics and Statistics at the University of Glasgow. He has published extensively in statistical modelling, including an OUP monograph, and he is particularly interested in methods which can track the flexible, non-linear behaviours which are exhibited by many real-life phenomena. His work with QuantIC involves the development of tools for the estimation of signals from noisy and sparse information, often exploiting spatial and temporal correlations.

Gerald Buller FRSE has worked in the field of single-photons since 1990, pioneering many developments in single-photon imaging, single-photon-avalanche detector (SPAD) and quantum communications, and leads an EPSRC Platform grant in this field. In 2002 he founded university spin-out company Helia Photonics Ltd. of which he remains a director.

David Cumming FRSE, WP4 leader, is Professor of Electronic Systems, Dean for Research in the College of Science and Engineering at the University of Glasgow and holder of a Royal Society/Wolfson Merit Award. He has a worldwide reputation in delivering integrated sensor systems for biomedical and imaging markets, founded university spin-out Mode Diagnostics and consulted for Ion Torrent, which commercialised his Complementary Metal-Oxide Semiconductor (CMOS) sensor technology for the personal genome machine. He is PI on EPSRC Programme Grant (EP/K021966/1).

Animesh Datta is an EPSRC Early Career Fellow at the University of Warwick, focusing on real-world quantum enhancements (EP/K04057X/1) (h-index 18, >2000 citations). His interests lie in the limits that quantum mechanics sets on information processing and the unique advantages that it provides in such tasks.

Martin Dawson FRSE has 30 years’ research experience in academia and industry and is both Director of Research at Strathclyde’s Institute of Photonics and inaugural Head of the UK’s first Fraunhofer Centre (Centre for Applied Photonics, CAP). His contributions span basic optical materials through semiconductor optoelectronics to lasers and optical microsystems, and he is currently PI of EPSRC Programme (EP/K00042X/1) and Platform (EP/I028141/1) grants.

Daniele Faccio, WP2 leader, is Professor of Physics at the University of Heriot-Watt. Since 1998 he has worked in top universities and companies worldwide in the fields of nonlinear photonics, optical telecommunications and imaging technologies. He currently holds an ERC Starter Investigator Grant (Light in

QuantIC builds upon a research portfolio exceeding £50m, complemented by a range of other substantial grants including five ERC grants, an STFC consolidated grant and awards from the EU, Royal Society, dstl and DARPA. The investigating team and their groups represent over 120 full-time researchers in quantum technology.
Roderick Murray-Smith is a Professor of Computing Science at the University of Glasgow. He works in the overlap between machine learning, interaction design and control theory and his research includes multi-modal sensor based interaction with mobile devices, mobile spatial interaction, brain computer interaction and non-parametric machine learning.

Giles Hammond is Reader at the Institute of Gravitational Research at the University of Glasgow. His research under QuantIC involves the development of ultra-sensitive micro-electro-mechanical systems (MEMS) gravimeters, which have significant industrial spin-offs in the fields of oil and gas prospecting, environmental monitoring and defence.

Robert Henderson is Professor at the University of Edinburgh and has industrial experience with VLSI Vision Ltd/STMicroelectronics. He leads SPAD sensor design programmes (e.g. EU MEGAFRAME and SPADNET) that have resulted in new products for STMicroelectronics. As part of an EPSRC Interdisciplinary Research Centre (EP/K03197X/1) he is exploring SPADs for in vivo molecular sensing. He holds an ERC Advanced Grant (TOTALPHOTON) to develop high-resolution SPAD cameras. 

Jim Hough FRS FRSE is Research Professor in Natural Philosophy in the School of Physics and Astronomy at the University of Glasgow. The culmination of his research career was reached this year with the direct detection of gravitational waves after 45 years, reflecting his dedication to innovation in precision measurement technology. In 2015 he received the Philips award of the UK IoP for distinguished service to the society.

Jonathan Leach is Assistant Professor in the School of Engineering & Physical Sciences at the University of Heriot-Watt in Edinburgh. He is part of the Experimental Quantum Optics group whose interests include the development of direct and indirect methods for the measurement of quantum states, the fundamental limits of super-resolution imaging and the development of ultra-sensitive photonic sensors.

Jonathan Matthews is an EPSRC Early Career Fellow at the University of Bristol and is a pioneer in the emerging field of Integrated Quantum Photonics, where his research now specialises in the development of quantum-enhanced sensors for interferometry and spectroscopy.

Roderick Murray-Smith is a Professor of Computing Science at the University of Glasgow. He works in the overlap between machine learning, interaction design and control theory and his research includes multi-modal sensor based interaction with mobile devices, mobile spatial interaction, brain computer interaction and non-parametric machine learning.

Douglas Paul FRS is the former Director of the James Watt Nanofabrication Centre at the University of Glasgow, which has an unparalleled reputation for component/system delivery. His research covers semiconductor devices for computation, quantum computing, Si photonics and sensing and he has been PI of >£14m of grants. He is a member of the Cabinet Office High Impact Threats Expert Group and previously sat on the MOD DSAC, Home Office CBRN Scientific Advisory Committee and the NATO CBP Panel. He has worked in collaborative projects with over 50 companies.

Sheila Rowan FRS is Director of the Institute for Gravitational Research at the University of Glasgow. Her research interests are directed at gravitational wave detection on the ground and in space. Professor Rowan’s research programme currently includes studies of ultrasensitive mechanical systems; investigation of materials of ultra-low mechanical loss and construction of mechanically stable optical systems for interferometric applications.

Michael Strain is a lecturer in Photonic Semiconductor Devices at the Institute of Photonics, based at the University of Strathclyde. His current research interests cover Photonic Integrated Circuits for applications from all-optical signal processing and sensing, to cavity enhanced non-linear interactions.
QUANTIC: ONE YEAR ON

The first year of QuantIC has flown by and we have been hard at work delivering our programme, refining our demonstrators and consolidating our team.

We have organised and participated in a number of events targeted at a broad range of stakeholders, from industry and users of technology to the general public.

An introduction to our research and technology development, our industry and stakeholder engagement road map and a more detailed account of our achievements are provided in this annual report.

Year one of QuantIC has been fast paced and very exciting. Our technology offering has advanced in line with our targets and our demonstrators have been refined, based on feedback from industrial users.

The central team has hit the ground running; we have established our governance structures and put in place a reporting and monitoring framework to manage the delivery of our objectives. Our Director, Principal Investigator, Programme Manager and Project Administrator were in place from the very beginning to oversee the project start-up phase.

We have developed a robust and responsive process for the administration of our PRF that allows us to flexibly respond to external opportunities and drivers, supporting our industrial engagement. The first call for projects was opened in January 2015, within a month from the official start of the project.

During our first year we have strengthened existing relationships with stakeholders in both the private and public sectors. We have consolidated and expanded our network through a number of events and workshops. We have held more than 60 meetings with companies leading to the award of six industry-led projects from our PRF and three additional innovation projects targeted at developing real applications in collaboration with industry.

QuantIC has developed its stakeholder engagement and worked with the Glasgow Science Centre and the SSERC to improve the understanding of quantum technology by the general public. Our academic team has participated in a number of outreach activities to engage in a two-way conversation on the public perception of quantum technologies.

RECOGNITION OF OUR WORLD-LEADING RESEARCH TEAM

£8m NEW research

3 Applications for use of the Innovation Space

42 Industry visits

42 Twitter followers

>200 Members of the public engaged

>1400 Technology exhibited at >10 events

3 Industry-led projects

5 Patent protected technologies

3 Partnership Resource Projects

~40 peer-reviewed publications

>60 Meeting partners

42 Industry-led projects

Thales - Centre for Defence Enterprise
ClydeSpace EngD CENSIS
NPL - InnovateUK

M Squared Lasers
STMicroelectronics
Lockheed Martin
Thales
Bridgeporth
Finmeccanica-Selex
ES

Fellowship of the Royal Society
Best Student paper at SPIE Optics Prague
Philip Leverhulme Prize
Medal from the Faculty of Nuclear Science of the Czech Technical University
Keynote at CLEO 2015

Prize for research into the science of light

Kevin Medal from the International Solid State Circuits Conference
Institute of Computational Engineering & Sciences

Best poster at the international solid-state circuits conference
During the last year, QuantIC has engaged with over 60 companies to discuss how we may be able to support them in developing new or improving their existing products and processes by adapting our technologies to meet their needs. We have a £4m PRF to support innovative technology development initiatives. The fund is controlled by our Market Opportunities Panel, which consists of representatives from across industry.

The Market Opportunities Panel has approved six Partnership Resource Projects since the launch of the scheme in January 2015. All projects are industry led and targeted to proving the feasibility of QuantIC’s technology in a commercial setting and include a matching in-kind or cash contribution from the industrial partner. Three of these projects are featured as innovation case studies in the following pages and are in collaboration with M Squared Lasers Ltd., STMicroelectronics and Finmeccanica-Selex ES. Three of the PRF projects were approved in November and are due to start; these are:

**Bridgeporth and the University of Glasgow** will work together on comparative field-testing of a miniaturised prototype of the "Wee-g" MEMS Gravimeter. "Wee-g" has been shown to work in the lab with a sensitivity of 30 ng per root hertz which is comparable to best in class devices. If proven to work in the field, the compact device has the potential to become the gravimeter with the best cost to performance ratio in the marketplace.

**Thales and the University of Heriot-Watt** have also secured funding to determine the design criteria for a novel imaging system, which will detect motion around corners. The system will use a multi-sensor approach. Initial modelling has suggested this set-up would offer advantages over the use of a localised array. The new technique should extend the distance over which a practical system can be utilised, a key performance criteria for field operation.

**Lockheed Martin and the University of Glasgow** will investigate the feasibility of developing a CMOS-based, low cost and easy to manufacture terahertz imager which can be mounted on an unmanned aerial vehicle for detecting water content of crops. The study will review key design criteria with a view to developing a full demonstrator.

In addition, QuantIC’s researchers have secured funding for innovation projects from Innovate UK, Centre for Defence Enterprise and CENSIS (Innovation Centre for Sensor and Imaging Systems) in collaboration with the National Physics Laboratory, Thales and Clyde Space Ltd respectively. Additionally QuantIC has worked together with Innovate UK to maximise the impact of our PRF by co-sponsoring projects under their up and coming call on Quantum Technologies. This is a very exciting opportunity for QuantIC to enable projects requiring a considerable amount of funding to be awarded to our industry partners.

Over the past year, we have also actively engaged with the Knowledge Transfer Network (KTN), CENSIS and dstl to expand our industrial network. The Market Opportunities Panel has also approved M Squared Lasers Ltd and Chromacity’s applications to be the first two companies to use QuantIC’s Innovation Space to work on new laser sources.

We are also in active discussions on two new proposals for PRF projects together with additional applications for use of the QuantIC Innovation Space.
Events and workshops

Meet the Hubs KTN event London Jan ’15
Hub Launch 120 attendees Glasgow Feb ’15
Dstl / Quantic QT Community Meeting 120 attendees Glasgow March ’15
MoD / DoD joint imaging workshop Loughborough September ’15
Quantum UK Conference, Oxford September ’15
Adastal Park cluster joint Hub event October ’15
Institute of Photonics 20th Anniversary Event Strathclyde November ’15
QT showcase 300 attendees November ’15

Projects in collaboration with industry

PRF launched in January for applications
M Squared Lasers and STMicroelectronic Partnership Resource Projects Approved
Selex Partnership Resource Project Approved
CENSIS EngD with Clyde Space Awarded
Centre for Defence Enterprise project with Thales awarded
Bridgeforth, Lockheed Martin and Thales Partnership Resource Projects Approved

Dec ’14

Nov ’15
Innovation Case Study: Gas Sight

The global gas sensing market was estimated at USD 1.78 billion in 2013 and is projected to be worth USD 2.32 billion by 2018. Gas sensing has relevant applications in sectors such as oil and gas, building and construction, food processing, healthcare and water treatment. There is a gap in the market for a low-cost, small-sized, low-power and highly portable remote gas detection system.

This technical feasibility project, lead by M Squared Lasers Ltd, will investigate the gas detection performance capabilities of the prototype Single-Pixel Camera (SPC) in an industrial setting. The project will enable testing of the SPC combined with M Squared Lasers’ tunable mid-infrared laser to form an active hyper-spectral imager system. Its sensitivity will be tested at different gas/air concentrations (down to less than 1000 ppm) and at extended distances (up to 10m).

The concept uses a telecoms laser diode to illuminate a scene at 1.65µm, exactly the wavelength corresponding to the absorption of methane gas. This image of the methane cloud is overlaid upon a high resolution RGB image of the overall scene, giving a composite full colour image where the methane appears as a red cloud.

