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INTERNATIONAL STANDARDS DEVELOPMENT FOR QUANTUM TECHNOLOGIES (NPL REPRESENTATION AND PROVISION OF TECHNICAL EXPERTISE)

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International standards development for quantum technologies (NPL representation and provision of technical expertise)

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Approved on behalf of NPLML by

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GLOSSARY/ABBREVIATIONS

Term	Definition
AG	Advisory Group
AIRQKD	ISCF project addressing short to mid-range quantum secure communication in free-space
AQUASEC	Agile Quantum Safe Communications (ISCF project)
BEIS	Department for Business, Energy & Industrial Strategy
BIPM	Bureau International des Poids et Mesures
BIPM	International Bureau of Weights and Measures (BIPM)
BSI	British Standards Institute
BSI(DE)	Federal Office for Information Security (Germany)
CCL	Consultative Committee for Length (CCL)
CCL-CCTF FSWG	Frequency Standards Working Group (WGFS) is a joint working group of the Consultative Committee for Length (CCL) and the Consultative Committee for Time and Frequency (CCTF)
CCPR-WG-SP TG7	Consultative Committee for Photometry and Radiometry Working Group on Strategic Planning, Task Group 7
CCs	Consultative Committees (CCs)
CCTF	Consultative Committee for Time and Frequency
CEN-CENELEC FGQT	Focus Group on Quantum Technologies
CGPM	General Conference of Weights and Measures (CGPM)
CIE	International Commission on Illumination
CIML	International Committee of Legal Metrology (CIML)
CIPM	International Committee for Weights and Measures (CIPM)
CIPM	International Committee for Weights and Measures (CIPM)
CPU	Central Processing Unit
DCMS	Department for Digital, Culture, Media and Sport
DI	Designated Institutes
DIN	German Institute for Standardisation
EMN-Q	European Metrology Network for Quantum Technologies
EMPIR	European Metrology Programme for Innovation and Research
ETSI	ETSI; formerly European Telecommunications Standards Institute
ETSI ISG-QKD	ETSI Industry Specification Group on QKD
FG-QIT4N	Focus Group on Quantum Information Technology for Networks
FPGA	Field Programmable Gate Array
FQS	Towards a Federated Satellite QKD System (UKSA project)
GPU	Graphics Processing Unit
H2020	Horizon 2020
HAL	Hardware Abstraction Layer
HMG	Her Majesty's Government
IEEE	Institute of Electrical and Electronics Engineers
INRIM	INRIM (the Italian National Metrology Institute)
IMEKO	International Measurement Confederation
ISCF	Industrial Strategy Challenge Fund

ISO/IEC	International Organisation for Standardisation/International Electrotechnical Commission
ISO/IEC JTC 1/SC 27	International Organisation for Standardisation/International Electrotechnical Commission Joint Technical Committee 1, Subcommitee 27
ISO/IEC JTC1/WG14	International Organisation for Standardisation/International Electrotechnical Commission Joint Technical Committee 1, Working Group 14
ITU-T	International Telecommunication Union Telecommunication Standardisation Sector
ITU-T/SG 13	ITU-T Study Group 13
ITU-T/SG 17	ITU-T Study Group 17
JC	Joint Committees
KRISS	The Korean National Metrology Institute
LNE-SYRTE	Laboratoire National de Métrologie et d'Essais-Systèmes de Référence Temps-Espace
MeTISQ	Metrology for Testing the Implementation Security of Quantum Key Distribution (EMPIR project)
NCSC	National Cyber Security Centre
NICT	National Institute of Information and Communications Technology
NISQ.OS	Noisy intermediate-scale quantum operating system
NIST	National Institute of Standards and Technology (the United States' National Metrology Institute)
NMI	National Metrology Institutes
NPL	National Physical Laboratory
NQCC	National Quantum Computing Centre
NQTP	National Quantum Technology Programme
OIML	International Organisation of Legal Metrology
OPENQKD	Open Quantum Key Distribution (H2020 project)
PRISMS	Protocol Randomness and Information Security Measures for Space (ISCF project)
QKD	Quantum Key Distribution
QPU	Quantum Processing Unit
QRNGs	Quantum Random Number Generators (ISCF project)
QT&E	Quantum Test and Evaluation
ROCIT	Robust Optical Clocks for International Timescales (ROCIT)
SDO	Standards Developing Organisations
SME	Small-to-Medium Enterprise
UKSA	UK Space Agency
WG	Working Group

EXECUTIVE SUMMARY

This report describes the current international activity in the development of standards for quantum technology. Through a description of the activities in which NPL scientists are directly engaged, and a report of a recent (virtual) international conference on quantum standards attended by the main SDOs involved, the report offers a summary of most if not all of the current standards development programmes.

The report describes the high level of engagement which NPL scientific experts have had in international standards organisations aiming to develop new standards for quantum technologies. NPL scientists are currently often the only representatives from the UK on international standards groups across multiple technology areas.

This report covers NPL's involvement in the development of future standards for Quantum Computing, Quantum Communications, Quantum Sensing and aspects of NPL involvement in international metrology for Time and Frequency.

