Quantum Imaging, Sensing and Metrology Workshop

6 March 2018

Malmasion Hotel, Leeds

Report on Outputs

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1. Motivation

Today the UK is leading a global race to industrialise this new technology, thanks to the National Quantum Technology Programme, an alliance of academia, industry and government brought together to exploit our research strengths. But international competitors are catching up fast. To stay in front and reap the rewards, we need to maintain the momentum that has been established in phase one of the programme.

Over the next 5 to 10 years, commercial quantum technology devices are likely to become as prolific and profitable as today's electronics. They will have a huge impact on our lives, benefitting healthcare, defence, security, aerospace, transport, civil engineering, telecoms and finance. Many advances that we expect to shape our future industrial strategy depend on technology that is not available today, but can be delivered by second generation quantum technologies.

EPSRC is planning for future investment in the area of quantum technologies and this involves identifying quantum technology research challenges and priorities for the UK. This workshop was focussed on the research challenges and priorities in the area of quantum imaging, sensing and metrology simulation.

2. Objectives

On 6 March 2018, EPSRC held a one-day workshop at the Malmaison Hotel, Leeds. In order to bring together a range of technical experts to discuss research challenges and UK expertise in the area of Quantum Imaging, Sensing and Metrology. The objectives of the workshop were:

- To identify research priorities that need to be addressed to deliver Quantum Imaging, Sensing and Metrology
- To identify innovation challenges for Quantum Imaging, Sensing and Metrology
- To discuss what challenges the UK can tackle and who needs to be involved

3. Background

The existing EPSRC Quantum Technology Hubs end in November 2019. There is agreement amongst the delivery partners and strategic advisors of the UK National Quantum Technologies Programme that a second phase of the National Programme should include a substantial technological research programme delivered through Hubs. This approach is supported by the Quantum Technologies: Blackett Review "The Quantum age: technological opportunities".

It is envisaged that the Quantum Technologies research programme will be a smaller proportion of a second phase of the National Programme than is the case in the first phase of the National Programme, and will be joined by new instruments such as Innovation Centres and Challenge Programmes.

Research conducted in the second phase should be integrated with the wider research and innovation landscape and investments. There is ongoing uncertainty over the financial envelope in a second phase period. The existing Quantum Technology Hubs have established capabilities and expertise which should be built upon.

3.1 Future Research priorities and Hub portfolio

There are three stages to identifying future research priorities and refreshing the Quantum Technologies Hubs portfolio

(A) Research priorities in quantum technologies and for research Hubs (January to March 2018).

Engagement with Quantum Technology Hubs, quantum technology researchers, non-quantum technology researchers, industry and users, to obtain perspectives on the research challenges and opportunities in quantum technology, and development of these into research priorities for a second period of the National Programme.

This workshop forms part of the activities under this early stage of the process:

a. Identifying technological research priorities
b. Providing information that can be used in scoping the research programme in a second phase of the National Quantum Technologies Programme, in terms of priorities, disciplines and perspectives that should be involved
c. Quantum Technology research hubs are envisaged as being part of an overall landscape of research and innovation in a second phase, and will need to work with other activities
d. It is only part of the process, and attending this workshop does not guarantee participation in Hub consortia, and non-attendance doesn't exclude it
e. EPSRC are working closely with our National Programme delivery partners, in particular Innovate UK in this process

(B) Identifying Hub partners (April to October 2018)

Identification of the research priorities that should be addressed by Quantum Technology Research Hubs in a second phase, development of a vision for a Hub portfolio, and the formation of consortia to deliver this Hub portfolio.

(C) Developing Hub proposals (November 2018 to March 2019)

Development of proposals Quantum Technology Research Hubs which will address the most important research priorities in quantum technologies for the UK in a second phase period of the National Programme. Including their assessment and preparation for making awards.

4. Selection of Participants

Delegates were selected based on their expertise in quantum imaging, sensing, metrology and associated areas of research. This included representatives from major investments made through the National Programme, including the Quantum Technology Hubs, Quantum

Technology Fellows, Quantum Technology Capital grant holders, as well as holders of other EPSRC grants.

Participants were selected based on advice from the National Programme Strategic Advisory Board (SAB), members of EPSRC's Strategic Advisory Network and Strategic Advisory Teams, and the Quantum Technology Hubs. This was to ensure a balanced group, with a diverse representation of technical expertise and a diverse representation of institutions and industry from across the quantum imaging, sensing and metrology domain. Attendees are shown in Annex 1.