The prototype camera has already demonstrated pure methane detection in a laboratory setting. Our challenge for the next stage will be to increase the sensitivity of the system so that its operational range can be increased to 3 meters or more.
Innovation Case
Study: SPADnet2

A partnership resource project in collaboration with STMicroelectronics

The combination of Positron Emission Tomography (PET) and Magnetic Resonance Imaging (MRI) is particularly desirable for clinical diagnostics in oncology, cardiology and neurology.

The SPADnet2 is a sensor developed under a European FP7 project. SPADnet sensors are smart, large area networked image sensors, based on conventional CMOS fabrication technology. These sensors, which have exquisite time resolution and are cheaper than existing devices, have the added benefit of being compatible with use in strong magnetic fields, a prerequisite for the integration of PET with MRI.

This feasibility study has the dual aim of transferring knowledge of product operation from the University of Edinburgh into STMicroelectronics in parallel with the creation of accompanying materials, results and documentation, which will allow immediate progression towards exploitation of the SPADnet chips.

The project will further consolidate the lead position held by STMicroelectronics in the area of SPAD development and lay the groundwork for further development in this area.
Innovation Case Study:
Dual-mode 3D Single Pixel Camera

A partnership resource project in collaboration with Finmeccanica-Selex ES

Finmeccanica-Selex ES will investigate the performance of an innovative compact dual mode 3D SPC, utilising pulsed laser sources operating in the visible and near infrared, in providing high spatial resolution image reconstruction of objects and real world scenes over distances of tens to hundreds of metres.

This will be the first time a 3D SPC will have been demonstrated for infrared ranging and profiling in a field trial and, if successful, could lead to the development of a robust 3D time-of-flight imaging LIDAR for the visible and infrared using low cost single-pixel detectors and cheaper detection optics to provide a more functional alternative to expensive scanning systems. While practical applications for the technology will be relevant for the defence sector, Finmeccanica-Selex ES and QuantIC will also explore the technology’s potential for other market sectors.

Robert Lamb, Chief Technologist at Finmeccanica-Selex ES, said: “We are excited about the prospect of developing a high resolution imaging capability using compressive sampling and computational imaging. The single pixel camera being developed by QuantIC is an innovative approach to a low-cost solution to visible and infrared 3D image fusion that isn’t possible with current focal plane array technology. It opens up a radically new technological approach to imaging where the emphasis is on high-speed mathematical reconstruction and processing rather than the conventional development of focal plane arrays and optical design.”
QuantIC made inroads into developing its "Wee-g" MEMS sensing technology by securing a 4-year CENSIS (Innovation Centre for Sensing and Imaging Systems) EngD studentship for a joint industry project with world-leading micro-satellite supplier, Clyde Space Ltd.

The aim of the industry-led project is to explore how QuantIC’s “Wee-g” sensing capabilities could be used for Clyde Space’s CubeSat systems, which is a type of miniaturised satellite for space research and is most commonly put into orbit due to its low cost of deployment. The research will focus on the modelling, precision sensing, fabrication and development of miniaturised gravity sensors for the attitude control of spacecraft, where there is a significant market need for accurate (+/- 2 degrees accuracy), lightweight (<1Kg) and low power (<5W) sensor systems in CubeSats. If successful, this will be an opportunity to create a transformative new space-based technology with unrivalled sensitivity.

Dr Giles Hammond, inventor of “Wee-g”, said, “Our MEMS technology has applications in areas such as oil and gas prospecting, civil engineering and environmental monitoring and I’m excited that we’re expanding our team to explore taking “Wee-g” to a new industry, space – the final frontier.”
Our early discussions with high technology companies highlighted a high level of interest in QuantIC’s technology development programme. A recurrent issue in our interactions with very small companies, typically university start-ups and small high technology enterprises, was the funding model associated with our PRF. PRF grants only cover the project costs of the academic partner but make no contribution towards the costs incurred by the industrial partner.

Small companies pointed out that, due to the early stage of some of the technology QuantIC is developing, enterprises face big challenges in managing feasibility studies and demonstrator projects from their own resources.

We have worked closely with Innovate UK to determine how best to help companies overcome this hurdle and how we can jointly support UK industry in maximising exploitation of quantum technologies. We agreed to align £500k of our PRF with the next Innovate UK call for proposals on Quantum Technologies. This will increase the overall funding available for projects and will make it easier for small companies to undertake PRF projects.

QuantIC’s funds will only be used for projects on imaging which would meet both PRF and Innovate UK criteria. We are very excited about this opportunity and look forward to working with Innovate UK to pioneer this model.
Innovation Case Study: What’s Inside That Building?

A Centre for Defence Enterprise funded project in collaboration with Thales

A collaboration between Thales and QuantIC has secured funding from the Centre for Defence Enterprise to develop a proof of concept demonstrator for a new technology system which will enable the user to track the presence of moving targets in concealed environments. The technology consists of shining a pulsed laser beam into a room or close to a surface (door, floor, ceiling, etc.) that allows the light to scatter into the room or around the corner. The light then acts similarly to sonar; it fills the environment and backscatters off the target. The backscattered signal is then recorded with a new generation of single-photon-sensitive cameras that have picosecond temporal resolution. It is this unique combination of super sensitive detection with picosecond timing that allows the precise location and movement of hidden targets to be determined using sophisticated computational techniques. The project builds upon collaborative work undertaken in the QuantIC’s programme on the development of camera systems that can both detect a single photon while also noting the time, to an accuracy of less than 50 ps, of when the photon arrived. It has been used to demonstrate the filming of “light in flight”. Photo credit EPSRC and Dan Tsantilis.
QuantIC Innovation Space

QuantIC made advances in expediting industrial collaboration to translate new emerging quantum enhanced imaging technology through its new purpose-built laboratory and hot-desking office space which was ready in October 2015.

Supported by a £3m investment from the Scottish Funding Council, the QuantIC Innovation Space, which is located above the James Watt Nanofabrication Centre at the University of Glasgow, will allow companies to co-locate with QuantIC’s researchers to refine demonstrator systems and advance their technology readiness level to full prototypes.

Access to and use of the facilities is free although applications must be made and approved by QuantIC’s Market Opportunities Panel. The innovation space is open to any company that:

- Requires office/lab space to carry out a QuantIC PRF project or to collaborate with QuantIC’s researchers, either on a one-off or on a regular basis;
- Requires space/lab for early stage start-up activities in the area of quantum enhanced imaging to advance the commercialisation or industry uptake of imaging technology.

Although not officially launched, the innovation space has already had applications from three companies to use the new facilities.
Professor Douglas Paul has joined some of the world’s most celebrated scientists in receiving the Institute of Physics President’s Medal. Just eight of the medals have been presented since the award’s inception in 1998. Past recipients include particle physicist and broadcaster Professor Brian Cox in 2012 and Sir Timothy Berners-Lee, inventor of the World Wide Web, in 2006.

Dr Frances Saunders, the Institute of Physics’ president, chose Professor Paul in recognition of his achievements in translating physics research into advanced technology: “I chose to present Professor Paul with the President’s Medal in recognition of his efforts to enable the prototyping and development of proof-of-concept nanoelectronics, quantum technologies and energy harvesting. Such enabling research is often unseen and unsung yet it is absolutely critical to translating the latest thinking in physics into something concrete that can benefit the economy and society”.

Professor Douglas Paul also secured an EPSRC Quantum Technology Fellowship. He has received more than £1.5m to work with a range of UK companies, government agencies, standards laboratories and universities to increase the industrial uptake of quantum technologies.

Professor Miles Padgett, QuantIC’s Principal Investigator and WP1 Leader, was awarded the 2015 Prize for Research into the Science of Light by the European Physical Society. The award recognises his international leadership in the field of optics and in particular orbital angular momentum. His best known contributions include an optical spanner for spinning micrometre size objects, use of optical angular momentum to increase the data capacity of communication systems and an angular form of the Einstein-Podolsky-Rosen paradox.

In addition Professor Padgett’s life-time work on orbital angular momentum was recognised by the Royal Society of Edinburgh through the award of the 2015 Kelvin Medal.

Professor Padgett was also a plenary speaker at the Conference of Lasers and Electro-optics (CLEO) in San Jose in May 2015. CLEO is the leading peer-reviewed meeting in laser and electro-optics, bringing together all aspects of laser technology, from basic technology to industrial applications.

Professor Padgett shared the stage with Professor Shuji Nakamura, last year’s Nobel Prize winner in physics, in a session celebrating the International Year of Light. A total of six nobel laureates spoke during plenary sessions at the 2015 conference.

Professor Daniele Faccio, QuantIC’s WP2 leader, was awarded the Philip Leverhulme Prize in Physics for his work on “light in flight”, which is one of QuantIC’s key technology demonstrators. The £100,000 prize recognises the achievement of this outstanding researcher who has already attracted international recognition and whose future career is exceptionally promising.

Professor John Rarity had the honour of being recently elected a Fellow of the Royal Society in recognition of his pioneering work in experimental one-photon and two-photon optics. The prestigious Fellowship was awarded in recognition of his “outstanding contributions to both the study of fundamental physical phenomena and the development of prototype devices. This requires specially designed sources and detectors, the former including parametric down-conversion and single-defect emitters. Rarity has made leading advances both to detector design and to such exotic sources and was, with his collaborators, for many years the sole UK representative in experimental quantum optics, his research telling us much about the nature of photons”.

Professor Rarity also secured a £1.6m EPSRC Quantum Technology Fellowship to develop technology that will dramatically reduce the scaling costs for building quantum information processors which could revolutionise classical optical networks.

Professor Gerald Bulfer secured a £1.4m EPSRC Quantum Technology Fellowship for research in sparse photon imaging. The fellowship will allow his group to take their quantum-enhanced imaging research to the next level, beyond the laboratory.

Professor Robert Hadfield was awarded a prestigious ERC consolidator grant (£1.7m) to engineer revolutionary photon counting infrared imaging and sensing solutions, with unprecedented spectral range, efficiency, timing resolution and low noise. He was also elected Fellow of the Institution of Engineering and Technology.

Dr Jonathan Matthews secured a £1.2m EPSRC Quantum Technology Fellowship. The award will allow him to work with companies, biologists, chemists and engineers to accelerate practical application of quantum technology. His fellowship, very well aligned with his technology development efforts in WP3, will enhance the performance and reduce the cost of imaging systems, allowing for delicate biological samples to be imaged in very low light conditions.

Professor Stephen Barnett has been awarded the Medal of the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. The medal recognises his contributions to the fields of quantum optics and quantum
information, especially in collaboration with researchers at the Czech Technical University.

Dr Stefan Hild is the 2015 winner of the Royal Society of Edinburgh/Sir Thomas Makdougall Brisbane Medal, for his outstanding research work in physics and his international profile in this field. Dr Hild is also a member of the RSE Young Academy of Scotland.

Our early career researchers have also been flying the Hub flag. Dr David Phillips, in Professor Padgett’s group, was awarded a Royal Academy of Engineering Research Fellowship to develop new imaging techniques targeted at single-cell biological systems. His work is well aligned and complementary to research ongoing in QuantIC and is targeted at developing new methods to understand and combat antibiotic-resistant pathogens.

QuantIC’s Genevieve Gariepy has been awarded the Johnstone and Florence Stoney Studentship by the British Federation of Women Graduates (BFWG). Founded in 1907, BFWG offers ten scholarships based on academic excellence to support and encourage women studying in the last year of their PhD. Based within the Extreme Light group at the Institute of Photonics and Quantum Sciences (IPaQS) at the University of Heriot-Watt, the award was granted to Genevieve as a result of her work in the field of imaging.

Guilsepe Intermite, PhD student in Professor Buller’s group at the University of Heriot-Watt, won the Best Student Paper Award at SPIE Optics in Prague for his work on “enhancing fill-factor of CMOS SPADS arrays using microlens integration”.

Neale Dutton, PhD student in Professor Henderson’s group at the University of Edinburgh, won best poster award at the International Solid-State Circuits Conference.