NPL scientists are now involved in almost all the international Standards Development Organisations (SDO) activity including ISO, IEC, ITU, ETSI, and cross technology groups such as CEN/CENELEC. NPL is also fully engaged with the international metrology community in groups such as the European Metrology Network for Quantum and the CCL-CCTF Frequency Standards Working Group reporting to the International Committee for Weights and Measures (CIPM).

The NPL quantum programme has supported a much wider and deeper involvement of NPL technical experts in standards work. Projects within the UK industry-led ISCF programme and the European EMPIR metrology research programme also contribute to the development of new measurement techniques which can underpin new standards.

Significant progress has been made with roadmaps in several areas being drafted, submitted and in one instance published. Likewise, progress is being made in detailing terminology, specific aspects of standards and provision of highly specialised technical information in support of standards.

CONTENTS

1 INTRODUCTION

This report is an output from the NPL quantum programme for the period April 20 – March 21. This period is the first year of a proposed four-year programme to enable the capabilities and expertise of the National Physical Laboratory to fully support the UK National Quantum Technology Programme (NQTP) and the UK's aspirations for quantum technologies. The NPL programme is funded by the government department of Business, Energy and Industrial Strategy (BEIS).

The NQTP vision to create a quantum-enabled economy is described in the 2020 strategic intent document for the national programme (UK National Quantum Technologies Programme Board, 2020). The strategic intent document details four main themes of work and a number of key areas within those themes which are required to deliver the desired outcomes and benefits for the UK.

Under the theme of "Stimulate market growth, unleash innovation, and create a thriving ecosystem", one of the key areas of work is described as "Strengthen engagement in international standards and benchmarking".

We have produced two reports which describe the work which NPL has delivered in support of that objective in the period 2020-21. The present report details NPL's representation for the UK and provision of technical expertise to a range of standards development organisations and describes the work of supporting, contributing to and leading in current Quantum standards efforts. We include a description of the work done as part of international metrology, within the European metrology community and as part of a global activity.

NPL already works in the field of standards development across many areas of technology as defined in the UK Measurement Strategy (Government Office for Science, 2016). This BEIS document clearly identifies that the commercialisation and technical delivery of market-ready products based on emerging and disruptive technologies such as quantum technologies requires the development of measurement infrastructure, access to facilities and the transfer of knowledge throughout the supply chain. BEIS calls on NPL to respond to these requirements by providing the leadership that delivers new technical measurement capability and international standards which will enable the partnership of UK industry, academia and government to make the UK the nation of choice for the commercialisation of Quantum Technologies.

2 CROSS-TECHNOLOGY STANDARDS ACTIVITY

Most Standards Development Organisations (SDOs) working in quantum technologies are focussed on either quantum computing or quantum communications. Our report describes these below. However, there are three organisations which are looking across multiple technologies for which standards might be needed. We describe the objectives of these organisations in this context here and describe the NPL involvement in each of the technology sections below.

2.1 CEN-CENELEC FOCUS GROUP ON QUANTUM TECHNOLOGIES (FGQT)

The Focus Group on Quantum Technologies (FGQT) was established by CEN-CENELEC in 2020 to develop a roadmap for standardisation activities related to quantum technology in Europe. The work within the FGQT is aligned with the H2020 quantum technology flagship projects and is organised along the lines of the flagship "pillars".

The terms of reference for the FGQT states that the goal is to create a roadmap for standardisation activities for quantum technologies in Europe, i.e. the goal is not to directly work on new standards but to (i) identify areas that need to be standardised, (ii) start to define a timeline for when standards will be needed, and (iii) finally to identify areas where activities could start in the near future.

Work on the roadmap for standardisation started in the third quarter of 2020 and a first draft will be made available mid-2021. The roadmap includes work on all quantum technologies, but the current interest in computing and simulation means that these areas will be a major part of the roadmap document.

2.2 EMN-Q: EUROPEAN METROLOGY NETWORK FOR QUANTUM TECHNOLOGIES

The European Metrology Network for Quantum Technologies (EMN-Q) is an element of the Euramet programme and provides active coordination of European measurement science research to maintain competitiveness in the field of quantum technologies. By promoting and facilitating knowledge sharing, collaboration and the uptake of measurement science in the development of quantum technology, the EMN-Q aims to establish globally accepted measurement services for quantum technologies and devices.

The main objective of the EMN-Q is to engage with the stakeholder community in order to co-ordinate the activities of the European NMIs to support industrial needs and ensure their efficient contribution to European competitiveness in quantum technologies. EMN-Q aims to establish a coordinated metrology infrastructure ready for quantum technology requirements in industry as well as academia. The EMN-Q is chaired by Ivo Degiovanni from INRIM (the Italian National Metrology Institute), and it comprises three technical sections - quantum clocks and atomic sensors, quantum electronics (which includes quantum computing) and quantum photonics. A cross-theme activity in metrology and sensing spans all three technical sections. NPL provides a UK representative to each technical area including one of the three EMN-Q vice-chairs.

2.3 IMEKO TC25: QUANTUM MEASUREMENT AND QUANTUM INFORMATION TECHNICAL COMMITTEE

NPL has joined forces with NIST and PTB to provide thought leadership in metrology and standardisation of quantum technologies. IMEKO is a non-governmental federation of 42 Member Organisations individually concerned with the advancement of measurement technology. Its fundamental objectives are the promotion of international interchange of scientific and technical information in the field of measurement and instrumentation and the enhancement of international co-operation among scientists and engineers from research and industry.