5. Agenda, Quantum Imaging, Sensing and Metrology Workshop

10:00 – 10:30	Registration- Tea and Coffee available
10:30 – 10:50	Aim of the workshop and the need for UK research priorities in QT Presenter: Liam Blackwell
10:50 – 11:00	Innovate UK activities Presenter: Simon Plant
11:00 – 11:30	"Quantum Imaging" Presenter: Miles Padgett
11:30 – 12:00	"Quantum Sensing and Metrology" Presenter: Kai Bongs
12:00 – 12:15	Q & A following presentations
12:15 – 13.00	Breakout session 1
	Research challenges in Quantum Imaging, Sensing and Metrology in the UK
13:00 – 13:45	Lunch
13:45 – 14:00	Breakout session 2
	Prioritising the research challenges
14:00– 15:15	3 Industry presentations and Q and A session.
	Presenters: David McLoskey, Trevor Cross, Mike Worburys.
15:15 – 15:30	Coffee break
15:30 – 16:15	Breakout session 3
	What are the key innovation challenges the UK should tackle and what expertise needs to be involved?
16:15 – 16:30	What Happens next?
16.30	Workshop closes

The day started with presentations from EPSRC's Liam Blackwell and Innovate UK's Simon Plant which introduced the two funders and their plans for future funding in the area of QT.

These were followed by presentations from the Quantum Imaging Hub Miles Padgett and the Quantum Sensing and Metrology Hub Kai Bong on their visions for research hubs in a second phase of the Quantum technology National Programme.

During the workshop, participants had the opportunity to contribute input via a number of facilitated sessions. In session 1 the groups discussed and then captured the research challenges that needed to be addressed to deliver Quantum Imaging, Sensing and Metrology over the 2019 – 2024 time period which would cover the second phase of the National QT Programme. The groups then discussed and captured the research priorities beyond 2024 which would be beyond a second phase.

In session 2 the attendees then prioritised the research challenges by voting with three coloured dots to select their three most important research priorities in Imaging, Sensing and Metrology. The flip charts from all the groups were hung on the walls and attendees used red sticky dots to identify their three most important challenges for imaging, blue sticky dots to identify their three most important challenges for sensing and Yellow sticky dots to identify their three most important challenges for metrology.

In the afternoon there was an opportunity to hear the perspective from 3 industrial speakers who were invited to share their perspective on the current state of the art and likely developments in the field over the next 5 years, as well as offering a general perspective on the role of quantum imaging, sensing and metrology in addressing wider challenges.

In session 3 the attendees then considered the key innovation challenges for Quantum Imaging, Sensing and Metrology in the UK. They then discussed what skills are required in a second phase in the UK and Internationally.

6. Outputs for QT Research priorities

At the start of the workshop participants were invited to split into a number of different groups. Participants were then asked, within their groups, to identify the research challenges in the area of Quantum Imaging, Quantum Sensing and Quantum Metrology. The flip charts showing the research priorities in Quantum Imaging can be found in Annex 2.

At the workshop there were five groups made up of attendees from 7 tables who moved to ensure a spread of expertise among the groups. Group 2 (which combined table 1 and 2), Group 3, Group 4 (which combined table 4 and 6), Group 5 and Group 7.

Four of the five groups filled in the Flip chart for Imaging Research Priorities Group 2, Group 4, Group 5 and Group 7. The typed up flip charts can be seen in Annex 2.

All of the groups filled in the Flip chart for Sensing Research Priorities Group 2, Group 3, Group 4, Group 5 and Group 7. The typed up flip charts can be seen in Annex 3.

All of the groups filled in the Flip chart for Metrology Research Priorities Group 2, Group 3, Group 4, Group 5 and Group 7. The typed up flip charts can be seen in Annex 4.

To note Group 4 filled in one flip chart which listed the priorities in Quantum Imaging, Sensing and Metrology on one sheet as they found it difficult to separate the areas during their discussions. Their flip chart can be found in Annex 3 with the Quantum Sensing flip charts.

6.1 Session 2: Prioritising of Research Priorities in the medium term (2019-2024)

The results from the prioritising exercise in session 2 are seen in Tables 1-3 below.

Table 1: Prioritised Research Challenges in Imaging in the medium term 2019 – 2024

Research Priority	**Votes (No of red dots)**
Scattering media – human tissue /unreadable water. Health. Offshore industries.	8
Imaging through complex media / obscurants and Imaging through difficult media Imaging with entanglement and correlation. Non-linear imaging and Shifting wavelength outputs detection – longer SPADS Ge-On-Si narrow gap III v on Si.	7
Linking together imaging in different spectral regions with/without entanglement and connect to gravity, electromagnetic fields - Rydberg atoms (2 red dots on Rydberg atoms). Through obscurants- fog, smog, smoke. Aircraft helicopter landing low level flight high frame rate good large. Auto LIDAR, DSTL. Photo sources (Entangled sources, Nonlinear crystals, Lasers, Fibre).	6
Quantum imaging beyond photonics and photons – single ions / electrons / neutrons/ OAM beams. Small cheap and efficient entangled pair and squeezed light sources at required wavelength.	5
System engineering	4
Magnetic field spatial imaging Space applications Biomedical applications	3
Healthcare applications need right wavelength and bandwidth Microwave and vf imaging Skills in machine learning Application - Ageing population Application - Autonomous vehicle Application - Defence/Security Application – civil engineering	2
Complimentary sensors, Sensing in real world environments SNR beyond quantum limits, 6 axis atom/MEMS sensors (linear acceleration and rotation), Structured imaging / principled imaging (time and frequency), Arrays or networked cold atom sensors Linking quantum imaging to quantum communications (Fibre networks, Free Space Systems and Space. Application –Space, Space qualifications Quantum listed sensing beyond laser/LED shot noise – drone detection Secure imaging, Software/Algorithms, Microscopy.	1