Photo credit: CLEO 2015
Research Highlights

Is the speed of light in vacuum always c?
The publication “Spatially structured photons that travel in free space slower than the speed of light” (D. Giovannini, J. Romero, V. Potoček, L. Ferenczi, F. Speirits, S. M. Barnett, D. Faccio and M. J. Padgett) published in Science proves that light can be slowed down.
The paper was covered by the BBC and featured by new outlets world-wide. In essence the apparent slowing of the light is analogous to the slowing that a zig-zag path entails compared to travelling in a straight line. This experiment began life in a collaboration between the Universities of Glasgow and Strathclyde. The historic first direct detection from gravitational radiation - announced on 11 Feb 2016 by the LIGO and Virgo Collaborations, and published in Physical Review Letters 100 years after Einstein’s prediction of the existence of such gravitational signals. The detectors of the Advanced LIGO Observatories form the most sensitive displacement measuring instruments ever constructed. These use laser interferometry to sense the position of 40 kg mirrors at a level equivalent to 1/10000”th of the diameter of a proton. The ultra-low-noise suspension systems responsible for supporting the mirrors and holding them almost motionless, ready to respond to gravitational waves from the cosmos, were designed by researchers who are members of QuantIC, with spin-offs from this work feeding directly into the QuantIC’s programme in gravity sensing. At design sensitivity the performance of these instruments will be limited by the Uncertainty Principle, making these astrophysical observatories simultaneously act as laboratories for fundamental tests of macroscopic quantum mechanics on a grand scale.

Gravitational Wave Detection
The Universities of Glasgow and Strathclyde were involved in the historic first direct detection from gravitational radiation - announced on 11 Feb 2016 by the LIGO and Virgo Collaborations, and published in Physical Review Letters 100 years after Einstein’s prediction of the existence of such gravitational signals. The detectors of the Advanced LIGO Observatories form the most sensitive displacement measuring instruments ever constructed. These use laser interferometry to sense the position of 40 kg mirrors at a level equivalent to 1/10000”th of the diameter of a proton. The ultra-low-noise suspension systems responsible for supporting the mirrors and holding them almost motionless, ready to respond to gravitational waves from the cosmos, were designed by researchers who are members of QuantIC, with spin-offs from this work feeding directly into the QuantIC’s programme in gravity sensing. At design sensitivity the performance of these instruments will be limited by the Uncertainty Principle, making these astrophysical observatories simultaneously act as laboratories for fundamental tests of macroscopic quantum mechanics on a grand scale.

Detection of objects hidden from view
The publication “Detection and tracking of moving objects hidden from view” (C. Cariepy, F. Tonolini, R. Henderson, J. Leach, and D. Faccio) was featured in Nature Photonics and highlighted the development of a camera system that can see around walls and locate hidden objects with centimetre precision and then track their movement in real time. The team has been able to detect objects behind walls and then track their movements within seconds.

Professor Daniele Faccio from Heriot-Watt University said, “The ability to detect the 3D shape of static hidden objects has been demonstrated before, but the long acquisition time required by existing methods meant locating and monitoring the objects was a major challenge. We can now track hidden objects in real time and we’re still making discoveries about how the light identifies the objects, and can picture them in considerable detail.”

Rescue missions, negotiating dangerous terrain and in-car systems that help avoid collisions are some of the real-life applications the team are exploring in collaboration with industry.

Whether the slowing of light in this way is useful only time will tell but QuantIC is now trying to apply the technologies we developed for timing photon arrival to depth resolved imaging.

Explain to each other what we each did - which just goes to show 2+2 can equal more than 4!"
During the first year the Hub’s team has been progressing the development of the technology demonstrators. The diagram provides a summary of the components and systems in each of the four work packages and an overview of the connectivity between the different technologies.

A more in depth description of each demonstrator and the technical progress achieved during year one is provided in the following pages, together with an outlook towards year two.
The focus of our first year within WP1 has been to establish a number of demonstrator systems to support our industrial engagement. The SPC has been transformed from a suitcase-sized device to a demonstrator that sits in the palm of one’s hand. The SPC capabilities have been demonstrated for different applications such as imaging hidden features behind layers of paint, viewing of images through highly tinted glass and imaging of leaking methane gas. Our second demonstrator, the wavelength transformation camera, has been embodied within a microscope system where the sample is illuminated in the infrared, yet the image is recorded using a high-performance visible camera. The data analysis and image reconstruction theoretical efforts in WP1 have played a major role in supporting the improvement of the performance of our cameras in WP1 and beyond by accelerating our data analysis and providing better and faster algorithms.

The level of industrial engagement is exemplified by the two company-led partnership resource projects building upon these demonstrators. M Squared Lasers Ltd are pursuing a system for gas leak imaging. In a further adaptation of the SPC, Finmeccanica-Selex ES Ltd is investigating its use in range selective imaging.
Configuration of single pixel cameras

How many pixels does your camera have? Whereas modern cameras have many millions of pixels, QuantIC is developing cameras that have only one. SPCs have the advantage of opening wavelength ranges where conventional cameras are extremely expensive or even unobtainable.

In essence a SPC resembles a data projector where the light source is replaced by a single element (pixel) detector which measures the total power transmitted through the display as superimposed upon the scene. By displaying a known series of complex masks and measuring the transmitted power associated with each mask, it is possible, by data inversion, to deduce the image of the scene (Edgar et al. Scientific Reports, 5:10909, 2015).

In year one QuantIC has developed a number of SPC demonstrator units that have featured in our various showcase events and have been central to our industrial engagement. Our primary technical effort has been in reducing the size of the camera system whilst maintaining performance levels. This goal was achieved by designing bespoke optomechanics, which have been manufactured using our in-house 3D printing facilities. In addition, software development for high-speed data inversion has been key to improving performance. During year one we have initiated two industry-led partnership resource projects. The first of these projects is with M Squared Lasers Ltd, seeking to develop a low-cost camera system for the visualisation of gas leaks. The concept uses a telecoms laser diode to illuminate a scene at 1.65µm, exactly the wavelength corresponding to the absorption of methane gas. The SPC was adapted to be sensitive to this specific wavelength by using a InSb detector, resulting in an image based on the backscattered light. When operating the camera in this mode, the methane appears as an absorbing cloud. The image of the methane is overlaid upon a high resolution RGB image of the overall scene, giving a composite full colour image where the methane appears as a red cloud. Our challenge for the next stage of the project is to increase the sensitivity of the system so that its operational range can be extended to distances of 3 metres or more.

The second partnership resource project is with Finmeccanica-Selex ES Ltd. It seeks to adapt the SPC to provide range information for every single element in an image in addition to a standard two-dimensional image. Unlike a conventional camera where each pixel in the detector measures only the intensity, a SPC can have exquisite timing resolution. When the SPC is combined with a pulse illumination source, the return signal has a complicated spatial profile dependent upon the 3D form of the scene. The data can then be invertible to obtain the full 3D information. This method allows very interesting applications where information can be selectively collected from one part of the scene, allowing the camera to view through semi transparent screens, such as clothing or a tree canopy. A surprising feature arises from the complexity of the data collected: this technique achieves a depth precision that exceeds the timing resolution of the detector. (Sun et al. under review, 2015). Our challenge for the next stage of the project will be to adapt the system into the infrared for covert illumination and to increase the data collection to obtain near video display rates.

Data analysis and image reconstruction

Central to all imaging systems is the reconstruction algorithm that converts the data recorded by the sensor to a displayed image. QuantIC has taken a number of different approaches to this problem, largely depending upon the nature of the sensor used. Central to many of these solutions is the recognition that real images are not a collection of random pixel values, and neighbouring pixels often show strong correlations between them. This assumption is central for example to the familiar JPEG file format, which is based on sparsity, not in the image itself but rather in its spatial frequencies. As a result, a high quality image can be stored in only a fraction of the anticipated memory. In terms of image reconstruction, the same principle can be employed to recover images from noisy or incomplete data.

For example, given a noisy image we are at liberty to adjust any of the pixel values, by an amount comparable to the noise. However, in the absence of any additional information, there is no basis on which to make these changes. If instead we assume sparsity in the spatial frequency domain (i.e. an image where many of the spatial frequencies are absent), we can use this additional constraint to select the optimum image from a range of all possible images with all possible pixel values within the noise range. This problem is solved computationally by optimisation of the image to satisfy both the constraint set by the data itself and the sparsity constraint. Within QuantIC we have used both Gaussian noise models (for the SPC) and Poissonian noise (for the low photon number images of the low flux camera) along with constraints associated with sparsity of spatial frequencies and total image variation. Furthermore we have accelerated the implementation of these algorithms by their implementation on a Graphics Processing Unit (GPU). (Sonnleitner et al. Optica, 2(11), 2015).

The next step is to apply these methods to the images generated by the devices operating within the consortium. We can expect the practicalities of the individual systems and the images they are seeking to recover to further refine our image-reconstruction algorithms.

During the first year we have also devised a quantum correlation-based technique to reconstruct an image that has been jammed or has been corrupted with noise. Our plan is to investigate the practicality of this system in real environments during the coming year.

Looking towards year two of the Hub, we also plan to introduce a new development within WP1. In 2015, members of the team patented a new spectroscopic technique for probing the properties of chiral molecules. Such molecules are ubiquitous in the biological world and are of crucial significance for the pharmaceuticals industry. Over the coming year, we shall seek to develop this idea further under the QuantIC’s programme with the aim of moving towards commercial development. We have already been in discussion with one of our existing industrial partners concerning this new opportunity.
Wavelength transformation / low flux camera
Conventional imaging systems rely on a) a light source to illuminate the object and b) a camera system to collect the back-scattered light after interaction with the object. This combination provides an image. In these conventional systems the wavelength of the light illuminating the object is the same wavelength that is recorded by the camera, as it is indeed the same light. At QuantIC we have developed a wavelength transformation camera that allows us to illuminate the object with infrared light, but collect the image in the visible range, using a high performance visible camera.

Ghost imaging systems use two identical illumination sources. One source is used to illuminate the object and the other source is recorded by the camera. In the quantum regime, these two light sources are identical even at the level of individual photons (produced using a method called parametric down conversion). Whenever a photon striking the object is back reflected, the camera takes an image of the identical photon in the other beam. After many such events the sum of all these individual photons, reveals an image of the object, even though none of the photons recorded by the camera has ever interacted with the object itself.

QuantIC has developed a ghost imaging technique where the photon correlated light sources are at different wavelengths, one in the infrared and one in the visible. This allows the object to be illuminated in the infrared and the images to be recorded in the visible spectrum. As a result we can use a conventional high specification camera that is much more sensitive than its infrared equivalent, thereby allowing us to image at extremely low light levels.

In year one we have built a laboratory demonstration system where this wavelength transformation concept has been embodied into a microscope. We have used this system to image both biological and nano-fabricated samples (Aspden et al. Optica 2015, 2(12) 1049). This imaging system is now at a performance level where it can be demonstrated to potential users. Our initial targets are camera manufacturers and we have now opened discussions with interested industry partners to develop a possible opportunity for collaboration.

Correlated photon spectrometer
The concept of wavelength transformation applies not just to imaging systems but to spectroscopy too. QuantIC has developed a demonstration system where the sample is probed at one range of wavelengths yet the spectrum is recorded at shorter wavelengths where the camera system is more sensitive. The concept can similarly be applied to noise reduction techniques. In conventional illumination, the number of photons recorded in any one data bin (image or spectrum) is subject to a shot-noise variation equal to the square root of the number of photons recorded. This noise floor represents the quantum limit of classical measurement. The use of correlated beams allows this limit to be overcome. Since the shot-noise is identical on the two beams, dividing the number of photons measured in one beam by the number of photons measured in the other yields a unity ratio. This ratio is noise free. A slight absorption in one beam appears as a change in this ratio and hence can be detected even in the presence of shot-noise. The extent to which this noise reduction can be implemented is critically dependent upon the measurement efficiency.

Meaningful reductions in noise require a measurement efficiency in excess of 90 percent. This high efficiency requirement applies not just to the detectors but to the sources too, hence the development within QuantIC of high-efficiency photon-pair sources.

The development of the correlated photon spectrometer is relying on the availability of the high-efficiency photon pair sources developed in WP3. Please see progress reported under “Squeezed-light / sub-shot noise imager” in WP3.
The focus of our first year within WP2 has been to establish a number of demonstrator systems to support our industrial engagement. The “light in flight” camera and hidden object tracker demonstrator has been used to track a pulse of light propagating through a fibre and to track the position and speed of an object moving behind a solid wall. Our second demonstrator, the quantum state imager, has been benchmarked against the performance of existing camera technologies - electron multiplying (EMCCD) cameras and intensified cameras (ICCD) – to detect pair-wise photon events arising from quantum entanglement. The quantum range finder has also been progressing through year one with the development of a high-efficiency correlated photon source, which will enable covert ranging using extremely low-light levels.

