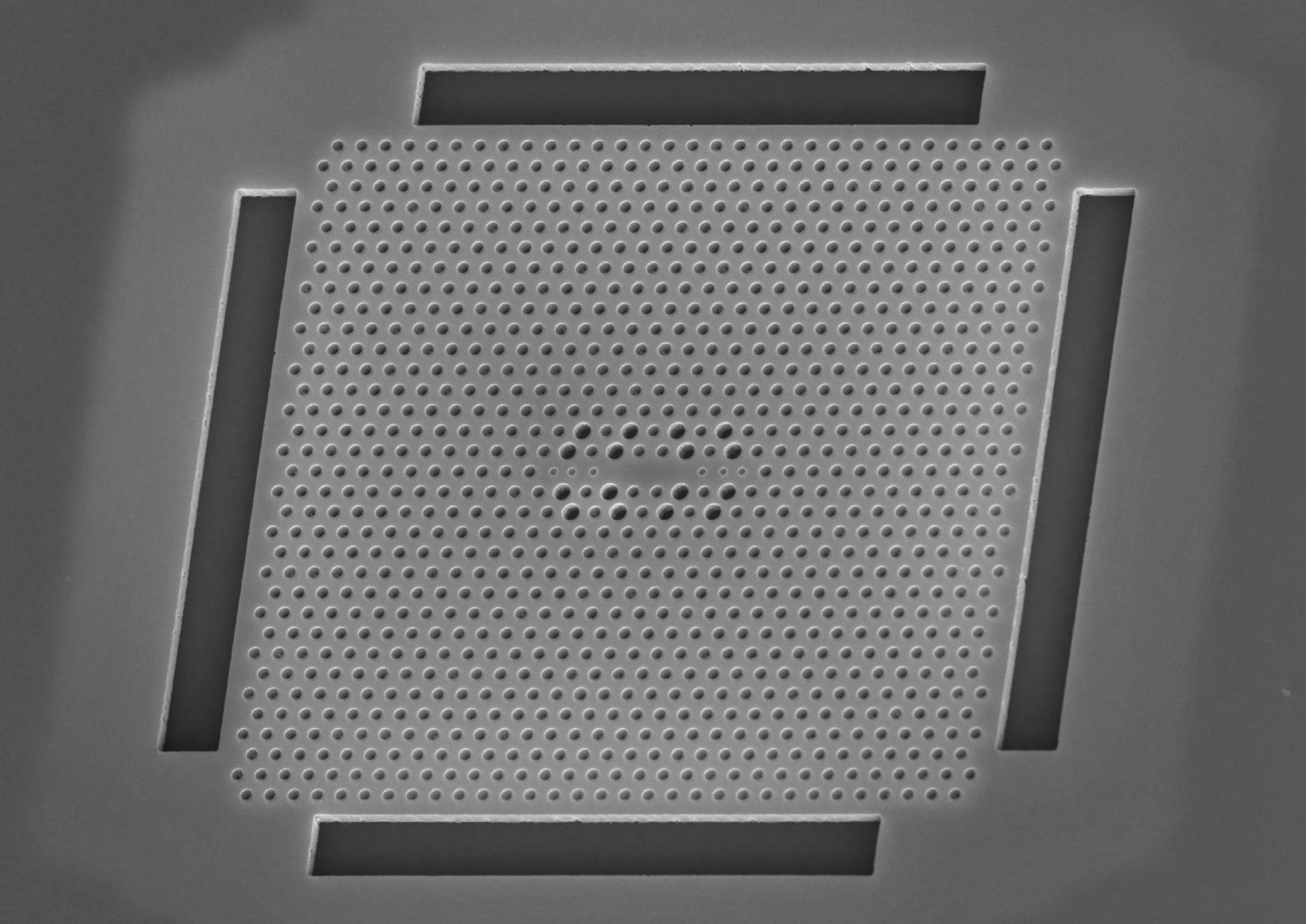
Engineering and Physical Sciences Research Council

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

10 YEARS

OF THE QUANTUM COMMUNICATIONS HUB

2014 - 2024



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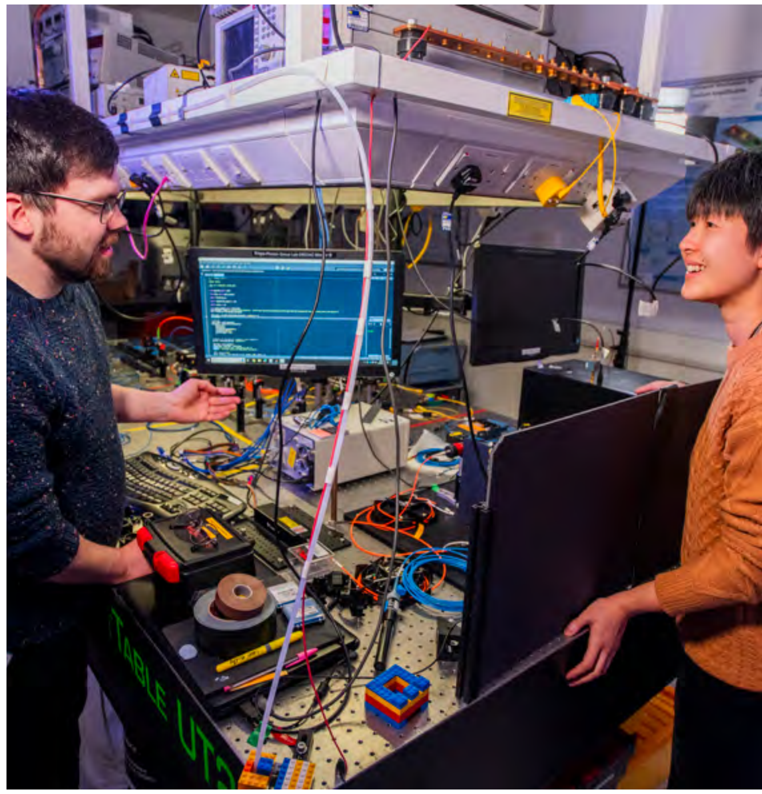
Executive Summary



The last decade (2014-2024) has been defined by new research paradigms in the UK across the field of quantum technologies, with the focus placed on addressing engineering challenges, in order to facilitate translation of leading quantum expertise into services and technology applications with commercialisation potential across sectors. The strategic framework for this effort has been set by the National Quantum Technologies Programme, a transformative initiative bringing together the country's academia, industry and government stakeholders in a collaborative effort to create a new quantum economy. Within this space, the Quantum Communications Hub, funded by the national programme through the Engineering and Physical Sciences Research Council and led by the University of York, has brought together a further 11 Universities, the National Physical Laboratory, RAL Space, plus more than 30 industry partners. Delivery of the Hub vision – integrated quantum secure communications at all distance scales – has been primarily through applications reliant on quantum key distribution (QKD), a mature quantum technology enabling ultra-secure distribution of encryption keys.

Much has been achieved in these ten years. Hub researchers have established the UK's first quantum networks over optical fibre – the UKQN and industry-focused UKQN*tel* – as flagship R&D testbeds; they have successfully demonstrated new hybrid networking architectures facilitating future seamless integration and device interoperability of the emerging technologies with existing classical communications and IT infrastructure on a national scale; and they have made huge progress towards performance optimisation and resilience, the establishment of a QKD systems CE certification process, the development of hybrid systems using quantum and post-quantum encryption to secure networks, and, importantly, next-generation quantum communications approaches, notably through the use of entanglement distribution.

Beyond fibre and over free space, the Hub has been responsible for proposing new strategic capability for the UK in the area of space quantum communications, bringing together leading expertise from the separate fields of space engineering, telecoms and quantum technologies; while also developing a fully-assembled miniaturised, reliable, low-cost, prototype handheld QKD system with tracking software, ripe for commercialisation. Hub researchers have revolutionised chip-based QKD technologies and advanced novel sources, detectors and prototype device components, through new approaches (quantum dots) and platforms (silicon), paving the way for scalable, cost-effective, energy-efficient, high-performance quantum secure technologies with high integration potential, enabling widespread, mass-market deployment and application.

Huge progress has been made with quantum random number generators and their certification, with device-independent randomness expansion more generally, and with next-generation security protocols beyond encryption: quantum digital signatures, oblivious transfer, secure tokens, quantum position verification, quantum alarm. Significant effort was invested in advancing security theory, hardware physical security of hybrid (quantum/classical) systems, the development of countermeasures against vulnerabilities, and the integration of post-quantum cryptography with the Hub's QKD technologies. Hub teams and partners led by NPL have driven the development of industry standards for the sector, and have worked on promoting the National Cyber Security Centre assurance principles for the emerging quantum security technologies.

Alongside the technical achievements, the Hub has been instrumental in delivering skills and training to the next generation of quantum technologists, including in schools through the Quantum STEM Ambassadors programme; engaging with international partners to promote key messages of the national programme; contributing to policy development; working closely with industry on the evolving needs and challenges faced by the community; participating in expansive outreach programmes to inform audiences about the potential of quantum technologies.

Director's Foreword

I have led the Quantum Communications Hub since its inception in 2014. The four Quantum Technology Hubs established at that time were a new approach for EPSRC – large collaborations of academic research groups, expertise from national laboratories and institutions, and a wide range of industry partners – distributed across the UK. We were tasked with turning our quantum science into quantum technology prototypes, moving these up in technology readiness level and undertaking "tech transfer", putting our work onto commercialisation pathways – in our Hub for the wider quantum communications sector.

I think we have delivered very strongly against this vision, from chip-based and short-range QKD systems, through national fibre-based quantum networking, to our QKD space demonstration to be launched in 2025. We have supported and founded start-up and spin-out companies. We have transferred work into numerous industry-led projects, contributing to the future quantum economy in the UK. We have provided skills and training to many students and early-career staff, whilst also contributing outreach, public engagement and the education of future scientists and technologists. The successes of the Hub-model are further evidenced by the establishment of new Hubs, that will continue the progress into the next phase of the UK National Quantum Technologies Programme.

Our Hub has been built on a brilliant team effort: senior academics, early career researchers and PhD students; scientists and technologists in national laboratories, institutions and industry; professional staff who have made everything work; international and other experts who have provided advice and guidance. Everyone has contributed to making our Hub greater than the sum of its parts. It has been my pleasure and privilege to lead this team – my thanks to you all.

Professor Tim Spiller
Director, Quantum Communications Hub
University of York

QUANTUM COMMUNICATIONS HUB | 10-YEAR REPORT

10 Years in numbers

£53,478,357
awarded to the Hub in phases 1&2

Over £6.7M
committed in in-kind academic contributions

Over £10M
committed in in-kind industry contributions

12
Universities involved in the core work

44
Non-academic partners

47
EPSRC DTP studentships allocated equalling more than £3.62M invested

39
Studentships funded by academic partners, equalling more than £2.96M invested

£5.97M
invested in PRF projects

Over £41M
value of ISCF projects incorporating Hub academic partner expertise

Over 770
published peer reviewed publications and more than 120 others still in peer review

7
International conferences/ workshops organised

12%
Percentage of former Hub researchers now working in quantum industry

16%
Percentage of former Hub researchers now in tenured academic positions

Milestone timeline

2014
- Launch of the £24M Phase I QCommHub

2015
- Secured £2M infrastructure grant to extend UK Quantum Network, linking Cambridge to BT's Adastral Park ICT industry cluster
- The start-up KETS Quantum Security Ltd is founded with support from the Hub
- First state comparison amplifier (SCAMP) experiment (high gains/fidelity) is published
- First Quantum Digital Signatures (QDS) kilometre-range system is fully demonstrated in the lab
- First national quantum technologies showcase in London, organised by the Network of Quantum Technology Hubs
- First UK-Japan Quantum Workshop
- Hub investigator Professor John Rarity is elected a Fellow of the Royal Society

2016
- Publication of the ETSI Group Specification papers on optical component characterisation and implementation security for QKD systems, with Hub input
- Organisation of the second national showcase, led by the Hub
- Publication of the Blackett Report into Quantum Technologies with substantial input by Hub investigators
- Work begins on the Cambridge to Adastral Park quantum network link (UKQNtel)
- Second UK-Japan Quantum Workshop
- First experimental transmission of QDS over 90-km of installed optical fibre and commercial prototype system
- First experimental demonstration of a secure optical network architecture combining Network Function Virtualisation orchestration and Software-Defined Networking control with QKD technology
- Hub organised international workshop in Satellite QKD Technologies
- Hub organised training workshops in modern (classical) cryptography

2017
- World-first chip-based QKD system
- Successful operational implementation of the Cambridge metropolitan quantum network
- Hub hosts the 7th international conference on quantum cryptography (QCrypt) at Cambridge
- Hub hosts the 5th international IQC/ETSI Quantum Safe workshop in London
- Hub participates in EPSRC commissioned public dialogue in quantum technologies with series of activities

2018
- Development of a high-gain/high-fidelity quantum amplifier on chip
- Organisation of two senior stakeholder meetings to discuss development of satellite quantum communications capability
- Participation in expert quantum mission to Canada
- Launch of Quantum City public engagement initiative with the other Hubs

2019
- Confirmation – following a peer review process – of a further 5 years of funding (£23.5M) for the Hub programme of work which now includes a quantum space mission
- Launch of the Bristol metropolitan quantum network over the city's 5G test network infrastructure
- Launch of the UKQNtel quantum network link between Cambridge and BT's Adastral Park over commercial grade fibre
- Participation in expert quantum mission to the US

2020
- Hub publishes quantum community response to the NCSC QKD White Paper, published earlier that year
- First ever demonstration of a trusted node–free eight-user metropolitan quantum network using entanglement distribution by Hub researchers
- Hub organises the first (virtual) QNetworks international workshop in quantum communications

2021
- First demonstration of enhanced security for random number generators
- First ever experimental demonstration of quantum conference key agreement using multipartite entanglement
- Hub investigators from the University of Strathclyde launch SatQuMA – Satellite Quantum Modelling & Analysis Software as an open source tool for the community
- Hub organises joint workshop with NCSC on quantum communications and cyber security

2022
- First experimental implementation of practical quantum tokens with standard QKD technology
- Hub organises second QNetworks workshop
- Hub selects Scotland as the location for installation of its Optical Ground Station
- Hub publishes first series of Careers in Quantum fact sheets
- ISISpace is announced as the chosen provider of satellite systems and services for the Hub's quantum space mission

2023
- First demonstration of a heterogeneous metropolitan quantum network supporting multi-user dynamic entanglement distribution, prepare-and-measure QKD and co-existence with classical channels
- Hub organises third QNetworks international workshop
- New £2.5B national quantum strategy gets published confirming funding for national rollout of Hub established Quantum Ambassadors scheme on a pilot basis
- First ever demonstration of a quantum communications link between the UK and Ireland using undersea fibre
- Breakthrough encryption performance over conventional optical fibre using quantum dots as single photon sources
- Participation in second expert mission to the US
- Hubs Network organises first international summer school in quantum technologies for UK and Canada students

2024
- Demonstration of the fully operational UK Quantum Network interconnecting two metropolitan quantum networks between Cambridge and Bristol
- Participation in third (virtual) workshop with Japan
- Hub publishes papers on NCSC's assurance principles for the quantum sector
- Hub publishes second series of Careers in Quantum fact sheets
- A new Quantum City public engagement website is launched jointly with the other Hubs

2025
- Launch of the Hub's SPOQC quantum space mission

QUANTUM COMMUNICATIONS HUB | 10-YEAR REPORT

Introduction: the UK National Quantum Technologies Programme

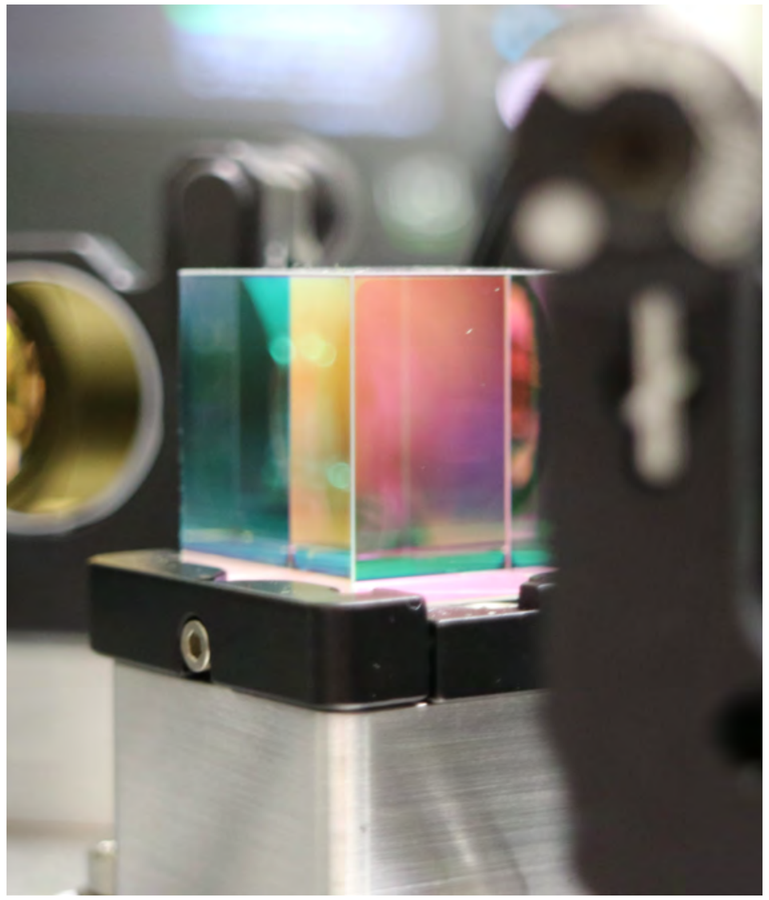
The UK National Quantum Technologies Programme (NQTP) is a transformative initiative aimed at translating the country's leading quantum research expertise into services and technology applications with wide commercialisation potential across numerous sectors and for economic benefit. Inspired by the maturity of technological advances and enabled through strong interest from industry, the programme has brought together academia, industry and government into a unique collaborative partnership best placed to take full advantage of the far-reaching potential of these emerging technologies.

Originally announced in 2013 by the then coalition government, the programme was launched as an initial investment of £270M over five years (2014-2019). It comprised a wide-ranging portfolio of schemes including investment into existing Centres for Doctoral Training in quantum science and technologies, research fellowships, a Quantum Metrology Institute hosted at the National Physical Laboratory, capital equipment allocations for existing projects, and training and skills projects to train the next generation of quantum practitioners.

By far the most substantial investment (of £120M) and the centrepiece of the programme has been the creation of a national network of four Quantum Technology Hubs. Led by a single university, each Hub has been a collaboration of academic research and industry, directed at translating science into technology across four main areas: quantum enabled sensors and metrology (Birmingham); quantum enhanced imaging (Glasgow); quantum computing (Oxford); and quantum secure communications (York)[1].

By the end of phase 1, the national programme had attracted further government investment (by now totalling £385M) and, significantly, substantial levels of industry funding, largely enabled through projects funded under the Commercialising Quantum Technologies Challenge, part of the Industrial Strategy Challenge Fund (ISCF). Overall, financial commitment exceeded £1B[2], and a new strategic intent document[3] was under preparation, refining the vision of the original 10-year strategy (2014-24) to make the UK a quantum-enabled economy through renewed focus across four main areas: stimulating growth; maintaining leadership in research and technology; investing in national assets while growing international partnerships; and growing, attracting and retaining talent. Importantly, the programme had turned into the blueprint for what a coordinated, collaborative, strategic national investment into emerging technologies should look like, in turn inspiring the creation of the EU (Quantum) Flagship Programme and influencing future iterations of national quantum strategies in countries such as Canada and – at a later stage – Singapore.

In early 2019, funding for the network of Hubs was renewed for a further five years (phase 2: 2019-24)[4] enabling the undertaking of a more ambitious programme of work and consolidating a critical mass of expertise (academic and industrial) that has in turn, and over the past decade, justified the investment into consortia of this scale, while also highlighting the added value gained through this innovative approach. Publication of a new UK government national quantum strategy[5] followed in the spring of 2023, committing a further £2.5B into advancement of quantum technologies over the next ten years while clearly laying out the country's five strategic quantum missions at the end of the same year[6]. The missions have been developed following consultations with academe and industry experts and aim to deliver enhanced computational power to support e.g. new drug and materials development, an advanced quantum network to provide the infrastructure for a future quantum internet, innovative quantum sensing devices to support medical applications such as earlier and more accurate diagnoses, more resilient quantum navigation devices including next-generation atomic clocks, and interconnected, mobile quantum sensing technologies to support critical infrastructure, including in energy and defence sectors. This investment and strategic vision has signalled the onset of a third phase of the national programme, starting with an £100M investment into a new national network of five Quantum Technology Hubs, to address the next R&D challenges required to deliver the five strategic missions[7].



Background: quantum communications technology development in the UK prior to 2014

The Hub's work over the last decade has focused primarily on technology applications reliant on quantum key distribution or QKD – a mature quantum technology with commercialisation potential, enabling ultra-secure distribution of encryption keys. In its most mature implementation (and certainly during many early demonstrations, including the first ever physical experiment[8]), QKD relies on the so-called BB84 scheme – a quantum cryptography protocol devised in 1984 by Charles Bennett and Gilles Brassard[9]. BB84 is provably secure as long as it is perfectly implemented. It describes the system conditions and quantum protocol under which two communicating parties (conventionally described as Alice and Bob) share a private key, which can then be used for secure one-time pad encryption.

The following two decades were marked by a number of breakthroughs primarily exploring the properties of entanglement as a critical component of future quantum networks, starting with the 1991 E91 Ekert protocol[10] and followed by the first entanglement distribution experimental demonstration of teleportation in 1997[11], the first entanglement-based QKD implementation in 2000[12] and first daytime operation of QKD using telecom wavelengths in the same year[13], development of a decoy state protocol to overcome photon number-splitting attacks against BB84 in 2003[14], and demonstration of entanglement-based QKD over free space (i.e. without using optical fibre) across a then record distance of 144km between the islands of Tenerife and La Palma[15]. At the same time, a number of collaborative consortia worked on implementing early quantum networks (e.g. the European project SEcure COmmunication based on Quantum Cryptography (SECOQC, 2004–2008), which brought together efforts from 41 research and industrial organisations.

It is fair to say that in the UK prior to the establishment of the national programme, most experimental quantum communications activity can be summarised in the work of two researchers, the Hub's Professor John Rarity FRS and the Hub External Advisory Board member Professor Paul Townsend. Rarity was involved in the international team that carried out the 2007 Canary Islands free-space experiments. Six years before, in the early 2000s and while working for DERA (The Ministry of Defence's Defence and Evaluation Research Agency), Rarity and colleagues achieved a then world record of 1.9km range for free-space secure key exchange using quantum cryptography[16]. This experiment was the precursor of the handheld consumer QKD work that was undertaken in this Hub's phase 1. It was followed by Rarity's collaboration with Munich's Ludwig-

Maximillian University, which successfully carried out free-space quantum communications over a distance of 23.4km (2002)[17] and joint work with researchers from Bristol HP Labs proposing a low-cost, compact free-space quantum cryptography system, with bespoke software and operating in daylight conditions, for use in short-range consumer applications (2006)[18]. Following earlier collaboration with Rarity and Tapster on underpinning photonics experiments, in the late 1990s, Townsend (then at BT) performed a number of important fibre-based QKD experiments. These included demonstration of QKD over fibre distances up to 30 km (1995)[19], operation of quantum cryptography on multiuser optical fibre networks (1997)[20], and simultaneous quantum cryptographic key distribution and conventional data transmission over installed fibre, using wavelength-division multiplexing (1997)[21].

By the early 2010s, industry was getting heavily involved in quantum communications networks research and development (R&D), both in the UK and abroad. This development is also reflected in the establishment around that time (2008) of the ETSI Industry Specification Group on QKD, *"Developing specifications that will enhance the security and interoperability of quantum communication networks being deployed around the world"* which involved UK representation from the outset. In the UK, this activity culminated in 2014, a few months before the establishment of the Hub, in a collaboration between future partners ADVA, BT, NPL and Toshiba, funded through the UK's Innovation Agency Technology Strategy Board (the precursor of Innovate UK). The team successfully operated the first QKD technology trial over a live 'lit' fibre network between BT's Adastral Park and Ipswich, a distance of 27km, using NPL-characterised Toshiba R&D equipment and standard commercial equipment provided by ADVA[22].