The aim of the new TC25 is to provide a forum to discuss advances in quantum-based measurement, the quantum technologies they support, and the changes they imply for the international metrology infrastructure and for applications. Topics include:

- Latest trends and best practices in quantum-based measurements across multiple disciplines
- How quantum technology in combination with the redefinition of the SI is changing the face of the realisation and dissemination of measurement standards and services
- Readiness of various quantum measurement technologies and prospects for future standardisation

- Connection between quantum information and quantum metrology, such as the use of quantum states for measurement
- Identification and communication of technical advances and novel applications that are made possible by quantum enhanced metrology. This includes discussion of use cases, and examples and limitations of quantum technology
- Creating a foundation for international acceptance and mutual recognition of field-deployable and chip-scale quantum-based standards.

TC25 will be chaired by Barbara Goldstein, Program Manager - NIST on a Chip, and Associate Director, Physical Measurement Laboratory, NIST, with Tim Prior, NPL Quantum Technology Program Manager, as a Secretary, and Alexander Tzalenchuk, NPL Head of Science for Quantum Technologies, as an Expert.

3 QUANTUM COMPUTING STANDARDS

3.1 INTRODUCTION

The field of quantum computing has seen rapid progress in the last few years and the interest from industry, governments and the general public keeps growing. Several landmark experiments, such as two demonstrations of “quantum supremacy”, have given the field increased credibility in the eyes of both public and private investors and have stimulated the emergence of a growing commercial eco-system. Today, this consists of a large number of quantum computing SMEs as well as an emerging specialised supply chain. Several large enterprises (Google, IBM, Amazon, Microsoft, Huawei to name but a few) are also investing heavily in this technology and see quantum computing as an integral part of their technology roadmaps.

Whereas it is important to remember that today’s quantum computers are mainly technology demonstrators and are still not advanced enough to be useful in “real-life” applications, most observers believe this will start to change in the next few years. Initially, applications are likely to be limited to a few very specific areas (such as chemistry and the generation of states following complicated distribution functions), but as the hardware continues to improve and the software becomes more capable, we are likely to see more widespread adoption. Eventually, quantum processors will become an integral part of the computing landscape where they will be used alongside classical technologies (CPUs, GPUs, FPGAs) and enable us to tackle a range of important problems.

A working quantum computer system consists of a huge number of different components. Whereas the core “quantum” component is typically a microfabricated chip, it will only work as a quantum processing unit (QPU) when used as part of a full system comprising read-out and control electronics, vacuum chambers, cryogenics, packaging etc. The question of what “standardisation of quantum computing” actually means in practice is therefore not straightforward; in many cases it is likely to mean standards for entirely “classical” components and software to enable interoperability between sub-systems from many different suppliers.

It follows from the above that the first steps towards standardisation of quantum computing is to define the scope and as well as roadmap for standardisation activities. All major international standardisation organisations have therefore established study or advisory groups to better understand their role in the future of quantum computing. In some cases (e.g. ISO/IEC and IEEE) these initial activities have already resulted in the start of further work towards formal standards.

NPL is involved in quantum computing standardisation activities within ISO/IEC and CEN-CENELEC. The ISO activities are focused on the development of a first standard, whereas the aim of the CEN-CENELEC Focus Group on Quantum Technology, which includes significant activities on quantum computing, is to develop a roadmap for standardisation.

3.2 QUANTUM COMPUTING - STANDARDS ACTIVITY

3.2.1 ISO/IEC JTC1/WG14

WG14 “Quantum Computing” in ISO/IEC was established in 2020 as a direct result of a report from an earlier advisory group (AG14). The first work item for WG14 is to develop a standard for “Terminology for quantum computing”; an initial draft of this is expected late 2021. This will be a foundational document which will define terminology commonly used in the field and serve as a reference for all future standards. It is worth noting that discussions have already started about possible future work items, such as standardisation of benchmarking of quantum

computing. ISO/IEC JTC1/WG14 has members from all over the world with the activities being coordinated from China.

The work in WG14 commenced late 2020. The terms of reference have been agreed and the technical work has started. The experts from NPL are contributing by participating in the meeting (typically held every 2-3 months), suggesting terms to be defined and then helping to write definitions of the terms.

Currently, two experts from NPL, *Dr Tobias Lindstrom* and *Dr Ivan Rungger*, are members of the WG (representing the UK on behalf on BSI) and provide input for the definition of a number of quantum computing terminology items. Both were also active in AG14 and contributed to the final report of that group.

3.2.2 CEN-CENELEC Focus Group on Quantum Technologies (FGQT)

Experts from NPL are participating in the FGQT meetings on Quantum computing (which take place every 4-6 weeks) and have already made several contributions to the main FGQT roadmap text. The NPL experts for quantum computing are *Dr Tobias Lindstrom* and *Dr Ivan Rungger*. Examples of topics that have been addressed by the NPL experts include standardisation of hardware-software interfaces for quantum computers. This contribution document was numbered N054 and has been accepted to be included in the current FGQT draft document. NPL has also co-authored two other contributions numbered N052 (“Editor’s note regarding the purpose of the terminology chapter”) and N053a (“Handling the clause on enabling technology”).