QuantIC’s researchers in WP2 have engaged extensively with users. This is exemplified by two ongoing industry-led projects in collaboration with Thales. The aim is to use the hidden object tracker technology to visualise objects inside a building. We are also holding discussions with potential users in the defence and medical sectors to explore further applications of our technology for imaging systems with enhanced abilities to see through turbid media.
"Light in flight" camera and hidden object tracker

Conventional cameras measure the light intensity but what about the distance of individual objects within the field of view? QuantIC is developing cameras that in addition to the intensity of each pixel can measure the arrival time of the individual photons. When used with a pulsed illumination source this arrival time gives the time-of-flight from source to object and hence the range of objects at each individual pixel. In year one, the QuantIC activity falls into two themes.

The first strand revolves around the "light in flight" camera. Our cameras have individual photon-counting pixels that allow us on the one hand to capture extremely low light intensities (at the single photon level) and on the other to obtain picosecond temporal precision, thus providing the ability to capture high speed action with an increase of over a million-fold in frame rate when compared to the best commercial high speed cameras. We have used this technology to capture for the first time "light in flight", that is high speed movies of pulses of light propagating in free space where we freeze light in motion and capture the fine details of its propagation. This represented our first demonstrator of the technology.

The second theme is the application of these SPAD arrays to achieve new and exciting imaging capabilities. The primary demonstration has been the concept of using a time resolved camera to detect objects outwith the line of sight, e.g. hidden behind the corner of a wall. In this application a pulsed laser is used to illuminate a spot on the floor some distance ahead of the camera. Light is scattered from this spot and strikes the object which is hidden. Light is then backscattered from the object back into the field of view of the camera where it is itself scattered (again) from a surface. The extreme single-photon sensitivity of the camera means that this triple-scattered light is still of an intensity that can be detected! This triple scattered light is imaged as a curve of light on the surface, the centre of curvature indicating the position of the object (c.f. the ripples on a pond). Although recovering the detailed image of the hidden object is as yet beyond the computational power of the analysis, the size and speed of object or objects can be clearly identified (Gariepy et al. Nature Photon 2015, 6, 602).

Our challenge for year two is to use the improved detector arrays to increase the operational range of this viewing of hidden objects, up to 10 m. Beyond the viewing of hidden objects, we will be extending the range of applications to take advantage of the timing resolution for the imaging through turbid media ranging from sand storms (brown-outs) to human bodies, potentially supplementing the use of X-rays. The Centre for Defence Enterprise, dstl and Thales have joined forces with us in order to bring this technology to the point where it will operate outside the lab and over large (up to 10-50 m) distances.

Quantum state imager

There is a very large market for cameras that can detect single photons with high temporal resolution, high quantum efficiency, and low noise performance. Target applications are fluorescence microscopy, quantum imaging, range finding, and low light level surveillance. Commercially available cameras do not have all the desired features at once: EMCCD cameras have a high quantum efficiency but relatively long exposures; ICCD provide very short exposure times and can be triggered at high repetition rates, but their single photon efficiency is very low. A very attractive solution is a camera based on single photon avalanche detector (SPAD) arrays. Our goal is to establish SPAD cameras as a viable alternative to the currently available EMCCDs and ICCDs.

The first year’s work within the QuantIC programme has been dedicated to testing the ability of SPAD cameras to detect single photons in the most stringent environment. To benchmark the performance of our SPAD camera against EMCCD and ICCD cameras, we are attempting to detect pair-wise photon events arising from quantum entanglement. We received a SPAD camera from Professor Henderson (WP4) at the start of 2015. We developed acquisition software in LabVIEW and detected entangled photons in the final quarter of 2015. We are currently detecting momentum correlations from a parametric down-conversion source – this is the first time that pair-wise correlations have been detected with a SPAD array sensor.

We have also supplied sparse single-photon data from the SPAD camera to Professor Padgett (WP1) to test the effectiveness of computational methods in reducing the noise level in images. We have now developed real-time de-noising algorithms to be implemented on data from the camera.

Each pixel of the SPAD camera is a single-photon sensitive detector that can be switched on for a very short period of time. The current generation of gated SPAD cameras has a spatial resolution of 320 by 240 pixels and a temporal resolution provided by a 2 ns gate that can be shifted by around 500 ps. The camera is operated via a 12 V power supply, weighs around 500 g, and provides data to a computer via a USB 3 link. Later generations are expected to have higher spatial and temporal resolutions. The specifications of the cameras are very impressive: very short exposures (2 ns), high quantum efficiencies (currently around 35 percent for 500 nm light), and very low fixed-pattern noise.

The focus in year two will be the development of an external gating system for the camera. This will enable the use of the camera triggered from an external source, opening up further applications of the SPAD sensor.
Quantum rangefinder

Laser range finders are common place both in the construction sector and defence applications. The time it takes for a laser pulse to reflect from an object and return to the source gives a highly accurate measure of distance. In the defence application it is desirable that the laser illumination is not detectable by anyone other than the sender. Achieving this covertness is problematic since, as anyone who has used a torch at nighttime knows, the torch itself is visible from a much larger distance than that which the torch itself allows you to see. A challenge for the next phase of the project is to use the highly efficient photon-pair source to form a quantum rangefinder. As discussed above, the source emits two photons into two modes at exactly the same time. One of these photons acts as a trigger to the user, alerting them to the emission of a second single-photon. This knowledge of exactly when the photon is produced provides the additional information allowing the ranging of objects with ultra-low intensity. On the other hand, since the object has no knowledge of this emission time, they cannot distinguish the illumination from the thermal background. The ranging of the object then becomes covert.

The development of the quantum range finder is relying on the availability of the high-efficiency correlated photon pair source developed in WP3. Please see progress reported under “Squeezed-light / sub-shot noise imager” in WP3.
The focus of our first year within WP3 has been to establish a number of demonstrator systems to support our industrial engagement. The squeezed-light/sub-shot imager demonstrator has been progressed through the development of a high efficiency correlated source, which is tunable in the near-infrared. This source opens up applications for spatial imaging and timing measurements such as range-finding (WP2) and spectroscopy (WP1). We have also advanced the development of a laboratory prototype of the MEMS-based gravimeter. The instrument has demonstrated sufficient performance and long-term stability to allow the measurement of the Earth-tides, something no MEMS-based instrument has never been able to perform before.

To open up applications in bioimaging, a highly squeezed pulsed light source suitable for pump-probe microscopy has been developed. In parallel, theoretical efforts have focused on the formulation of a complete theory of quantum imaging, based on multi-parameter estimation theory. This multi-parameter approach will enable the imaging of entire samples rather than scanning across them.

The level of industrial engagement is exemplified by the two company-led projects in collaboration with Bridgeporth and Clyde Space. The first is focused on the development of a field-prototype gravity imager and the second on the design and development of MEMS-based instruments for space applications.
**Squeezed light / sub-shot noise imager**

Today, lasers are the cleanest source of light that is commonly used for optical measurement. However, they are fundamentally limited in precision measurement applications by shot-noise. In addition, other common practical limitations arise, such as beam stability, detector noise and environmental noise sources. In QuantIC, we seek to surpass the practical and fundamental limits of noise in precision measurement by using our understanding of quantum mechanics and quantum states of light. We use correlated photon pair sources, together with varied detection techniques including CCD, to achieve sub-shot noise precision.

A single photon source can be constructed to have the same key operational requirements as a laser, including long coherence length, directionality and single frequency, and they can also provide timing information. Unlike lasers, single photon sources have a reduced uncertainty on an intensity measurement, which results in a better signal to noise per unit of optical intensity. The quantum nature of light means that we have binomial uncertainty absorption measurements because there are only two possible outcomes: to detect either 0 photons or 1 photon. This results in a reduced uncertainty of measuring optical absorption. To achieve this, we use non-linear optics to down convert a laser beam into two beams of frequency, time and momentum correlated photons. Detecting one of the photon “heralds” the presence of its twin, which we can then use for imaging.

QuantIC has developed a compact photon pair source that is tunable in the near-infrared that can be used for spatial imaging, timing measurements such as rangefinding and spectroscopy. This source achieves a quantum-advantage over classical sources of light. Potential applications for this setup outside initial driving applications include a pre-built photon pair source for academic research and as a calibration apparatus for low-level light detectors, including single photon detectors and single photon sensitive CCDs. The next steps will be to improve capability of subsequent setups, including wavelength range and bandwidth, and increase robustness for deployment in noisy environments.

**Chi-3 sensor**

The conventional wisdom suggests a sensor built with classical resources achieves at best the $1/N^{1/2}$ sensitivity of the standard quantum limit (SQL). For example, one would find such a scaling with input mean photon number for the precision of an estimate of optical phase in a linear system. Non-linear interactions, however, allow for measurement sensitivities that scale well beyond the tradition SQL, and even beyond the conventional “quantum” limit of $1/N$, even using classical resources. Non-linear physics has already delivered valuable tools to microscopy and sensing, notably techniques based on two-photon absorption or Raman scattering.

The Chi-3-sensor directly probes the Kerr non-linearity of a sample with sensitivity beyond the conventional quantum limit. This means it has the potential for a label-free probe of molecules. We anticipate high per-photon sensitivity compatible with low light level imaging of biological samples. The highly sensitive measurement of the Kerr non-linearity also has industrial relevance for accurate characterisation of non-linear materials.

The Chi-3-sensor utilises time-bin polarimetry to probe the Kerr coefficient of a sample, where self-phase modulation of the probe light (independent of cross-phase modulation) gives direct access to the magnitude of the Kerr interaction. By harnessing the non-linearity of the interaction between the probe and the sample, the sensor achieves per-photon sensitivities beyond the conventional quantum limit.

In year one QuantIC has constructed prototype demonstrator, with the prototype realizing the anticipated $1/N^{3/2}$ scaling when probing the Kerr coefficient of an optical fibre. The sensitivity of the first generation device is still to be improved via the integration of low noise detection electronics, before application to the sensing and imaging of bulk samples.

The Chi-3-sensor complements the established z-scan technique, circumventing the latter’s limitations due to two-photon absorption and demonstrating enhanced resolution for thin samples. To identify and capitalise on potential for commercialisation, QuantIC’s researchers have engaged with Lein Applied Diagnostics, who have developed a suite of non-contact measurement technologies for a number of optical material and system parameters.

In year 2, the initial focus will be on enhancing sensitivity performance of the prototype device. We will then emphasise the extension of the Chi-3-sensor to image the non-linearity profile of bulk materials. The performance of the technique will then be accurately benchmarked against existing techniques, such as z-scanning. The focus will then turn to the potential of Chi-3 based microscopy schemes.
MEMS gravimeter

Measurement of gravity enables the local mass density to be imaged. Gravity surveys are regularly used for oil and gas prospecting, environmental monitoring and security applications. Current state of the art instruments are high performance and high cost. There is a gap in the market for cheaper, highly sensitive devices that provide high-resolution gravity maps at a fraction of the cost.

A relative gravimeter monitors the local change of gravity by sensing the position of a mass on a spring. Changes in the local gravitational acceleration, due for example to mass anomalies associated with oil reserves, change the vertical height of the mass. Our MEMS (Micro Electro-Mechanical Sensor) is an all silicon micro-fabricated device with a proof mass of 0.02 mg. The device is readout with an optical sensor, enhancing sensitivity over traditional capacitive readouts and providing a system which is immune to electromagnetic interference.

During year one, we have developed the fabrication process and optical read-out techniques approaching the shot-noise limit. This laboratory prototype device has proved sufficient long-term stability to perform a first measurement of the Earth tides with a MEMS device (Middlemiss, Nature, Accepted). This measurement has shown the transformative nature of our work. The device outperforms all other MEMS devices in the low frequency regime by utilising closed loop thermal control. Integrated on-chip thermal control has not been widely used in MEMS devices to-date and its implementation in our sensor provides a system which is stable over several days, showing better drift performance than a commercial CG-5 relative gravimeter.

The performance of our device has attracted users’ interest. We are currently working on three industry-led projects: a) a dstl-funded studentship to develop a practical MEMS gravimeter for security application; b) a PRF with Bridgeporth and c) a CENSIS EngD in collaboration with Clyde Space.

Our dstl project is very well aligned with work currently undertaken in QuantIC. We are capitalising on our MEMS sensor and developing on-chip Ge photodiodes and waveguide-based interferometers for position read-out. This will feed back into the QuantIC’s programme.

Our PRF is targeted at developing a MEMS gravimeter field unit, which will be used in comparative surveys by Bridgeporth. This proposal will further develop the technology, miniaturising the electronics and developing a battery powered prototype device.