The network of Quantum Technology Hubs

The network of Quantum Technology (QT) Hubs was established in phase 1 of the UK National Quantum Technologies Programme (NQTP) as one of its key initiatives. Funded by EPSRC through the original £270M investment, each Hub was set up as a large consortium bringing together expertise from academia, industry, national laboratories and government agencies, and focusing on a distinct quantum applications sector. NQIT (the Networked Quantum Information Technologies Hub, led by the University of Oxford and succeeded in phase 2 by the QCS – Quantum Computing and Simulation – Hub) explored approaches underpinning the development of quantum computing. QuantIC (Quantum Enhanced Imaging Hub, led by the University of Glasgow) developed new technologies relevant to quantum imaging applications. The UK National Quantum Technology Hub in Sensors and Metrology (succeeded in phase 2 by the UK QT Hub in Sensors and Timing, led throughout by the University of Birmingham) made advances in the area of quantum sensors and timing devices. And finally, the University of York-led Quantum Communications Hub has delivered future-proof, practical, quantum secure communications with commercialisation potential, in response to very real cybersecurity challenges inherent in today's interconnected world.

The Hubs, through their academic and industrial partners, have built a critical mass of expertise, now trusted as the key stakeholder in the field, to help shape and implement policy in each QT area under their remit. Indeed, their impact has been greatly enhanced and to a large degree made possible through collaborative activities amplified through the Hubs network. The network has helped to advocate and promote the aims of the national programme, both domestically through interaction with Department for Science, Innovation and Technology (previously BEIS) and abroad through joint participation in key user engagement events. Furthermore, the Hubs have:

- contributed input towards the vision and ambition for Phase 3 of the NQTP;
- helped to shape the UK quantum landscape through coordinated support of strategic, infrastructure-scale proposals such as NIQI (National Institute of Quantum Integration);
- seeded the creation of new start-ups born out of Hubs-generated research development;
- supported and promoted key community events and investment, e.g. ISCF briefings and consortia-building workshops;
- jointly lobbied on issues affecting the NQTP (e.g. the UK's relationship to the EU Horizon scheme or the implications of the government's immigration policy on recruitment) and the wider quantum community (e.g. joint collaboration with the National Protective Security Authority – former CPNI – on promoting the Trusted Research Guidance, and working with the Regulatory Horizons Council on their QT regulation report[23]);
- worked together to promote uptake of quantum technologies applications in specific sectors (e.g. finance/banking, telecommunications);
- addressed technical and user engagement issues in a cross-disciplinary manner, to maximise benefits (e.g. at the quantum communications/quantum computing interface, or for quantum technologies in space);
- coordinated their approaches to staff retention, EDI, skills and training, public engagement (via Quantum City) and communications strategies to effect real impact;
- acted as the main focus of industry engagement within the NQTP through their own programmes of work, involvement of many academic partners in shaping and delivering ISCF projects, seeding and supporting start-ups, attracting industry buy-in through partnership resource projects, and promoting the benefits of quantum technology applications through sustained business development effort across the network.

The Hubs network investment has been a truly visionary element of the NQTP and one that has provided inspiration for national quantum technologies strategies abroad (e.g. Canada). The model will persist in the third phase of the national programme with new Hubs largely aligned with the UK Government's new quantum missions as outlined in the most recent iteration of the national quantum strategy.

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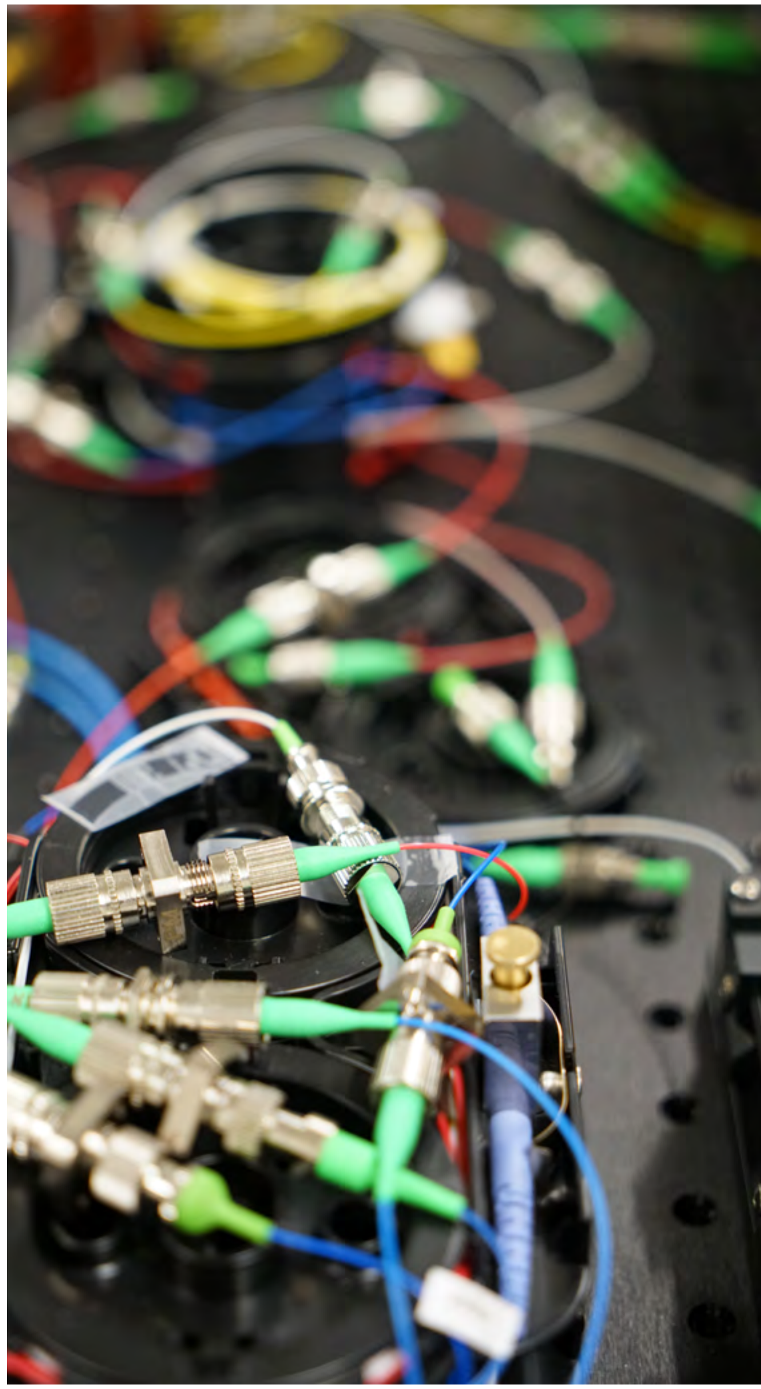
The Phase 1 Hub consortium: aims and remit

The Phase 1 Hub (2014-2019) comprised the UK's academic leaders in quantum communications, complemented by the country's foremost photonic networks and information security researchers, in partnership with several of the world's leading industrial players (ADVA, BT, ID Quantique, Toshiba, and others). From its outset, the grand vision of the Hub was to develop new quantum communications technologies that would reach new markets, enabling widespread use and adoption in many scenarios – from government and commercial transactions through to consumers and the domestic sphere. Existing products at the time consisted of primarily testbed systems for use in controlled environments. The new Hub proposed to move beyond those limitations, facilitating widespread application and use outside laboratory settings; and to deliver the underlying quantum technology for products and services that were competitive, compelling and that addressed the requirements of commercial and government end users, and consumers. The focus was primarily on technology applications reliant on Quantum Key Distribution or QKD – a mature quantum technology which enables ultra-secure distribution of encryption keys.

Delivery of this vision involved a two-component strategy: firstly, to take already proven concepts and advance these to a commercialisation-ready stage, engaging relevant external partners at the appropriate stages; secondly, to advance new directions and applications in quantum communications, through theory and experiment to technology demonstrations. Work was structured primarily along four main strands: 1) Development of short-range, free-space QKD technologies progressing to integrated, practical and affordable "Alice" and "Bob" (communicating parties) units with their supporting hardware and software, enabling many-to-one short-range communications for consumer, commercial and defence markets. 2) Advancement of chip-scale QKD technology through miniaturisation of existing prototypes and their integration as components onto communication devices to produce robust, highly portable sender, receiver and switch systems, "QKD-on-a-chip" modules. The aim here was to address cost, energy-efficiency and manufacturability issues to enable widespread, mass-market deployment and application of QKD. 3) Establishment of a national quantum communications networking infrastructure through development of a UK Quantum Network (UKQN), integrating QKD technology at access, metropolitan and inter-city scales. Such a national network could facilitate device and system trials, integration of quantum and conventional communications, and demonstrations for stakeholders, customers, the media and the wider public. 4) And finally, exploration of potential next-generation quantum communications technologies (quantum digital signatures, multiple-user scenarios, quantum relays/repeaters/amplifiers and device-independent technologies), to open up new markets for this sector, beyond key distribution.

The phase 1 consortium included all eight UK leading Universities in these research areas (Bristol, Cambridge, Heriot-Watt, Leeds, Royal Holloway, Sheffield, Strathclyde, and the lead – York) alongside global industry corporations such as Toshiba – who led the quantum networking activity, the National Physical Laboratory, international organisations such as ETSI (for standards development) and public sector bodies such as GCHQ.



The Phase 2 Hub vision

The grand vision of the Quantum Communications Hub in Phase 2 has been the delivery of integrated secure quantum communications technologies, applications and services at all distance scales: from short (metre)-range communications requiring the flexibility of free-space transmission; to access, through metropolitan, and up to inter-city scale quantum technologies based on fibre and leveraging integration with conventional communications; to even longer-distance cross-continental secure communications requiring ground-to-satellite quantum links.

To achieve delivery of this vision, the phase 2 work plan involved the further development of handheld technologies, incorporating point-and-track capabilities to automatically establish links, alongside new approaches for interfacing fibre and free-space links. It comprised further work on new networking approaches, to be tested on the Hub's national UK Quantum Network, established during the first phase of the project. And of course, it incorporated clear plans for the development and testing of advanced transmitter and receiver technologies for the delivery of space QKD solutions.

In parallel, the phase 2 Hub proposed to continue next-generation work on chip-based systems, providing economies of size, weight and power, and the route to eventual mass-manufacture capability; explore quantum communications security scenarios beyond key-sharing, thus developing new applications; contribute to the establishment of national capability in key quantum technology components – detectors and sources – which form the respective centrepieces of receivers and transmitters and which currently represent systemic security risks for the UK industry reliant on foreign imports.

The final theme of the work during the last five years was on security – of devices, systems and end-to-end. This theme cut across all other technology approaches and comprised three activities: metrology and calibration, contributing further to relevant standards; exploration of a range of cryptographic approaches underpinning the integration of quantum and post-quantum technologies; and security analysis, vulnerability analysis and testing, alongside the development of countermeasures as required – all from the perspective of providing practical and secure applications and services.

The phase 2 Hub consortium included many of the original delivery partners (Bristol, Cambridge, Heriot-Watt, NPL, Sheffield, Strathclyde – led again by York), alongside contributions from other leading institutions (Glasgow, Kent, Oxford, Queen's Belfast) and with space engineering expertise provided by STFC's RAL Space laboratory.

Key Milestones

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Key Milestones: Quantum Networking in the UK

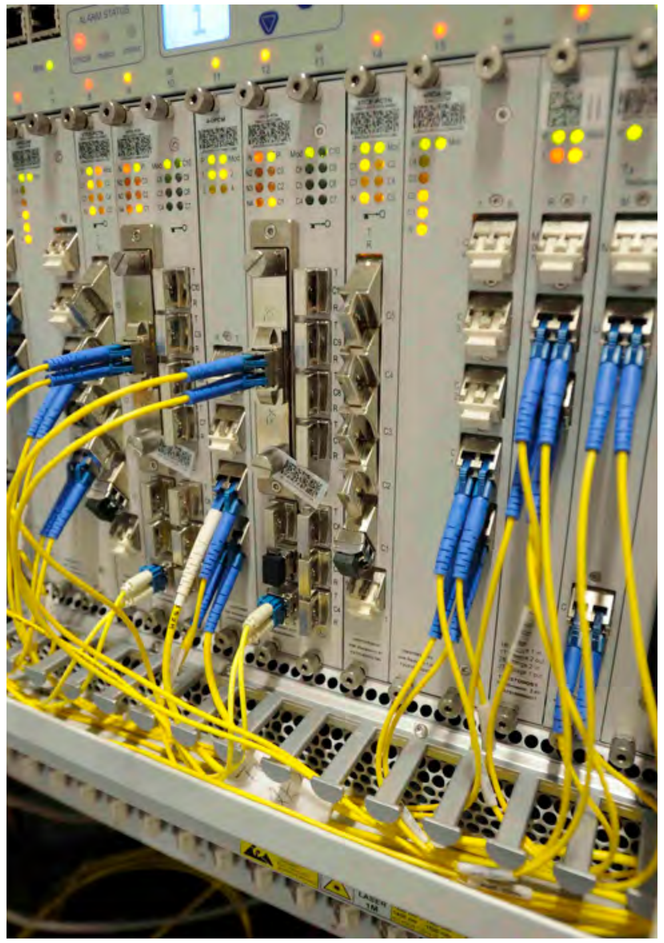
Delivery partners: Bristol, Cambridge, Leeds, York, plus ADVA, BT and Toshiba Europe

Quantum communications, as both the technology enabling future-proof security in data exchanges and as the underlying technology necessary for implementing other networked technologies such as distributed quantum computing or sensing, had been at a relatively mature stage of development by the time the Hub started its programme of work. But during their decade of operation, Hub teams working closely with industry partners have truly transformed the landscape in the UK, setting and realising the quantum networking innovation and policy agenda in this country, terrestrially – over fibre – and in space.

In establishing the UK's first Quantum Network (UKQN)[24, 25, 26] and industry focused UKQN*tel*[27] as flagship R&D testbeds, the Hub provided a national capability (comparable to similar efforts abroad), which can help inform future investment in this area. It also enables Hub investigators to usefully interact with and help shape the future development of key infrastructure projects, such as the future expansion and functionality of the UKRI funded National Dark Fibre Facility (NDFF).

The UKQN comprises two metropolitan-scale quantum networks around the cities of Cambridge and Bristol respectively, connected via four long-distance optical fibre links spanning 410km with three intermediate nodes and utilising single mode fibre over the NDFF network. All locations have low-loss optical switches allowing reconfiguration between classical and quantum signal traffic; the former is fed through the QKD system, which adds quantum and control wavelengths. The four links between trusted nodes cover fibre distances of 129, 112, 51 and 118 km; the attenuation rate on the longest of these links is 28dB, the longest and highest loss QKD field trial to date, though still achieving secure key rates of 2.0kb/s in the presence of 100Gb/s of classical traffic. The Cambridge metro network has been performing stably since 2018; it encompasses four nodes (incl. one at the Toshiba Europe research lab on the Cambridge Science Park) with secure rates on all links consistently above 1Mb/s (the highest recorded long-term key rates in a deployed network) and concurrent 100Gb/s traffic over all links. The Bristol metro ultra-low latency/high-bandwidth quantum network launched a year later over the city's established 5G test network infrastructure, using specially developed Open Source software over four optical network nodes. On it, Hub teams achieved the first ever experimental demonstration of QKD secured Network Function Virtualisation orchestration with Software Defined Networking control[28], replacing the need for purpose-built hardware appliances with standard off-the-shelf IT network equipment. This setup provides manageable, cost-effective network architecture with proven resistance to security breaches, adaptable to integration with classical communications and leading to improved UK infrastructure and device interoperability on a national scale.

Alongside this national quantum network, Hub researchers set up an 125km-long extension (the UKQN*tel*) from Cambridge to the BT Labs in the Adastral Park ICT industrial cluster, near Ipswich. This mini quantum network operates with fully commercially available components (including commercial-grade optical fibre) and is an important testbed comprising three BT Exchanges acting as intermediate trusted nodes and five x 100Gb/s classical channels. UKQN*tel* was set up to test QKD integration into a real-world network and in the process test and optimise performance and resilience, thus helping to develop strategies for large-scale rollout. The successful deployment of the UKQN and UKQN*tel* set the foundations for the subsequent world-first commercial trial of quantum secured communications services implemented by Hub partners BT and Toshiba Europe over commercial-grade fibre along the M4 corridor[29].



Beyond establishing the UK's national quantum networking capabilities over optical fibre, the Hub has led research development into next-generation quantum communications approaches, notably exploring the use of entanglement distribution. In 2020, Hub teams led an international collaboration which demonstrated experimentally for the first time a trusted-node–free eight-user metropolitan quantum communication network, with improved scaling and data traffic – the largest of its kind at the time[30]. Since then, significant steps have been taken towards improving the compatibility of current networks with interconnecting quantum technologies, entanglement swapping, frequency conversion and memories, and alongside, identifying preferred operation wavelengths for these setups and demonstrating new multi-party entanglement protocols such as conference key agreement[31]. Hub studies on dynamic network performance, can be directly adopted to long-term field trials and simulator/AI control tools developed can be used by others to deploy and maintain quantum networking as a commercial service.

In the last five years, the Hub's programme of work was expanded to include technology development for quantum communications at the longest scales, namely via satellite over free space. QKD's inherent distance limitations over fibre point to the eventual use of satellite constellations as the next logical proposition in network architecture for cross-continental quantum communications. Hub teams have been responsible for proposing the establishment of new strategic capability for the UK in the area of quantum communications in space, bringing together leading expertise from the separate fields of space engineering, telecoms and quantum technologies. Using innovative Hub-developed quantum payloads and ground receiver technologies, and leveraging RAL Space expertise in space component integration, this effort will culminate in the launch of the Hub's own satellite mission in 2025.

Alongside core work on quantum networks over optical fibre and free space, the Hub has also enabled a number of novel quantum communications approaches to be tested via partnership resource funded feasibility studies and proof-of-concept investigations, many involving industry partners. Impressive results have been achieved on a cross-country QKD link between the UK and Ireland using submarine fibre[32], pilot field-deployment of QKD over railway track-side fibre[33], hybrid systems using quantum and post-quantum encryption to secure networks, QKD via high altitude platforms[34], integration of QKD with physical layer encryption, and many more.

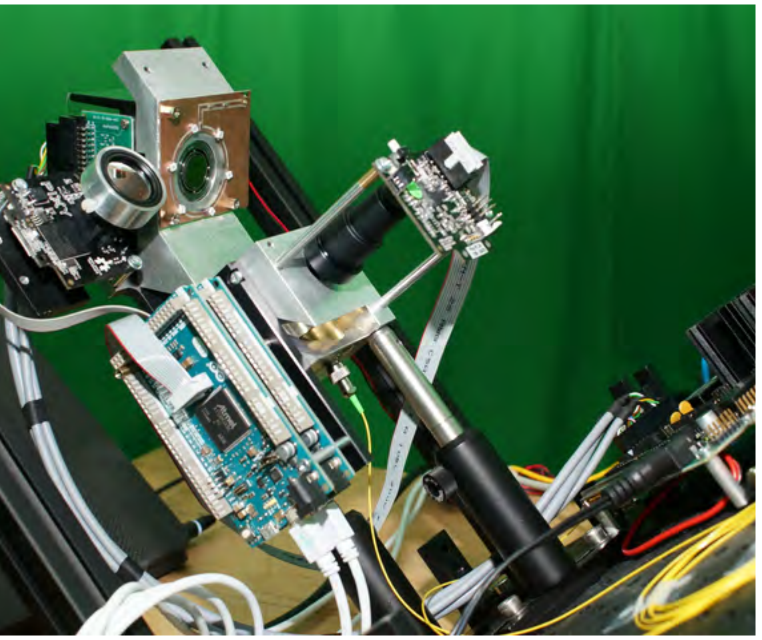
Beyond the research innovation led by the Hub, substantial contributions were also made in establishing a CE certification process for QKD systems embedded in the UKQN and, by extension, the national safety critical infrastructure. Coupled with all the work undertaken separately on network metrology and the development of relevant industry standards, the Hub's legacy in establishing the UK's quantum networking foundation will have a lasting effect.

Key Milestones: Quantum Communications on Chip and for Consumers

Delivery partners: Bristol, Cambridge, Oxford

The engineering debt inherited by the Hub in the area of quantum communications was for devices that were technologically mature but bulky and thus costly to manufacture, both substantial barriers to commercialisation. From the beginning, the Hub set out to address these challenges by aiming to scale down and integrate QKD component devices to produce robust, miniaturised sender, receiver and switch systems, i.e. "QKD-on-a-chip" modules. This chip-scale approach delivers devices with low Size, Weight and Power (SWaP) requirements, to support the production of scalable, cost-effective, energy-efficient, high-performance communications security technologies with high integration potential, enabling widespread, mass-market deployment and application.

To this end, the Hub has achieved impressive results starting with the world-first chip-to-chip QKD demonstration instigated in 2017[35]. By integrating all of the photonics components required (bar the single photon detectors) into sender/receiver chips, cheap, robust, low SWaP and industrially fabricated devices were produced with performance comparable to state-of-the-art devices. The newly developed technology formed the core of internally developed stand-alone QKD systems with custom control electronics, software and packaging all developed to accelerate the graduation from lab to real-world scenarios. In parallel, this technology was further leveraged to demonstrate a quantum secure router, a critical component of deploying QKD devices in real-world networks – able to switch both classical data and QKD channels, while maintaining the fidelity of both. By that point, the Hub supported start-up KETS had already been founded, with marked success at securing venture capital and being recognised through numerous industry awards.



Following these solid achievements, the focus shifted to overcoming inherent limitations of the QKD procedure. Progress was made with Measurement Device Independent (MDI) technologies (reducing reliance on trustworthy detectors, commonly manufactured by third parties, compromising security); Wavelength Division Multiplexing (WDM)-specific chips for increasing the utilisation of fibre networks; the use of Silicon on Insulator (SOI) substrates for high performance QKD transmitters, facilitating even greater benefits of cost and a more diverse supply chain, and also Quantum Random Number Generators conducive to mass manufacture. Throughout the second phase of the Hub, our teams have continued to explore new techniques to address the demand for ever-increasing communication rates, improve the base technology to maximise performance and enable new functionality, address challenges such as lowering on-chip losses, optimising on-chip structures and components, and improving coupling to off-chip channels, and progress the generation and manipulation of chip-to-chip entanglement capabilities to facilitate quantum computing distribution technologies, underpinning the establishment of a future quantum internet.

In parallel, our investigators have explored handheld "consumer"-owned QKD devices for privacy scenarios where individuals need access to ready and constant supplies of encryption keys, for uncompromisingly secure data exchanges with banks, government agencies, e-commerce service providers, employers etc. To this end, Hub teams have developed a fully assembled miniaturised, reliable, low-cost, prototype handheld QKD system with accompanying tracking software that is ripe for commercialisation. In the process, the world's first demonstration of fibre-wireless (free space)-fibre QKD transmission has been achieved[36].

QUANTUM COMMUNICATIONS HUB | 10-YEAR REPORT

Key Milestones: Hub Space Mission

Delivery partners: Bristol, Heriot-Watt, RAL Space, Strathclyde, York

Satellite QKD provides an elegant solution to the currently limited range of terrestrial optical fibre for key distribution, thereby extending the use of QKD from metropolitan and inter-city to international scales. The UK has world-leading research in terrestrial QKD, and the aim of the Hub's space work has been to support accelerated translation of that expertise and leadership into satellite quantum communications, for an in-orbit-demonstration (IOD) mission of Hub developed technologies. This has strongly leveraged engineering know-how developed by STFC's RAL Space for the UK/Singaporean Speqtre mission, which combines UK space expertise with Singaporean quantum technology. The Hub IOD has also built on feasibility studies in support of space quantum communications, funded by the phase 1 Hub partnership resource fund, and prototype receiver development work by Hub partners enabled through Industrial Strategy Challenge Fund awards.