3.2.3 IEEE standards

IEEE has a number of working groups related to quantum computing (P7130, P7131 and P1913). The work is primarily being driven by the quantum computing industry in the USA and this is reflected in the topics that are being addressed, there is for example more focus on computing based on quantum annealing than in other international efforts. Currently, NPL is not directly engaged with the work within IEEE but is in contact with UK experts who are members of the three IEEE groups.

3.2.4 Work within the ISCF Standards projects related to standards

NPL is also involved in development projects on quantum computing (QC) that could contribute to future international standards. An example is the Innovate UK ISCF funded NISQ.OS project coordinated by Riverlane, which involves most of the UK’s leading QC SMEs, as well as some large enterprises (ARM, Hitachi etc). One of the goals of this project is to create a unified specification for a quantum software-hardware interface that works across all architectures. One output of this work is a technical specification which is very likely to be created together with BSI (currently under discussion). This would put the UK in a good position if the work later can be feed into Standards Development Organisations (SDO) and contribute to international standards in the QC area.

Within the NISQ.OS project NPL has worked with Riverlane and the hardware companies to start to build the common software hardware interface. NPL leads the work package on the hardware abstraction layer (HAL) specification (mainly Dr Ivan Rungger and Dr Tobias Lindstrom), thereby coordinating the input of the hardware companies and collecting it into one

specification document. NPL has talked to each hardware company individually to understand their needs. Based on this the first draft document has now been produced, with agreed sections on the general aspects of the HAL. In the next half year detailed use cases and HAL command specifications will be added. At the past review meetings, the hardware companies all gave positive feedback on NPL's and Riverlane's work on this.

3.2.5 EMN-Q: European Metrology Network for Quantum Technologies – Quantum computing

The work within the Quantum Electronics section of the EMN-Q includes a subsection on quantum computing. A roadmap for the European NMIs work on developing science and technology related to quantum computing will be included in the strategic research agenda. NPL is well ahead of the other European NMIs when it comes to work on quantum computing, and we have therefore been leading this work. This also means we have been able to strongly influence the contents of the roadmap. This work is being led by *Dr Tobias Lindstrom*, NPL.

4 QUANTUM COMMUNICATIONS STANDARDS

4.1 STANDARDS DEVELOPING ORGANISATIONS

Quantum Key Distribution (QKD) activity by Standards Developing Organisations (SDOs) is currently focussed on fibre QKD hardware and networks. It is anticipated that this will expand into satellite/free-space hardware and networks in the future.

ETSI was the SDO that initiated QKD standardisation in 2008. The ETSI Industry Specification Group for Quantum Key Distribution (ISG-QKD) was born from the QT community established by the European FP6 project, SECOQC. To date it has produced 10 Group Specifications and Reports in areas such as protocol security, implementation security, component and module characterisation, key delivery, and use cases. Two of these were led by NPL (*Dr Christopher Chunnilall* and *Dr Alastair Sinclair* serve on this committee).

The ISO/IEC JTC (Joint Technical Group) 1/SC27 “Information security, cybersecurity and privacy protection” has recently started work on QKD and is currently working on two documents concerned with security requirements and test and evaluation methods of QKD. NPL has an expert member (*Dr Christopher Chunnilall*) on this committee and is also represented on the BSI mirror committee.

ITU-T has two study groups working on QKD: (i) Study group 13 “Future Networks” is working on recommendations for standardisation of QKD network structure and architecture and (ii) study group 17 “Security” is working on standardisation of security aspects of QKD networks. NPL does not participate in these activities, but these groups have established a liaison with the ETSI ISG-QKD, and so information about their activities is shared with the ISG-QKD. There is also the ITU-T focus group on Quantum Information Technology for Networks (FG-QIT4N), which does not itself draft standards, but seeks to understand where gaps exist, and propose work items.

There is also the IEEE P1913 Software-Defined Quantum Communication (SDQC) Working Group which is drafting a standard on SDQC. NPL is not a member of this group, and SDQC is not a current concern of NPL, which is focussed on the quantum layer.

Finally, there is the recently-established CEN/CENELEC FGQT – see Introduction Section 1.1.

4.2 QUANTUM KEY DISTRIBUTION-RELATED STANDARDS ACTIVITY

4.2.1 Introduction

Standards for quantum communications can be grouped under the following topics - “Quantum communications module security”, “Fibre network interoperability”, “Quantum network security”, and “Other standards” (European Commission, 2021). In its engagement with SDOs, NPL focusses on standardisation activity in “Quantum communications module security” and “Other standards”. The former includes NPL’s primary focus, which is on standards concerned with testing QKD hardware, while the latter include standards dealing with vocabulary and terminology.