The recently funded EngD project in collaboration with Clyde Space is focused on the development of miniaturised MEMS sensors for controlling the angular alignment (attitude) of CubeSats produced by our industrial partner. The further development of the technology towards a miniaturised, low power, highly ruggedised system that can withstand the requirement for space launch will feed directly into device development for QuantIC in other applications.

Over the next year, we will conduct field trials in collaboration with users and further qualify the performance of our system compared with commercial devices in a set of different applications and conditions. Based on these results and on further research on optical readout strategies, we will down-select the most appropriate set-up.

Pushing beyond the shot-noise limit of our optical read-out, we are going to work in collaboration with Professor John Rarity’s group (WP3) and Glasgow-based expertise on four wave mixing for the development of on-chip squeezing.

Squeezed light stimulated spectroscopy

While fluorescence-based microscopy is the workhorse of modern biology, many biologically important molecules absorb light but do not fluoresce, with their relaxation dominated by non-radiative decay mechanisms. Stimulated-emission microscopy (SEM) exploits stimulated-emission as a contrast mechanism for optical microscopy, allowing background-free imaging of these “dark” molecules. Crucially, the classical performance of SEM is shot-noise limited, and hence suitable for quantum enhancement and the first demonstration of sub-standard quantum limit (SQL) measurement of a biological system.

SEM requires the accurate resolution of minuscule changes in the intensity of a probe field, with the current sensitivity of such microscopes limited by the shot-noise of the probe light. At this shot-noise limit (SNL), the limiting fluctuations in the intensity are a direct consequence of the quantum nature of light, with quantum mechanical enhancement being the only path to increased sensitivity. Quantum squeezing allows the intensity noise associated with the probe light to be robustly reduced below the SNL. The integration of squeezed light into SEM will enhance the resolution of the technique beyond the SQL.

Year 1 has focused on the development of a highly squeezed pulsed light source suitable for pump-probe microscopy. The demonstration of a sub-SQL measurement of a biologically relevant system will need a strongly squeezed state - a large advance on the current state-of-the-art in pulsed squeezed light.

We have engaged with Martin Booth (Professor of Engineering Science and Director of Aurox Ltd) and Ilian Davies (Professor of Biochemistry and Head of MICRON biomedical imaging facility) to provide us with connections to instrument and microscope manufacturers. The distributed MICRON imaging facility at the University of Oxford develops, uses and commercialises leading-edge optical microscope systems and methods for imaging biological materials. Partnership with the facility and its industrial partners gives us access to cutting edge systems engineering as well as microscopy techniques and samples. Our approaches complement current classical techniques and will add a new capability for researchers. The links from MICRON to the biological microscopy industry (Zeiss, Leitz, Nikon, BioRad and Olympus, among others) will be critical in helping to identify and capitalise on routes to commercialisation.

The focus of year 2 will be the demonstration of the first-generation prototype of a quantum-enhanced SEM, with an operational resolution beyond the SQL by the end of year 2. Alongside further development of a highly squeezed pulsed light source, we will also develop a highly efficient microscopy system compatible with squeezed light enhancement. The development of the microscopy demonstrator will be done in partnership with MICRON. With a view to the development of a miniaturised demonstrator, we will also investigate integrated and miniaturised sources of squeezed light.

In parallel with the development of quantum imaging demonstrators, we are also developing a complete theory of a quantum imaging based on multi-parameter estimation theory. This multi-parameter approach will enable the imaging of entire samples rather than scanning across them, as will be case for SEM. In any demonstrator that is deployed in the real world, this feature is essential to its utility. The class of probe states to be considered are restricted to Gaussian, which are already being developed in QuantIC (for the SEM). Indeed, some of the challenges encountered in the inevitable multimode structure of the squeezed light for SEM can be exploited as a feature in the approach. Our results also show that in the quantum regime, multi-parameter estimation is fundamentally better than individual estimation. The detection system will also be restricted to those employed for the SEM, eventually moving to the use of EMCCDs. This multi-parameter approach can also be applied to the chi-3 sensor, and its performance compared with the z-scan approach.
The focus of our first year within WP4 has been to establish a number of components to support the development of advanced demonstrators in the system's work packages of QuantIC. We have designed new CMOS SPAD arrays with higher fill factor that will underpin improved performances of demonstrators in WP2. Our superconducting detectors have also progressed and a stable electron beam lithography process for device fabrication has been established. Four pixel devices suitable for fibre coupling have been benchmarked at low temperatures. The micro-LED arrays have been applied to a new LED ambient lighting demonstrator that allows objects to determine their position within a room and can be coupled with fast data transmission. We also made advances in our single-pixel Ge-on-Si SPADs with a 1000 fold reduction in surface trapped charge density. InSb photo diodes and plasmonic filters for application in imaging, spectroscopy and telecommunications have been advanced, with different structures designed, fabricated and tested.

The development of a pre-commercial time-tagging system is also ongoing and discussions around the commercialisation of a product targeting the scientific community are ongoing.
Miniaturised photon counting cameras implemented in low-cost CMOS technologies have made the transition in the last decade from research prototypes to a number of important commercial products. The picosecond time-of-arrival detection of single photons in a robust solid-state camera enables applications such as positron emission tomography (PET), laser ranging (LIDAR), fluorescence lifetime imaging (FLIM) and quantum key distribution (QKD). In QuantIC we are pushing this camera technology to the limits of photon detection efficiency and temporal resolution by employing the latest stacked 3D-integrated circuit manufacturing processes in advanced nanometer CMOS nodes.

The technology breakthrough was the implementation of SPADs in CMOS in 2003. A SPAD is a reverse-biased diode junction operating above the breakdown voltage in the so-called Geiger mode. SPAD devices were originally proposed in older 0.8 µm or 0.35 µm CMOS technology nodes but have been rapidly integrated in nanometer geometries. This is motivated by the need to optimise optical sensitivity (due to low fill-factor) and benefit from high speed digital signal processing and embedded timing circuitry. Our early adoption of stacked 3D manufacturing is the culmination of that trend enabling independent optimisation of the optical detector and the digital pixel electronics.

In year one QuantIC has designed and sent for fabrication two CMOS SPAD camera chips. These new cameras build on the success of our past MegaFrame cameras which have been employed in a number of time-of-flight demonstrators resulting in two Nature publications. We have sought to make considerable advances on the performance of the MegaFrame camera (32x32 pixels, 50 µm, 50 ps, 1.5% fill-factor) based on the advanced nanometer CMOS technology made available to us through industrial partners STMicroelectronics and the ENIAC POLIS project. This has allowed aggressive scaling of the pixel pitch whilst increasing fill-factor by more than 10x in front-side and back-side illuminated versions respectively. At the same time the number of pixels was increased to 192x256 and a modest reduction of timing resolution of 35 ps was targeted. The improved performance is expected to allow outdoor and long range implementation of the “seeing round corners” and underwater time-of-flight research being undertaken in WP2.

During year one, we also initiated an industry-led partnership resource project with STMicroelectronics to evaluate the performance of a SPAD sensor for positron emission tomography. The SPADnet2 sensor was designed within a recently completed EU FP7 project with medical imaging manufacturer Mediso as a key exploitation partner. The QuantIC’s partnership project evaluated key electro-optic performance measures of the sensor, allowing the consortium to make informed exploitation decisions. The spectral response, timing impulse response, timing uniformity and linearity, power consumption, approximate yield and dark count rates were characterised. An issue was revealed in the performance of the time-resolving electronics which would require a metal mask change to correct. CEA-LETI (one of the original SPADnet partners) were able to measure energy resolution of the sensor based on the results and continue to work on the device in a gamma testing environment.

In September, Richard Walker, a researcher in Professor Henderson’s group, founded spin-off company Photon-Force to commercialise MegaFrame single photon cameras. Richard was awarded a Royal Society of Edinburgh Enterprise Fellowship and won the first prize in the Scottish Converge Challenge as well as Scottish Edge round 7 funding.

### Time gated SPAD arrays

### Superconducting detectors

One of Einstein’s seminal contributions to modern science was the insight that light, at a fundamental level, is comprised of quantised packets of energy known as photons. A century later, the ability to detect low energy infrared photons holds the key to a host of applications, spanning secure communications, atmospheric remote sensing and medical diagnostics.

QuantIC is developing some of the world’s most advanced infra-red photon counting technologies, developing superconducting nanowire single photon detectors. In year one, substantial progress has been made on superconducting nanowire device fabrication using the state of the art nanofabrication capability of the James Watt NanoFabrication Centre (JWNC) at the University of Glasgow. Growth of crystalline and amorphous superconducting thin films has been perfected using a dedicated UHV sputter deposition system. A stable electron beam lithography process for superconducting nanowire device fabrication has been established. Four pixel devices suitable for fibre coupling have been benchmarked at low temperatures using advanced nano-optical mapping techniques. We are partners in an Innovate UK Quantum Technology Feasibility Study led by the UK National Physical Laboratory, focusing on integrated superconducting readout electronics for superconducting detector arrays. In year two, we aim to increase the active area and number of detector pixels, and combine with efficient readout electronics to create a low-noise high-speed near-to mid-infrared single photon imaging camera.

In tandem, the groundwork has been laid for a significant leap forward in practical cryogenic systems for superconducting detectors. A miniaturised 4 K cryostat has been designed by partners at the UK’s STFC Rutherford Appleton Laboratory (world leaders in miniaturised cooling for space applications). A highlight of year two will be the delivery of this demonstrator system to QuantIC which is anticipated for the summer 2016.

In year one, we have also engaged with UK industry partners and stakeholders. We commissioned a market survey on infrared photon counting (by the French consultancy Yole Development, enabled by EPSRC Impact Acceleration Account Funding) which was completed in March 2015. Superconducting detector technology was showcased at the QuantIC’s launch and dsiit national meetings in Glasgow.

Industry visits have taken place with Lockheed Martin and e2v. Discussions are underway with Kelvin Nanotechnology on enabling commercial access to Glasgow-developed superconducting film and device technology and with Honeywell Hymatic on future manufacture of miniaturised cryogenic systems. We have recently partnered with Chromacity UK in setting up a compact optical parametric oscillator near- to mid-infrared laser source in the QuantIC Innovation Space. This will enable QuantIC to carry out improved detector benchmarking and mid-infrared imaging and sensing demonstrations.
Micro-LED arrays

LED devices are becoming a standard lighting technology for domestic, automotive and industrial applications with long lifetimes and high electrical-optical conversion efficiencies. These devices typically operate in the continuous illumination regime with little extra functionality. In QuantIC we are developing next-generation LED micro-displays that can transmit data, send ultra-short pulses of light into an environment and track objects in a room, or on a microscope slide. Our micro-LED displays are fabricated using Gallium Nitride with pixel sizes of a few tens to hundreds of micrometres across. This small size allows each pixel to be switched at GHz rates. Devices can be made with hundreds of individually controllable pixels, allowing for extremely fast pattern generation and data projection. The key to harnessing the high speed of these arrays is the integration of the LED chips with dedicated CMOS electronics drivers.

In the first year of the QuantIC’s programme, we have developed a new high speed positioning system based on our LED micro-displays. By illuminating a scene using a series of complex patterns (very similar to those used in single pixel cameras), a unique time series of illumination is created in each pixel of the scene. Photodetectors located in the scene can therefore locate themselves simply by detecting the light they see from the LED emitter as a function of time (J. Herrnsdorf et al. IEEE Photonics Conference, 28-29, 2015). Thus far we have demonstrated pattern rates of around 2 kframes/s limited only by the electronic interface to the chip. This rate allows real time tracking of multiple objects that can then be sent individual data streams from the same LED source. A demonstrator unit was featured as part of QuantIC’s engagement activities and showcase events.

During year two we will continue discussions with potential users to identify areas of application of the technology. We also intend to extend the functionality of this technology to incorporate imaging, data communication and location sensing in a single system.

Single pixel Ge-on-Si SPADS

Semiconductor-based photon-counting detectors have risen to prominence in the last decade as new application areas, such as quantum technology, have emerged. Silicon-based SPADs were first demonstrated in the early 1980’s, and since then they have come increasingly into widespread use for detecting ultra-low light levels with picosecond time resolution. Applications areas include LIDAR (including ground to low earth orbit satellites), fluorescence analysis, and quantum technologies, particularly in quantum communications, and quantum-enhanced imaging.

In the near-infrared, there are substantial issues with SPAD detectors, as their performance deteriorates at higher wavelengths due to the increased noise levels associated with the narrow bandgap semiconductors normally used. We are working to establish a new class of germanium-on-silicon SPADs that will operate efficiently in the near-infrared, particularly at the strategically important telecommunications wavebands at wavelengths around 1300 nm and 1550 nm, and combine the advantages of low-noise Si single-photon avalanche multiplication with the infrared sensing capability of Ge. These devices will also provide the much-needed compatibility with silicon photonics circuitry, enabling full on-chip detection in the infrared for the first time.