The Hub's mission includes two essential components: the SPOQC (Satellite Platform for Optical Quantum Communications) nanosatellite and the HOGS (Hub Optical Ground Station) facility. SPOQC is a 12U CubeSat, which will be placed into a Low-Earth Sun-Synchronous Orbit (SSO) and provide overpasses of HOGS. Following a competitive tender process, the Hub selected the Dutch company ISISpace Group as the provider of satellite systems and services in support of the Hub's mission to demonstrate distribution of quantum encryption keys from space. Founded in 2006, ISISpace is one of the leading companies in the small satellite market, specialising in small satellite missions, and including launch and operations for in-orbit delivery.

The SPOQC mission is unique in its ambition to launch a dual quantum source operating a Continuous-Variable (CV) QKD protocol (engineering model developed by the team at the University of York); and a Discrete-Variable (DV) QKD protocol (as developed by the team at the University of Bristol). The DV source will employ weak coherent pulses (approximate single photons) in a decoy-state implementation of the well-known BB84 QKD protocol. The source will use two separate wavelengths to increase the quantum key rate. The CV source will transmit modulated quantum light pulses, alongside a reference beam for measurement. It is designed to explore CV advantages, including daylight operation. The source outputs combine in a passive optical device in the satellite, before entering an Optical Transmission Alignment Module (OPTAM) for transmission to the ground. Only one source (DV or CV) will operate at any time, with the corresponding receiver on the ground being active.

The HOGS is situated at the Heriot-Watt campus in Edinburgh, Scotland, at a site identified following extensive review of available locations, which included light pollution measurements and visits to assess groundwork/cabling/ducting, to assessment for dark optical fibre connectivity. Additional benefits include access to local lab infrastructure, improved sustainability measures and ready engagement with resources across the wider academic community at the university. The HOGS consists of a Baader Allsky 4.5m robotic observatory dome and Planewave 70cm-wide observatory reflective telescope with metallic coatings, used to track the low-Earth orbit satellite path with high precision and receive the quantum signals. Adaptive optics are being used to further enhance the telescope capability. Both HOGS and SPOQC will employ laser beacons to accurately point towards each other; once aligned, transmission of quantum signals will commence. The HOGS will utilise one of two quantum receivers, dependent upon which quantum source on SPOQC is active. The facility is also directly connected to a local optical fibre network, allowing deployment of optical, quantum, and hybrid communication networks. The HOGS facility will support future R&D over many years, providing the capability to communicate with future quantum space missions, a gateway to fibre networks and scope for international collaboration. Launch of the Hub SPOQC mission is planned for June 2025.

To understand the capability and performance of satellite QKD, the Hub has developed an extensive open-source modelling package, SatQuMA[37]. As communications with satellites are limited to time periods when the satellite is visible to the partner OGS, it is important to allow for this in the key extraction.

HubOpticalGroundStation

SATELLITE PLATFORM FOR OPTICAL QUANTUM COMMUNICATIONS SPOQC

SatQuMA

Key Milestones: Sources, Detectors and Devices

Delivery partners: Glasgow, Heriot-Watt, Sheffield

Development of components crucial for quantum communications technologies has been an important aspect of the phase 2 Hub work. The changing economic and political landscape worldwide, and relevance of import and export controls for security technologies, gives a strong incentive for development of a UK national capability in key components – detectors and sources – which form the respective centrepieces of receivers and transmitters – necessary in the supply chain for any future UK quantum communications industry.

Targets for this theme have been key component gaps in quantum communications: single-photon sources; entangled photon pair sources; next generation single photon avalanche diode (SPAD) detectors; and superconducting nanowire single-photon detectors (SNSPDs). The aim has been to advance UK capabilities beyond the state-of-the-art, support the effort across all experimental Hub work and thus consolidate UK supply chains in these strategic underpinning components. Specifically to do so through: investigating quantum dots (semiconductor nanoparticles) as high-repetition-rate single-photon sources for optical-fibre-based QKD (at the 1550 nm wavelength bands), enhancing emission (and thus available key) rates by the Purcell effect in photonic crystal cavities; overcoming the deleterious effects of after-pulsing in current InGaAs/InP SPADs which affect data acquisition rates, by focusing on Ge-on-Si SPAD detectors instead, investigating integration with silicon photonic platforms and taking advantage of much reduced after-pulsing found in these semiconductor devices; developing, benchmarking and packaging next generation SNSPDs with optimised designs.

The Hub teams have established that the photon emission rate from quantum dots can be enhanced when positioned within a very small cavity, made by patterning the semiconductor chip on nanometre-length scales using techniques of electron-beam lithography[38]. The results are important as they facilitate faster bit rates for quantum networks that use quantum dots as the photon light sources. In parallel, Hub teams have achieved the first demonstration of a high-avalanche-gain and low-excess-noise performance avalanche photodiode at λ=1550 nm at room temperature on a silicon platform[39]. These prototype devices outperform commercially available InGaAs/InP avalanche photodiodes. They have also developed an improved planarisation and passivation approach, which successfully reduced device dark current and improved device robustness. The research on Ge-on-Si SPADs has demonstrated the potential of single-photon detection in the short-wave infrared using a silicon multiplication layer. Silicon offers fabrication advantages of low-noise single-photon detector devices, component integration and scalability. There is also evidence that the Ge-on-Si SPAD approach offers performance advantages – increased detection efficiency and reduced after-pulsing compared to alternative InGaAs/InP SPADs. Ultimately, silicon will provide significant cost advantages in volume manufacture, when compared to III-V semiconductor material systems such as InGaAs/InP. We feel the Ge-on-Si SPAD platform is already the main semiconductor competitor to InGaAs/InP, despite its relatively immature technology status. Many of the technical developments outlined in the Hub's work have the potential to make Ge-on-Si SPADS the standard single-photon semiconductor detector used in QKD in the long term.

The ability to detect single photons is crucial for the expansion of quantum secure communications. Part of the Hub's legacy has been the creation of bespoke, ultra-fast, large-area, low-noise single photon detectors for use in quantum communication systems at telecom wavelengths.

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Key Milestones: Device Independence and Quantum Random Number Generators

Delivery partners: NPL, York

The security guarantees offered by quantum cryptographic protocols rely on the devices involved working to particular specifications. In reality, practical implementations of these theoretical setups are not immune to physical vulnerabilities, leading to security compromises that are purported to negate the promise of ultimate security offered by principles of quantum mechanics. One way of countering this issue is to use device-independent security protocols, though – predictably – this is a deceptively simple suggestion with these protocols being much harder to implement in practice. Hub investigators have grappled with this challenge throughout the last decade, with impressive results both in terms of theory development and experimental manifestation on quantum random number generators or QRNGs – the most technologically mature class of devices that is now moving towards assurance and certification, thanks largely to the legacy of the Hub.

Hub teams have achieved major advances towards demonstrating device-independent randomness expansion[40], critical for QRNGs and laying the foundations for use in future randomness beacons, where a trusted body releases random numbers at certain intervals for use by anyone else. They have also optimized the rate of randomness based on the quality of entanglement available[41], thus giving a complete picture of the maximum randomness achievable. This work illustrates how modelling the noise that may be seen in a real system can help improve randomness rates. The team have also made developments in protocol design, which can lead to substantial improvements in expansion rates[42], further increasing this technology's potential for commercial exploitation.

The Hub has also contributed to the commercialisation of QRNGs, devices that utilise the inherent randomness of natural physical processes to create their output, assured unique to each device and unpredictable by any other party provided that the process is quantum. QRNGs are thus superior to their classical equivalent as they produce truly random (i.e. unpredictable) numbers, with no risk of the same random sequence being produced by identically manufactured technologies. Hub partnership resource investment towards a feasibility study, informed by our work on establishing and testing quantum randomness and its limits, underpinned a much more substantial project, funded by the Industrial Strategy Challenge Fund and led by NPL. The AQuRand project (Assurance of Quantum Random Number Generators) addressed the need to provide authoritative certification of this class of devices, which requires the ability to physically model and characterise these devices to overcome this barrier to full commercial exploitation.

Key Milestones: Next-generation Quantum Security Protocols and PQC

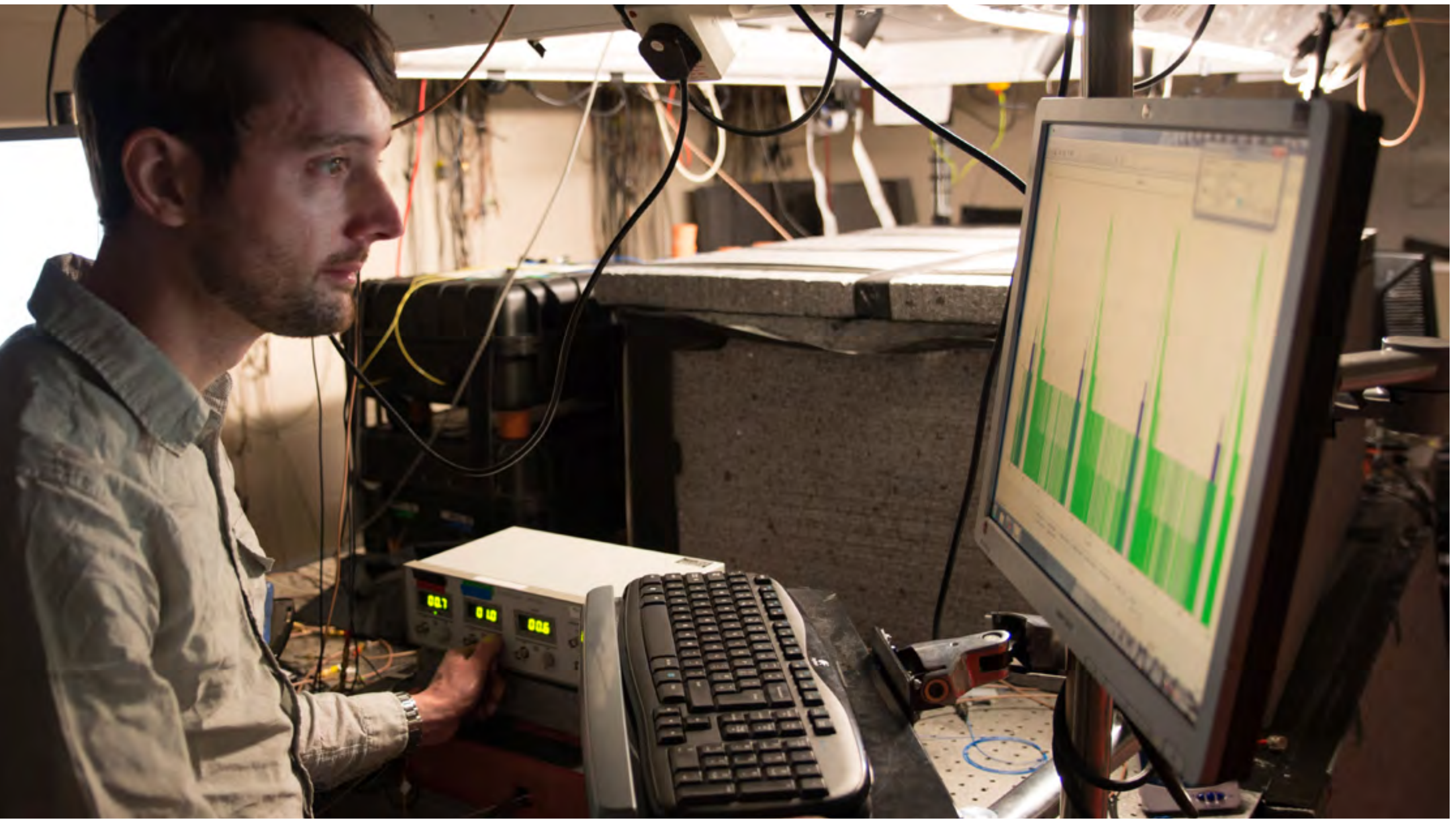
Delivery partners: Cambridge, Heriot-Watt, Kent, Royal Holloway, Sheffield, Queen's Belfast, York

Deployment of future quantum networks will require secure schemes for a wide range of applications, beyond encryption via key distribution. To this end, Hub teams have investigated next-generation quantum security protocols throughout the last decade, both in core work and through partnership resource investment in feasibility studies, in an effort to develop practical schemes for commercially significant tasks.

In the last decade, Hub teams have developed the application of quantum digital signatures (QDS) from laboratory demonstrations over several meters of optical fibre to real-world implementation via dark fibre in metropolitan networks over 100km distances[43]. In parallel, they have conducted the first experimental demonstration of measurement-device-independent QDS[44].

There have been advances made in quantum security theory, most notably tackling problems of QKD protocol optimisation, determining secret key capacities of transmission channels, and establishing the ultimate limits for repeater-assisted quantum communications[45]. Hub investigators have further pursued practical approaches to quantum position verification and quantum oblivious transfer cryptographic schemes[46, 47], while also advancing bold new approaches such as quantum secure tokens to ensure unforgeability and secure authentication in high-value/high-sensitivity financial transactions[48, 49].

During the last five years there's also been an increased focus on hardware physical security of hybrid (quantum/classical) systems and the integration of post-quantum cryptography into the Hub's QKD technologies. Hub investigators have worked extensively to provide counter-measures against security vulnerabilities (e.g. Trojan horse-style or side-channel attacks), analyse the quantum technologies impact on cryptocurrencies, explore quantum software modelling, scrutinise the candidate cryptographic algorithms under consideration in the NIST PQC standardisation process, and consider their effective implementation [e.g. fast Kyber PQC on FPGA[50]], and finally, develop reliable solutions for hardware roots of trust via FPGA-based, ultra-compact Physically Unclonable Functions or PUFs for device authentication[51], thus providing additional layers of security for physical hardware.



Key Milestones: Contributions to Standards Development

Delivery partners: NPL, York

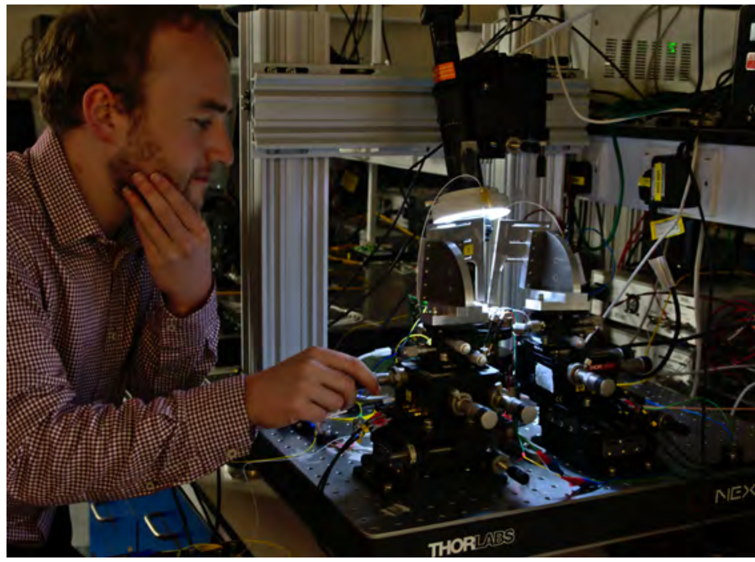
Industrial standards are essential for ensuring the interoperability of equipment and protocols in complex systems, as well as stimulating a supply chain for components, systems and applications through the definition of common interfaces. New standards are required to integrate quantum communications into networks and to stimulate their commercialisation.

The UK has been leading the creation of international standards for quantum communications and in particular Quantum Key Distribution, an achievement that can be primarily attributed to the work of partners Toshiba and NPL. Unsurprisingly then, development of industry standards has been an integral part of the Hub's work throughout the last decade. Featuring prominently in key deliverables for both phase 1 and phase 2 work, this activity has been led by Hub partner NPL through both extensive metrology tests carried out across the Hub's quantum networks and alongside active participation in a number of relevant bodies such as the ETSI Industry Specification Group on QKD, chaired by fellow Hub partner Toshiba, ISO/IEC JTC1, CEN/CENELEC JTC22 and the recently formed IEC/ISO JTC3 (the last three via NPL's membership of BSI – the British Standards Institute).

In parallel to contributions made to the drafting of formal documentation by these bodies, the Hub NPL team also participated in a number of other large-scale international metrology projects (H2020 OPENQKD, EMPIR MeTISQ), while also acting as vice-chair of the EURAMET European Metrology Network for Quantum Technologies, co-ordinating quantum photonics metrology activities in the EURAMET area.

In the last decade, Hub investigators and industry partners have:

- Provided input on standards and assurance for quantum technologies to the 2016 Blackett report[52] published by the Government Office for Science.
- Participated in various relevant events, including the 2022 Quantum Communications Standards and 2023 Quantum Industry workshops, both organised by NPL.
- Contributed to the drafting of a number of formal standards documents, including on: characterisation of optical components for QKD; implementation security of QKD systems; security requirements, test and evaluation methods for QKD, protection profile for a pair of prepare-and-measure QKD modules[53-57].
- Contributed to the CEN/CENELEC standardisation roadmap on quantum technologies[58].
- Pioneered new approaches for the assurance of Quantum Random Number Generators, starting with a feasibility study on this topic funded by the Hub Partnership Resource Fund at the end of phase 1, then expanded to a national-scale Industrial Strategy Challenge Fund-supported project, led by NPL with support from the National Cyber Security Centre, and involving six QRNG developers in the UK.
- Reviewed the NCSC Principles-Based-Assurance framework for best practice and published NCSC's relevant Technology Assurance Principles documentation annotated with specific commentary on the implications of applying them to the quantum communications sector (see also below).



Partnership Resource Fund Investment

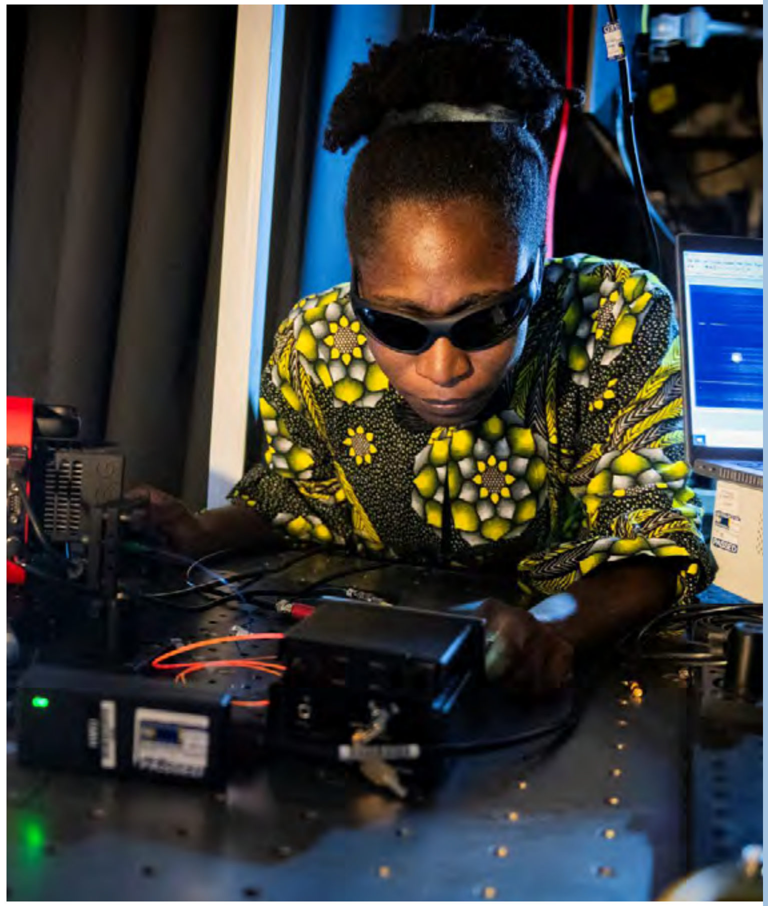
One of the boldest and most visionary initiatives of the national programme since its inception has been the incorporation of a Partnership Resource (PR) Fund within each Hub structure, with resource allocated to be used flexibly. The scheme was set up to allow support for key external developments to be brought into each Hub, enhancing their overall capability through expanded partnerships. Examples of this additional funding scope included: engagement with new partners, support for activities on a scale appropriate to seeding future work in research and innovation, cross-Hub collaborations for greater impact, user engagement events such as sandpits or workshops, pump-priming activities, networking events, and support for responsible innovation, including investment into public engagement initiatives.

From the outset, the Quantum Communications Hub has allocated PR funds to support new collaborations which are closely aligned with the work of the Hub. Proposals were considered under criteria such as strategic fit to the Hub's existing programme of work, impact, commercialisation potential, alongside essential standard considerations such as measurable deliverables, realistic timelines and sensible costs. To this end, the Hub has supported numerous projects with strategic potential: feasibility studies; proofs of concept; preliminary developments; demonstrators and major commercialisation initiatives that further supported, expanded and added value to the Hub programme. £5.97M has been invested by the Hub in this activity, key examples of which include:

- Assurance of Quantum Random Number Generator devices: feasibility study that sought to develop the necessary theoretical and experimental understanding, expertise and techniques to test physical quantum random number generators
- Realistic Threat Models for Satellite QKD: in-depth security study examining assumptions about the physical channel between satellites and ground stations
- UKIQL: feasibility study of a data centre-to-data centre quantum link between UK and Ireland via low-loss submarine optical fibre
- QEYSSat: international collaboration with the Canadian space mission
- QuID: development of quantum security tokens for the IoT
- HiQ: QKD on high altitude platforms feasibility study
- QTRAX: pilot field deployment of CV QKD over track-side fibre
- Measurement Device Independent QKD: realisation of an MDI-QKD prototype system addressing existing challenges
- QPID: proof-of-concept pilot and demonstrator of a model utilising quantum and post-quantum approaches to secure networks
- Quantum STEM Ambassadors – bringing quantum into the classroom: pilot scheme of specially developed resources to introduce A-level students to the potential of quantum technologies and career pathways in the field

Hub investment into PR projects led to numerous high-impact peer-reviewed publications along with significant developments such as:

- ISCF funded projects (e.g. AQuRand, 3QN and others)
- Pilot rollout of a national quantum ambassadors scheme implemented by DSIT
- Theoretical modelling and prototype technology underpinning the Hub's phase 2 space mission
- Establishment of Quantum City as the public engagement arm of the national programme and the National Showcase as the flagship user engagement event for the UK quantum community (both cross-Hub collaborative activities)



QUANTUM COMMUNICATIONS HUB | 10-YEAR REPORT

Impact

Impact: Skills & Training

Support for a skilled workforce in quantum technologies has been central to the national programme's strategic outlook since its outset in 2014 and has remained one of the most important aspects of the most recent national quantum strategy, published in 2023. Unfortunately, delivery of a suitably skilled workforce faces a number of challenges, including: UK government policies around immigration and the effect of Brexit on recruitment; the dual use nature of many of the quantum technologies under development, which in turn has implications for sovereign capability in the current geopolitical context; and the pay discrepancy between academia and industry, and between the UK and North American countries (US and Canada) in particular. The situation is further framed by the context of lack of proper quantum provision in the school curriculum – and more general difficulties in achieving diverse representation in STEM subjects – and is exacerbated by the current global landscape of massive investment into these emerging technologies, meaning that training challenges soon become retention ones, for skilled staff who have the option of moving and working abroad.

The Hub has responded to these challenges, through investing in strategic and planned activities, but also with flexibility to take advantage of ad hoc opportunities. In the last decade, we have:

- Organised two training workshops in classical cryptography, bringing together the usually siloed communities of cyber security experts and quantum technologists;
- Invested in bespoke entrepreneurial training for quantum researchers provided by the University of Bristol's highly successful QTEC programme;
- Allocated more than £3.62M of EPSRC Doctoral Training Partnership funding across Hub partners for training PhD students on research topics that were strategically aligned to the Hub's programme of work, thus creating our own talent pipeline;
- Invested an additional £500k of EPSRC funding into specialist capital equipment to enhance learning for the next generation of quantum technologists and a total of 10 PhD+ short-term training fellowships for early career Hub researchers;
- Invested £336k in the development and implementation of the Quantum STEM Ambassadors scheme, working with schools across the country and kick-starting a national conversation about the need to incorporate quantum into the curriculum;
- Launched a website blog featuring interviews with various members of the UK quantum community, highlighting diverse career pathways and training opportunities;
- Published a series of "careers in quantum" fact sheets offering detailed information on the required skills background, education, progression potential, working conditions, etc.;
- Contributed input to the government's specially convened Quantum Skills Taskforce tasked with ensuring that the UK has the workforce needed to develop and adopt quantum technologies;
- Rolled out an online outreach programme of school assemblies and events, including through partnerships with quantum skills enhancement organisations such as Qsium;
- Supported initiatives such as the University of Bristol's Quantum in the Summer, aimed at instilling interested students with basic photonic/quantum skills;
- Leveraged EPSRC funding to co-organise with the network of Hubs the first international summer school in quantum technologies for UK and Canada students;
- Provided extensive mentorship to Hub early career researchers;
- Allocated generous travel budgets to all Hub researchers and PhD students to support their professional development, including through conference attendance.