Table 2: Prioritised Research Challenges in Sensing in the medium term 2019 – 2024

Research Priority	Votes (No of blue dots)
Enhanced signal processing to translate from sensor to useful action.	8
Reduce size weight, weight, power and cost of cold atom sensor.	7
LIDAR single photon detector	5
Operation / ruggedisation for real world environments. Navigation- atom sensor and MEMS + complimentary sensing.	4
Rotation sensing Deployment in space Reduced SWAP lasers with sub kHz – Hz bandwidth at novel frequencies – integrated references for improved environmental isolation Novel sources of squeezed light Spin - Sensing with spin, Entanglement enhanced spin, Interaction of spin and surfaces) Enhanced photonic sensors for gases, extreme environments (At inaccessible wavelengths – Quantum RADAR, Mapping optical to microwave and return from Space. Complete and further develop portable demonstrators. New wavelengths tailored to atoms 369nm, 397nm, 422 nm – lasers. Wavelength conversion PPLW, PPLT, OP CAAS – waveguides and packaged components.	3
Imaging through obscurants fog, snow, rain, turbid media, water. Imaging through different media – non invasive Navigation with gravity gradient map matching Deployment of sensors moving platforms Magnetic- (Femto tesla – tesla, - Single spin sensing) Electric – bioelectrics neurons Use of superposition and entanglement (Enhance performance, Reduce systematic error) Improving SNR – beyond Quantum limits Technology - Vapour cell Application - gravity Gravity Sensors- Miniaturisation – integration and micro optics.	2
THz sensors Magnetic microscopy in advanced material/device development(e.g. load screens/solar cells) Sensors in bio-medical applications (microscopic and imaging) Concepts for GPS alternatives including demonstration Sensing in real world environment Technology - Cold atom Application – defence Application- space science/big science Application - Magnetic field Application - Magnetic field – medical Application - Network and distributed sensing Inertial – time - Acceleration Associated components Optical coupling/gratings Associated components Photonic integration. Methodology and standards assurance Magnetic field - Ion chips Rotations - Atom chips Low power electronics – operation on mobile platforms	1

Needs to work – systems engineering CNI national critical for defence	

Table 3: Prioritised Research Challenges in Metrology in the medium term 2019 – 2024.

Quantum Metrology Research priorities for the UK	Votes (No of yellow dots)
Taking photonic QM to other wavelengths - Long RADAR, - Short e.g. PET scanner.	7
Navigation (- Inertial, - Mapping – gravity) Photon timing for 3D vision microscopy (lifetime) – Detectors Taking quantum metrology to commercial manufacturing. Taking quantum measurements into real world environments, e.g. space, shop floor, tank turret, etc.	6
Compact, deployable standards free of calibration.	5
Reduced SWAP lasers with sub KHz – Hz bandwidths at novel frequencies, - integrated references, -Stabilised dual frequency, -Novel gain materials Metrology on a chip – self test and calibration.	4
Agreed standards – international. Standards for specification of quantum devices, e.g. Atom trap lifetime, SWAP, Detectors, time, Sources). Atomic metrology / rotation sensor – engineering ruggedized systems Optical metrology in difficult environments - Turbid media – through fog, - Round corners. optical clock cold flow band microwave	3
Microscopy - Low light / noise Microscopy -Unusual wavelength Application – Flywheel Reduced trade off of accuracy versus low SWAPC for portable standards.	2
Technologies - Nonlinear element Application – magnetic field Effect of precise timing on communication network architectures. CSAL competitor at 10^{-13} level, <£2k, <1w Develop ion chips for large number of ions and long life times (trap depots) Portability of primary standards (or more likely secondary standards) – or as close to primary as possible. Metrology centres dedicated to providing test and evaluation and traceability. Precision agriculture and natural resources management	1

6.2 Session 2: Prioritising of Research Priorities in the long term (beyond 2024).

Tables 4-6 below show the long term priorities in Quantum Imaging (Table 4), Quantum Sensing (Table 5) and Quantum Metrology (table 6).

Table 4: Quantum Imaging Research Priorities in the long term beyond 2024.

Research priority	**Votes (No of red dots)**
Quantum RADAR and quantum LIDAR	7
Non demolition sensing / imaging without illumination	4
Quantum radar	2
100% efficient detectors at all wavelengths Up conversion detector Long wavelength OP-GAAS 100% efficient detectors at all wavelengths Optics 2.0, Lens, Diffractive, Adaptive	1

Table 5: Quantum Sensing Research Priorities in the long term beyond 2024

Research Priority	**Votes (No of blue dots)**
Technology for mass, low cost production (Optics – integrated systems, wavelengths?)	2
6 axis atom / MEMS sensors (linear acceleration and rotation) Interfacing / exploiting Quantum computation backplane onto Quantum sensors Rotation sensors for navigation demonstrators Quantum sensors (magnetic) in routine medical diagnostics <£1k gravity sensor for precision agriculture Fully integrated cold atom source at <100cm^2 <1w, <1Kg, <£1k	1

Table 6: Quantum Metrology Research Priorities in the long term beyond 2024.