In a previous collaboration, Heriot-Watt and Glasgow Universities were the first to fully demonstrate single photon counting at 1300 nm using Ge-on-Si SPADs [Warburton et al. IEEE Transactions on Electron Devices, 60, 3807 (2013)]. These devices had large dark count rates due to high threading dislocation densities and no surface passivation. In the first year of QuantIC, solutions to both of these detrimental problems have been pursued and potential solutions realised in addition to demonstrating the first Ge-on-Si SPAD devices realised from commercially grown epitaxial materials from the UK company IQE.

A new Ge passivation has been developed with a 1000 fold reduction in surface trapped charge density, and limited area growth has demonstrated mesas of the required sizes for pixels without threading dislocations.

In the second year of the project we will demonstrate new Ge-on-Si SPAD devices using both these solutions to determine the improvements to performance. We have also had discussions with e2v and IQE about translating the technology into UK industry.
InSb avalanche photo diodes (APD)

High resolution cameras imaging the visible wavelength range are now widely available. Imagers in the infrared range and especially in the medium infrared range, however, are not yet as widely available. Cooled indium antimonide (InSb) photodiodes (PDs) are the detectors of choice for many applications in the mid-infrared region, such as gas cloud imaging, astronomical and environmental observations, and medical diagnostics.

At QuantIC we are developing InSb avalanche photodetectors (APDs) which will provide higher speed, lower noise and superior sensitivity. Our APDs are fabricated on a Gallium Arsenide (GaAs) platform. This allows development of a monolithically integrated imager, since the addressing circuitry can be made using the GaAs layers. The device architecture is similar to that of a standard InSb PD and it is based on a p-i-n structure. The layers’ thicknesses, however, are modified for optimised avalanche operation.

In our first year we have started our investigation by testing InSb PDs integrated with switching METal Semiconductor Field Effect Transistors (MESFETs). The multi-layer integrated structure was grown by Gas Sensing Solutions (GSS) Limited. On this material we successfully demonstrated an active InSb-based mid-infrared photopixel with addressing provided by the underlying GaAs MESFET (C. Xie et al. IEEE Electron Devices, Transactions on, 2015). For avalanche operation, several layer structures were designed and trialled. A separate absorption and multiplication (SAM) layer structure based on InSb, gallium antimonide (GaSb) and GaAs layers was trialled and proved unsuitable for mid-infrared sensing. An APD structure based on super-lattice layers was optimised, and another suitable design based on an InSb p-i-n structure was identified. Arranging growth of III-V wafers required ongoing discussions with GSS. The company also helped developing a carbon dioxide sensing demonstrator. The demonstrator was used to showcase our research at the following events: the European Researchers’ Night (Explorathon '15) at the Glasgow Riverside Transport Museum in September 2015; the Quantum Technology Showcase at the Royal Society in London in November 2015; more recently, the closing event of the International Year of Light at Herriot-Watt University in December 2015. These events gave us the opportunity to engage with a wide variety of audiences, from the general public, to industry, and primary school pupils.

The main challenge for this year is the successful demonstration of avalanche operation in the two material structures which have been identified as best candidates. Our focus will also be on seeking partnerships with industry about commercially exploiting the integration of InSb PDs and GaAs MESFETs.

Nanophotonics / plasmonics

Nanophotonics encompasses a wide field that deals with light-matter interaction on a quantum and classical level that can yield devices that can be used for applications such as imaging, spectroscopy and bio-sensing. The focus of our research is designing plasmonic filters and metasurfaces in the near-infrared and mid-infrared regimes. These would hold a key integration step in making components for filters for APDs and SPADs (See InSb Avalanche Photo Diodes above).

The plasmonic filters are nanohole arrays in gold film fabricated on a glass slide. The design is optimised to provide a narrow linewidth transmission of any wavelength that would be suitable for the desired application, for example: 1651 nm for detection of methane. A number of novel approaches have been designed and the fabrication of these devices has started.

The metasurface on the other hand provides a large pass band for desired wavelengths for mid-infrared APDs. Due to the capabilities of these metasurfaces to manipulate the phase of the incident light, it can be designed to form a lens for the wavelengths it has been designed to act as a pass band for. Further research on metasurfaces will be done to obtain orbital angular momentum, carrying beams that can provide sources to extract more information from the incident light with respect to spin and angular momentum.

The aim of the coming year will be successful integration of plasmonic filters and metasurfaces with APDs and we will pave the way to design devices for converting linear/circular polarised light to orbital angular momentum carrying light beams.

Pre-commercial multichannel time tagging system

Much of our work in quantum imaging and in quantum communications, and general quantum information experiments in general, relies on the detection/selection of coincident firing patterns of multiple detectors. The accuracy of timing these coincidences has in the past been limited to nanosecond timescales based on the clock rates of programmable logic circuits. Here we are working on a scalable time tagging concept where the programmable logic is configured to measure time of arrival to an accuracy limited only by the logic jitter in the logic platform. We have demonstrated a few channel time tag device that has timing jitter down to ~17 ps rms and are now working to turn this device into pre-commercial prototype with many channels. We are in talks with leading players towards developing a UK subsidiary around this technology.

Moving into year two, we aim to have a working prototype located in the QuantIC Innovation Space by autumn 2016. In parallel, we will continue to make significant commercialisation progress, working with a range of industrial partners.
QuantIC’s marketing and stakeholder engagement strategy is focused on raising the awareness of the Hub’s technology as well as laying the foundation for responsible research and innovation and promoting the understanding of quantum physics to a new generation of potential quantum engineers.

The Hub has had a busy first year; key highlights have included the development of QuantIC information packs, the Hub’s official launch event, organising the first “UK National Quantum Technology Showcase” at the Royal Society, hosting a quantum imaging workshop for the UK Ministry of Defence and US Department of Defense, participating in “European Researchers’ Night” and running a pilot quantum physics workshop for secondary school science teachers.

Key to successful communication and engagement are a strong brand and a strategic approach to marketing and stakeholder engagement and QuantIC set out to do this to achieve the Hub’s vision.

Key factors we reflected upon in this process included the lack of public awareness and possible misconceptions around “quantum technology”, implementation of the responsible research and innovation agenda, and generation of more industrial interest and collaboration for our technology.

As a result, the Hub outlined the following objectives for its marketing and stakeholder engagement strategy:

- Raise awareness of QuantIC and its research in the UK and internationally, as one of the Hubs in the UK National QT Programme;
- Support the development of QuantIC’s industrial partnerships;
- Demonstrate QuantIC’s value in building and shaping the UK as a leader in QT;
- Educate and increase understanding of quantum technology.

The stakeholder map that was developed recognised that there were a wide variety of audiences for QuantIC to develop targeted engagement with, from funders of research and innovation, government officials and industry bodies to the general public and science educators.

The following pages feature some of QuantIC’s marketing and stakeholder engagement key highlights this year.
QuantIC’s brand identity embodies a logo that was designed to graphically represent simultaneously the imagery of an atom, an eye, the aperture of a lens and an abstract form of the letter “Q”, all of which conveyed the Hub’s aim of translating quantum imaging science into new technological applications for industry. The use of the RGB colour model, in which the primary colours of light — red, green and blue — are used to produce a broad spectrum of colours for the sensing, representation and imaging of electronic systems, further emphasised the focus of the Hub’s technology.

Communicating new research and technology to a non-technical audience was also something that we were mindful of, especially with the diversity of stakeholders we had to engage. With this in mind, each technology was given a friendly product name like “QuantiCam” and “Wee-g” to help aid recall. Product information flyers were also developed to aid discussion with industry and to help other audiences engage and understand the Hub’s research. The flyers focussed on the technology’s benefits to potential users and suggested sectors where the Hub’s technology could have useful applications. These printed materials were complemented with eye catching banner stands, QuantIC corporate folders and branded USB memory sticks containing PDF versions of our information packs. This suite of materials was used at events and exhibitions to promote our brand and our technology offering.

QuantIC has also been active in the digital marketing environment; our website was set up in January 2015 and has been developed to inform visitors on the Hub’s research, news and events as well as innovation case studies and application forms to the PRF. Web traffic has been building and quantic.ac.uk is now one of the top listings on Google for the search term “quantic”. The Hub has also found social media to be the tool of choice in keeping academia and industry connected with news and research development. Our Twitter account, @QuantIC_QTHub, has over 200 followers and continues to grow. In addition to this, we also publish a quarterly e-newsletter, which is sent out to around 300 subscribers.
Over a hundred guests attended the official launch of QuantIC. Held at the Glasgow Science Centre, the focus of the day was on the live exhibition of our early stage technology demonstrators. A camera which uses inexpensive single pixel detectors to create video rate images in the infrared attracted considerable interest from the visitors. The camera can be used to visualise gas leaks and see through smoke in a fire and applications are being explored under a Partnership Resource Project in collaboration with M Squared Lasers Ltd. Another crowd pleaser was a new camera developed by researchers at the Universities of Heriot-Watt and Edinburgh which uses advanced photon-timing techniques to see under layers of organic tissue. Also on display was the first prototype of the gravity imager, a revolutionary sensor that promises an inexpensive route to monitoring gravity for applications such as oil and gas and environmental monitoring.

Alongside the exhibition, QuantIC’s Director Professor Steve Beaumont introduced the project aims and objectives and put forward a vision for QuantIC which is centred around user engagement and delivering real benefit to UK industry. Professor Miles Padgett, QuantIC’s Principal Investigator, gave a technical overview of the workpackages and highlighted early opportunities for industry to engage with the programme through the PRF. Guest speakers at the event included Professor Paul Hagan, from the Scottish Funding Council, who had awarded QuantIC an additional £3m for the creation of a purpose-built innovation space. The innovation space opened in October 2015 and companies can co-locate with QuantIC’s researchers to develop prototype technology. Dr Graeme Malcolm from M Square Lasers Ltd and Dr John Bagshaw from BAE System were also invited as keynote speakers to provide an industry perspective on the UK investment in Quantum Technology and shared their enthusiasm for the opportunities this would open for UK industry.
Quantum imaging has been identified as a critical disruptive technology for defence and security applications where both the US and UK academic base have world-leading and complementary capability. Both countries are making significant investment in the basic research and its translation into applications.

With support from the UK Ministry of Defence and US Department of Defence, QuantIC hosted a "by-invitation only" workshop. Held at Mar Hall, the two-day event, brought together quantum imaging leaders in both the US and UK academic communities to explore how their research could complement each other.

The format of the workshop comprised short (10min) presentations with an emphasis upon discussion (>50 percent). The departure from the traditional conference format and the residential nature of the workshop was welcomed by the participants and contributed to positive small group discussions. Feedback at the end of the workshop confirmed that the event exceeded expectations of even the most enthusiastic of participants. Immediate technical collaboration opportunities were identified around a number of research areas ranging from superconducting detectors to the combination of various camera technologies with alternative signal/data processing methodologies. The latter opportunity in particular, recognises how processing can yield hitherto-unobtainable information, even from existing sensor systems. Perhaps most importantly was the identification of how quantum imaging could contribute to addressing grand challenge areas, including through building visualisation, non-line-of-sight imaging (and sensing), hyper-spectral imaging/interrogation and non-Identification Friend or Foe (IFF) spoofing.

Mechanisms to accelerate the activity and drive forward these collaborations included small investments such as initiating a pair-wise graduate student exchange programme through to larger investments around grand challenge demonstrators.
In October, Minister for Universities and Science Jo Johnson paid a visit to the University of Glasgow and expressed an interest in learning more about QuantIC’s activities. Gathering several demonstrators into the Vice Chancellor’s Office so that the Minister could experience first-hand the various technologies, the “pop-up QuantIC lab” featured the Single Pixel Camera, “Wee-g” and “light in flight” technology demonstrators. Dr Graeme Malcolm, Chief Executive of M Squared Lasers Ltd., was also on hand to speak with the minister about industrial collaboration as the company had recently been awarded a QuantIC PRF to explore the technical feasibility of gas detection with the single pixel camera.

Professor Miles Padgett said, “The Minister really engaged with our demonstrators and spent a fair amount of time asking technical questions, which was a nice surprise. And if a re-tweet by Jo Johnson on his visit is anything to go by, I hope he was impressed that QuantIC and the other quantum technology Hubs are very much focussed on translating technology with industry into new market opportunities for the UK.”
The UK Quantum Technologies Programme celebrated its first anniversary with the inaugural UK National Quantum Technology Showcase which was held at the Royal Society in London on 11 November 2015. Organised by QuantIC in collaboration with the other Hubs in the National Programme, the purpose of the event was to introduce the work of the Quantum Technology Hub Network to industry and government.