Impact: The Quantum STEM Ambassadors Scheme

Nowhere is the Hub's commitment to the development of skills and training better exemplified than its long-term investment into the development and implementation of the Quantum STEM Ambassadors scheme, aiming to bring quantum into the curriculum. Originally started as a partnership resource feasibility study involving the National STEM Learning Centre and the University of York Science Education Group, the scheme has since evolved into a national pilot funded by DSIT for delivery to schools across the country[59].

The Quantum Ambassadors programme was conceived as a comprehensive scheme of quantum-related CPD and classroom-based activities for A-level students and their science teachers to promote the uptake of STEM subjects, highlight the benefits and applications of mature quantum technologies and signpost career pathways for quantum graduates. Over an initial two-year period (2017-19), and through a suite of specially developed education resources for use both in classroom and online, delivered by specially trained quantum early careers researchers and PhD students from across the network of Quantum Technology Hubs, the scheme sought to increase awareness of the importance and relevance of quantum technologies to society and the UK economy through the work of the national programme. In parallel, an independent impact evaluation was carried out to measure engagement levels.

This feasibility study was very successful, with over 100 schools signing up to the scheme from across the whole of the UK and high levels of engagement reported. Although the evaluation found that the perception of quantum physics being difficult was fairly prevalent amongst the students (and teachers!), the majority of them were happy to take on the challenge and find out more about the emerging technologies. Further, both ambassadors and teachers appreciated the opportunity for their own professional development.

These encouraging results drove further investment into a second, wider deployment phase of the scheme, initially planned for the period 2020-22 and unfortunately coinciding with the onset of the global Covid pandemic. This resulted in substantial delays and less time for extra-curricular activities in the classroom, but led to a major re-design of the programme for online delivery, which in turn inspired its current – third – iteration. Reassuringly, the evaluation of the second phase presented again evidence of continued positive impact on students' and teachers' interest in, and engagement with, learning about quantum science and technology and the careers involved, while it also recommended the expansion of the programme to include biology.

On the basis of this evidence, the Hub and National STEM Learning Centre engaged into discussions with the then BEIS (now DSIT) team looking at ways to advance quantum literacy in younger generations. These discussions culminated in DSIT's decision to fund the programme for a third phase, as referenced in the Government's 2023 national quantum strategy, which featured a major focus to boost quantum skills and contribute to the creation of a world-leading quantum workforce.

The new investment will seek to recruit an even larger number of schools across the country by focusing on teacher CPD, instilling science educators with the confidence and knowledge to deliver quantum related activities. It will also support delivery of a large number of quantum kits to disadvantaged area schools, currently lacking the resources to carry out science demonstrations. The development and provision of a 'quantum physics in a suitcase kit' will allow teachers to help students visualise and understand quantum physics. STEM Learning's extensive network will be used to provide kits to schools for free, ensuring that those most in need of further support and provision can access materials and resources.

QUANTUM COMMUNICATIONS HUB | 10-YEAR REPORT

Impact: The relationship with Industry

By far the most innovative aspect of the national programme, and one that has served as the model for many national quantum strategies across the globe since, has been the facilitation of close collaboration between academia and industry (and to a somewhat lesser degree, government) to jointly exploit the potential of emerging quantum technologies. This partnership has been an inherent feature in the network of Hubs from the outset. Over the last decade of its operation, the Quantum Communications Hub's relationship with industry has gone beyond symbiotic to become synergistic, with Hub work informed by industry needs and performed with active (as well as advisory) industrial input. Specifically:

- During phase 1 (2014-19), the establishment of the UK Quantum Network programme of work was led by Toshiba Europe's Andrew Shields in a unique example of academia/industry collaboration. This model was replicated in phase 2 (2019-24) through Chris Erven's – from Hub start-up KETS – leadership of the chip-based QKD work;
- Similarly, the Hub has involved the National Physical Laboratory as an active partner through incorporation of standards development in its programme of work throughout and secondment of research associates to its labs to assist with delivery;

- There has been industry representation (BT, ADVA, ETSI, Catapults, etc.) in the Hub external advisory board throughout;
- Using partnership resource funds, the Hub has invested more than £3M in projects involving industry partners;
- Hub work has directly seeded two big ISCF projects (3QN: Towards a New UK Industry for Novel Quantum Receivers in Nascent Satellite QKD Global Markets, and AQuRand: Assurance of Quantum Random Number Generators) worth £6M and Hub academic partners have been involved in numerous industry-led ISCF projects worth in excess of £41M;
- Hub researchers have worked directly with companies such as BT, ADVA and Toshiba Europe to extend the UK Quantum Network into BT's Adastral Park industrial complex, utilising previously installed standard commercial grade optical fibre and commercial QKD equipment, thus providing a real-world environment for field trials of new quantum secure communications technologies and systems;
- Over the last decade, the Hub has contributed to the organisation of various user engagement events bringing together industrialists and academics, including that of the flagship community event, the National Showcase;
- The Hub team have featured many interviews with industry-based quantum role models on the Hub's website outreach blog, aiming to inspire younger children to pursue a career in the field. This material has also formed the basis of a series of career fact sheets, again highlighting career pathways in quantum industry;
- Hub PhD students have been co-supervised by industry based researchers.

Below we provide some specific examples of this collaborative partnership by presenting some case studies of the relationship the Hub has cultivated with industry, ranging from work with global corporations (BT, Toshiba), to smaller start-ups (KETS, Craft Prospect), to a public corporation (NPL).

Case Study: the partnership with BT

BT Group is one of the world's leading telecommunications and network services providers with customers in 180 countries. The company is investing heavily each year in security research and development of technologies ranging from quantum secure networks to industry-leading AI and data visualisation capabilities, with the aim of future proofing national communications infrastructure in a quantum-enabled world.

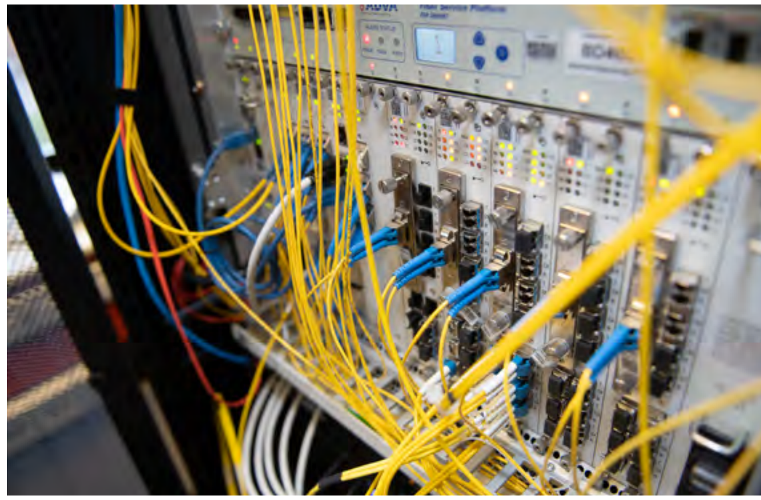
BT's association with the Hub dates back to Phase 1 when the company came on board as a major Hub partner with a strong interest in the Hub's work in quantum networking. This relationship was firmly established in 2015 when a consortium of Hub, BT and Toshiba Europe Ltd investigators secured additional EPSRC funding to extend the Hub's UK Quantum Network (UKQN) from Cambridge Science Park to the ICT tech cluster in and around Adastral Park, BT's Research & Innovation Labs campus, and Innovation Martlesham (a concentration of over 100 tech companies). Their work with the Hub on UKQN*tel*, the 125km-long UKQN extension to the telecommunications sector, demonstrated the successful integration of emerging, high-performing quantum communications technology over standard commercial grade optical fibre which comfortably accommodates quantum and non-quantum data traffic. The deployed QKD technology shares data encryption keys via an ultra-secure quantum channel over the same fibre that carries the encrypted data itself. UKQN*tel* has been established as a testbed for device and system trials, proof of principle experiments, integration of quantum and conventional communications, and quantum application and service demonstrations for stakeholders, customers and the wider public.

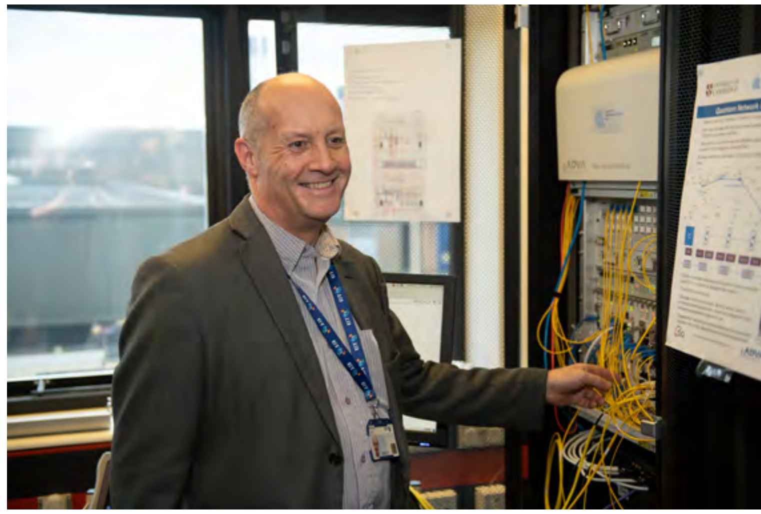
Since the establishment of the UKQN*tel* testbed, BT has cemented its status as a major stakeholder in the research and development of quantum communications products and services through their ongoing partnership with the Hub coupled with their involvement in a number of high-profile ISCF (notably AQuaSec, 3QN and AIRQKD) and EU funded projects. They have continued their collaborative relationship with Toshiba launching a first commercial trial of quantum secured communication services in 2022 [29], alongside EY and now also HSBC. This commercial quantum network connected sites in London's Docklands, the City and the M4 Corridor, providing data services secured with QKD and PQC.

Beyond the UK, BT is involved in large-scale research consortia, notably the European Union Horizon 2020 funded OpenQKD, with long-term collaborators and Hub partners ADVA, ID Quantique, NPL, Toshiba and the University of Cambridge. The project created a prototype pan-European quantum network infrastructure comprising many "local" networks that experimentally trialled the future security of critical data applications in the fields of telecommunications, health care, electricity supply and government services to kick-start a competitive European QKD industry. Similarly, BT is pursuing its interests in global-scale, free-space quantum communications through involvement in the international QKDSat consortium, partly funded by the European Space Agency, seeking to demonstrate how quantum communications technologies integrated inside space-based infrastructure can help secure critical infrastructure at long-distance scales.

Speaking about BT's partnership with the Hub, Andrew Lord, BT Senior Manager, Optics and Quantum Research, said:

"We couldn't have been even close to the position we are in today on quantum without the close interaction with the Quantum Communications Hub and the associated support from Innovate UK. The access to world-class research has unlocked the power of quantum for us and I am excited to see how we now start to commercialise it."





Case Study: the partnership with Toshiba Europe Ltd

Toshiba Europe Limited is a world-leading R&D organisation founded by Toshiba Corporation, Japan, and dedicated to fostering innovation through basic and applied research in physics, engineering and computer science. It has invested heavily in the development of quantum technologies in the UK for over 20 years.

Toshiba Europe has been a major collaborator of the Hub since the start in 2014, with Dr Andrew Shields, having led an entire programme of core Hub work on quantum networking, throughout phase 1. The company was integral to the Hub's work to establish the UK Quantum Network (UKQN), which connects metro-scale and long-distance optical fibre links for quantum communications. Specifically, their QKD systems were installed in the metro-scale network which was deployed between three of the University of Cambridge's buildings and the Toshiba laboratory on the Cambridge Science Park; and in the long-distance links connecting Cambridge to Bristol. The company was also involved in the planning of the proposal for the UKQN*tel* arm of the network, linking Cambridge to BT's Adastral Park.

Another area of strong collaboration between Toshiba Europe and the Hub was as part of the Hub's work to investigate "next generation" quantum communications technologies. Toshiba engaged heavily in experiments on quantum digital signatures, quantum teleportation and Measurement Device Independent (MDI) QKD, including through a joint project funded through Hub Partnership Resource. The project ('Autonomous System for Measurement Device Independent QKD') sought to realise an MDI-QKD prototype that could operate continuously and with spatial separation of the two communicating parties, tackling challenges such as realisation of high-speed, real-time modulation of indistinguishable pulses from remote locations, and synchronisation of those remote locations.

In parallel to this, and alongside NPL, Toshiba Europe were significantly involved in the Hub's work to generate industry-wide standards for quantum technologies. Andrew Shields was the Chair and co-founder of the ETSI Industry Specification Group for QKD and led the work in the ETSI ISG on the characterisation of components used in QKD systems and the implementation security of QKD systems.

Toshiba Europe are also taking part in various large-scale ISCF projects involving numerous Hub partners, including AQuRand (led by NPL, with the Universities of York and Kent, CryptaLabs, ID Quantique, KETS Quantum, NuQuantum, Quantinuum, Quantum Dice and Toshiba Europe), which sought to address the need for authoritative certification of the unique randomness produced by QRNGs and to overcome the existing important technological barriers to their commercial and industrial exploitation. Beyond the UK and alongside other Hub partners, the company is also involved in the European Union Horizon 2020 funded OpenQKD. Through their Quantum Technology business division, they aim to commercialise their quantum communication technology; they released their first products for QKD in Oct 2020 (already now deployed in networks in UK, Europe, US, Japan and South Korea) and in 2022 launched a network for commercial QKD services in London in collaboration with BT.

Speaking about Toshiba's partnership with the Hub, Dr Andrew Shields, Vice President, Toshiba Research Europe Ltd commented:

"Our association with the Quantum Communications Hub has been very valuable, allowing us to establish important collaborations with several academic and industrial groups in the UK. It also provided a springboard for Innovate UK projects which have further strengthened these linkages. We appreciate the great work they have done in fostering new quantum technologies and training the next generation of researchers that will drive its industrial take up in the future."

Case Study: the partnership with Craft Prospect

Craft Prospect is a space engineering company seeking to harness new approaches to support the emergence of QKD from space through development of their mission-enabling products and architecture services that include AI-enabled space technologies, quantum technology products, and mission systems design. Since its inception in 2017, Craft Prospect has built a reputation for agile, smart satellite architecture, as recognised through their involvement in various UK and European Space Agency funded missions.

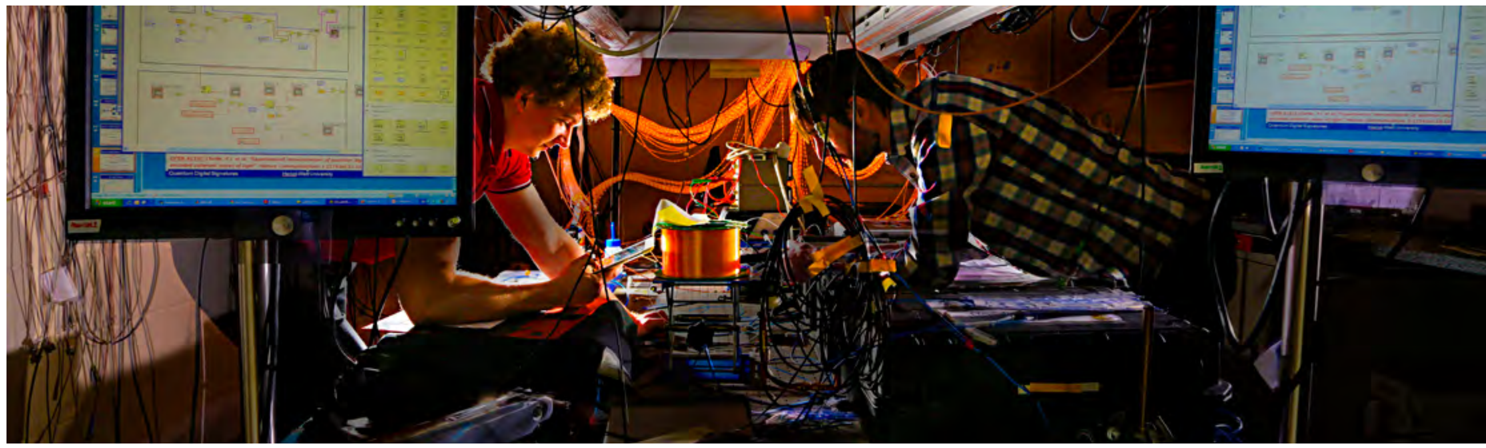
Craft Prospect's earliest collaboration with the Hub was in 2017, ahead of their successful bid for an Innovate UK funded study to look at the commercial and technical feasibility of deploying CubeSats to deliver QKD (part of future communications networks project AQKD – Augmenting QKD with nanosatellites). The company credits engagement with the Hub for gaining an understanding of the quantum technology landscape within the UK and opportunities for smaller satellites to contribute to wider quantum communication goals and capability. The company then formed a consortium with several Hub partners and industry to propose an In-Orbit Demonstration (IOD) mission in part funded by the Satellite Applications Catapult to investigate how CubeSats could operate and provide value in QKD networks.

During Phase 1, Craft Prospect was an industrial partner on a Hub Partnership Resource funded project 'CubeSat QKD and Ground Stations' working closely with Hub partners, the Universities of Bristol and Strathclyde, to provide space systems engineering knowhow for miniaturising QKD systems. Through Hub and UKSA support, Craft Prospect sought to begin the real engineering challenge of taking these demonstrations of quantum technology from the lab into an industrial setting for space applications. The work culminated in a technology roadmap, tested engineering model and terrestrial demonstration of a CubeSat QKD system and optical ground station. In 2020, the Hub established discussions between a consortium led by Craft Prospect with Hub partners the Universities of Bristol and Strathclyde, and the University of Waterloo, in the context of the joint UK/Canada Quantum Technology Programme CR&D competition. The successful submission, project JADE, aimed to implement a new approach and protocol that improves the integration and alignment of a satellite quantum transmitter. The technology developed on this project will be tested on the Canadian QEYSSat mission. Partners on the Canadian side include Honeywell, the Canadian Space Agency and Ontario Research Fund Excellence.

Craft Prospect is currently involved in a number of high-profile collaborative quantum projects. Following the award of the IOD mission, the company is now leading efforts to deliver a complete payload for the mission thanks to the UK Space Agency National Space Innovation Program. It also led the ISCF project 'PRISMS' (Protocol Randomness and Information Security Measures for Space) addressing the vulnerability of nanosatellites or small hosted payloads to backdoor attacks on quantum payloads.

Speaking about Craft Prospect's partnership with the Hub, Steve Greenland, Managing Director of Craft Prospect said:

"The emergence of QKD will mark an important and further stepping stone towards radical new capabilities for quantum-enabled sensing and computing underpinned by a future communications infrastructure. Taking these demonstrations from the lab into robust and secure space systems presents a fantastic engineering challenge and commercial opportunity for our business. The Quantum Communications Hub has been a fantastic resource for us to engage with in our start-up and scale-up journey, allowing our whole team from graduate through to myself to upskill in this strategically important area and contribute our own expertise in space systems. We look forward to further opportunities to align our capabilities to their growing network developing unique offerings for global markets within the UK."



Case Study: the partnership with KETS

KETS Quantum Security Ltd is an award-winning start-up aiming to enable future-proofed, ultra-secure communications for devices and networks through the commercialisation of integrated photonic technologies. The company's chip-scale QKD device has low size, weight and power (SWaP) requirements. Because it is manufactured in standard semiconductor foundries, it can be easily integrated into modern electronics and is a flexible and scalable option for cryptographic key distribution. The device enables equipment manufacturers to build a variety of new quantum secured products, with the integration of KETS' chips, which can be utilised for secure communications in data-sensitive sectors. KETS' patented product range also includes a high-speed Quantum Random Number Generator which can provide Gbits/sec cryptographic-grade entropy at low cost and with low SWaP requirements, meaning it can be seamlessly integrated in a range of devices.

KETS is a direct spinout of the phase 1 Hub (2015). The founders of the company were based at the University of Bristol and led the world's first chip-to-chip demonstration of QKD by the Hub [35]. The demonstration saw cryptographic keys securely exchanged using microchip circuits able to control, communicate and detect quantum states of light. The chips were created using components and manufacturing processes already used within the telecom industry, therefore paving the way for large-scale integration of QKD devices within conventional consumer devices and telecommunications networks. Having built a prototype QKD device as part of the Hub programme, KETS was created to focus on commercialisation. The company has remained closely involved with the Hub, collaborating on many projects and leveraging access to the UK Quantum Network to test and validate their devices.

KETS has been a quintessential entrepreneurial success story and to a large degree the inspiration behind the University of Bristol's QTEC (Quantum Technology Enterprise Centre) innovation incubator scheme. This success is manifested through numerous industry awards and realisation of funding from various funding rounds. In parallel, the company has fast become a key collaborator in many large-scale, strategic projects in the area of quantum secure communications, both within the UK (projects Q-DOS Light, ViSatQT, AQuaSec, AQuRand, and others) and internationally. KETS led the UK side of the 'Building a standardised quantum-safe networking architecture' project, jointly funded by Innovate UK and the NSERC in Canada. The aim was to combine quantum-aware networking architectures and software systems developed independently in Canada at the University of Waterloo and in the UK by the University of Bristol, as well as incorporate QKD and PQC technologies and designs from both countries in order to develop a Canadian-UK secure network built on the security principles of quantum-safe technologies. KETS has also opened an international office in Paris, France to support the ParisQCI national testbed project.

Speaking about KETS' partnership with the Hub, KETS' CEO, Chris Erven, said:

"The Quantum Communications Hub was fabulously supportive of us, first as academics with our world first chip-to-chip QKD experiments, and then even more so when we created KETS to commercialise this technology and get it out into the real world protecting our private information. We continue to be proud industrial partners of the Quantum Communications Hub which enables us to access the UK national quantum network, keep abreast with and contribute to the latest cutting-edge quantum communications research, and grow our team from the wonderful talent the Hub is producing. With the support of the Hub, the UK's National Quantum Programme, and the wider quantum community we're realising our dream of providing a quantum-safe future."

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Case Study: the partnership with NPL

The National Physical Laboratory (NPL) is the UK's national metrology institute, with responsibility for developing and maintaining the national primary measurement standards. It is also home to the Quantum Metrology Institute (QMI), bringing together all of NPL's leading-edge quantum science and metrology research, to provide expertise and facilities for the UK's industry and academia to test and validate new quantum technologies, ahead of commercialisation.