4.2.2 ETSI ISG-QKD

Work items that NPL has contributed to in the last year are:

- *ETSI GR QKD 007 V1.2.1 Quantum Key Distribution (QKD); Vocabulary. Version 2 [In draft]*. (2020-05)
- *ETSI GR QKD 010 V0.0.4 Quantum Key Distribution (QKD); Implementation security against Trojan horse. Version 1 [In draft]*. (2020-06)
- *ETSI GR QKD 013 V0.0.4 Quantum Key Distribution (QKD); Transmitter module characterisation. Version 1 [In draft]*. (2021-01)
- *ETSI GR QKD 016 V0.1.1 Quantum Key Distribution (QKD); Protection Profile. Version 1 [In draft]*. (2020-12)

NPL are one of the major contributors to ETSI GR QKD 013. Participation in these activities is through two biannual meetings (June 2020, December 2020), monthly teleconferences, and the ad-hoc teleconferences. The June 2020 meeting was due to be hosted by NPL, but that was moved to a virtual meeting because of Covid-19.

4.2.3 ISO/IEC JTC 1/SC 27

There are currently two work items in draft:

- *ISO/IEC, Information security—Security requirements, test and evaluation methods for quantum key distribution—Part 1: Requirements. Committee Draft 1. (2021-01)*
- *ISO/IEC, Information security—Security requirements, test and evaluation methods for quantum key distribution—Part 2: Test and evaluation methods. Committee Draft 1. (2021-01)*

NPL provided comments on Working Draft 3 in June 2020, and participated in discussions of these comments at the 61st meeting of ISO/IEC JTC 1/SC 27/WG 3 in September 2020. The editors then created the Committee Draft 1 in January 2021, and NPL will provide comments by the end of March 2021.

4.2.4 ITU-T FG-QIT4N

This group is open to anyone. NPL scientists participated in a joint meeting of this group and the ETSI ISG-QKD in June 2020.

4.3 CEN-CENELEC FOCUS GROUP ON QUANTUM TECHNOLOGIES (FGQT) – QUANTUM COMMUNICATIONS

In the field of Quantum Communications, we note that ITU-T recently established a QT Focus Group with very similar goals to those stated by CEN/CENELEC for its FGQT. This comes on top of the other initiatives already running in ETSI, ISO/IEC, ITU-T SG13, ITU-T SG17, IEEE etc. Given the large number of ongoing or planned SDO initiatives, it remains to be seen which of these will be able to make an impact. Ultimately, QT vendors and end users will decide to which of these competing initiatives they can commit their limited resources [3].
The FGQT held an ‘Unconference’ in October 2020, to enable all interested persons to learn about the various subject areas and plan future work towards the roadmap.

The FGQT has to date constructed a table of contents for its roadmap and populated it with a first set of entries. It aims to provide a first draft by the summer of 2021.

The subject areas in the roadmap reflect the structure of various QT programmes, together with a section on 'Enabling Technologies'. NPL contributed to defining what constitutes an enabling technology. The decision was taken that to maintain momentum, it was better to accept all contributions and decide later whether that content would best sit in 'Enabling technologies' of one of the other subject areas. NPL also contributed to the section on Quantum Communications.

4.4 EMN-Q: EUROPEAN METROLOGY NETWORK FOR QUANTUM TECHNOLOGIES – (Q COMMS)

The principal activity of EMN-Q within the Quantum Communications arena is to strengthen engagement with the stakeholder community. Draft roadmaps were presented at the 2nd General Meeting held on 4th November 2020 and attended by all of NPL's "section experts" along with approximately 45 other EMN-Q members from across Europe. These roadmaps have been reviewed by the representative members of the EMN-Q and are now being circulated to the Stakeholder Advisory Board and the relevant EURAMET Technical Committees.

From NPL, *Dr Christopher Chunnilall* leads the EMN-Q section on Quantum Photonics and is also the UK representative in this area, while *Dr Rhys Lewis* is the UK vote holder.

NPL's contribution to the technical section on quantum clocks and atomic sensors is detailed within Section 5.2.

4.5 STANDARDS WORK IN QUANTUM COMMUNICATIONS UNDER ISCF

NPL participates in the following ISCF projects which are relevant to standards work: AQUASEC, 3QN, PRISMS, AIRQKD, QRNGs.

AQUASEC is concerned with developing hardware for fibre QKD systems. However, a significant component of the project is developing the experimental methods for testing QKD hardware, and document them to create an assurance process for QKD hardware in the UK. This aspect is led by NPL, and this project therefore also contributes to NPL's engagement with the ETSI and ISO/IEC SDOs. 3QN and PRISMs are concerned with satellite QKD, while AIRQKD is concerned with short-range, free-space QKD. No standardisation activity in these areas has so far begun. QRNGs (and to a lesser degree PRISMS) is concerned with developing an evaluation process for quantum random number generators. This project is led by NPL. It started in November 2020, and aims to engage with ISO, BSI(DE), ITU, NIST, and other bodies working on RNG standards.

4.6 STANDARDS WORK IN QUANTUM COMMUNICATIONS UNDER EMPIR

A normative project MeTISQ was started in September 2020. The principal stakeholder of this project is the ETSI ISG-QKD. This project aims to develop robust, SI-traceable measurements, at the single-photon level, to characterise assembled QKD transmitter and receiver modules. The expertise gained in developing measurements for practical QKD-implementation security will be used to lead the drafting of measurement specifications and standards by the ETSI ISG-QKD. This project is led by INRIM, but NPL is the biggest partner in the project.