Research Priority in the long term beyond 2024	**Votes (No of yellow dots)**
Clocks demonstrating distributed RADAR and SAR on moving platforms (10^{-16} level clock). Fully integrated seamless navigation techniques (unreadable inertial and GNSS) for communication. Quantum in a phone (Atoms, Clocks, Communications, Measurement).	3
Atomic standards for B, E, etc. An entanglement metrology system. Reaching a 1 10dB world Reaching quantum, at radio 4 long wave. Manufacturing techniques.	2
Integration in autonomous vehicles Low power, smaller size, for timing and (ultra-high reliability) navigation in mobile systems or all mobile communications systems. Improved resilience. Time and accelerometry based navigation moving towards commercial. Volume, size, shape for gravity Chip scale cold atom clock (Generations) Novel atom sources	1

7. Outputs for QT Innovation priorities

The typed up flip chart from session 3 are shown in Annex 5.

In summary the main points that were not discussed in the morning sessions are listed below.

- Translating sensor raw output to useful user output
- Training Quantum entrepreneurs
- Deployment and operability in real world applications domain
- Robust and resilient demonstrators
- Create application specific idiot proof user interface
- Improvement in size, weight, power and cost
- Create robust supply chains
- Establish testing and validation capabilities including calibration
- Application specific devices
- Early prototypes (demonstrators) into real saleable products
- More intelligent supply chain and finance community engagement
- Tax efficient VCT type investment fund?
- Supply chain considerations for each type of system
- Centralised validation and environmental testing
- Quantum small business incubator
- Co-ordinated IP portfolio and management

7.1 What disciplines and skills need to be involved?

Business development and market development skills. Multidisciplinary researchers with physics and engineering skills. Engagement with engineering skills such as CMOS design, photonic integrated circuit expertise, product development engineers, electronic engineering, control, system engineering, mechanical engineering, Industrial design – user interface. Increased end user engagement from Geophysics, Medical, Civil engineering and Space applications.

7.2 Who do we need to collaborate with internationally?

International academic partners where the collaboration will enable the UK to maintain its sovereign capability.

Collaborate with international standardisation bodies.

8. Summary

8.1 Imaging Priorities

In Imaging the following three Research priorities were identified

- Imaging through complex media / obscurants and Imaging through difficult media.
- Imaging with entanglement and correlation.
- Non-linear imaging and shifting wavelength of detection.

8.2 Sensing Priorities

In Sensing there was a wider spread of priorities identified the top 5 are listed below.

- Enhanced signal processing to translate from sensor to useful action.
- Reduce size ,weight, power and cost of cold atom sensor.
- LIDAR single photon detector
- Operation / ruggedisation of sensors for real world environments.
- Navigation - atom sensor and MEMS + complimentary sensing.

8.3 Metrology Priorities

In Metrology there was a wider spread of priorities identified the top 6 are listed below.

- Taking photonic QM to other wavelengths - Long RADAR, - Short e.g. PET scanner.
- Navigation (- Inertial, - Mapping – gravity)
- Photon timing for 3D vision microscopy (lifetime) – Detectors
- Taking quantum metrology to commercial manufacturing.
- Taking quantum measurements into real world environments, e.g. space, shop floor, tank turret, etc.
- Compact, deployable standards free of calibration.

9. Next Steps

This report will be emailed to attendees and added to the EPSRC website. The report will be considered as a key input in discussions with our delivery partners on the National Quantum Technologies Programme and its Strategic Advisory Board on priorities for Quantum Technologies Research Hubs in a second phase.

EPSRC have run workshops in other quantum technology areas and there will be workshop reports produced for each of the workshops. In addition to the workshops, EPSRC are gathering input from a range of sources which will also feed into discussions on research and innovation priorities. The scope for Quantum Technologies Research Hubs in a second phase of the National Programme will be published in June, with details of how to register an interest in being part of a Hub’s consortia.

The input received from the workshops and other engagement will also be used by the EPSRC Quantum Technologies Theme when planning future activities and funding.

Annex 1 – Workshop Attendees, Quantum Imaging, Sensing and Metrology Workshop, Malmaison Hotel, 1 Swinegate, LS1 4AG, Leeds, 6 March 2018.