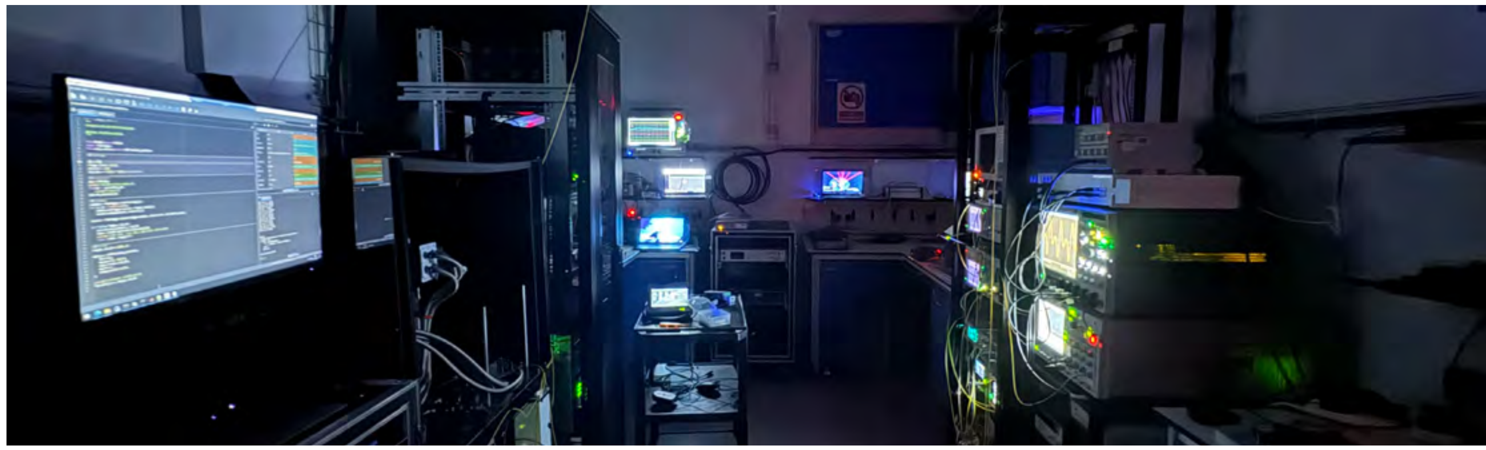
NPL has been a major delivery partner of the Hub's work since phase 1. The Quantum Communications Hub is the only one in the network of Hubs with dedicated investigative activity focused on the development of industrial standards for the sector, a natural outcome of the commercialisation readiness potential in this field. A number of Hub researchers and students have been seconded to NPL, working closely with NPL metrology experts to develop and implement methods for characterising quantum communications hardware, addressing laboratory prototypes including chip-scale devices, as well as systems deployed on the Hub's UKQN*tel* network. NPL is a member of the ETSI Industry Specification Group for QKD, members of which sit on the Hub's advisory board. Test standards developed by this group will be used to verify and validate system performance, thus providing a mechanism for QKD to become trusted in the marketplace, deployed by service providers and used with confidence. The work with the Hub has contributed to expertise that NPL has brought to ETSI, such as the Group Specification on QKD component characterisation and ETSI White Paper on implementation security of quantum cryptography [55].

Beyond testing hardware on Hub networks and work on standards, a major area of NPL/Hub collaboration relates to Quantum Random Number Generators, building on foundations established by a Hub Partnership Resource funded feasibility study. That study led to the AQuRand ISCF project on Assurance/Certification of QRNGs, co-ordinated by NPL and involving Hub partners, and the National Cyber Security Centre in an advisory role.

NPL's involvement in quantum communications field trials predates their collaboration with the Hub; in 2014, as part of an Innovate UK funded project (with BT, ADVA, Toshiba), it participated in the UK's first successful trial of QKD over a live 'lit' fibre network. Since then, NPL has lent its expertise to many large-scale quantum networking projects within the UK (AQuaSec, 3QN, AIRQKD) and abroad (OpenQKD – which created and tested a prototype pan-European quantum network infrastructure). NPL was a partner in the European Metrology Programme for Innovation and Research project MeTISQ, which developed SI-traceable measurements for QKD systems and technologies to support standards development. And it is involved in the European Metrology Network for Quantum Technologies which aims to co-ordinate European measurement science research to maintain competitiveness in quantum technologies. Recently, NPL launched the 'Measurement for Quantum' programme which aids the development of quantum products and services in the UK by offering quantum measurement advice and short-term measurement projects to companies at no charge. Through this programme, NPL aims to bridge the gap between prototypes and market-ready products and thus facilitate more products going to market, more quickly, within the UK.

Speaking about NPL's partnership with the Hub, Head of the NPL Quantum Metrology Institute, Rhys Lewis, said:

"The collaboration between NPL and the Quantum Communications Hub is an important part of the National Programme. We are very appreciative of the resources which the Hub has placed alongside NPL scientists and are very pleased to offer an additional environment for research and training. The wider collaboration between our two organisations and the quantum community will undoubtedly grow in importance and value to the UK over time."



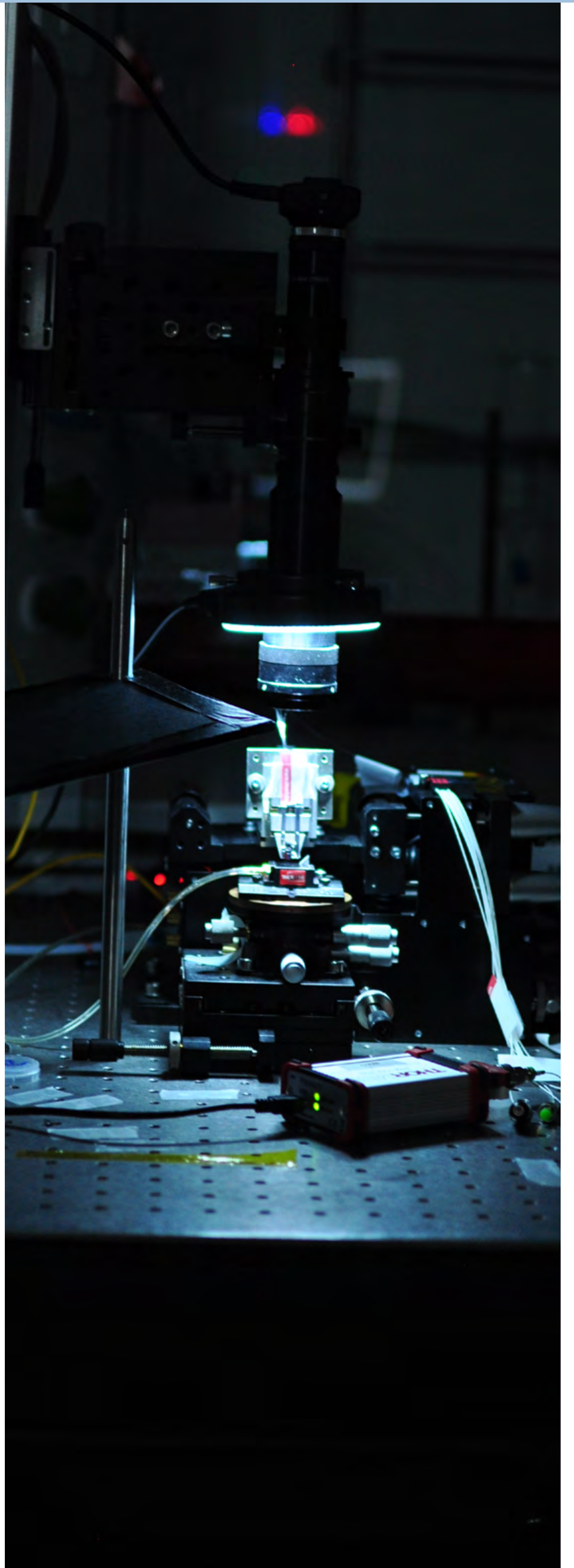
Impact: Assurance technologies principles for the quantum communications sector

In late 2021, the UK's National Cyber Security Centre (NCSC) published a White Paper[60] outlining a new approach to technology assurance and plans for its implementation. This approach partly arose following the publication of the 2021 Integrated Review of Security, Defence, Development and Foreign Policy[61] which emphasized the need for "cutting edge cyber capability" and outlined the UK's ambition to become a "science and technology superpower" by 2030. NCSC acknowledged that the technology assurance systems in place at the time fell short of enabling this ambition and so a new approach to the assurance of cyber security technologies had to be implemented. For this to happen, a paradigm shift was necessary.

The new approach introduced by NCSC focused on demonstrable outcomes that reduce the risk of systemic cyber security failures. It was termed Principles Based Assurance (PBA) and comprises three main pillars: development ("an assessment of the security of the vendor and where appropriate this would include the security of the development environment"); design & functionality ("an assessment of the resilience of the product to cyber attack and the efficacy of any security functionality"); and through-life ("an assessment of how well the security of the product or service will be maintained during its operational lifetime"). Importantly, these technology assurance principles are not meant to apply to security products alone, but rather to all inter-connected technologies whose potential compromise could have a significant security impact.

Quantum Communications Hub investigators considered the application of these principles in the context of quantum communications technologies, and produced annotated versions of the NCSC documentation with added commentary on quantum implications where necessary[62]. The purpose of these Hub documents is to highlight, with comments and examples, particular aspects of the NCSC principles that should be considered, or expanded upon, for quantum security products.

Many of the comments and additions provided to the original NCSC principles text raise the important matter of quantum side channels, as identification and understanding of these is crucial for quantum-security-product assurance. This highlights the most important area of focus for the assurance and certification of existing quantum security products. However, in addition, it also highlights the desirability and importance of future device-independent technologies that leverage quantum entanglement. Within these systems, many of the current side channels will not exist, making these systems much easier to assure and certify.



Impact: Contributions to policy development

The 2017 Public Dialogue in Quantum Technologies[63] highlighted regulation and policy development around them as one of the key concerns and priorities that the public had towards these emerging technologies and applications. This was already anticipated in the UK's original national quantum technologies strategy of 2015 which sought to create "the right social and regulatory context"[64] for adoption. Like other stakeholders of the national programme, Hub investigators have been aware of this challenge and have responded to it by contributing to discussions around policy development both nationally and internationally. Specifically, they have:

- Provided input to the European Commission Future and Emerging Technologies Unit as early as 2015, followed by further expert discussions (at e.g. the 7th European Innovation Summit) about responsible exploitation of quantum technologies, which ultimately led to a Pact for Innovation and the 2016 Quantum Manifesto that preceded the creation of the €1B EU Quantum Flagship investment programme.
- Contributed significantly to the 2016 Blackett Review (The Quantum Age: technological opportunities)[52] issued by the Government Office for Science, and have since acted on its recommendations for joint technical development and integration of quantum and mathematical cryptography; pilot trials of quantum key distribution in real-world environments; continued work on standards and testing towards accreditation; and further engagement with end-user sectors such as the finance industry.
- Submitted oral and written evidence to the Government Science and Technology Select Committee's various inquiries into quantum technologies (2018, 2023/24) and the societal issues pertinent to their commercialisation. Separately, they contributed to the 2020 'Future Horizons for Photonics Research 2030 and beyond' report[65] published by The Photonics Leadership Group and the All-Party Parliamentary Group in Photonics and Quantum.
- Contributed to the 2021 Emerging Technologies report published by Ofcom[66] and the Financial Conduct Authority's report of the same year on the impact of quantum information technologies on the sector.
- Held extensive consultations with the Regulatory Horizon Council team ahead of the publication of their 2024 Regulating Quantum Technology Applications report[23].
- Worked extensively with the Cambridge Centre for Science and Policy on discussions around the impact of quantum technologies with stakeholders of commercial and public policy backgrounds.
- Provided expert reviewer input on the drafting of the Singapore national quantum strategy and held discussions with Canadian colleagues on the evolution of their national strategy.
- Participated in specially convened government advisory groups to help map out future policy, including in the areas of telecommunications, defence and quantum literacy in education.
- Worked closely with the National Cyber Security Centre to issue guidelines on added considerations for adopting NCSC's technology assurance principles for the quantum sector.
- Responded to the Government's call for evidence to help shape the next, third phase of the national programme and the country's future quantum strategy (published in 2023).

Impact: Establishment of new research capability

In June 2016, the Quantum Communications Hub and KTN organised an international workshop on Satellite Quantum Key Distribution (QKD) at ECSAT on the Harwell campus. The event brought together leading researchers in Satellite QKD from around the world to present their latest developments, providing a snapshot of the current state of the art, and – in so doing – confirming the strength of research across Europe, Asia (notably Japan and Singapore at that time) and Canada.

Also confirmed was the lack of any comparably substantial UK research in the field at the time. The UK had in fact been a pioneer in establishing the feasibility of long-distance free-space quantum communications through EU-funded collaborative projects. However, dramatic reduction in both EU funding and ESA commitment to free-space quantum communications contributed to the lack of substantial further development in the UK. Work was continued by other leading countries, notably Austria, Germany, Italy, and, a little later, Canada – all of whom presented at the June workshop, and all of whom subsequently confirmed a willingness to collaborate with the Hub.

The absence of this research of any kind in the Hub's phase 1 development programme was a reflection of the gap in UK capability - with larger, strategic, implications. At the time, the UK was not unusual in this respect but this state of affairs swiftly changed following sustained international investment into quantum (coupled with active industry interest) and, importantly, the launch of the Chinese Satellite QKD mission in August 2016 – the most dramatic expression of Chinese strategic commitment into the emerging technologies, which ranges from space and large scale (2000+ km) terrestrial fibre networks, to secure defence communications.

So by mid-phase 1, the international landscape was already very different to how it was at the start of the national programme: China, with a fully-fledged satellite QKD mission, focused on research and demonstration; Japan, with a discreet but active small-satellite programme demonstrating QKD science; Canada, committed as part of a new national quantum technologies programme (largely influenced by the NQTP), to a quantum communications mission; Germany, with an established ESA programme (EDRS, then GlobalNet) committed to multiple satellites for other purposes (and proposing that these be adapted for use in satellite QKD); Switzerland, then at the second stage of development towards a Swiss quantum communications satellite; Singapore, committed to the use of small satellites for its own advanced photon sources; ESA, having announced a new Programme (Scylight) for optical/quantum communications and including a 3-year satellite communications project with a QKD research mission led by a commercial consortium.

In the UK, although growth of the space sector itself is a national strategic priority, and satellite communications one of the central application areas within it, up to 2017 there had been little attention to satellite quantum communications. It was obvious therefore that there were significant and distinctive but entirely discrete national strategic objectives, programmes and investment in three related areas: space; satellite communications; quantum technologies. Satellite quantum communications was not included in any of these.

This would soon change, as developments in the UK started to reflect increasing interest in, and the perceived importance of, satellite quantum communications. These included: investment of £99M via ISCF in the creation of a new National Satellite Testing Facility (NSTF); UK Government commitment to ESA and its programmes; UK Space Agency initiative to secure a new ESA Quantum Space Lab for Harwell; commitment of major industry players to the commercial case for satellite QKD – notably, and compellingly by BT, as both consumer and reseller of service – globally; establishment of a modest EU programme of research (QUANTERA) development where the UK played a leading part; the initiative to develop a sector deal for the space industry, which included satellite applications in sensors and in quantum communications; proactive development by STFC of international collaboration – primarily with Singapore; willingness of other countries with strategic commitments to satellite quantum communications to collaborate with the UK across research, development, innovation and exploitation.

The UK already had significant strengths in a number of key areas: in the fundamental science of quantum communications, including world-class research in photonics, optical communications and QKD across universities and industry (then focussed on terrestrial and short-range free space communications); in world-class commercial facilities for building satellites and the integration of payloads; in collaborative international research; new capability in testing through the NSTF at the Harwell Space Cluster; experience in the operation and management of commercial satellite communications services.

Therefore, the timing was right for a national initiative, given recent structural changes to the funding and support of collaboration between research and industry with: UKRI providing the framework for coherent strategy and planning in research and research impact; the UK Innovation Strategy providing the stimulus for large-scale development; the Industrial Strategy Challenge Fund providing the mechanism for funding both research and development, and research-led, but industry-driven implementation on the necessary scale.

The Hub organised a number of meetings with senior stakeholders of the national programme to present this position and propose the integration of a coherent package of work around quantum technologies in space – starting with communications and sensors as the two areas closest to practical implementation – as an integral part of the national quantum technologies programme. Such a programme would embrace: research, building on core UK scientific strengths, and enriched by international collaboration; industry and engineering, adapting manufacturing strengths to new devices/components; testing and space qualification, exploiting new and prospective UK-based facilities; capitalizing on UK strengths in cross- and inter-disciplinary work to develop operational models for new commercial applications; full participation in ESA initiatives designed to support satellite optical/quantum communications; commercialisation.

By the end of phase 1 in 2019, these ideas had matured to fruition with the UK Government announcing[67] a £10M UK/Singapore bilateral satellite-based Quantum Key Distribution collaboration (the Speqtre mission), eventually coming under the auspices of the national programme. As part of this joint programme of work, Singapore would provide the quantum communications technology, while STFC's RAL Space would contribute its expertise in space engineering technology.

In turn, the Speqtre project provided the engineering model for the Hub's own satellite mission (SPOQC), replicating the non-quantum space engineering work with corresponding cost savings, allowing Hub researchers to propose a boldly innovative research plan of dual quantum payload technology development as part of their phase 2 programme of work, thus firmly establishing new UK R&D capability in this exciting area and confirming the UK as a worthy collaboration partner in future international missions.

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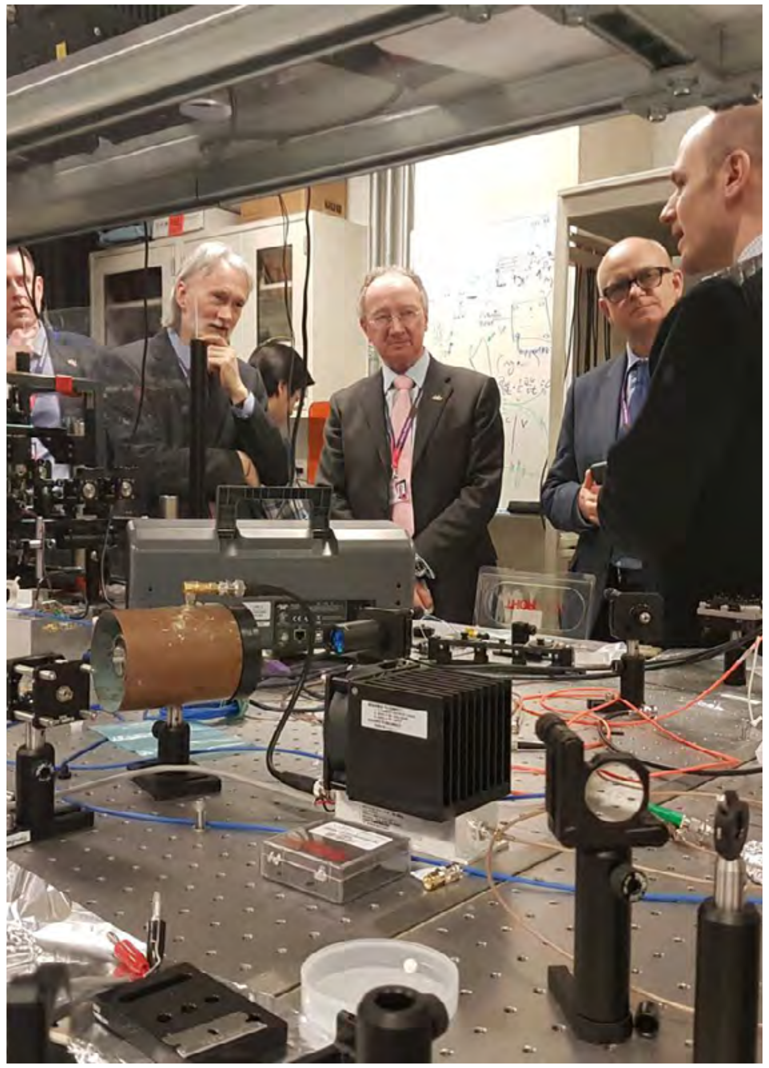
International engagement

International engagement has always been a key tenet of the National Quantum Technologies Programme. It was listed in 2015 as one of five areas requiring further action in the original national strategy for quantum technologies[64], through reference to "maximising benefit to the UK through international engagement". It was reiterated in the NQTP Strategic Intent document of 2020[3] as a central objective towards achieving the programme's long-term vision ("Build a resilient network of national assets and mutually beneficial international relationships"). And it was consolidated as an essential approach in the UK Government's 2023 new national quantum strategy[5], where a whole section was dedicated on international partnerships.

The Hub has been engaging with individuals, institutions and companies involved in various international initiatives (whilst being aware of ITAR or export control considerations), for both development and exploitation. These efforts have been supported throughout the last decade via a number of targeted approaches:

- Expert input from international experts in the Hub's External Advisory Board from the outset and throughout the project lifetime (NTT Basic Research Labs, Japan; Tyndall Institute, Ireland; University of Waterloo, Canada; ETSI, Europe);
- Active participation in NQTP global expert Quantum Technology missions to Canada in 2018 and the US in 2019. More recently (2023), the Hub took part in a third expert mission to the US, organised with a sole focus on quantum networking and resulting in a firm plan for a follow-up workshop to shape up future collaboration in this area;
- Involvement in numerous UK/Japan quantum technologies workshops, in person and online, in 2015, 2016, 2022 and 2024. Signing of an MOU between the Hub lead partner the University of York and Japan's NICT during the 2016 trip;
- Hub organisation and hosting of key international user engagement events including: the International Satellite QKD Technologies Workshop (2016), the ETSI/IQC Quantum Safe Workshop (2017), the 7th QCrypt – International Conference in Quantum Cryptography in 2017, the QTX-3: Quantum Technologies in Space international workshop in 2019, the QNetworks series of international technical workshops (in 2020, 2022, 2023);
- Hub strategic investment of partnership resource funds in projects with potential to lead to large-scale international collaborations such as satellite research infrastructure (MOU between Hub partner Heriot-Watt and University of Waterloo managing the QEYSSat Canadian space mission) or large-scale terrestrial fibre networking (UK/Ireland underwater quantum communications link);
- Hub development of its Optical Ground Station in Scotland as a long-term facility with the potential to also be used by international research teams with relevant interests;
- Substantial involvement in the development of industry standards for the emerging technologies, which by definition are discussed at international level;
- Joint organisation with the other UK Quantum Technology Hubs of the inaugural International Summer School in Quantum Technologies (ISSQT) in the summer of 2023 for UK and Canadian students to stimulate knowledge exchange;
- Expert advisory input into the drafting of foreign national quantum technology strategies (Canada, Singapore, EU Quantum Manifesto leading to the EU Flagship) by members of the Hub leadership team;
- Numerous academic collaborations with researchers in EU, Australia, Singapore, China, Canada and the US, alongside involvement into large-scale consortia such as the EPSRC International Network in Space Quantum Technologies, led by Hub investigator, Dr Daniel Oi.



User engagement

The main focus of the national programme has been to address specific user application needs, through quantum technology solutions offering superior functionality compared to their classical analogues. It follows then that in-depth understanding of user requirements across the quantum communications sector would be pivotal to the success of the Hub. To this end, the Hub leadership team has put in place a considered user engagement strategy that has been expansive, creative, iterative, evolving and informed by both national and international developments. Over the last decade, the main aspects of this strategy have been:

- Appointing an experienced business development manager with responsibility for overseeing and growing the Hub's partnership with industry;
- Partnering with an expansive industry base from global corporations to SMEs and organisations responsible for development of industrial standards (NPL/ ETSI);
- Embedding industry into the Hub's programme of work (ADVA, BT, Toshiba as key delivery partners in the implementation of the UK Quantum Network; NPL in hardware security, metrology and standards);
- Developing a coherent communications strategy with bespoke resources, strong social media presence and a sophisticated website with different portals into distinct content areas specially customised for research, industry/government/media, and wider community/school audiences;
- Overseeing the strategic allocation of partnership resource funds towards new collaborations exploring technology development into new areas and new sectors, beyond the scope of Hub work;
- Collaborating with industry on large-scale Industry Strategy Challenge Fund projects, many of which were seeded through Hub-funded feasibility studies;
- Delivering a huge range of user engagement events, ranging from small-scale specialist technical workshops (e.g. on Quantum Digital Signatures or CV QKD) to expert stakeholder meetings (IQC/ETSI Quantum Safe Cryptography conference), and from big, international conferences (QCrypt, QNetworks series) to exploratory events bringing diverse communities together (workshops on quantum communications in space, joint workshop with NCSC on cyber security and quantum communications). The Hub is also responsible for shaping the National Quantum Technologies Showcase into the event that is today, after it undertook its organisation in 2016 and expanded the delegate base and exhibiting scope;
- Working closely with the other Hubs (and DSIT – formerly BEIS - plus Innovate UK) to understand industry needs in specific sectors (energy, defence, finance);
- Engaging with stakeholders of other large-scale infrastructure projects (e.g. the National Dark Fibre Facility) to help develop a strategic and joined-up approach for the country's communications infrastructure;
- Remaining aware of international developments through extensive participation in expert missions, conferences, consultations, research collaborations and of course international representation on the Hub's advisory board;
- Interacting thoughtfully initially with GCHQ and latterly with NCSC (and National Protective Security Authority) to represent the potential of quantum (and post-quantum) safe technology approaches to national security, and act as an advocate for, and intermediary on behalf of, the wider quantum community and industry;
- Providing input into various national-scale consultations relevant to the Hub's work;
- Using the Hub's quantum networks as testbeds for demonstrations of prototype technologies.