4.7 CCPR-WG-SP TG7

The CCPR-WG-SP TG7 has a work item on Single-photon Terminology. In the last year, NPL created a SharePoint to facilitate the drafting of this item, which is now planned to be published by the CIE as an open-access Technical Note. This work item is led by KRISS (the Korean National Metrology Institute). In principle, this document should provide the basic definitions for single-photon terminology that can be referenced by ETSI, ISO/IEC and other more application-related standards.

4.8 STANDARDS WORK IN QUANTUM COMMUNICATIONS UNDER H2020

H2020 OPENQKD brings together a multidisciplinary team of 38 Partners from 13 European countries comprising leading European telecommunication equipment manufacturers, end-users and critical infrastructure providers, network operators, QKD equipment providers, digital security professionals and scientists from 13 countries to reinforce Europe's position at the forefront of quantum communication capabilities globally.

NPL is the only NMI involved in OPENQKD, and is the main partner in the standardisation work package whose aims are to:

- Follow and shape international progress of QKD standardisation
- Develop standards for coexistence and interoperability of QKD links and within ETSI
- Develop a Common Criteria framework for certification of QKD

Therefore, the work in OPENQKD also supports NPL's engagement with relevant SDOs.

The recent publication by this project [3] of a roadmap for quantum communications standards is expected to inform future work in this area.

NPL's contributions in this technical area are led by *Dr Christopher Chunnilall.*

5 QUANTUM SENSING STANDARDS

5.1 CEN-CENELEC FOCUS GROUP ON QUANTUM TECHNOLOGIES (FGQT)

Within the Quantum Sensing chapter of the CEN-CENELEC Focus Group on Quantum Technologies (FGQT) the following standardisation sections are envisaged and currently under development (NPL participation is marked as appropriate):

- Single-photon detectors and sources, entangled-photon sources [NPL contributes]
- Ion traps for spectroscopy, optical clocks, quantum computers and quantum simulation
- Generation of microwave signals using optical frequency combs
- Colour centres in (nano)diamonds and other crystals (e.g. SiC) as sensors, for e.g. magnetic/electric field, temperature and strain [NPL leads]
- Quantum electrical standards (Voltage and Resistance)
- Resistance (Graphene, GaAs) [NPL contributes]
- Cryogenic microwave measurements
- Optomechanical sensors

Within a larger chapter of the FGQT on Quantum Sensing, NPL leads the contribution N072 'Standardisation of colour centres in (nano)diamonds and other crystals (e.g. SiC) as sensors of magnetic/electric field, temperature and strain'. The aim of this contribution is to develop a proposal for possible standardisation of colour centres in solids (diamonds, SiC, hBN, etc.) as sensors. NPL has outlined the use of colour centres in solids for quantum sensing of various physical observables (e.g. electromagnetic fields, thermal effects, strain) and their forthcoming applications in such diverse areas as quantum information, spintronics and Life Science. NPL has also summarised the potential in quantum metrology and outlined the current pre-normative gaps and standardisation needs. There are no existing standardisation documents in the area of colour centres in solids and their application within quantum technology.

The techniques of colour centre magnetometry is emerging as a powerful, major and versatile tool for the implementation of quantum measurements and quantum technologies. In the document under consideration in FGQT, specifically identified the existing pre normative gaps:

- *Materials standardisation*: characterisation methods for colour centres in solids, allowing for reliable and comparable spec sheets in terms of purity of the base material, chemical type, density, spatial distribution of colour centres
- *Infrastructure standardsation*: guideline for development of characterisation infrastructure and defining measurement procedures and figures of merits
- *Device standardisation:* performance of colour centres in quantum sensing, imaging and computation technology

The N072 draft has been discussed at FGQT meeting on 25 February 2021 and the revised version addressing the comments of the panel will be prepared later on in 2021.This work is being led by *Dr Olga Kazakova*, NPL.

6 TIME AND FREQUENCY – STANDARDS RELEVANT TO TEST AND EVALUATION OF QUANTUM TECHNOLOGIES

In the Time and Frequency area, two activities were identified as being directly relevant to the test and evaluation of quantum technologies: our contribution to the CCL-CCTF Frequency Standards Working Group and to the technical section of EMN-Q concerned with quantum clocks and atomic sensors. The contribution to the CCL-CCTF is rather different to the other activities described in this report as it relates to physical standards, rather than being a contribution to a documentary standard.

6.1 CCL-CCTF FREQUENCY STANDARDS WORKING GROUP

The overarching technical committee that oversees international metrology is the International Committee for Weights and Measures (CIPM). Reporting into the CIPM are a number of Consultative Committees dealing with specific technical areas, the work of which is coordinated by the International Bureau of Weights and Measures (BIPM).

The CCL-CCTF Frequency Standards Working Group (WGFS) is a joint working group of the Consultative Committee for Length (CCL) and the Consultative Committee for Time and Frequency (CCTF). Its terms of reference are

- To make recommendations to the CCL for radiations to be used for the realisation of the definition of the metre and to make recommendations to the CCTF for radiations to be used as secondary representations of the second
- To maintain, together with the BIPM, the list of recommended frequency standard values and wavelength values for applications including the practical realisation of the definition of the metre and secondary representations of the second
- To take responsibility for key comparisons of standard frequencies such as CCL-K11
- To respond to future needs of both the CCL and CCTF concerning standard frequencies relevant to the respective communities.

