NPL

Metrology Research Roadmaps

September 2022

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Contents

"I joined NPL to make a difference – I wanted to be able to put my skills to help build a better world for my children. Today in my role I am lucky enough to work with such a brilliant team tackling issues and supporting companies across so many areas. My passion to improve the environment and health are met daily by supporting the scientists that deliver projects across these areas and this is what makes me proud to work for NPL."

Amal Lavender
Head of Department
Chemical & Biological Sciences

Foreword

The NPL Metrology Research Roadmaps outline our research agenda covering the next ten years. They will guide the development of specific research programmes, both within and across disciplines, as we seek to answer current scientific questions and reduce scientific and measurement uncertainties.

NPL's mission is to provide the measurement capability that underpins the UK's prosperity and quality of life. We are a major enabler of innovation by delivering scientific and metrology capability to key national challenges: Environment, Health, Security & Resilience and Prosperity. By providing confidence in measurement data, we enable innovation, ensure trade can flourish and ensure a sound scientific foundation for future policy development.

Our Metrology Research Roadmaps will:

- provide an information source for research collaborators, policy makers and national metrology institutes (NMIs)
- demonstrate the requirement for metrology in research and development across many disciplines
- indicate key scientific and technical milestones in each area
- support NPL's drive to be a leading scientific destination for talent and investment

By showcasing our research agenda, we hope to confirm NPL's role in supporting the UK's position as a science and technology superpower.

JT Janssen
NPL Chief Scientist

Introduction

By publishing NPL's Metrology Research Roadmaps, we seek to strengthen our engagement and support for the UK research, development and innovation (RDI) landscape and demonstrate our commitment to leadership in metrology.

In 2021, our leading scientists created twelve roadmaps for our highest priority research areas based on the findings of NPL's Technology and Measurement Foresighting exercise that was carried out with external stakeholders and metrology experts. The structure of each Roadmap is based on the International Technology Roadmaps for Semiconductors and shows the critical metrology that needs to be in place over the next decade, as well as highlighting the measurement challenges and barriers. Many of these cannot be solved by NPL alone and by publishing our Roadmaps we hope that they will stimulate collaboration and accelerate progress.

Each Metrology Research Roadmap:

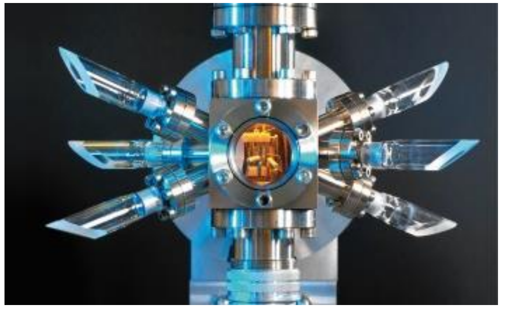
- identifies some of the greatest metrology challenges for the next decade and the advances in metrology that are required.
- provides a framework from which researchers, funding bodies and businesses can engage with us and coordinate efforts to increase and realise impact.
- enables NPL and other research organisations to identify future workforce skills requirements.
- enhances career pathways and offers fulfilling careers by providing a long-term perspective on research programmes.

The Roadmaps are aspirational in terms of the research and resource required. Publication of the roadmaps is an invitation to collaborate with us and collectively find solutions to the metrology grand challenges more quickly and efficiently.

Ian Gilmore
NPL Senior Fellow and Head of Science

"NPL has enabled me to make valuable contributions to the international temperature metrology community. Following the redefinition of the SI unit, the kelvin, my research will be on developing practical thermometry techniques for realising the kelvin directly, a key NPL goal. As a minority representative, I am exceptionally proud to be part of the NPL diversity. My culture and traditions help to make NPL a place open for all people, which brings in the best talent."

Radka Veltcheva
Senior Research Scientist
Temperature and Humidity



The role of NPL: Metrology matters

Metrology plays a fundamental role in sustaining a fair, efficient and modern society. Global trade and new products are supported by an established infrastructure of measurements linked to internationally recognised standards.

The globally-agreed 'International System of Units', more usually known as the SI, has seven ‘base units’ from which derived units may be formed, underpinning every type of measurement. As the UK’s National Metrology Institute (NMI), NPL provides confidence in measurement results and traceability to SI units – we are the highest point of reference nationally. NPL also compares its national standards with those held by partner NMIs around the world. We play a key role in the development of measurement standards from research through to real services delivering impact and long-term benefit to customers, often via cooperation with national and international quality infrastructure partners. Metrology also provides confidence in data from physical measurements and the algorithms or methods used to process measurement data.