Tariq	Ali	University of Birmingham
Yoann	Altman	Heriot-Watt University
John	Bagshaw	Independent Technology Consultant
Simon	Benett	University of Birmingham
Liam	Blackwell	EPSRC
Kai	Bongs	University of Birmingham
Vincent	Boyer	University of Birmingham
Matthias	Brookes	University of Nottingham
Gareth	Brown	DSTL
Gerald	Buller	Heriot-Watt University
Wendy	Carr	EPSRC
Colin	Coates	Andor Technology
Trevor	Cross	Teledyne e2v
David	Cumming	University of Glasgow
Martin	Dawson	University of Strathclyde
Jeremy	Everard	University of York
Mark	Fromhold	University of Nottingham
Corin	Gawith	University of Southampton
Patrick	Gill	National Physical Laboratory
John	Girkin	Durham University
Giles	Hammond	University of Glasgow
Jennifer	Hastie	University of Strathclyde
Winfried	Hensinger	University of Sussex
Beth	Horton	EPSRC
Amanda	Howes	EPSRC
Bryn	Hughes	DSTL
Helen	Hunt	EPSRC
John	Jeffers	University of Strathclyde
Matthias	Keller	University of Sussex
Peter	Knight	NPL
Peter	Kruger	University of Sussex
Jonathan	Leach	Heriot-Watt University
Alan	Malvern	UTC Aerospace Systems
Jonathan	Matthews	University of Bristol
Roger	McKinlay	Independent
Loyd	McKnight	Fraunhofer
David	McLoskey	HORIBA
Nicole	Metje	University of Birmingham
Richard	Murray	Teledyne e2v
Miles	Padgett	University of Glasgow
Doug	Paul	University of Glasgow
Tom	Pike	Imperial College London

Simon	Plant	Innovate UK
Andrew	Powell	UK Government
Jason	Ralph	University of Liverpool
John	Rarity	University of Bristol
Erling	Riis	University of Strathclyde
Yeshpal	Singh	University of Birmingham
Maurice	Skolnik	University of Sheffield
Peter	Smith	University of Southampton
Victoria	Smith	NERC
Michael	Strain	University of Strathclyde
George	Tuckwell	RSK Environmental
Kevin	Weatherill	Durham University
Mike	Worboys	Independent
Glyn	Wright	Aralia Systems

Annex 2: Workshop Flip charts from the Research Challenges Session 1 - Quantum imaging in the UK

<u>Group 2</u>

What are the Quantum Imaging Research priorities for the UK?

In the medium term 2019-2024

- Linking quantum imaging to quantum communications
    - Fibre networks
    - Free space systems
    - Space
- Linking together imaging in different spectral regions with/without entanglement and connect to gravity, electromagnetic fields - Rydberg atoms
- Quantum imaging beyond photonics and photons – single ions / electrons / neutrons/ OAM beams
- Optimised single photon detectors outside of near infrared
- Imaging through complex media / obscurants
- Take advantage of UK expertise in underpinning science (some world leading activities not currently linked to hubs)
- Structured imaging / principled imaging (time and unreadable)
- Measuring uncertainty in data / information extracted

In the long term beyond 2024

- Non demolition sensing / imaging without illumination
- Quantum RADAR and quantum LIDAR
- More accurate / higher resolution imaging sensors in non-visible bands at low swap
- Imaging round corners

Group 5

What are the Quantum Imaging Research priorities for the UK?

In the medium term 2019-2024

Applications

- Through obscurants- fog, smog, smoke
    - Aircraft helicopter landing low level flight high frame rate good large
    - Auto LIDAR
    - DSTL
- Scattering media – human tissue / unreadable water
    - Health
    - Offshore industries
- Healthcare apps need right wavelength and bandwidth
- Quantum listed sensing beyond laser/LED shot noise – drone detection
- Imaging with entanglement and correlation
- Non-linear imaging
- Shifting wavelength of detection – longer SPADS Ge-On-Si narrow gap III v On SI
- Room temperature for application - Peltier cooled
- Data processing for all this
    - Long wavelength
    - Short (high energy) wavelength
- Detectors from single pixels to detector arrays
- Magnetic field spatial imaging
- Small cheap and efficient entangled pair and squeezed light sources at required wavelength
- Microwave and vf imaging
- Secure imaging – background suppression.
- Quantum computer enhanced image processing?

In the long term beyond 2024

- Room temperature THz single and photon detector (how we do it, not sure?)
- 100% efficient detectors at all wavelengths
- Totally lens less imaging – maybe optical equivalent of bistatics radar. Sensitive imaging skin?
- Room temperature single photons emitters

Group 7

What are the Quantum Imaging Research priorities for the UK?

In the medium term 2019-2024

APPLICATIONS	TECHNOLOGIES	CHALLENGES
Autonomous vehicles	Photo sources • Entangled sources • Nonlinear crystals • Lasers • Fibre (unreadable0	System level approaches
Space	Components • Fibres • SPADI • Hostile environment • Space qualification	Skills • Machine learning • Data fusion • Image processing
Geophysics	Software / algorithm • Data fusion • Machine learning	
Biomed	Enabling component • Connector • Mechanical/optomechanical • Material e.g. SPDC with THz	
Defence/security	System engineering	
VR/games		
Aging population		

In the long term beyond 2024

- Quantum radar
- Up conversion detector
- Long OP-GAAS
- Non illumination imaging
- Non demolition
- Optics 2.0
    - Lens
    - Diffractive
    - Adaptive
- Machine learning meets imaging

Annex 3: Workshop Flip charts from the Research Challenges Session 1 - Quantum Sensing in the UK

Group 2

What are the Quantum Sensing Research priorities for the UK?