The format of the event was structured to allow for short presentations and lively Q&As with breaks in between for attendees to network and view the live demonstrator exhibits from the Hubs. The presentations featured a diversity of speakers, from funders (EPSRC and Innovate UK) to Hub directors and industry partners, which provided a good overview of the UK National Quantum Technologies Programme from inception to its current direction of travel.

There certainly is a buzz about Quantum Technology; the showcase was a resounding success with the event being oversubscribed and exceeding the maximum capacity of the venue. More than 67 percent of attendees were from industry and government and a post event survey indicated that over 93 percent of respondents felt that attending the event had improved their understanding of the programme and the work of the Hubs. The following comment from a survey respondent summarises the positive feedback that had been received, “The structure of the timings, with short sharp talks, then time to explore the exhibits, interlaced, worked very well. There was also a good broad invitee list, with many new faces.”

There were even enquiries made to the Royal Society from the general public wanting to attend the event after QuantIC’s Professor Miles Padgett was featured on the TODAY Programme on BBC Radio 4 on the day. He said, “It’s good to know there is so much interest in quantum technology, not just from industry and government but from the public as well. We’ve spoken to many new companies today who are interested in possible collaborations and it was also good to see what the other Hubs were working on as well. I’m looking forward to the next one already!”
I now feel I have a better understanding of quantum physics and what research is being carried out at present. Also, I am aware of other experiments which can be carried out by pupils in this area. This will help me make this part of the course relevant and more enjoyable for my pupils.

“I was very pleased with the introduction to the Quantum world, taking me from an area I perceived that I was comfortable with all the way thru to aspects of probability and Heisenberg’s Uncertainty Principle. Seeing these concepts being utilised in a practical and beneficial context further enhanced the session.”

Quantum Physics Teachers’ Workshop

26 November 2015, University of Glasgow, Glasgow

Developing the next generation of quantum technologists is essential if the UK is to position itself as a world leader in the field and QuantIC has supported this by encouraging the learning of quantum physics at Scottish Highers and Advanced Highers level.

Together with the Scottish Schools Education Research Centre (SSERC), QuantIC developed a pilot quantum physics workshop for teachers, which was held on 26 November 2015 at the University of Glasgow. The workshop aimed to provide a better understanding of the subject through up to date research and real life examples of quantum technology in action provided by QuantIC’s researchers.

Professor Miles Padgett, who led the workshop, said, “It’s fantastic that quantum physics is being taught at the Highers and Advanced Highers level and we’re delighted to have the opportunity to offer support to teachers in developing their understanding of what remains a challenging topic. Scientists are increasingly looking to the quantum realm to develop new forms of technology. Clearly, offering a comprehensive grounding in quantum physics to young people in their studies will be increasingly important in keeping the UK technology sector competitive with the rest of the world”.

Feedback from the workshop has been overwhelmingly positive. Over 90 percent of the teachers who attended the workshop rated it as “very good” in meeting their professional needs in the feedback evaluation survey. Gregor Steele, Head of Section at SSERC, said, “I’m sure I speak for the whole physics teaching community in Scotland when I say we are extremely grateful for the way that world-class academics have been willing to engage with us to support the introduction of new, exciting content in schools.”

Plans are in place to maintain a relationship between the teachers who attended and the experts they met from the University. Informally known as ‘Quantum Buddies’, the system will pair teachers with an expert who will provide follow-up contact to help keep the teachers informed of new developments.

At the request of SSERC, QuantIC will be running the Quantum Physics Teachers’ Workshop again in Aberdeen in March 2016.

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Since its inception, QuantIC has considered the importance of RRI and how it should engage stakeholders.

QuantIC’s approach of developing its technology with industry through its Market Opportunities Panel and PRF aims to ensure that it is delivering innovation that is relevant to market need.

A BIS funded Sciencewise report had also indicated a lack of public awareness and understanding of quantum technology and with its marketing and stakeholder engagement strategy QuantIC’s researchers are laying the ground work for a more informed RRI discussion through science education and public engagement.

Some of the key highlights and new exciting opportunities are featured here.
Funded by the European Commission, Explorathon is an annual event which gives the public an opportunity to meet academics and engage with them on their research and find out how it benefits society in an interactive and engaging way.

QuantIC was excited to be involved this year and our researchers were at Edinburgh Zoo, Glasgow Riverside Museum and the Glasgow Science Centre. We had the opportunity to present our research to more than a thousand people over the course of the event.

Explorathon first timer Johannes Herrnsdorf from the University of Strathclyde, who presented his work on LED Illumination, said, “I got the most interest from the parents of the kids (especially from the dads) and it was good to showcase some actual research out of the lab.” Johannes’s research focuses on LED illumination capable of projecting patterns and sending information at such fast speeds they are undetectable to the human eye. These patterns can be used by sensing devices to determine their position accurately within an environment and the information can be used to undertake tasks.

Other research projects included visualising “light in flight”, seeing behind paint with a single pixel camera and the modelling of the human face in 3D. About 175 people volunteered to have their faces taken in 3D, with the images becoming useful data in computer vision, statistical and mathematical techniques required to model facial shape for medical and biological applications.

Researchers also found Explorathon a good networking opportunity to discuss ideas and collaboration. QuantIC’s Richard Middlemiss from the University of Glasgow said, “We had about 200 people visit our stand and we even spoke to researchers from the Engineering department who make drones, since we hope one day to fly our gravimeters on one of these and it was a useful conversation to have.”
2015 had been designated by the United Nations as the International Year of Light to celebrate and highlight the importance of light and optical based technologies as it marked a large number of anniversaries of significant discoveries, including Maxwell’s electromagnetic theory of light and Einstein’s theory of general relativity. Given the Hub’s research focus on quantum enhanced imaging, QuantIC was delighted to be invited to exhibit at “Illuminations”, the closing event for the International Year of Light in Scotland.

Over 900 people attended the event, of which more than half were school children, who were treated to light shows and were also able to try hands-on experiments with researchers. QuantIC’s Vincenzo Pusino, who was there exhibiting the “IndiPix” technology, which showcases mid-infrared sensing and imaging technology said, “I think my simple experiment using a straw to show carbon dioxide detections made it easy for people to understand what my research was trying to do and the school kids really enjoyed blowing bubbles to see how much CO² they had!”
Visitors would initially explore the fundamentals of light and the electromagnetic spectrum through hands-on exhibits such as the “Light Table” and “Light Island” so that they could start to appreciate the underpinning aspects of QuantIC’s technologies.

At the next level, the displays will “deconstruct” some of the Hub’s technologies – single pixel camera, mid-infrared sensing and imaging and “light in flight” to allow visitors to understand how they work and to appreciate both the complexity and simplicity of the ideas and delivery, and then to explore their potential uses.

Lastly, there will be an interactive “Object Theatre”, which will allow visitors to hear directly from QuantIC’s researchers on the direction of travel for quantum technology. Visitors will be encouraged to feedback their thoughts and engage with QuantIC on how these technologies can have an impact.

QuantIC’s Exhibition at the Glasgow Science Centre

QuantIC has been working with the Glasgow Science Centre on a new permanent exhibition that will take the public on a journey in understanding and appreciating quantum technology. Provisionally titled “Making the Invisible Visible”, the hands-on interactive exhibition will:

• Raise awareness of the physics and engineering behind quantum technologies giving insight into fundamental physics and challenges;
• Showcase and highlight the career opportunities these technologies will bring;
• Create a space for dialogue to support Responsible Research and Innovation and the impact these technologies will have on the way society works, communicate and lives.

Developing a scientific display can be challenging, especially when having to distil very technical and academic information that needs to be understood by the general public, and the team at Glasgow Science Centre and QuantIC’s researchers worked together to present the information in a way that could be appreciated at different levels.

Located on the 2nd floor of the Glasgow Science Centre, “Making the Invisible Visible” will be situated next to “My World of Work Live!” which encourages school students to explore career opportunities in STEM subjects and will provide lots of opportunities for QuantIC’s researchers to deliver “Meet the expert” activities and further showcase the career opportunities in quantum technology.

The Glasgow Science Centre is one of Scotland’s must-see visitor attractions and has a reputation for presenting concepts of science and technology in unique and interesting ways that will inspire, challenge and engage to increase awareness of science for all and to enhance the quality of science and technology learning. It attracts more than half a million visitors annually from across Scotland and QuantIC is excited to be working with them on this exhibit which will launch in Spring 2016.
Our MOP meets quarterly and has representatives from across industry and from key stakeholders. Their active support and commitment to QuantIC has been invaluable. Individual members have facilitated introductions and supported collaborative ventures such as working closely with Innovate UK. They also advise on management and exploitation of intellectual property and on internationalisation.

The MOP membership includes:
- Alastair Wilson, Chair of the MOP
- William Alexander, Thales
- John Bagshaw, independent consultant
- Simon Bennett, Innovate UK
- Colin Coats / Colin Duncan, ANDOR, an Oxford Instruments Company
- Trevor Cross, e2v
- Tony Espie, BP Group Technology
- Robin Hart, NPL
- Robert Lamb, Finmeccanica-Selex ES
- Anke Lohmann, KTN
- Graeme Malcolm, M Squared Lasers Ltd
- Andrew Middleton, dstl
- Bruce Rae, STMicroelectronics
- Andy Smout, Toshiba Medical Visualisation Systems
- Aidong Xu, IP group
- Nick Weston, Renishaw

QuantIC Strategic Advisory Board (SAB)

The QuantIC SAB advises the Management Board on the overall strategic framework of the Hub, including research and commercial exploitation.

Members of the QuantIC SAB are listed below:
- Elisabeth Giacobino, Chair
- John Bagshaw
- Jonathan Flint
- Dan Gauthier
- Amanda Howes
- Peter Knight
- Peter Saraga

The SAB met for the first time in November 2015 and its second meeting is scheduled to take place in April 2016.

QuantIC organises quarterly scientific meetings where the Hub’s research community is brought together. Research Associates directly funded from QuantIC as well as students and researchers with aligned interests that are funded by other sources gather for networking and scientific discussions.

External speakers are also invited to the meetings to offer an overview of related technologies and developments that are of interest to the programme.

QuantIC’s “Year One Stocktake”

All co-investigators provide quarterly progress reports, which are compiled by work-package and tabled at the Management Board meeting for discussion. In addition, after the conclusion of year one, all QuantIC’s co-investigators gathered to take stock of the technological and commercial progress of the Hub during year one. An important focus of the discussions was the pipeline of industrial engagement for each of our technology demonstrators. The aim was to ensure that technical progress in each of the work packages was not only on track but was targeted to address real industrial needs.

The results of our stocktake have been reported to the Management Board and will be discussed at the next MOP and SAB meetings.
QuantIC's central team is responsible for the overall management and co-ordination of the Hub, working closely with our scientists, industry partners and stakeholders to ensure the smooth delivery of the Hub’s vision.
"Simultaneous real-time visible and infrared video with single-pixel detectors"

"Generalized photon sieves: fine control of complex fields with simple pinhole arrays"

"Photon-sparse microscopy: visible light imaging using infrared illumination"

"Two-photon interference at telecom wavelengths for time-bin entangled single photons from quantum-dot spin qubits"

"Amorphous molybdenum silicon superconducting thin films"

"Infrared single-pixel imaging utilising microscanning"

"Underwater depth imaging using time-correlated single-photon counting"

"Development of a 3D printer using scanning projection stereolithography"

"Divergence of an orbital-angular-momentum-carrying beam upon propagation"

"A fast 3D reconstruction system with a low-cost camera accessory"

"Optical Metrology with Lights Orbital Angular Momentum"

"Near video-rate linear Stokes imaging with single-pixel detectors"

"Imaging with a small number of photons"

"Single-pixel infrared and visible microscope"

"Spatially structured photons that travel in free space slower than the speed of light"
"Development of InSb dry etch for mid-IR applications"

"Picosecond laser ranging at wavelengths up to 2.4 µm using an InAs avalanche photodiode"

Conferences and Events

4 December 2014: A Casaburi, R. H. Hadfield "Superconducting nanowire for infrared detection and imaging" nanoFIS 2014 Graz, Austria (Oral).


12 – 23 January 2015: D. Faccio – Invited talk at The "International School and Workshop on Strongly Correlated fluids of light and Matter" – Villazzano (Trento, Italy). Presented results on "light in flight".