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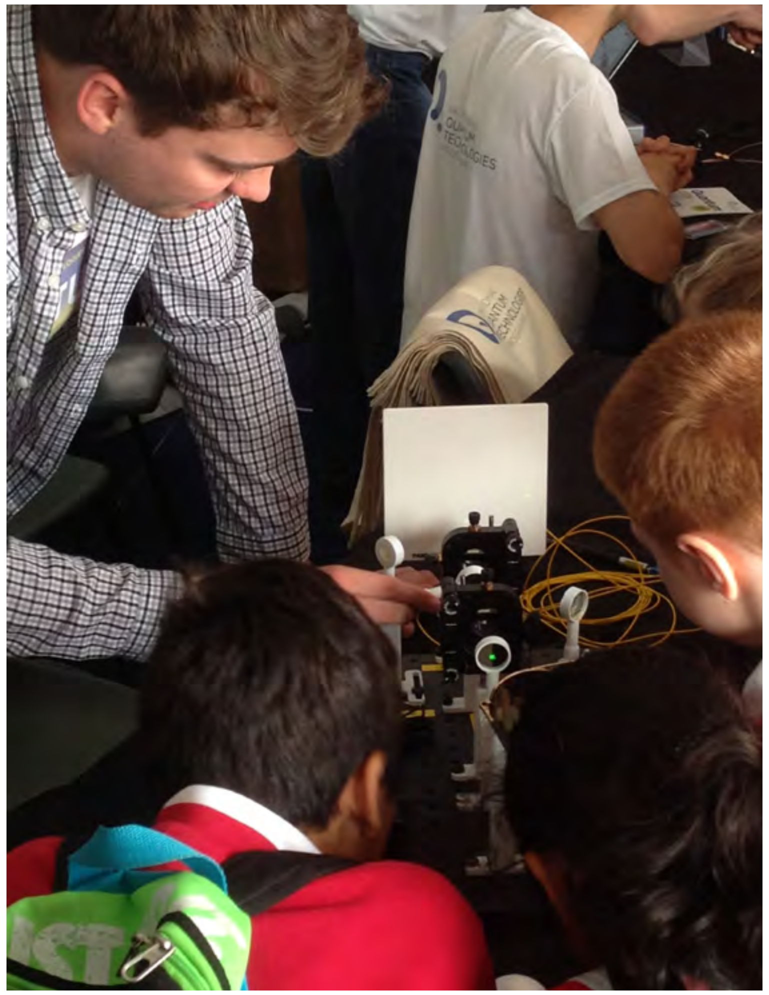
Public engagement

Hub engagement with stakeholders beyond those in the research and industry communities has been facilitated through a considered and continuously evolving communications and outreach strategy. This focused on: publicising the work of the Hub in an accessible manner to the widest audiences possible; disseminating the key messages of the national programme on the benefits of the emerging technologies and the many applications across numerous economic sectors; and encouraging student interest with the aim of inspiring the next generation of quantum technologists. Implementation of this strategy revolved around a multi-channel approach to convey key messages to the audiences identified. Specifically, and over the last decade, the Hub has developed:

- A partnership with the National STEM Learning Centre and University of York Science Education Group to implement and evaluate a comprehensive scheme of quantum-related CPD and classroom based activities for A-level students and their teachers, highlighting the benefits and applications of mature quantum technologies and signposting career pathways for science graduates. In its latest iteration, the scheme has been adopted by DSIT for a pilot school rollout at national level.
- A dedicated Wider Community & Schools portal on the website employing accessible language and incorporating lots of information on technology applications, explainers on the principles behind quantum communications, FAQs, specially developed school and careers resources and a blog featuring interviews with role models from the national programme quantum community about their career trajectories.
- Targeted outreach activities, making an effort to prioritise hard-to-reach groups through collaborations with outreach officers across all academic institutions in the partnership and charities such as the Ogden Trust. And purposeful involvement in science festivals such as New Scientist Live North and regional initiatives, aimed at expanding public engagement beyond the capital.
- Substantial support, alongside the other Hubs and NPL, for the Quantum City initiative, which has come to represent the public engagement arm of the national programme, and which seeks to raise the profile of quantum technologies amongst the public and schools, to inspire the future quantum workforce and facilitate discussions about the role of these technologies in society. Since it was established in late 2017, and withstanding the pandemic disruption, Quantum City has engaged with over 18,000 visitors at outreach events and has recently launched a brand new interactive website[68].



- Established partnerships (including through Quantum City) with STEM Learning Hubs collaborating on a series of online assemblies on careers in quantum with over 50 schools registered to take part; and with the Royal Institution for a programme of quantum specific activities, including panel discussions and exhibitions.
- Continued promotion and financial support for impactful outreach activities developed by Hub partners, e.g. the Careers in Quantum jobs fair and the Quantum in the Summer schools engagement programme, both hosted by the University of Bristol over a number of years with considerable success.
- Targeted outreach demonstrators such as the Heriot-Watt Atomic Architects exhibit specially developed for the Royal Society Summer Science Exhibition (2017) to explain the fabrication of nanoscale devices. And the Macrophoton teaching aid, developed in 2018 by Heriot-Watt Hub researcher, Dr Robert Collins, who used the concept of photons scaled to the macroscale to explain the principles behind quantum communications. In 2019, the Macrophoton demonstrator won the Heriot-Watt University Principal's Public Engagement Prize in the Public Engagement Partnership category.

RRI, EDI and Research Culture

Since the outset of the National Quantum Technologies Programme, the creation of the "right social and regulatory context" for these emerging technologies has been central to its strategy. Addressing this challenge has been particularly pertinent to the work of the Hub given that data security raises (potentially different) issues for individuals, institutions, companies and governments.

During Phase 1, the Hub team engaged extensively with the other Hubs and in particular the Oxford-led NQIT (the predecessor to the Quantum Computing and Simulation Hub), which had dedicated research activity investigating Responsible Research and Innovation (RRI) for the quantum community. Through a series of meetings and workshops, Hub researchers reflected on the societal challenges associated with this area of research, offering views on potential issues and mitigating actions, in line with EPSRC's AREA framework guidance[69].

This activity was followed by EPSRC commissioning a public dialogue into quantum technologies, which was carried out in 2017/18 by Kantar Public – an independent social research agency – with the aim of introducing members of the public to the capabilities of the technologies under development, and understanding any concerns, aspirations and priorities relating to their future implementation and eventual deployment. As part of this process, the Hub organised two waves of reconvened, full-day public workshops and an interim activity (a technical demonstration of quantum secured video transmission between two users and intercepted hacking attack, organised with partner BT). Participants included trained facilitators from Kantar, expert stakeholders from the Hub and a diverse (in terms of age, gender, ethnicity, socioeconomic status and interest in science) group, randomly selected from members of the public, and with no (required) previous knowledge of the subject matter. Although the potential use of quantum communications applications in the context of a global "arms race" or by criminal/terrorist groups was raised as a concern, overall the group were very vocal about the need for this technology to be prioritised and for UK investment in this area to counteract the threat posed in cybersecurity by developments in quantum computing. Overall, the results of the public dialogue[63] were hugely informative in shaping the Hub's future research planning and introducing teams into the concept of co-creation.

This approach, of reflecting on key challenges and priorities for different stakeholder groups in this application space and identifying effective ways of addressing them, has underpinned the Hub's approach into the second phase of its operation. In practice, this was manifested through a programme of work that was founded on the legacy of phase 1, now substantially expanded to incorporate next-generation quantum networking technologies at all distance scales for different sector needs, coupled with an underlying strong focus on security of devices, systems and end-to-end, and embracing: work on metrology, calibration and worldwide certification of standards for industry; integration of quantum and post-quantum technologies; cryptographic and security analysis, vulnerability analysis and testing, combined with the development of countermeasures. The breadth of multidisciplinary expertise from the cybersecurity, quantum and classical communications communities has been mirrored in the expansion of the Hub's partnership base through new industrial partners, government organisations and international collaborators.

The Hub's commitment to the theme of co-creation has been reflected by renewed focus on its relationship with industry, user engagement strategy, and targeted outreach initiatives, but also approach to Equality, Diversity and Inclusivity (EDI), and research culture. The Hub has been committed to the promotion and implementation of EDI principles across all aspects of its operation, with a strategy that has been constantly undergoing review and iteration, continued investment of resources towards the development of appropriate materials and support of relevant schemes; and consideration of the EDI impact of all policies. The Hub has established and promoted structures advocating equal opportunities, progress and success for all, ensuring that this approach has the widest reach possible. Specifically, the Hub has:

- Promoted a strong EDI ethos in recruitment and training, including through support of flexible working arrangements, wide-ranging advertising of all vacancies, and diverse interviewing panels;
- Integrated EDI in everyday practice through: promoting a good work/life balance, diverse representation in the Hub's governance structures and decision-making bodies, advance notice for all meetings which take place during core hours and with provision for hybrid participation, accessible venues and use of digital accessibility technologies;
- Supported continued professional development, career progression and wellbeing, through mentorship, investment in resources and specialist training, allocation of generous budgets for collaborative travel and conference attendance to promote networking, full acknowledgement of personal contributions, support for the Research Development Concordat and Technician Commitment Charters, alongside the emerging PRISM network for research support professionals;
- Embedded EDI in all communications materials, promoting relevant principles, such as accessibility, inclusive language and imagery, allyship to raise awareness and help effect change especially for disadvantaged minority groups;

- Implemented targeted outreach for hard-to-reach groups and promoted the STEM agenda through initiatives such as the Quantum STEM Ambassadors programme, school assemblies and careers resources;
- Made EDI a matter of personal responsibility.

Beyond the success of these RRI and EDI activities, the impact of the Quantum Technology Hubs network in general and our Quantum Communications Hub more specifically is evident in the initiatives implemented that relate to wider research culture. These include:

- Developing new models of working with partners, e.g. through having an industry leader oversee the quantum networking activities (Toshiba, phase 1) and seconding researchers at NPL, thus creating a template for future collaborations with stakeholders outside academia;
- Working closely with the National Protective Security Authority (formerly CPNI) to promote principles of Trusted Research guidance across all Hubs' partnerships;
- Focus on developing and sharing best practice policies at the operational level across the network of Hubs, through regular meetings of various groups – Hub Directors, Business Directors, programme managers, communications officers;
- Substantial support for skills and training initiatives through: specialist courses, strategic allocation of studentships, investment in PhD+ mini training fellowships;
- The Hub taking on the role of advocate for the quantum communications community, as exemplified by the coordinated publication of a community response to NCSC's position on QKD; and the published work applying NCSC's technology assurance principles in the quantum communications sector.

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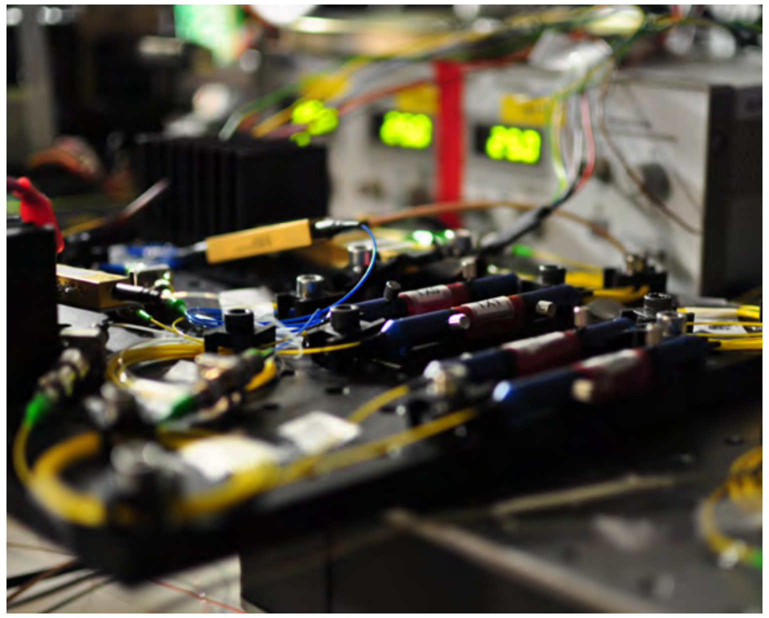
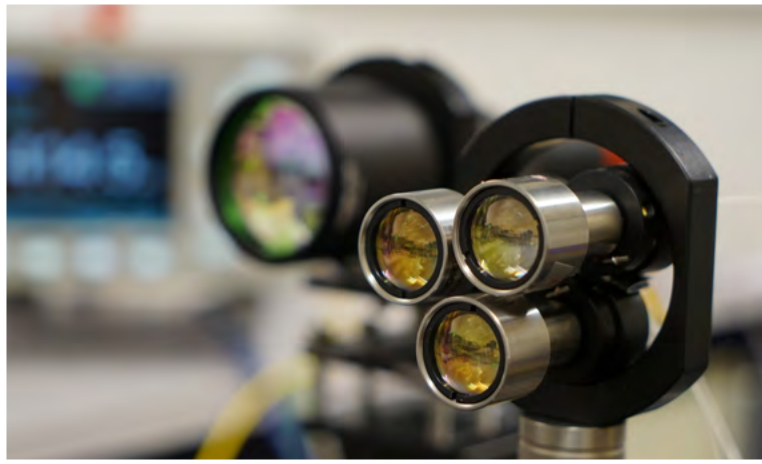
The Future: moving towards Integrated Quantum Networks

Publication of the UK Government's new national quantum strategy in 2023 [5], which set out a next ten-year vision and plan for quantum in the UK with a commitment to spend £2.5B towards research, innovation, skills and other supporting activities in that period, secured the continuation of the National Quantum Technologies Programme into a third phase (2024-29). At the same time, it provided a framework for future direction, through publication of five quantum strategy missions for the country [6]. Mission 2, which specifies that *By 2035, the UK will have deployed the world's most advanced quantum network at scale, pioneering the future quantum internet*, was developed with input from Hub investigators and industry partners and clearly builds on previous work, the foundations of which have been laid in the last decade.

Following confirmation of the funding for a third phase and specific reference to £100M allocated to the creation of new Quantum Technology Hubs in the new strategy, the Engineering and Physical Sciences Research Council launched a funding call in early 2023, inviting proposals against three broad scope areas: quantum networks for distributed entanglement; quantum computing research to improve quantum computing performance; and engineering quantum technology devices and components for sensing, imaging, positioning and timing. A core team of current Hub investigators took the lead in creating a new consortium, bringing in new partners and industry support, to work on an ambitious proposal addressing the first scope area, covering quantum communication, computing and sensing approaches and including underpinning technology in control systems, and integration.





Led by the research team at Heriot-Watt University, this new Integrated Quantum Networks (IQN) Hub will lay the foundations for a quantum internet, where entanglement distribution and quantum memories will enable secure and scalable links between quantum computers, improved quantum communication and distributed quantum sensing. Its vision is to extend quantum entanglement networks to national scale, and eventually secure global interconnections facilitated by satellites. The five-year goals of the project include demonstration of a multi-node metropolitan-scale network; the use of existing fibre networks to create multi-user entanglement, implementing numerous quantum communications protocols; and linking entanglement networks to space via the current Hub's existing Optical Ground Station (HOGS). The IQN Hub will further develop critical quantum component technology to underpin future national supply chains, feeding the emerging quantum economy. It will invest in and contribute to the development of a future skilled workforce to support the expansion of the emerging quantum ecosystem. And it will translate cutting-edge research into expert input towards standards and policy formation, thus responding to new societal challenges arising from the emerging quantum technologies.

The IQN Hub will build on the foundations established by the Quantum Communications Hub, in the areas of both terrestrial quantum networks over standard optical fibre, and in space, via satellite, whilst also leveraging work in quantum memories generated in the phase 2 Quantum Computing and Simulation Hub. Further, it will continue the work of the Quantum Communications Hub on development of emerging regulatory standards for the quantum industry and by carrying out extensive work on post-quantum cryptography (with NCSC) to bolster national security.

Beyond the scope of the IQN Hub, the current Hub's legacy of know-how from both the UK Quantum Network and the IOD space mission, alongside the next generation of researchers trained through the Hub, will be valuable assets for future projects, industry-led initiatives and international collaborations.

Afterword

For all of us who have provided support, suggestions and challenge over the past 10 years, it has been a delight to see all the progress outlined in this report, and the many excellent outputs from the Hub. The coming together of individuals from academia, from different disciplines, from industry, small and large, and from government, all with differing views, to tackle head on the potential barriers to realising benefits, has been inspiring. In particular, how important is QKD, and why do physicists and those working in cyber security have different perspectives? Can we roll out a quantum network at pace that is capable of offering commercial services whilst leaving room for small companies to innovate and enter the market? Importantly the Hub has not just produced scientific, technological and policy outputs, but has resolved tensions and brought together the many skills and expertise needed for the UK to be at the forefront of quantum networking. The next chapter will be even more exciting.

Martin Sadler OBE
Chair, External Advisory Board
University of Bristol

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References

1. Moskvitch K. Four UK hubs to make 'spooky' quantum physics useful. *Nature* 2014. https://doi.org/10.1038/nature.2014.16426
2. Knight P, Walmsley I. UK national quantum technology programme. *Quantum Sci. Technol.* 2019;4: 040502 DOI: 10.1088/2058-9565/ab4346
3. *UK National Quantum Technologies Programme Strategic Intent*. 2020. https://uknqt.ukri.org/wp-content/uploads/2021/10/UKNQTP-Strategic-Intent-2020.pdf [Accessed 6th June 2024]
4. *New phase of UK quantum secure communications research and development announced.* https://www.quantumcommshub.net/news/new-phase-of-uk-quantum-secure-communications-research-and-development-announced/ [Accessed 6th June 2024)
5. Department for Science, Innovation and Technology. *National quantum strategy*. 2023. https://www.gov.uk/government/publications/national-quantum-strategy [Accessed 6th June 2024]
6. Department for Science, Innovation and Technology. *National Quantum Strategy Missions*. 2023. https://www.gov.uk/government/publications/national-quantum-strategy/national-quantum-strategy-missions [Accessed 6th June 2024]
7. Department for Science, Innovation and Technology, and Peter Kyle, MP. Over £100 million boost to quantum hubs to develop life-saving blood tests and resilient security systems (press release) 2024. https://www.gov.uk/government/news/over-100-million-boost-to-quantum-hubs-to-develop-life-saving-blood-tests-and-resilient-security-systems [Accessed 31st July 2024]
8. Bennett CH, Brassard G. Experimental quantum cryptography: the dawn of a new era for quantum cryptography: the experimental prototype is working! *ACM SIGACT News.* 1989;20:4:78–80 https://doi.org/10.1145/74074.74087
9. Bennett CH, Brassard G. Quantum Cryptography: Public Key Distribution and Coin Tossing. In: *Proceedings of IEEE International Conference on Computers Systems and Signal Processing*, December 1984, Bangalore India, pp 175-179.
10. Ekert A. Quantum cryptography based on Bell's theorem. *Phys. Rev. Lett.* 1991;67(6):661-663 DOI: https://doi.org/10.1103%2FPhysRevLett.67.661
11. Bouwmeester D, Pan JW, Mattle K, Eibl M, Weinfurter H, Zeilinger A. Experimental quantum teleportation. *Nature* 1997; 390:575-579 http://dx.doi.org/10.1038/37539
12. Jennewein T, Simon C, Weihs G, Weinfurter H, Zeilinger A. Quantum Cryptography with Entangled Photons. *Phys. Rev. Lett.* 2000: 84;4729 https://doi.org/10.1103/PhysRevLett.84.4729
13. Hughes RJ, Buttler WT, Kwiat PG, Lamoreaux SK, Morgan GL, Nordholt JE, Peterson CG. Free-space quantum key distribution in daylight. *Journal of Modern Optics* 2000;47(2–3): 549–562. https://doi.org/10.1080/09500340008244059
14. Hwang WY. Quantum Key Distribution with High Loss: Toward Global Secure Communication. *Phys. Rev. Lett.* 2003;91:057901 https://doi.org/10.1103/PhysRevLett.91.057901
15. Ursin R, Tiefenbacher F, Schmitt-Manderback T, et al. Entanglement-based quantum communication over 144 km. *Nature Physics* 2007; 3:481-486 https://doi.org/10.1038/nphys629
16. quiprocone.org. DERA Scientists achieve world record 1.9km range for free- space secure key exchange using quantum cryptography. (press release, now archived) 2001. http://www.quiprocone.org/pressrelease_JRarity.htm [Accessed 13th June 2024]
17. Kurtsiefer C, Zarda P, Halder M, et al. Long-distance free-space quantum cryptography. In: Liu S, Guo G, Lo HK, Imoto N (eds) *Quantum Optics in Computing and Communications*, SPIE, 25-31 (2002). DOI: 10.1117/12.483036
18. Duligall JL, Godfrey MS, Harrison KA, et al. Low cost and compact quantum key distribution. *New J. Phys.* 2006; 8:249 DOI 10.1088/1367-2630/8/10/249.
19. Marand C, Townsend PD. Quantum key distribution over distances as long as 30 km. *Optics Letters* 1995; 20:16, pp. 1695-1697
20. Townsend PD. Quantum cryptography on multi-user optical fiber networks. *Nature* 1997; 385:47
21. Townsend PD. Simultaneous quantum cryptographic key distribution and conventional data transmission over installed fiber using wavelength division multiplexing. *Electron. Lett.* 1997;33:188
22. National Physical Laboratory. Toshiba Research Europe, BT, NPL and ADVA explore 'quantum leap' in encryption technology (press release) 2014. https://www.eurekalert.org/news-releases/779742 [Accessed 13th June 2024]
23. Regulatory Horizons Council. *Regulating Quantum Technology Applications*. 2024. https://www.gov.uk/government/publications/regulatory-horizons-council-regulating-quantum-technology-applications [Accessed 13th June 2024]
24. University of Cambridge. Cambridge launches UK's first quantum network. (press release) 2018. https://www.cam.ac.uk/research/news/cambridge-launches-uks-first-quantum-network [Accessed 13th June 2024]
25. Dynes JF, Wonfor A, Tam WWS, et al. Cambridge quantum network. npj *Quantum Inf* 2019; 5:10 DOI: https://doi.org/10.1038/s41534-019-0221-4
26. Wonfor A, White C, Lord A, et al. Quantum networks in the UK. In: *Proceedings Volume 11712, Metro and Data Center Optical Networks and Short-Reach Links IV; 1171207* SPIE OPTO 2021 DOI: https://doi.org/10.1117/12.2578598
27. BT. Testing begins on UK's ultra-secure Quantum Network Link (UKQNtel) between research and industry (press release) 2019. https://newsroom.bt.com/testing-begins-on-uks-ultra-secure-quantum-network-link-ukqntel-between-research-and-industry/ [Accessed 13th June 2024]
28. Aguado A, Hugues Salas E, Haigh PA, et al. Secure NFV Orchestration over an SDN-Controlled Optical Network with Time-Shared Quantum Key Distribution Resources. *Journal of Lightwave Technology* 2017; 35(8) DOI: 10.1109/JLT.2016.2646921.
29. Toshiba. BT and Toshiba launch first commercial trial of quantum secured communication services (press release) 2022. https://www.global.toshiba/ww/news/corporate/2022/04/news-20220427-01.html [Accessed 13th June 2024]
30. Joshi SK, Aktas D, Wengerowsky S, *et al.* A trusted node–free eight-user metropolitan quantum communication network. *Sci. Adv.* 2020; 6:eaba0959 DOI: 10.1126/sciadv.aba0959
31. Proietti M, Ho J, Grasselli F, *et al.* Experimental quantum conference key agreement. *Sci. Adv.* 2021; 7:eabe0395 DOI: 10.1126/sciadv.abe0395
32. Amies-King B, Schatz KP, Duan H, et al. Quantum Communications Feasibility Tests over a UK-Ireland 224 km Undersea Link. *Entropy* 2023; 25:1572. DOI: https://doi.org/10.3390/e25121572
33. Kumar R, Nayar B, Lane T, Spiller T. Field trial of continuous variable quantum key distribution on trackside fibre. In: *Proceedings Volume 12335, Quantum Technology: Driving Commercialisation of an Enabling Science III*, 123350H (2023), SPIE Photonex 2022, Birmingham, UK. DOI: https://doi.org/10.1117/12.2647203
34. Chu Y, Donaldson R, Kumar R, Grace D. Feasibility of quantum key distribution from high altitude platforms. *Quantum Sci. Technol.* 2021; 6:035009 DOI: 10.1088/2058-9565/abf9ae
35. Sibson P, Erven C, Godfrey M, et al. Chip-based quantum key distribution. *Nat Commun* 2017; 8:13984 DOI: https://doi.org/10.1038/ncomms13984
36. Schreier A, Alia O, Wang R, et al. Coexistence of Quantum and 1.6 Tbit/s Classical Data Over Fibre-Wireless-Fibre Terminals. *Journal of Lightwave Technology* 2023; PP(99):1-7. DOI: 10.1109/JLT.2023.3258146
37. Computational Nonlinear & Quantum Optics Group. Satellite Quantum Modelling & Analysis Software. 2024. https://cnqo.phys.strath.ac.uk/research/quantum-information/satquma/ [Accessed 30 June 2024]
38. Phillips CL, Brash AJ, Godsland M, *et al.* Purcell-enhanced single photons at telecom wavelengths from a quantum dot in a photonic crystal cavity. *Scientific Reports* 2024; 14(1):4450, ISSN 2045-2322 DOI: 10.1038/s41598-024-55024-6