In the medium term 2019-2024

- Reduce size weight, weight, power and cost of cold atom sensor
- Atom based standards for E fields
- Gravity gradient for border portals
- Low phase noise oscillators for radar (10^{-16} Clock)
- TH_Z sensors
- Sensor arrays for imaging (gravity, mag-fields etc.)
- Magnetic microscopy in advanced material/device development(e.g. load screens/solar cells)
- Rotation sensing
- Deployment in space
- Navigation with gravity gradient map matching
- Reduced SWAP lasers with sub kHz – Hz bandwidth at novel frequencies, integrated references for improved environmental isolation
- AI / signal processing / machine learning tools for systems design
- Sensors in bio-medical applications (microscopic and imaging)
- Novel sources of squeezed light
- Down borehole gravity sensors
- Deployment of sensors moving platforms
- Concepts for GPS alternatives including demonstration
- Radiation hard sensors
- Chip scale gravimeter
- Robust and fast algorithms for large data volumes

In the long term beyond 2024

- Fully integrated cold atom source at <100cm^2 <1w, <1Kg, <£1k
- Magnetic sensors for livestock monitoring at <£10
- Rotation sensors for navigation demonstrators
- Quantum sensors (magnetic) in routine medical diagnostics
- <1k gravity sensor for precision agriculture

Group 3

What are the Quantum Sensing Research priorities for the UK?

In the medium term 2019-2024

- Magnetic and electric
    - Magnetic
        - Femto tesla – tesla
        - Single spin sensing
    - Electric – bioelectrics neurons

  (Spin - Sensing with spin, Entanglement enhanced spin, Interaction of spin and surfaces)

- Use of superposition and entanglement
    - Enhance performance
    - Reduce systematic error
- Sensing in real world environment
- Enhanced photonic sensors for gases, extreme environments
    - At inaccessible wavelengths – Quantum RADAR
    - Mapping optical to microwave and return
    - From Space
- Improving SNR – beyond Quantum limits
- Enhanced signal processing to translate from sensor to useful action

In the long term beyond 2024

- Wavelength translation from UV to and from microwave
- Interfacing / exploiting Quantum computation backplane onto Quantum sensors

Group 5

What are the Quantum Sensing Research priorities for the UK?

In the medium term 2019-2024

- Develop multi-sensor platforms
- Quantum sensing – building block of system

- Understand where fits in application
- Have knowledge of application spec – application pull
    - For two bullets above – materials and tech developed for that pull (c.f. laser industry – a new motor of laser architecture was developed for each application
- Complete and further develop portable demonstrators

Magnetic Field Sensors	Gravity Sensors	Rotations	Distance Depth
Com part vacuum systems			LIDAR single photon detector – imaging through fog, snow, rain, turbid media, water
Optical delivery			
Miniaturised electronics	Miniaturised electronics	Miniaturised electronics	
Laser systems including low power drivers			
Ion chips	Atom chips	Atom chips	
Control systems	Control systems	Control systems	
Make smaller size & low power demonstrators – stabilisation	Miniaturisation – integration and micro optics		
Low power electronics – operation on mobile platforms			

- Getting device and system performance specs tied down
    - Roadmap
    - Methodology and standards assurance

In the long term beyond 2024

- Full system prototypes to SWAPC, platform integration, software
- Development of scalable platform technologies – minitiaturisation integration, reduced SWAP and cost
- Cheap, small and practical

Group 7

What are the Quantum Sensing Research priorities for the UK?

In the medium term 2019-2024

APPLICATIONS	TECHNOLOGIES	CHALLENGES
Gravity • Civil engineering • Defence • Navigation • Space science/big science	Cold atom Vapour cell MEMS	Skills • Atomic physics • System design • Hardware/electronic interface • Statistics/numerical filters • Business development / entrepreneur / requirement capture
Magnetic field • Medical • Navigation • Buried services • Defence	Associated components • Lasers – detectors • Traps • Materials • Optical coupling/gratings • Vacuum systems • Photonic integration • Algorithms and software • Fusion/hybridisation	Operation / ruggedisation for real world environments
Inertial – time • Acceleration • Rotation	Materials • For vacuum	
Transport and autonomy	User interface / user environment	
Network and distributed sensing		

In the long term beyond 2024

- Assurance / decision integration
- Rich dataset
- Fusion maintain accuracy
- Constrained inversion (geology)
- Impact / ergonomics
    - Train
    - High vibration
- Down well?
- Real time – geo-located

Group 4

Quantum Sensing in the UK

What are the Quantum Sensing Research priorities for the UK? * Please note this table has indicated that it included Quantum imaging and metrology in the information below.

In the medium term 2019-2024

- Robust – applications of current approaches "show science"
- Imaging through different media
- Needs to work – systems engineering
- Supply chain?
- Navigation atom sensor and MEMS – complimentary sensing
- Novel atom sources – optical clock cold flow band microwave
- Higher band width and phasing of sensors
- Novel detector techniques
- Radars platform adaptability
- Micro nana fabrications for atoms / MEMS
- Add healthcare and agriculture into Hubs - for real clinical challenges
- New wavelengths tailored to atoms 369nm, 397nm, 422nm – lasers. Wavelength conversion PPLW, PPLT, OP CAAS – waveguides and packaged components
- Imaging in manufacturing. Conversion of low light (single photons) to measureable wavelengths (1K to visible)
- Science – technology – practical / robust – data processing – real world examples
- Applications to food security / production / agriculture
- Align with EPSRC / Innovate goals
    - Ageing society (brain scan)
    - Autonomous vehicles (navigation, imaging
    - AI (data fusion)
    - Intelligent cities (scanning, gravity, construction
    - Precision medicine
- Network synchronisation using optical clocks, e.g. Telecomm finance
- Precision agriculture and natural resources management
- Navigation – gravity, clock rotation
- Stronger equipment with end users
- Gravity mapping for underground
- CNI medical clinical, defence