NPL has two representatives on this working group: *Dr Andrew Lewis* (covering aspects related to length) and *Prof. Helen Margolis* (covering aspects related to time and frequency).

The work carried out under the auspices of the WGFS as part of the NPL Quantum Test and Evaluation programme concerns an update to the list of recommended frequency values, which includes the frequencies of atomic transitions that may be used as secondary representations of the second. These secondary representations of the second may be used, in a similar way to caesium fountain primary frequency standards, for steering of International Atomic Time. They are important for test and evaluation of quantum technologies because they provide high accuracy references against which the performance of other clocks can be assessed.

The analysis underpinning this update to the list of recommended frequency values was performed by a sub-group of the main working group, consisting of six people, in which Prof. Helen Margolis played a key role. Other members of the group were from LNE-SYRTE (France), NICT (Japan), NIST (USA) and the BIPM. After an initial preparatory meeting in May 2020, this work involved a further 16 meetings during the period October 2020 – March 2021 to discuss progress with the analysis, as well as significant email correspondence in between meetings.

The updated recommended frequency values and underpinning analysis will be published by the CCL-CCTF Frequency Standards Working Group in due course.

6.2 EMN-Q: EUROPEAN METROLOGY NETWORK FOR QUANTUM TECHNOLOGIES – QUANTUM CLOCKS AND ATOMIC SENSORS

A central activity this year for EMN-Q within the Quantum Clocks and Atomic Sensors area has been developing science and technology roadmaps as part of the strategic research agenda. Inputs are being compiled from metrology organisations as well as industry stakeholders in order to capture the emerging industry needs and the associated research that is required.

NPL has had an influence on these roadmaps and specifically added Test & Evaluation as an important part of future activities in the area of quantum clocks and atomic sensors. Draft roadmaps were presented at the 2nd General Meeting, held online on 4 November 2020 and attended by all of NPL's 'section experts' along with approximately 45 other EMN-Q members from across Europe. NPL contributions in this area are being led by *Dr Rachel Godun*.

7 CONCLUSIONS

This first of two reports on NPL's quantum standards activities during Year 1 of the Quantum Programme has detailed NPL's involvement in the quantum standards activities for many technology areas and across the matrix of different standards bodies (ISO, IEC, ITU, ETSI, CEN-CENLEC, EURAMET and CCL- CCTF),

More general aspects of the importance of standards, the engagement with the UK quantum community and planning for the future are the focus of the second NPL report on quantum standards.

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APPENDIX 1: JOINT SYMPOSIUM ON STANDARDS FOR QUANTUM TECHNOLOGIES

The International Telecommunication Union (ITU) in collaboration with the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE) UK and Ireland Photonics Chapter organised a **Joint Symposium on Standards for Quantum Technologies** which took place virtually on **23 March 2021 from 15h00 to 18h00 CET/Geneva Time.**

The website for the symposium gives links to all the presentations and a complete recording of the event including the discussion.

https://itu.int/go/QIT-01

The description on the website of this conferences is as follows:

"This joint symposium brought together world-leading speakers to introduce different aspects of quantum technologies: quantum communication, quantum computation and quantum measurement. This was followed by an extensive panel discussion involving representatives from various SDOs including ISO, IEC, ITU-T, NIST, ETSI, ISO and CEN/CENELEC to discuss the general importance of standards for quantum technologies, identify and prioritise areas in which standards would be most required and according to which timeline (road-mapping).

In particular, it explored the most important lessons learnt from previous efforts to standardise new technologies (such as optics and photonics) and discussed how past methods could be applied to ensure that different SDOs could achieve the correct level of harmonisation from the outset, avoiding unhelpful divergence without impacting healthy competition between SDOs.

Participation in the symposium was open for ITU Member States, Sector Members, Associates and Academic Institutions and to any individual from a country that is a member of ITU. This included individuals who are also members of international, regional and national organizations, specifically the members of IEC and the IEEE UK and Ireland Photonics Chapter.

Participation in the symposium was free of charge. Registration to the event was mandatory.

***Symposium chairs: Dr Richard Pitwon,** CEO, Resolute Photonics & **Dr Bernard Lee,** Director of Technology & Innovation, SENKO Advanced Components"*

Programme:

Moderator: Richard Pitwon, CEO, Resolute Photonics

- *Welcome address:* **Bilel Jamoussi,** Chief of Study Group Department, TSB, ITU

Session 1: Introduction

Moderator: Bernard Lee, Director of Technology & Innovation, SENKO Advanced Components

15:10 - 16:40

- *Keynote address:* **Sir Peter Knight,** Professor, Imperial College London [Presentation]
- *Quantum communication:* **Andrew Lord**, Senior Manager, Optical Networks and Quantum Research, BT [Presentation]
- *Quantum computing:* **Ian Walmsley,** Professor of Experimental Physics and Provost, Imperial College London, UK [Presentation]

Session 2: Standardization Approaches for Quantum Technologies - Standards Organisations Panel