QUANTUM COMMUNICATIONS HUB | 10-YEAR REPORT

39. Fleming F, Yi X, Mirza MMA, *et al*. Surface-normal illuminated pseudo-planar Ge-on-Si avalanche photodiodes with high gain and low noise. *Opt. Express* 2024; 32:19449-19457 DOI: 10.1364/OE.521417

40. Liu WZ, Li MH, Ragy S, *et al*. Device-independent randomness expansion against quantum side information. *Nat. Phys*. 2021; 17:448–451. DOI: 10.1038/s41567-020-01147-2

41. Wooltorton L, Brown P, Colbeck R. Tight Analytic Bound on the Trade-Off between Device-Independent Randomness and Nonlocality. *Phys. Rev. Lett*. 2022; 129: 150403. DOI: 10.1103/PhysRevLett.129.150403

42. Bhavsar R, Ragy S, Colbeck R. Improved device-independent randomness expansion rates using two sided randomness. *New J. Phys*. 2023; 25:093035 DOI 10.1088/1367-2630/acf393

43. Yin HL, Wang WL, Tang YL, *et al.* Experimental measurement-device-independent quantum digital signatures over a metropolitan network. *Phys. Rev.* A 2017; 95:042338 DOI: 10.1103/PhysRevA.95.042338

44. Roberts GL, Lucamarini M, Yuan ZL, *et al.* Experimental measurement-device-independent quantum digital signatures. *Nat Commun* 2017; 8:1098 DOI: 10.1038/s41467-017-01245-5

45. Pirandola S. End-to-end capacities of a quantum communication network. *Commun Phys* 2019; 2:51 DOI: 10.1038/s42005-019-0147-3

46. Stroh L, Horová N, Stárek R, *et al*. Noninteractive xor Quantum Oblivious Transfer: Optimal Protocols and Their Experimental Implementations. *PRX Quantum* 2023; 4(2): 020320 DOI: 10.1103/PRXQuantum.4.020320

47. Lupo C, Peat JT, Andersson E, Kok P. Error-tolerant oblivious transfer in the noisy-storage model. *Phys. Rev. Research* 2023; 5(3):033163 DOI: 10.1103/PhysRevResearch.5.033163

48. Kent A. S-money: virtual tokens for a relativistic economy. *Proc. R. Soc*. A. 2019; 47520190170 DOI: 10.1098/rspa.2019.0170

49. Kent A, Lowndes D, Pitalúa-García D, *et al.* Practical quantum tokens without quantum memories and experimental tests. *npj Quantum Inf* 2022; 8:28 DOI: 10.1038/s41534-022-00524-4

50. Ni Z, Khalid A, Kundi DeS, O'Neill M, Liu W. HPKA: A High-Performance CRYSTALS-Kyber Accelerator Exploring Efficient Pipelining. *IEEE Transactions on Computers* 2023:72;12

51. Ni Z, Khalid A, O'Neill M. High Performance FPGA-based Post Quantum Cryptography Implementations. In: *Proceedings of 32nd International Conference on Field-Programmable Logic and Applications (FPL)*, Belfast, United Kingdom, 2022, pp. 456-457, DOI: 10.1109/FPL57034.2022.00076

52. Government Office for Science. *Quantum technologies: Blackett review.* 2016. https://www.gov.uk/government/publications/quantum-technologies-blackett-review [Accessed 13th June 2024]

53. ETSI GS QKD 011 V1.1.1 (2016-05): Quantum Key Distribution (QKD); Component characterization: characterizing optical components for QKD systems

54. ETSI GR QKD 003 V2.1.1 (2018-03): Quantum Key Distribution (QKD); Components and Internal Interfaces

55. ETSI White Paper No. 27: Implementation Security of Quantum Cryptography. Introduction, challenges, solutions. First edition – July 2018. ISBN No. 979-10-92620-21-4

56. ISO/IEC 23837:2023 Information security — Security requirements, test and evaluation methods for quantum key distribution. ISO/IEC 23837-1:2023: Requirements; ISO/IEC 23837-2:2023: Evaluation and testing methods

57. ETSI GS QKD 016 V2.1.1 (2024-01): Quantum Key Distribution (QKD); Common Criteria Protection Profile - Pair of Prepare and Measure Quantum Key Distribution Modules

58. Standardization Roadmap on Quantum Technologies, Release 1, 2023-03, CEN/CENELEC

59. STEM Learning. Funding for specialist STEM Ambassadors scheme aims to boost young people's skills in quantum physics. (press release) 2023 https://www.stem.org.uk/all-news/funding-for-specialist-stem-ambassadors-scheme-aims-to-boost-young-peoples [Accessed 13th June 2024]

60. National Cyber Security Centre. *White paper: The future of NCSC Technology Assurance*. 2021. https://www.ncsc.gov.uk/collection/technology-assurance/future-technology-assurance [Accessed 13th June 2024]

61. Cabinet Office. *The Integrated Review 2021*. 2021. https://www.gov.uk/government/collections/the-integrated-review-2021 [Accessed 13th June 2024]

62. Chunnilall C, Spiller T. *Technology Assurance Principles Documentation (for the quantum sector)*. 2024 https://www.quantumcommshub.net/industry-government-media/resources/technology-assurance-principles-documentation/ [Accessed 13th June 2024]

63. Engineering and Physical Sciences Research Council. *Quantum Technologies: Public Dialogue Report*. 2017 https://nqit.ox.ac.uk/content/quantum-technologies-public-dialogue-report.html [Accessed 13th June 2024]

64. UK National Quantum Technologies Programme. *National strategy for quantum technologies: A new era for the UK*. 2015. https://uknqt.ukri.org/wp-content/uploads/2021/10/National-Quantum-Technologies-Strategy.pdf [Accessed 13th June 2024]

65. UK Photonics Leadership Group. *Future Horizons for Photonics Research 2030 and Beyond*. 2020. https://photonicsuk.org/wp-content/uploads/2020/09/Future-Horizons-for-Photonics-Research_PLG_2020_b.pdf [Accessed 13th June 2024]

66. Ofcom. *Report: Technology Futures – spotlight on the technologies shaping communications for the future*. 2020 https://www.ofcom.org.uk/internet-based-services/technology/emerging-technologies/ [Accessed 13th June 2024]

67. Department for Science, Innovation and Technology, Foreign, Commonwealth & Development Office, Foreign & Commonwealth Office and Department for Business, Energy & Industrial Strategy. Facilitating a £10m UK-Singapore satellite-based Quantum Key Distribution Collaboration. 2019 (press release) https://www.gov.uk/government/publications/facilitating-a-10m-uk-singapore-satellite-based-quantum-key-distribution-collaboration [Accessed 13th June 2024]

68. UK Quantum Technology Hubs. Quantum City launches new website to engage next generation of quantum scientists. 2024 (press release) https://www.quantumcity.org.uk/news/quantum-city-launches-new-website-to-engage-next-generation-of-quantum-scientists [Accessed 13th June 2024]

69. EPSRC. *Framework for responsible research and innovation*. https://www.ukri.org/who-we-are/epsrc/our-policies-and-standards/framework-for-responsible-innovation/ [Accessed 13th June 2024]

Appendices

Appendix 1: The Investigating Team

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Wilson Luke, University of Sheffield

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Researcher Co-Investigator – Phase 1 & 2:

Wonfor Adrian, University of Cambridge

Researcher Co-Investigators – Phase 2:

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Hugues Salas Emilio, University of Bristol
Kanellos Georgios, University of Bristol
Lowndes David, University of Bristol
Pitalúa-García Damián, University of Cambridge

Appendix 2: The Research Team

Research Associates – Phase 1:

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Minaud Brice, Royal Holloway University London
Newton Beth, University of Leeds
Ntavou Foteini, University of Bristol
Ou Yanni, University of Bristol
Ottaviani Carlo, University of York
Pearce Mark, University of Sheffield
Price Alasdair, University of Bristol
Proux Raphael, Heriot-Watt University
Puthoor Ittoop, Heriot-Watt University
Ragy Sammy, University of York
Rambach Marcus, Heriot-Watt University
Sahin Dondu, University of Bristol
Salas Hugues Emilio, University of Bristol
Santana Ted, Heriot-Watt University
Sibson Philip, University of Bristol
Spencer Peter, University of Cambridge
Tadza Mohd Nina, University of Cambridge
Tang Xinke, University of Cambridge
Vasilyev Petr, University of Cambridge
Vaquero-Stainer Antonio, University of York
Vinay Scott, University of Sheffield
Wilson Frey, University of Leeds
Woodward Robert, University of York
Xuang Zixin, University of Sheffield

Research Associates – Phase 2:

Alhussein Muataz Mezaal Hussein, University of Cambridge
Alia Obada, University of Bristol
Arabul Ekin, University of Bristol
Barrow Peter, Heriot-Watt University
Boubriak Andriy, University of Bristol
Bosher Jennifer, STFC RAL Space
Brierley Calvin, University of Kent
Clark Marcus, University of Bristol
Dumas Derek, University of Glasgow
Eso Elizabeth, Heriot-Watt University
Faruque Imad, University of Bristol
Fleming Fiona, Heriot-Watt University
Fuster-Almenar Sofia, STFC RAL Space
Ghalaii Masoud, University of York
Guo Ke, University of York
Harwin Rebecca, STFC RAL Space
Hastings Elliott, University of Bristol
Hebdige Tom, University of York
Ho Joseph, Heriot-Watt University
Hoang Anh-Tuan, Queen's Belfast University
Huang Zixin, University of Sheffield
Jabdaraghi Robab Najafi, University of Sheffield
Jain Vaibhav, University of Bristol
Kalkar Shruti Kishor, University of Bristol
Kanellos George, University of Bristol
Khan Safiullah, Queen's Belfast University
Khan Zia, Queen's Belfast University
Kirdoda Jaroslaw, University of Glasgow
Konieczniak Igor, University of York
Kundi Dur-e-Shahwar, Queen's Belfast University
Li He, University of Cambridge
Lupo Cosmo, University of Sheffield
Malik Imran, Queen's Belfast University
Millington-Hotze Peter, University of Sheffield
Mirza Muhammad, University of Glasgow
Morozov Dmitry, University of Glasgow
Nie Weijie, University of Bristol
Oliveira Romerson Deiny, University of Bristol
Oun Abu Osama, University of Kent
Ovenden Charlotte, University of Sheffield
Papachristou Nikolitsa, STFC RAL Space
Papanastasiou Panagiotis, University of York
Pearson David, STFC RAL Space
Phillips Catherine, University of Sheffield
Pickston Alexander, Heriot-Watt University
Pitalua-Garcia Damian, University of Cambridge
Pont Jamie, University of Kent
Ranu Shashank, University of York
Rao Vinod, University of York
Rosenfeld Lawrence, University of Bristol
Saalbach Lisa, Heriot-Watt University
Sagar Jaya, University of Bristol
Schreier Andy, University of Oxford
Shah Yasir, Queen's Belfast University
Sidhu Jasminder, University of Strathclyde
Stefko Milan, University of Bristol
Tebyanian Hamid, University of York
Tessinari Stange Rodrigo, University of Bristol
Toupchi Morteza, University of York
Ulibarrena Andres, Heriot-Watt University
Venkatachalam Natarajan, University of Bristol
Yang Rvizhi (Mark), University of Bristol
Zanforlin Ugo, Heriot-Watt University
Zhang Peide, University of Bristol

Appendix 3: The Professional Support Team

Andrea Klitos, Business Director, University of York
Hardy Ruth, Communications and Outreach Officer, University of York
Mortzou Georgia, Project Manager, University of York

Additional support:

Mawdsley Helen, University of Bristol
Sharpe Belinda, University of Bristol
Whittington Charles, STFC RAL Space
Woodland Emma, University of Bristol

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Appendix 4: Recipients of Hub allocated EPSRC PhD DTP studentships

Ainley Ellis, University of Oxford
Al-Abdali Sanna, University of Bristol
Albosh Sophie, University of York & NPL
Amies-King Ben, University of York
Barber Matthew, University of York
Bartlett Jennifer, University of York
Bathgate Euan, Heriot-Watt University
Beattie Adam, Queen's University Belfast
Bhausar Rutvij, University of York
Canning David, Heriot-Watt University
Clark Marcus, University of Bristol
Ghosh Avijit, University of York
Gonçalves Daniela Filipa Carradas, University of York
Hance Jonte, University of Bristol
Harney Cillian, University of York
Hughes Nathan, University of York
Hutchins Kyle, Royal Holloway University London
Jaeken Thomas, Heriot-Watt University
Kong Zhe Hui, University of York & RAL Space
Laurent Xavier, University of York
Llewellyn Dan, University of Bristol
McCarthy Charlie, University of Glasgow
Martin Nicholas, University of Sheffield
Morris Alexander, University of Sheffield
Moses Nathan, University of Bristol
Mountogiannakis Alexandros, University of York
Muir Dave, Heriot-Watt University
Nelmes Chad, University of York
Niblo Joseph, Heriot-Watt University
Paterson Cameron, University of Strathclyde
Pearse Joseph, University of York & BT
Politi Alexandra, University of York
Render Ry, University of York
Salih Hatim, University of York
Schatz Karolina, University of York
Simmons Cameron, Heriot-Watt University
Slater Benjamin, University of Bristol
Smith Raymond, University of Cambridge & Toshiba Research Europe Ltd.
Spencer Jack, University of York
Stephenson, Laura Jayne, University of York
Stroh Lara, Heriot-Watt University
Tatsi Gion, University of Strathclyde
Thomas Molly, University of Bristol
Tomlinson Anna, University of Sheffield
Vieira Giestinhas Juan Antonio, University of York
Wilkinson Kieran, University of York
Wooltorton Lewis, University of Bristol

Appendix 5: The External Advisory Board

[N.B. Affiliations correspond to those held at the time of Board membership]

B, Jeremy – National Cyber Security Centre
Carr, Wendy – Engineering and Physical Sciences Research Council
Compans, Sonia – ETSI
Edge, Lucy – Satellite Applications Catapult
Edwards, Tim – ADVA
Howes, Amanda – Engineering and Physical Sciences Research Council
Lenhart, Gaby – ETSI
Lütkenhaus, Norbert – University of Waterloo, Canada
Mealing-Jones, Catherine – UK Space Agency
Munro, Bill – NTT Basic Research Labs, Japan
S, Dan – GCHQ
Sadler, Martin – University of Bristol
Sands, Henny – UK Space Agency
Seeds, Alwyn – UCL
Stewart, Will – Institute of Electrical and Electronics Engineers
Townsend, Paul – Tyndall Institute, Ireland
Wale, Mike – UCL & Eindhoven University of Technology
Westwood, Joe – Engineering and Physical Sciences Research Council
Whitley, Tim – BT

Appendix 6: Logos of all partners

ADVA
AAC Clyde Space
AegiQ
ARQIT
Auriga aerospace
Bristol City Council
University of Bristol
BT
University of Cambridge
Cambridge Network
Cisco
Cognizant
covesion
Craft Prospect
CR Cryogenics
Crypta Labs
Duality Quantum Photonics
Dundee Satellite Station
The University of Edinburgh
elson space engineering
ETSI
eunetworks
University of Exeter
Fraunhofer UK
University of Glasgow
Heriot Watt University
IDQ

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ISISPACE
JWNC The James Watt Nanofabrication Centre
KETS
University of Kent
L3 TRL Technology one step ahead
University of Leeds
Leonardo
National Cyber Security Centre a part of GCHQ
NDFF EPSRC National Dark Fibre Facility
Network Rail
NPL National Physical Laboratory | QMI Quantum Metrology Institute
NPL
nu quantum
OCLARO
University of Oxford
Quantum Computing & Simulation Hub
QUANTIC The UK Quantum Technology Hub in Quantum Enhanced Imaging
Queen's University Belfast
Royal Holloway University of London
UKRI Science and Technology Facilities Council RAL Space
The University Of Sheffield.
STEM Learning
University of Strathclyde Glasgow
Teledyne Technologies Everywhereyoulook™
Toshiba
UK Quantum Technology Hub Sensors and Timing
UK Space Agency
University of Waterloo
wideblue making technology happen
University of York
University of York Science Education Group

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Appendix 7: Partnership resource investment

3D Photonic Components for Quantum Optical Communications: £171,172. Heriot-Watt University (Lead), University of Bristol

Project designed to take advantage of the world leading expertise at Heriot Watt in the technology of ultrafast laser inscription – a laser writing technology that facilitates the fabrication of three-dimensional optical waveguides inside dielectric materials. The primary goal is to develop 3D integrated multiport interferometers for state elimination measurement in quantum optical fibre communications systems. Such components offer considerable benefits over bulk optic systems, including stability, compactness and manufacturability, with higher throughputs than are currently achievable with other integration platforms e.g. silicon-on-insulator. A secondary and higher risk aim is to investigate the feasibility of developing mode-coupling and sorting components based on "photonic lanterns", for the implementation of space-division-multiplexed quantum communications (both free-space and optical-fibre based). These components can then be used in different communications links, including potential free-space applications with an eye to communicating with orbiting satellites.

Autonomous System for Measurement Device Independent QKD: £138,935. Toshiba Europe (Lead), University of York.

Realisation of a MDI-QKD prototype that can operate continuously and with spatial separation of the two communicating parties, tackling challenges such as realisation of high-speed, real-time modulation of indistinguishable pulses from remote locations, and synchronisation of those remote locations.

Continuous Variable-QKD: £119,000. University of York

Continuous Variable Quantum Key Distribution (CV-QKD) has recently seen a revival of interest as a potentially high performance technique for secure key distribution over limited distances. Demonstration of CV-QKD based on regeneration of reference frame at the receiver shows compatibility with classical coherent detection schemes that are widely used for high bandwidth classical communication systems. Most importantly, seamless integration into existing DWDM classical network makes it a potentially a highly viable quantum secure key distribution technology over current networks: a most appealing aspect of CV-QKD is that it can use telecommunications equipment which is readily available and which is also in common use industry wide. However, a lower clock rate and data processing complexities affect commercial interests and widespread use of CV-QKD systems in secure data communication networks. The aim of this project is to explore the feasibility of a demonstration of a CV-QKD system that runs at higher clock rates with enhanced secure key rate. An additional aim is to implement key distribution protocols that require reduced complexities in data processing – which is also advantageous towards early commercialization.

CubeSat QKD and Ground Stations: £301,673. University of Strathclyde (Lead), University of Bristol, Craft Prospect

Realisation of satellite QKD with cube satellites, through exploitation of their lower development, launch costs and rapid development, and culminating in a terrestrial demonstration and engineering model of a CubeSat QKD system and optical ground station ready for full mission capability and in-orbit-demonstration.

Fibre-coupled Room Temperature Single Photon Sources: £104,177. University of Exeter, Aegiq

Single photon sources (SPS) are an enabling component technology for applications including unbreakable cryptography, precision metrology and quantum information processing. The aim of this project is to develop single photon sources based on the two-dimensional semiconductor hexagonal boron nitride (hBN). Colour centres in hBN have considerable promise thanks to bright and stable fluorescence, narrow linewidths and nanosecond lifetimes at room temperature. And, as a two-dimensional material, hBN can be incorporated into complex structures using simple transfer and placement techniques. This provides an edge over other materials as it opens up the possibility for high quality heterostructure devices, and a route to the integration of colour centres with high performance photonic devices. The focus in this project will be to produce a high-efficiency, high-repetition rate, single photon source prototype, through the integration of hBN and silicon nitride based nanophotonics.

Flexible Quantum Wireless System: £234,072. University of Oxford (Lead), University of Bristol

Investigation of practical application of QKD in securing short-range wireless communication between a terminal such as an Automatic Teller Machine (ATM) and a handheld device (e.g. mobile phone). This quantum security model can be extended to mobile phone payment and other indoor wireless applications. Both partners are working together to develop a flexible platform for future quantum wireless technology.

Frequency Down-Conversion to Telecom Wavelengths of On-Demand Indistinguishable Single Photons from a Quantum Dot: £82,015. Heriot-Watt University

This project is aiming to realize the world's brightest on-demand telecom wavelength source of single photons. This is achieved by frequency down-conversion of single photons, emitted on-demand from a single InGaAs quantum dot at 950 nm wavelength, to the telecom C-band (1550 nm wavelength) using periodically poled lithium niobate (PPLN) crystals for difference of frequency generation. Success will enable ground-breaking next generation quantum communication technology demonstrations, including experiments in hybrid single photon entanglement and teleportation, and quantum digital signatures and QKD.

Fully Device-Independent Quantum Key Distribution at Building-Scale Distances: £89,920. University of Oxford

The project aims to extend the link distance between two remote nodes (Alice and Bob - each containing a trapped-ion qubit and connected by an optical fibre link) to building-scale distances (up to 200m). The feasibility of replacing the fibre link with a free-space link will also be tested by adapting IR wavelength free-space hardware to visible wavelength (422nm). The isolation of Alice and Bob's qubits from the optical link beyond the 30dB-40dB level achieved in previous work will be improved and efficiency improvements to the key-exchange protocol, to allow extraction of a larger number of secret bits from the same number of Bell pairs, will be sought. Finally, the project will produce a roadmap of the path to real-world usable trapped-ion-based DIQKD with higher key rates and over conventional fibre infrastructure.

Ground-based entanglement transmitter for the Canadian QEYSSAT mission: £127,792. Heriot-Watt University (Lead), University of Waterloo Canada

This project, led by researchers at Heriot-Watt University will develop an ultra-bright entangled photon transmitter compatible with the Canadian Quantum Encryption and Science Satellite (QEYSSat) mission, led by partner the University of Waterloo. One photon will match the operating wavelength of the QEYSSat BB84 receiver, while the other will be at telecom wavelength for interfacing terrestrial networks. The modular transmitter will be compatible with all optical ground stations (OGS) deployed by the Hub. This project will make entanglement-enhanced intercontinental QKD between the UK and Canada possible.