2 February 2015: S. Barnett – Lecture at University of Bristol to meeting of Southwest UK Quantum technologies Group "Quantum retrodiction: from Philosophical puzzle to applications".


15 – 17 February 2015: M. J. Padgett, Tel Aviv Centre for Nanoscience and Nanotechnology Workshop, Israel.

ORGANISED: 12 March 2015, dstl Defence & Security Quantum Technology Community Meeting, Glasgow, UK.


13 April 2015: G. Intermite, G. Buller, SPIE Optics + Optoelectronics, Prague, Czech Republic. This paper was presented by PhD student, Giuseppe Intermite, who won Best Student Paper award. (CONF. 9504, PHOTON COUNTING APPLICATIONS 9504-18; Enhancing the fill-factor of CMOS SPAD arrays using micro-lens integration).

15 – 17 April 2015: J. Matthews, Presented quantum-enhanced imaging and sensing at BQIT, Bristol, UK.
4 – 7 August 2015: M. J. Padgett, International Conference on Optical Angular Momentum, New York, USA.


22 April 2015: D. Faccio, Invited talk at SPIE Defense Security & Sensing, Baltimore, USA.


22 May 2015: M. Edgar, Invited Speaker, Physics and Astronomy Colloquium, Southampton, UK.

1 June 2015: M. J. Padgett, The Rochester Lecture, Durham, UK.

5 – 10 June 2016: M. J. Padgett, Plenary speaker, Conference of Lasers and Electro-optics (CLEO), San Jose, USA.


7 – 11 June 2015: G. Buller, Invited talk at OSA Imaging and Applied Optics, Arlington, USA.


6 – 10 July 2015: M. J. Padgett, Central European Conference in Quantum Optics Warsaw, Poland.


16 – 20 July 2015: G. Intermite, J. Matthews, Presentation on Quantum Imaging and Applications at Conference of Lasers and Electro-optics (CLEO), San Jose, USA.


31 October - 7 November, 2015: R. Henderson, Nuclear Science Symposium (NSS-MIC), San Diego, California, USA.


18 – 19 November 2015: D. Faccio, Invited presentation at "Active Imaging Workshop", St. Louis, France.
Public Engagement

Matthias Sonnleitner — A public talk on ghost imaging in the 7 minutes of science session at the University of Glasgow on 2 December 2014.

Daniele Faccio — Article in New Scientist. 31 January 2015, “First film of laser’s path in mid flight”.

Steve Barnett — Lecture to the Newton Mearns branch of the University of the 3rd of February 2015: “Security, insecurity, paranoia and quantum mechanics”.

Jonathan Leach — QuantIC’s work was showcased at the launch event for the International Year of Light, which was held at the Royal Society of Edinburgh. This was a one-day event which was open to the general public on the 23 February 2015.

Genevieve Gariepy — (PhD) student with Daniele Faccio: interviewed by Quentin Cooper for BBC4 Material World Radio programme broadcast on 24 March 2015.

Daniele Faccio — Physics world article, “More than meets the eye”, March 2015.

Matt Edgar — Exhibit in the Hunterian Museum – April – September 2015 “Single Pixel Cameras”.


Jonathan Leach — Participated in a high school event at the Scottish Museum. We worked with around 100 school children, showing them the light-in-flight camera.

Daniele Faccio — TEDxHeriotWattUniversity talk, September 2015.

Antonio Samarelli and Richard Middlemiss — Exhibiting the MEMS gravimeter at Kelvingrove Art Gallery, 15 September 2015.

Bristol PhD student Rebecca Whittaker organised with Bristol Optical Student Society (OSA student chapter) an “Afternoon of Optics” (cross disciplinary event, primarily aimed at local PhD students). September 2015.

25 September 2015 – Exploration ‘15 – the Hub exhibited:
• Exhibit of single pixel camera demonstrator by M. Edgar and M. J. Padgett.
• Exhibit of micro-LED array position sensing demonstrator by J. Herrnsdorf and I. M. Watson.
• Exhibit of “Wee-g” MEMS gravimeter demonstrator by R. Middlemiss and G. D. Hammond.
• MiR and THz sensing demonstrator exhibited at the Riverside Museum by V. Fusino and C. Xie.

Bristol PhD student Rebecca Whittaker with the Bristol Optical Student Society took part in Bristol Bright Night at @Bristol with a stand on “Communicating with Light”, speaking to school children and adults. Rebecca was interviewed at the event, with the interview and footage of the stand appearing on Made in Bristol TV channel.

ORGANISED: Gerald Buller led the team that organised the “Illuminations” event on 2 December 2015 to mark the end of the International Year of Light in Scotland. The event involved public lectures for school students and the general public by the broadcaster Professor Jim Al-Khalili. Science and technology demonstrations were made by numerous universities and companies and competition for science outreach and microscope-based photography were part for the event. In total, there were over 1000 attendees. Examples of exhibits from the Hub:
• Vincenzo Pusino exhibited on MiR sensing. M. Edgar exhibited single pixel camera and
• J. Herrnsdorf, M. J. Strain, E. Gu, I. M. Watson and M. D. Dawson, “micro-LED technologies”. ORGANISED: 26 October 15 – Visit of the Minister of State for Universities and Science Jo Johnson to QuantIC.

ORGANISED: M. Dawson organised the Institute of Photonics 20th Anniversary event on 4 November 2015 (TIC/Strathclyde): plenary speakers, 250 attendees and technical stands/exhibits including QuantIC. Keynote from Dame Ann Dowling.

ORGANISED: 26 November 15 – P. Chua - Quantum Physics Teachers’ Workshop with Scottish Schools Education Research Centre (SSERC).

Daniele Faccio — Published video on “imaging hidden objects” 7 December 2015.

Connected Nation: Thriving in a Digital World (EPSRC), British Library, 8th December 2015.

Esteem Indicators

Professor Douglas Paul was awarded the Institute of Physics President’s Medal.

Professor Miles Padgett was awarded the 2015 Prize for Research into the Science of Light (European Physical Society).

PhD student Giuseppe Intermite, was awarded Best Student Paper Award at SPIE Optics in Prague, April 2015.

Professor John Rarity — Elected Fellow of the Royal Society, 1 May 2015.

Professor Miles Padgett — Plenary speaker, Conference of Lasers and Electro-optics (CLEO), San Jose, USA, May 2015.

Professor Daniele Faccio was awarded the 2015 Leverhulme Prize in Physics.

Professor Robert Hadfield was elected Fellow of the Institution Engineering and Technology 2015.

Professor Robert Hadfield was awarded European Research Consolidator Grant 2015.

Professor Stephen Barnett was awarded the Medal of the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague.

Dr Stephen Hild was awarded the 2015 the Royal Society of Edinburgh/Sir Thomas Makdougall Brisbane Medal.

Dr Animesh Datta was recognised for outstanding contribution towards New Journal of Physics peer review process during 2014 and awarded a Certificate of Recognition. The Editorial Board acknowledged him among the top 5 percent of referees and awarded this certificate to mark his dedication and professional excellence within the journal.

Dr Animesh Datta was awarded the 2015 Prize for Research into the Science of Light (European Physical Society).
Funding

Research Funding


“Photonic Quantum-Enhanced Sensors”, (£1.184m), Jonathan C. F. Matthews, EPSRC Early Career Fellowship. Start date: April 2015. Partners: AstraZeneca, Australian National University (ANU), Defence Science & Tech Lab (dstl), University of Heriot-Watt, Imperial College London, National Physical Laboratory, Sandia National Laboratory, University of Adelaide, University of Glasgow, University of New South Wales, University of Queensland, University of Tokyo. Grant number: EP/M024385/1.


“IRIS Infrared Imaging and Sensing: the single photon frontiers”, (£1.792m), Robert Hadfield. ERC Consolidator Grant. Project ref: 648604.


Knowledge Exchange And Innovation Funding


Direct Company Funding / Consultancy / Contract Research
Miles J. Padgett. Consultancy Contract with BAE Systems = £20k.

“Optical Quantum Detection Techniques for Rapid Assessment of Depth Images”, (£160k), Gerald Buller - dstl National PhD scheme.
Media Coverage

Slow light paper from Miles Padgett group attracted considerable PR coverage. Some examples below.
http://www.bbc.co.uk/news/uk-scotland-glasgow-west-30944584

QuantIC’s Launch received substantial coverage

Key role for universities in science hubs, bbc.co.uk, 28 Nov 2014, http://www.bbc.co.uk/news/uk-scotland-30211003
http://www.scotsman.com/business/companies/tech/27m-quantum-research-centre-to-open-in-glasgow-1-3699200
http://www.bbc.co.uk/news/uk-scotland-30211003
Miles Padgett, Giles Hammond and Richard Middlemiss were interviewed by Ken MacDonald for BBC Reporting Scotland lunch and evening bulletin.

24th Feb 2015. This coincided with the launch of the QuantIC Hub.
Richard Middlemiss was interviewed by STV Glasgow Riverside Show, 25 February 2015.
Laser camera sees round blind corners, Press Coverage
Times, 7 December, p. 24, Independent, 7 December, p. 12; Scotsman, 7 December, p. 13; Press and Journal, 7 December, p. 16; The National, 7 December, p. 14; Coventry Telegraph, 7 December, p. 5; Western Morning News, 7 December, p. 16; Metro, 7 December, p. 23; Daily Record, 7 December, p. 18; Courier and Advertiser, 7 December, p. 13; Irish Examiner, 7 December
TV coverage:
• STV News at Six (Edinburgh), December 7 2015
• Daily Planet (Discovery Channel Canada), 8 December 2015

We also had a number of other features covering research publications and awards:
Matt Edgar: Publication in Physics World as a feature article: “More than meets the eye”; http://live.iop-pp01.agh.sleek.net/2015/02/25/more-than-meets-the-eye/
Miles Padgett provided a news feature in Nature titled “Shaping Light”: http://www.nature.com/news/optics-leading-lights-116900
Scientists slow the speed of light, bbc.co.uk, 23 January 2015; http://www.bbc.co.uk/news/uk-scotland-glasgow-west-30944584


Other coverage:
Genevieve Gariepy - (PhD) student with Daniele Faccio: interviewed by Quentin Cooper for BBC4 Material World Radio programme broadcast on 24th of March 2015.
Bristol PhD student Rebecca Whittaker with the Bristol Optical Student Society took part in Bristol Bright Night at @Bristol and was interviewed at the event, with the interview and footage of the stand appearing on Made in Bristol TV channel.
11th of November 2015, Today Programme, BBC Radio 4, 8.55 am, interview Miles Padgett.
Non-academic project partners
In addition we would like to thank all of the partners that believed in our vision and supported our application:

- CENSIS - Innovation Centre for Sensor and Imaging Systems
- Defence Science and Technology Laboratory (dstl)
- Government Office for Science
- KTN
- Scottish Enterprise
- Scottish Funding Council
- Andor Technology Ltd
- AstraZeneca plc
- AWE
- BP British Petroleum
- Bridgeporth
- Cascade Technologies Ltd
- Chromacity Ltd.
- Coherent Scotland Ltd
- Compound Semiconductor Tech Gl
- e2v technologies plc
- Fraunhofer UK
- GE Healthcare
- Helia Photonics
- Honeywell Hymatic
- Horiba Jobin Yvon IBH Ltd
- ID Quantique
- Kelvin Nanotechnology Ltd
- Lein Applied Diagnostics Ltd
- M Squared Lasers Ltd
- Malvern Instruments Ltd
- Micro-g LaCoste
- mLED Ltd
- OPTOS plc
- Quantum Imaging ltd
- Renishaw Plc
- Finmeccanica-Selex ES Ltd
- STMicroelectronics Limited
- Thales Optronics Ltd
- Toshiba Medical Visualisation Systems
- Tullow Oil
- UK Astronomy Technology Centre

QuantIC’s boards
The QuantIC’s team would like to sincerely thank all of the members of the Market Opportunities Panel and the Strategic Advisory Board for their time and commitment.

You are all very busy individuals and we really appreciate the time you are committing to help us achieve our objectives. We have found your insight invaluable and we truly believe your experience and guidance is key to making sure the QuantIC investment delivers value to the UK.

Academic Partners: QuantIC is a collaboration between the Universities of Glasgow, Bristol, Edinburgh, Heriot-Watt, Oxford, Strathclyde and Warwick.

Funding: QuantIC is the UK Quantum Technology Hub in Quantum Enhanced Imaging. The project is supported by the EPSRC UK Quantum Technologies Programme under grant EP/M01326X/1 Additional funding was also provided by the Scottish Funding Council under grant H14051.