In the long term beyond 2024

- Space borne platforms – Earth observation (MEMS gravimeter
- Hyperspectral imaging – multi sensor platforms Earth observation
- Entanglement between sensors (quantum correlations / entangled states shared across sensors)
- MEMS with squeezed light sources and entanglement
- On chip light sources
    - Atoms
    - MEMS

- Sagnac interometers in MEMS
- 6 axis atom / MEMS sensors (linear acceleration and rotation)
- Uptake of quantum sensors into industry / end users
- Further space based application
- Consumer applications beyond cars
- Technology for mass, low cost production
    - Optics – integrated systems, wavelengths?
    - Prepared atoms?
    - Detectors?
    - Data / signal processing?
- New standards e.g fair alignment in navigation, timing
- Those areas that demonstrator are no longer addressing therefore directed from 2019- 2024 output therefore be agile.

Annex 4: Workshop Flip charts from the Research Challenges Session 1 - Quantum Metrology in the UK.

Group 2

What are the Quantum metrology Research priorities for the UK?

In the medium term 2019-2024

- Effect of precise timing on communication network architectures
- Reduced SWAP lasers with sub KHz – Hz bandwidths at novel frequencies
    - Integrated references
    - Stabilised dual frequency
    - Novel gain materials
- Compact, deployable standards free of calibration
- CSAL competitor at 10^{-13} level, <£2k, <1w
- Time sources for astrophysics (competitor H-MASER)

In the long term beyond 2024

- Clocks demonstrating distributed RADAR and SAR on moving platforms (10^{-16} level clock
- AI for signal processing in RADAR
- Atomic standards for B, E, etc.

Group 3

What are the Quantum Metrology Research priorities for the UK?

In the medium term 2019-2024

- Metrology as standards
- Taking quantum metrology to commercial manufacturing
- Standards for specification of quantum devices., e.g.
    - Atom trap lifetime, SWAP
    - Detectors, time
    - Sources
- Tolerancing of quantum devices
    - Engineering repeatability
    - Fidelity/errors
    - Trap reproducibility
- Time – defining time Distribution of standard
- Metrology as measuring things
- Taking quantum measurements into real world environments, e.g. space, shop floor, tank turret, etc.
- Taking photonic QM to other wavelengths
    - Long RADAR
    - Short e.g. PET scanner
- Atomic metrology / rotation sensor – engineering ruggedized systems
- Optical metrology in difficult environments
    - Turbid media – through fog
    - Round corners
- Sensor scalability
    - Multiple
    - Imaging

In the long term beyond 2024

- Time and accelerometry based navigation moving towards commercial
- An entanglement metrology system
- Reaching a 1 10dB world (squeezing, nooiv) reaching quantum at radio 4 long wave
- Quantum in a phone
    - Atoms
    - Clocks
    - Communications
    - Measurement
- Quantum embedded into systems
- Continued standards research

Group 5

What are the Quantum Metrology Research priorities for the UK?

In the medium term 2019-2024

- Large overlap with quantum sensors in terms of subsystem development
- Focus on small size and small power consumption
- New quantum definition of SI units
- Test and evaluation of the various quantum systems for time, navigation, magnetometer, gravimeters, communication protocols and Q computing protocols. Quality Assurance of QT – QKD happening now(ish).
- Agreed standards – international
- Metrology on a chip – self test and calibration
- Be application specific
- Develop ion chips for large number of ions and long life times (trap depots)
- Portability of primary standards (or more likely secondary standards) – or as close to primary as possible
- Establishment of few step evaluation and calibration procedures stats (e.g. clocks) or via internet / fibre links
- Standards and metrology for calibration of navigation systems on submarine, aerospace platforms
- Direct non GPS dependent metrology of communication networks and/or resilient systems with holdover in GPS denial situations.
- Focus on systems integrations
- Reduced trade off of accuracy versus low SWAPC for portable standards
- Metrology centres dedicated to providing test and evaluation and traceability

In the long term beyond 2024

- Fully integrated seamless navigation techniques (unreadable inertial and GNSS) for communication
- Capable of providing location on land, sea, sub-sea, and aerospace
- Integration in autonomous vehicles
- Low power, smaller size, for timing and (ultra-high reliability) navigation in mobile systems or all mobile comms systems
- Improved resilience
- Integrated in multi sensor platform. Quantum part of the system solution – so have to think at science level about integration level
- Metrology from primary standard directly to manufacturing and user sites (e.g. in city conurbations) and into the field via free space, internet, and fibre delivery

Group 7

What are the Quantum Metrology Research priorities for the UK?