HiQ – QKD on High Altitude Platforms: Proof of Concept & Demonstration: £223,694. University of York (Lead), Heriot-Watt University, Auriga Aerospace Ltd, Elson Space Engineering

High Altitude Platforms – HAPS – are designed to operate in a stratosphere at 17 – 22km altitude, a benign band in the atmosphere that enables efficient station-keeping. Here, they are closer to the Earth than satellites, with improved link budgets, and a field of view sufficient for regional coverage. HAPS station-keeping facilitates continuous service and re-location, providing flexibility in the point of service delivery. QKD from HAPS has the potential to fulfil an increased number of requirements beyond satellites, while also playing a part in the strategic visions of a global quantum-secured network backbone based on Space and Near-Space – especially the Stratosphere. HiQ builds on a previous feasibility study at York that established the viability of QKD from HAPS. An experimental free-space testing phase is currently underway, using line-of-sight test ranges up to 20km, as well as a tethered Helikite aerial platform operating up to 400m with greater positional instability than that of the relative calm of the stratosphere at 20km. The next stage in the testing / demonstration process is a flight at high altitude on platform with an operational QKD payload. The project will build a CV-QKD payload, which will be tested in conjunction with UK industry partners who have expertise in the design, building and operation of HAPS. CV-QKD offers particular advantages for stratospheric delivery, operating with transmitters and receivers of reduced size and physical complexity, in addition to offering daylight operation.

High Speed (100 Gbps) Encrypted Optical Communications System Based on QKD and Optical Code Scrambling: £99,306. Heriot-Watt University (Lead), University of Cambridge, ADVA

Quantum key exchange is used to seed optical code scrambling (OCS), in order to provide significantly enhanced security at high speed (>100 Gbps) data rates.The aim of the project is to investigate the feasibility of combining QKD and TDSPE (time domain spectral phase encoding) techniques to provide double-security in high speed optical communication systems. The integrated system will be demonstrated using the deployed link in the Cambridge Quantum Network (part of the Hub's UK Quantum Network).

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Integrated Multi-Channel Bell State Generator: £170,932. University of Bristol

Current quantum networks suffer from a lack of scalability, creating an immediate need for easily manufactured compact and efficient sources of entanglement to replace bulk optic sources that are difficult to build and maintain. Our proposed integrated sources improve scalability, leveraging the mature manufacturability of the SOI platform. By engineering phase matching in the SOI (Silicon-On-Insulator) platform entangled photon-pairs covering the whole C-band will be generated with future potential for other bands. We aim to demonstrate the first chip-scale Bell-state generator for quantum networks, while also generating photons with high purity which are ideally suited to future demonstrations of entanglement swapping and teleportation.

Integrated Quantum Key Distribution and fast Optical Code scrambling for secure Gbps data transmission: £220,811. Heriot-Watt University (Lead), University of Cambridge, BT

Ensuring the security of information exchange in optical communication systems has become one of the primary challenges in telecommunication networks. In current communication systems the security measures are mainly implemented by digital data encryption methods (such as AES). The strength of the security is determined by the computational difficulty of breaking the encryption algorithms, described as computational security. On the other hand, time domain spectral phase encoding (TDSPE) implements network security in the optical physical layer by rapid (bit-by-bit) encoding of the high-speed optical signal into a noise-like optical signal, which is referred to as physical level security. In Phase 1 of the Quantum Communication hub, the academic teams (Heriot Watt and Cambridge) carried out a feasibility study of a hybrid system using quantum key distribution (QKD) and TDSPE to enable both computational and physical level security in an optical communication system. In this project, the academic groups will team up with industrial partner (BT) to integrate QKD for secure key distribution with TDSPE for physical layer high speed signal scrambling in one system and quantum level security in the key exchange and physical level security in data transmission. By using such physical layer encryption, we are able to provide ultra-high security whilst maintaining Gbps data transmission rates. We aim to develop a fully integrated system that acts as a "plug-and-play" security module, and apply this to higher data-rate optical communication and demonstrate in a series of field trials. Intellectual properties on the technology will be generated from this project.

Long-distance quantum key distribution with on-demand single photons in the telecom-C band: £127,420. Heriot-Watt University

Realisation of long-distance quantum key distribution (QKD) based on the BB84 protocol using telecom wavelength single photons. The aim is to optimize the pump laser stability, the down-conversion efficiency, and then implement the BB84 protocol, benchmarking the secure key rate versus fibre length and opening a path towards measurement-device-independent QKD between telecom photons generated from parametric down-conversion and the quantum dot.

Novel high performance InP-based single-photon avalanche detectors for quantum key distribution at 1550 nm: £141,965. University of Sheffield (Lead), Heriot-Watt University, Leonardo

Next-generation Quantum Key Distribution (QKD) systems will have to rely on high-performance single-photon avalanche diode (SPADs) detectors, which are capable of detecting an individual quantum of light at $\lambda > 1400$ nm. This project generates a new class of SPAD detector, which is particularly suited to quantum communications, due to its higher trigger probability, lower dark current, lower breakdown voltage (Vbd) variation with temperature and higher external quantum efficiency at $\lambda = 1550$ nm. This should translate to higher single-photon detection efficiency (SPDE), reduced dark count rate (DCR), reduced jitter and weaker temperature dependence.

Quantum Ambassadors, phases 1&2: £336,317. National STEM Learning Centre (Lead), University of York Science Education Group

Partnership with the National STEM Learning Centre and the University of York Science Education Group to deliver a comprehensive scheme of quantum-related CPD and classroom-based activities for A-level students and their science teachers, with the specific aim of promoting the uptake of STEM subjects, highlighting the benefits and applications of mature quantum technologies and signposting career pathways for science graduates. The scheme is seeking to increase awareness and understanding of the importance and relevance of quantum technologies to UK society, culture and the economy. The Hub has already completed a a 2-year pilot phase of this scheme, during which the project partners worked closely with the other UK technology hubs using the science and technologies of the national quantum technologies programme as a context in which to develop and deliver an inspiring enrichment scheme across the UK. The scheme is UK wide – and following successful completion of the pilot phase, has now been funded for a further two years.

QCHAPS – Quantum Communications & HAPS: A Feasibility Study: £148,612. University of York (Lead), Heriot-Watt University

Interest in the use of aerial platforms for communications has steadily grown, as has the number and types of platform available. These range from tethered hybrid helium balloon kite-like systems at relatively low altitudes, to aircraft or airships at high altitudes. These higher altitude systems (typically 17-22km) are often referred to generically as HAPS / HAPs (High Altitude Platform Stations / High Altitude Pseudo Satellites, or High Altitude Platforms). The usefulness of specific platforms for any application is determined by multiple variables and constraints, including altitude and stability of the platform, as well as payload size / weight, power requirements etc. This project is a feasibility study intended to provide the basis for future experimental work / technical demonstration by bringing together the relevant expertise across HAPS, HAPS-based communications, QKD in free space, and sat QKD receivers / ground-stations, with input from industry perspectives.

Quantum Network Token Schemes: £247,999. University of Cambridge

The project is developing quantum-enabled secure tokens, which can be used on financial and other networks where time is critical and the light speed signalling bound is significant. The tokens allow access authentication and prevent multiple access without involving the delays that cross-checking across the network would require, without requiring long term quantum memory. We plan to implement these token schemes using quantum key distribution devices and networks developed by Hub partners, in order to demonstrate and optimize them with current quantum technology and identify further gains that could be made by building dedicated devices. We are seeking to commercialize this technology for target markets in partnership with Cambridge Enterprise.

Quantum N.O.D.E (Network Operational Device rEceiver): £295,693. University of Bristol (Lead), University of Glasgow

This project seeks to establish the foundations for developing a quantum NODE (Quantum Network Operational Device rEceiver) Architecture, using silicon-based waveguide circuits with integrated superconducting nanowire single photon detectors (SNSPDs). This new node-based network architecture will dramatically reduce the resources required for secure quantum communication networks, relieving the users from the need to have bulky and costly high performing detectors, and concentrating these expensive resources into a single central location. Integrated photonics approaches will be utilised to significantly reduce the technology footprint, whilst simultaneously enabling scaling.

QPID: UKQNtel Pilot Implementation and Demonstrator: £122,228. University of Cambridge (Lead), CISCO, BT

Current demonstrations of quantum secured networks within the Quantum Communications Hub have relied upon QKD secured optical communications. For future widespread adoption of quantum secure communications, it will be advantageous to combine QKD secured transmission with post-quantum cryptography in order to address the difficulty of 'last mile' access to end-users. Additionally, it is necessary to integrate 'quantum-safe' encryption technologies seamlessly into the internet protocol (IP) services which are the world's de facto communication standard. QPID is a proof-of-concept pilot and demonstrator of a model utilising quantum and post-quantum approaches to secure networks. This entails use of a new system-level interface from Cisco to secure encryption that exploits both quantum and post-quantum technologies. This is the company's Secure Key Import Protocol – SKIP. The system will be overlaid on the Hub's quantum-secured short and long distance optical links. The intention is for the pilot to demonstrate the value of both approaches as a means of securing distributed access to multiple users in the real world. The pilot will subsequently be used as part of the evidence-based case for scaled-up implementation involving company users from a range of industry sectors. The project combines QKD networking expertise and infra-structure already developed within the Hub, with expertise in IP-routing and post-quantum cryptography developed by Cisco to realise a hybrid, post-quantum QKD-secured IP network.

QTRAX (A Pilot Field-Deployment of Continuous Variable Quantum Key Distribution over Track-Side Fibre): £270,944. University of York (Lead), Network Rail, ADVA

Continuous Variable (CV) Quantum Key Distribution (QKD) is a specific implementation of QKD with inherent properties that make it particularly attractive as a means of integrating QKD in modern optical networks operating with standard telecommunications equipment. Following feasibility studies and tests, QTRAX will deploy CVQKD systems designed and built by the University of York over fibre that is part of the Network Rail Trans Pennine Initiative. This will be the first field trial of CVQKD in the UK, and the first use of QKD over track-side fibre. The QKD systems will be installed in York, Leeds, Huddersfield and Manchester creating a 4-node network between the four cities. QTRAX will demonstrate both CVQKD itself and its integration with standard data encryption and transmission equipment from ADVA Optical Networking.

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QuID – Entanglement-Based Token for Quantum PIN Identification: £174,782. University of Sheffield (Lead), Heriot-Watt University, University of Bristol, Duality

Security tokens underpin a number of operations that require access to an electronically restricted resource, for example, online banking, medical records, database of public administrations and large corporations. However, tokens that implement algorithms such as RSA (Rivest–Shamir–Adleman) are vulnerable to quantum computers and will ultimately become insecure. The goal of this project is to explore new types of security tokens for the quantum age, and compare them with existing technology. These tokens are being constructed using millimetre-scale chips that generate quantum states of light and link a Server and Client via entangled photons. Our vision is that quantum security tokens will find applications for securing the Internet of Things and self-driving cars, and will in the long run, be integrated into the quantum internet.

Realistic Threat Models for Satellite Quantum Key Distribution: £99,270. University of Leeds (Lead), University of York, ID Quantique

In-depth security study of satellite QKD, examining various assumptions about the physical channel between satellites and ground stations and aiming to add new capabilities through maximising the user exploitability of current and future quantum satellite missions.

Satellite Visibility Simulator for Quantum Optical Services and Experiments: £124,500. University of Edinburgh (Lead), RAL Space

Development of an atmospheric visibility model, based on high temporal and spatial resolution data used to determine realistic optical transmission statistics derived from short (90 minutes) to medium (1 year) timescale data, and of value to missions currently in planning.

Shot-noise sensitivity at higher detection bandwidths: £59,711. University of York

The signal generation rate of quantum coherent communication is limited by the detection bandwidth of the coherent receiver, typically at a few MHz to a few hundreds of MHz. This project will demonstrate, as a world-first, shot noise sensitivity at bandwidth beyond 10GHz. quantum coherent communication closer to classical coherent communications.

Towards Assurance/ Certification of Physical Quantum Random Number Generators: £321,988. University of York (Lead), NPL, ID Quantique

This project seeks to develop the necessary theoretical and experimental understanding, expertise and techniques to test physical quantum random number generators. The importance of quantum random number generators is widely acknowledged, as is the size of the market for component level devices that are small and cheap enough to be incorporated into small systems, e.g. mobile phones; for authentication purposes e.g. in the Internet of Things; and as essential components in quantum communication systems. Authoritative accreditation of the output is an outstanding issue for QRNGs. Current tests are based on numerical analysis of the output sequence, which cannot provide a confident bound on the degree of randomness. Stronger certification is possible for physical QRNGs (PQRNGs), since the physical process used to create the output sequence can be theoretically analysed and physically tested. The developed approach will be applied to one or two selected implementations, including a commercial device (adapted to facilitate interrogation).

Towards integrated entanglement sources for space: £38,973. Heriot-Watt University (Lead), Covesion

The UK has entered the `quantum space race' in force, with missions such as SPEQTRE, ROKS the QEYSSat collaboration and the Hub's own cube-sat demonstration. These projects can be considered first-generation space quantum technology, with payloads based on bulk optics setups. Up-scaling performance, reproducibility and the number of deployable satellites for network constellations requires a move to chip-scale integrated devices with smaller size, lower weight and power (SWAP). In this proposal we will work with Covesion, a leading supplier of nonlinear PPLN crystals, to develop ultra-bright and ultra-compact quantum light sources for space. We will benchmark the performance of space qualifiable Covesion waveguides for entangled photon creation and establish a technology roadmap towards integrated entanglement sources in space.

Twi-Fi: Enhanced Twin-Field Quantum Key Distribution: £241,843. University of York (Lead), INRiM (Istituto Nazionale Di Ricerca Metrologica)

This project focuses on Twin-Field (TF) Quantum Key Distribution (QKD), a recent scheme that enables increased secret key rate and transmission distance for QKD as well as more robust implementation security through the use of an intermediate quantum node and commercially available components. TFQKD has the capability to behave like an effective quantum repeater and cover intercity distances in optical fibre. The project will address some of the current limitations of TFQKD, increasing its practicality in field trials, making it easier to deploy in existing fibre networks and closer to commercial exploitation. The project also includes research into the physics underlying the TFQKD scheme to better understand and exploit its counter-intuitive properties for quantum communications.

UKIQL: Enabling a data centre-to-data centre quantum link between UK and Ireland via a low-loss submarine optical fibre: £54,042. University of York (Lead), euNetworks

This is a pilot study aiming to establish the feasibility of a quantum communications link between data centres in the UK and Ireland connected by three legs of optical fibre including a 224-km low-loss submarine optical fibre between Southport and Portrane. No quantum link has ever been established between the two countries, and none has ever been attempted worldwide covering as long a distance as this one over deployed submarine optical fibres. The experimental setup will utilise a new submarine fibre link, named "Rockabill", recently deployed by project partner euNetworks, which features low attenuation and short latency. When combined, these are key advantages in e.g. high-speed financial transaction scenarios requiring the future-proof security provided by quantum communications. If successful, this QKD connection will further extend the Hub established UK Quantum Network (UKQN), currently confined to the South of England, by paving the way to linking Manchester and Dublin Data Centres and an even longer backbone quantum network between York and Cork. Importantly, this development will also mark the first ever quantum communication link in the Irish Sea over industrial low-latency cables at a considerably longer distance compared to anything similar performed before.

Uplink and field tests for the Hub-QEYSSat mission: £114,115. Heriot-Watt University (Lead), Dundee Satellite Station

In a previous QEYSSat funded project, we established an exclusive international collaboration between the Hub, the University of Waterloo, and the Canadian Space Agency (CSA), for implementing intercontinental QKD via an uplink from the Hub's optical ground station (HOGS) to the QEYSSat satellite. An entangled photon source has been engineered that generates up to 100 MHz of photon pairs at 785 nm for the satellite uplink and 1550 nm for connection to a telecom network. In this phase-2 proposal, we will (i) increase the source output to 1 GHz detectable photon pairs, (ii) equip the HOGS at Errol airfield with point-ahead uplink tracking capability and polarization reference control, and (iii) with our partners DSS, conduct field tests at Errol airfield in preparation for QEYSSat QKD experiments scheduled for late 2023.

Wide Angle Receivers for Long-Distance Free-Space QKD: £263,107. Heriot-Watt University

The biggest challenge to overcome in long-distance QKD is optical loss. Current mission designs foresee separate optical telescopes, light sources and detectors for the quantum channel and the classical guiding beacon, which strains the stringent size and payload limitations any space mission is subject to. A new design is proposed, that combines quantum key detection and pointing-and-tracking hardware into a single receiver. The goal is to build up a quantum receiver for time-bin qubits with a large field of view, and that will provide spatial information for pointing and tracking directly from the quantum signal. This project reflects the growing interest in quantum communications in space.

Appendix 8: List of ISCF projects which include Hub input

- 3QN: Towards A New UK Industry for Novel Quantum Receivers in Nascent Satellite QKD Global Markets. Funding granted: £3,251,717. Partners: Arqit Ltd (Lead), Teledyne E2V (UK) Ltd, University of Cambridge, BT, University of York, Heriot-Watt University, Redwave Labs Ltd, Fraunhofer UK Research Ltd, NPL Management Ltd, Wideblue Ltd.
- AQuaSec. Funding granted: £5,798,748. Partners: Toshiba Europe Ltd (Lead), Heriot-Watt University, BT PLC, IQE PLC, Queen's University Belfast, BT Dashboard Ltd, University of Sheffield, Senetas Europe Ltd, University of Cambridge, Tethered Drone Systems Ltd, Bay Photonics Ltd, KETS Quantum Security Ltd, NPL Management Ltd, University of Glasgow, Royal Holloway University of London
- AirQKD. Funding granted: £5,791,335. Partners: BT (Lead), University of Warwick, University of Strathclyde, University of Bristol, Fraunhofer UK Research Ltd, University of Edinburgh, Heriot-Watt University, NPL Management Ltd, Arqit Ltd, Compound Semiconductor Applications Catapult Ltd, Bay Photonics Ltd, Angoka Ltd, Openlightcomm Ltd, Nu Quantum Ltd.
- Next generation satellite QKD. Funding granted: £4,505,983. Partners: Arqit Ltd (Lead), STFC Laboratories, Heriot-Watt University, Fraunhofer UK Research Ltd, BT, Toshiba Europe Ltd, Nu Quantum Ltd, ORCA Computing Ltd, Aegiq Ltd.
- AQuRand: Assurance for quantum random number generators. Funding granted: £2,753,822. Partners: NPL Management Ltd (Lead), University of York, University of Kent, CryptaLabs, ID Quantique SA, KETS Quantum Security Ltd, Nu Quantum Ltd, Quantinuum, Quantum Dice, Toshiba Europe Ltd.
- QuEOD. Funding granted: £2,464,893. Partners: Photon Force Ltd (Lead), University of Sheffield, Cardiff University, Heriot-Watt University, Leonardo MW Ltd, Arqit Ltd, Compound Semiconductor Applications Catapult Ltd, IQE PLC, QLM Technology Ltd.
- QFoundry. Funding granted: £3,727,598. Partners: Compound Semiconductor Centre Ltd (Lead), University of Sheffield, University of Cambridge, Integrated Compound Semiconductors Ltd, Cardiff University, NPL Management Ltd, Microchip Technology Caldicot Ltd, Bay Photonics Ltd, IQE PLC, Toshiba Europe Ltd, Compound Semiconductor Applications Catapult Ltd, Amethyst Research Ltd, CS Connected Ltd
- PRISMS. Funding granted: £385,434. Partners: Craft Prospect Ltd (Lead), Dotquantum Ltd, University of Glasgow, Barrier Networks Ltd, NPL Management Ltd
- ViSatQT. Funding granted: £358,644. Partners: Airbus Defence and Space Ltd (Lead), University of Strathclyde, Satellite Applications Catapult, Craft Prospect Ltd, KETS Quantum Security Ltd, Nu Quantum Ltd, Archangel Lightworks Ltd.
- The quantum data centre of the future. Funding granted: £8,919,656. ORCA Computing Ltd (Lead), BP PLC, BT, Digital Catapult, Imperial College London, KETS Quantum Security Ltd, NCC Group Security Services Ltd, NCC Operations Ltd, PQShield Ltd, Riverlane, University College London, University of Bath, University of Bristol, University of Southampton
- Towards a Quantum enabled Cloud. Funding granted: £2,930,501. Partners: Arqit Ltd (Lead), Babcock Integrated Technology Ltd, BT, Fraunhofer UK Research Ltd, Heriot-Watt University, Photon Force Ltd, Wideblue Ltd
- Towards a Quantum Internet. Funding granted: £421,244. Partners: Arqit Ltd (Lead), Fraunhofer UK Research Ltd, Heriot-Watt Univeristy, ORCA Computing Ltd
- Building a standardised quantum-safe networking architecture. Funding granted: £298,178. Partners: KETS Quantum Security Ltd (Lead), University of Bristol
- ReFQ: Modular WCP Sources & RFI Protocols for Space-based QKD Demonstration. Funding granted: £300,386. Partners: Craft Prospect Ltd (Lead), University of Strathclyde, University of Bristol

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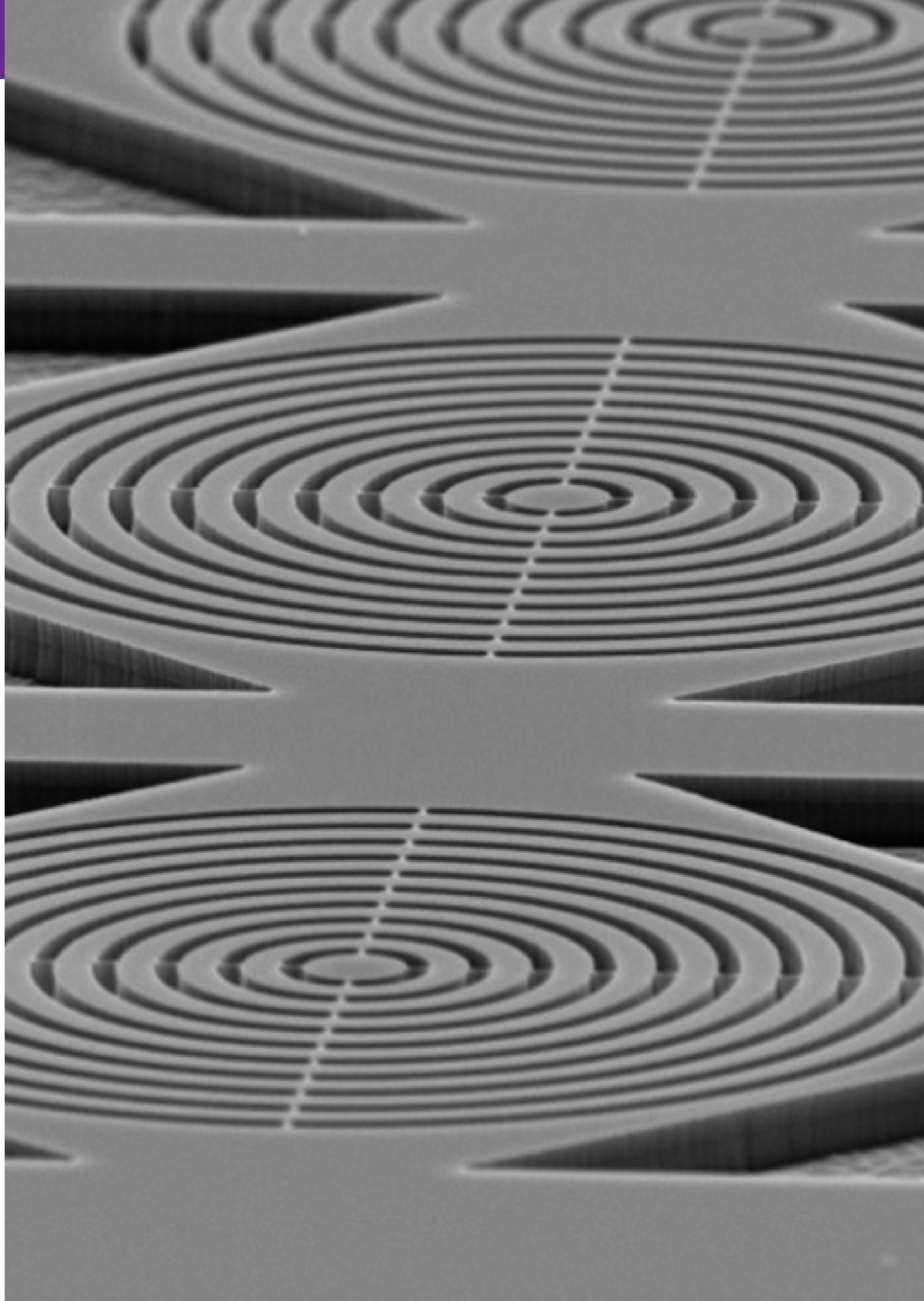

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