Moderator: Richard Pitwon, CEO, Resolute Photonics

- **ITU-T: James Nagel,** Lead Photonic & Laser Systems Engineer, L3Harris Technologies and **Qiang Zhang**, OSA Fellow, Professor, University of Science and Technology of China (USTC) [Presentation]
- **IEC: Peter Pondillo,** Senior Manager, Standards & Policy, Corning and **Andre Girard**, Senior Consultant, Fibre Optic Telecommunications [Presentation]
- **IEEE: Andrew Ochoa,** Director of Partnerships, Strangeworks Inc. [Presentation]
- **ISO/IEC JTC1 WG14: Hong Yang,** Convenor of ISO/IEC JTC1 WG14, Quantum Computing; China Electronics and Standardization Institute (CESI) [Presentation]
- **CEN/CENELEC: Momtchil Peev,** Quantum Lab, Huawei Technologies Duesseldorf GmbH (HWDU), Germany [Presentation]
- **NIST: Barbara Goldstein,** Associate Director, Physical Measurement Laboratory, NIST and **Clare Allocca,** Senior Advisor for Standardization - Standards Coordination Office, NIST, United States [Presentation]
- **BSI: Emelie Bratt,** Lead Standards Development Manager, British Standards Institution (BSI) and **Richard Ednay**, Technical Director, Optical Technology Training Ltd. [Presentation]
- **ETSI: Martin Ward**, Senior Research Scientist, Toshiba Europe Limited [Presentation]

Summary of the conference:

The three opening presentations set the scene for the later discussion. Sir Peter Knight gave an introduction to the global effort to develop new capabilities based on quantum technologies, using the UK programme as the example. He also introduced the process of standards development to those attendees who were familiar with quantum technology but had not been involved in standards previously.
Sir Peter referred also to the report on a European conference held in 2019 called Standards4Quantum. Accessible here: https://publications.jrc.ec.europa.eu/repository/handle/JRC118197.

Andrew Lord of BT presented on quantum communications and the work BT is doing with Toshiba and others to create a new service offering based on Quantum Key Distribution.

Ian Walmsley of Imperial College presented on the field of Quantum Computing, describing the principles behind it, the various technologies which could implement the principles, and the potential for impact which quantum computing can deliver.

Each of the standards development organisations then presented the areas of work which their organisation was focusing on. More detail is available in the slides used by the presenters, accessible via the links above.

ITU

The ITU telecommunications sector (ITU-T) develops technical standards that ensure that networks and technologies seamlessly interconnect. ITU-T has initiated three branches of work on quantum since 2018.

Study group 13 future networks (Q16/13 and Q6/13) focusses on network architecture aspects of QKD
Study group 17 security (Q15/17) focusses on security aspects of QKD and
X1702 on QRNGs

Focus group on quantum information technology for networks (FG-QIT4N) is about pre-standardisation activities to study the implications of quantum information technologies for both quantum and ICT networks.

IEC (International electrotechnical commission)

IEC have a technical committee TC86 on fibre optics with relevance to quantum technologies. They have three subcommittees: SC86A fibres and cables; SC86B fibre optic interconnecting devices and passive components; and SC86C fibre optic systems and active devices.

IEEE standards association

P7130 Standard for quantum technologies definitions is being developed to provide general nomenclature for quantum technologies that may be used to standardise hardware and software terminology. This group has a dictionary for quantum technologies in draft form which it will be releasing for review in a couple of months and interested parties are invited to offer themselves as reviewers.

ISO/IEC

ISO-IEC-JTC1 working group 14 includes 19 national bodies and110 members. This working group has released a working document ISO/IEC WD 4879 quantum computing terminology and vocabulary.

ETSI

There is an Industry specification group on QKD looking at security testing and interoperability. There is also a Technical committee cyber working group on quantum safe cryptography.

CEN/CENELEC

In the last year a new focus group on quantum technologies has been launched with a scope to ensure interaction between relevant European stakeholders to map ongoing activities to define needs and opportunities and to recommend further action to ensure that standards support the deployment of quantum technologies in industry. This is currently realised in joint work on a standardisation road map for quantum technologies. CEN/CENELEC has over 140 members from almost all EU countries. The intention is to develop a road map while liaising and coordinating with other standard development organisations through active communication channels including ISO-IEC-JTC1 WG 14, euro QC quantum communications infrastructure, and European quantum industry consortium. The intention is to have a version one of the road map by September of 2021.

BSI

BSI, supported by NPL, are in the process of recruitment for a new quantum panel which they intend to take on the discussions on UK focus priority areas.

NIST-QEDC

In the US, the national quantum initiative act calls on NIST to establish a consortium of stakeholders to identify needs to support development of a robust quantum industry in the US list selected a company Sri international to manage that consortium home maybe half this consortium is called the quantum economic development consortium (QED-C). Its mission is to enable and grow a robust quantum-based industry and supply chain in the US. It has over 150 participants from industry academia and government and has a number of activities focused on workforce development (skills and training), establishing use cases for quantum technologies, developing enabling technologies, and developing standards and benchmarks.

Within the standards and benchmarks section there is work on developing prototype benchmarks, providing inputs to standards development organisations, and defining standardisation readiness levels (looking at how appropriate it is to develop standards in particular technology areas). https://quantumconsortium.org