In the medium term 2019-2024

- Photon timing for 3D vision microscopy (lifetime)
    - Detectors
    - Sources (cheap)
    - Software
- Navigation
    - Inertial
    - Mapping – gravity
- Microscopy
    - Super resolution
    - Low light / noise
    - Unusual

APPLICATIONS	TECHNOLOGIES	CHALLENGES
GNSS resilience	Diamond colour centre	How to get out of Lab
Flywheel	Ions	Quantum RADAR
Small form factor	Atoms	
Quantum candela	Superconducting • Gate • Qubit • Detectors	
Magnetic field	Space qualified optical lattices	
Space	Laser	
Metrology of networks	Cavity	
	Fibres	
	Microwave	
	Nonlinear element	
	Parametric systems	

In the long term beyond 2024

- Volume, size, shape for gravity
- Chip scale cold atom clock (Generations)
- Lower cost
- Manufacturing techniques
- Magnetic field small scale
- Metrology of optical network RF NetWare

Annex 5: UK’s innovation priorities in Quantum Imaging, Sensing and Metrology

Group 2

What are the UK’s innovation priorities in Quantum Imaging, Sensing and Metrology

In the medium term 2019-2024

- Supply chain considerations for each type of system
- Commercial OEM use of SPAD arrays
- Commercial sensors manufactured in UK in <3 years
- Centralised validation and environmental testing
- Fibre network for clock/timing distribution
- Quantum small business incubator
- Co-ordinated IP portfolio and management

In the long term beyond 2024

- Investment in long term UK manufacturing base

Group 3

What are the UK's innovation priorities in quantum Imaging, Sensing and Metrology

In the medium term 2019-2024

- QIS in autonomous vehicles, driver assistance
    - Fog cameras
    - Navigation
    - Quantum AI
- Agriculture – crop
- Oil and gas
    - Environmental – leaks methane, ethane, CO2
    - Prospecting
- Space – remote sensing
- Biomedical
    - Imagining
    - Assays
- Understanding, tolerancing and manufacturing repeatability of QIS & M
- Translating sensor raw output to useful to user output
- Data and info is the product.
- Training Quantum entrepreneurs

In the long term beyond 2024

- Quantum computer/sensor hybrids
- Few photon sensor
- Chip scale sensor and processing
- Quantum in a phone – QG mobile networks

Group 4

What are the UK's innovation priorities in Quantum Imaging, Sensing and Metrology

An overall comment: Innovation in scale – appropriate level of funding - lots

In the medium term 2019-2024

- GNSS denial & GNSS resilient capability and capacity
- Compact and precise clocks – optical clock
- Deployment and operability of all sensor tech & demonstrator in real world applications domain
- Non-invasive detection and diagnostics for medical sensor
- Self-sustained vacuum chamber (e.g. without active pumping requiring power)
- System integration
- System of system's integration
    - E.g. Li/Radar system integrated with autonomous car
    - Cold atom sensor on a copter/drone
- Scaling up
- Mapping of underworld using gravity sensors
- Quantum navigator / quantum enabled navigator
- QT in space
- Novel atom source
- Quantum / quantum enabled Radar
- Improvement in SWAPC

Other parties interested in QT – UK Space, NERC, ESRC, MRC, HMT, ESA, STFC

In the long term beyond 2024

- Landscape activity to identify skill and tech gaps in the UK
- International collaboration with inputs from the Landscape document

Group 5

What are the UK's innovation priorities in Quantum Imaging, Sensing and Metrology

In the medium term 2019-2024

- Make sure subsystems cater for multiple demonstrators
- Tech demo satellite
- Create robust supply chains
- Join subsystems to produce robust demonstrators
- Application and field testing
- Using outputs of device, create application specific idiot proof user interface
- Robust and resilient subsystems
- Establish testing and validation capabilities including calibration
- Make use of synergies to quantum computing
- Develop platform technology to allow integral systems for many applications / design kit, components, integration, test, validation, calibration >>>> test
- Application specific devices
- Work on low power, low size - create application roadmap. Navigation systems that do not rely on GNSS >>> automotive and automatous vehicle enabler (clock, rotation, inertia, LIDAR, gravity gradients, 3D radar)

In the long term beyond 2024

- Reduce size and power consumption
- Reduce price
- Biomarkers for brain health using magnetic sensors
- Space deployment

Group 7

What are the UK's innovation priorities in quantum Imaging, Sensing and Metrology

In the medium term 2019-2024

- Early prototypes (demonstrators) into real saleable products
- Support protects covering full value chain leading to prototype devices rather than supporting components, subsystems, etc.
- Appropriate standards and avoiding inappropriate.
- Adventurous, at scale, large programmes, (£5m public, £5m private)
- Diverse and engagement with supply chains (spotting and working with early adopters)
- More intelligent supply chain and finance community engagement
- Tax efficient VCT type investment fund?
- Development of confidence in sensor performance for different applications (no repeat of GPR sensor)
- After early adopters funders like DSTL and ESA/UKSA sustains opportunities for funded demonstrators / early production
    - Get DUT / NHS/ GCLRC engaged and incentivise for use gravity sensing for brown field development