The revision of the SI in 2019 was one of the greatest recent stories of scientific progress and international endeavour. It involved:

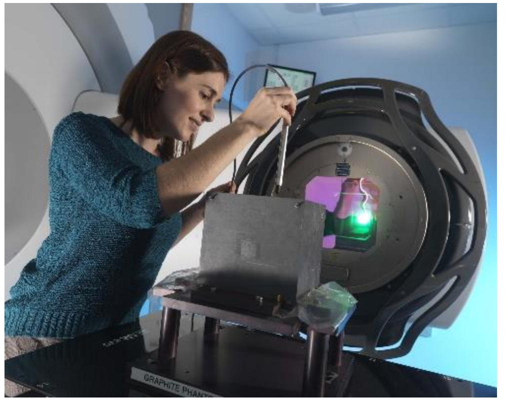
- close interdisciplinary collaboration to achieve the technological advances required to drive down experimental measurement uncertainties
- great teamwork locally to make these experiments a practical reality
- widespread international cooperation to bring together capability from different countries and demonstrate the reproducibility of the science developed.

This complementarity and cooperation between institutes will continue as the revised SI is implemented, together with benefits of the improved technologies being realised nationally and internationally.

There is growing awareness and concern about poor reproducibility in research and its consequences. It is important to academia, industry and government and since most research is publicly funded, to the taxpayer as well. Metrology is key to ensuring reproducibility and NPL supports society and the research community through establishing traceability to the SI, reducing uncertainty, provision of calibration and measurement capabilities, leadership in the development of international standards and global intercomparison studies.

“The most rewarding part of my job is having the opportunity to skill-up to improve my science and abilities. NPL attracts a diverse mix of people which creates a culture of mutual respect. My team work hard and look out for each other. I find it exciting that my future research has the potential to quickly develop into real world solutions for measurement challenges and create real impact in society.”

Michael Ward
Higher Research Scientist
Gas Metrology



Metrology leadership for national challenges

NPL leads large-scale, multi partner, research programmes that tackle national challenges and exemplify the importance of metrology and collaboration.

Advanced Machinery and Productivity Initiative (AMPI) – a consortium, led by NPL, has secured £22.6m funding for a 5-year Strength in Places innovation programme to grow the UK manufacturing capacity for high technology machines and automation systems. AMPI will be based in Rochdale, Greater Manchester.

Cancer Research UK's Grand Challenge Rosetta – NPL leads this $20M project.The multidisciplinary team is developing a reproducible, standardised way to fully map tumours with extraordinary precision. The research is set to transform our understanding of cancer and open the door to new ways to diagnose and treat the disease.

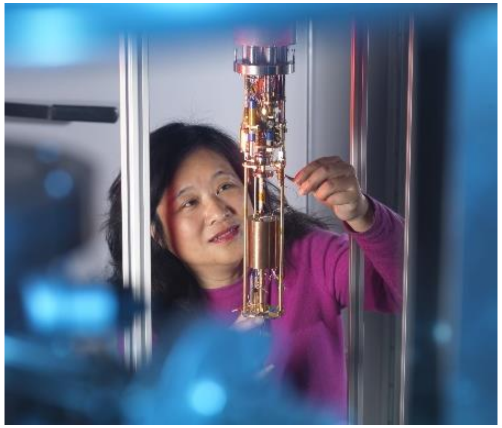
National Timing Centre Programme – NPL is developing the UK's first nationally distributed time infrastructure. As the UK's timing authority, NPL is enabling the UK to move away from reliance on a single Global Navigation Satellite System and deliver resilient UK time and frequency that provides confidence to our critical national infrastructure.

NPL Quantum Programme – NPL supports UK industry's need for independent test and evaluation, standards and measurement to deliver new quantum technologies. Our work helps to ensure that the UK generates the full economic and societal benefits from the National Quantum Technology Programme and the application of quantum technologies.

The breadth and depth of our capabilities, together with our unique facilities, allow us to tackle hard measurement problems and deliver real impact from science.

"I like working at NPL because all projects have real-life applications. It is good to know that what I do is useful. The most rewarding part of the job is when a colleague or customer tells me that my published paper or my report has been useful for them, and has helped them with their work or their project."

Mira Naftaly
Senior Research Scientist
Electromagnetic Technologies



Delivering research and training in partnership

The Postgraduate Institute for Measurement Science was created by the strategic partnership between NPL and the Universities of Strathclyde and Surrey. The outputs of our Roadmaps will only be fully realised if they are advanced though cooperation with our Strategic Partners, wider academia, other National Laboratories and the international network of NMIs.

The Postgraduate Institute for Measurement Science (PGI) will enable the provision of skills and broker partnerships for the advancement of measurement science and technology via postgraduate research and training. As a 'virtual institute' for measurement science, the PGI's collaborative model of investment in PhD studentships enables the creation and development of meaningful research collaborations at a national scale via around 200 Postgraduate Researchers (PGRs) partnered with more than 30 academic institutions around the UK. The PGI Five Year review provides a detailed account of how this model provides significant advantages to all the partners, including:

- Increased access to a wide variety of knowledge, facilities, and capability.
- A diverse and enriching range of experiences and professional skills for PGRs.
- A mastery of scientific and engineering metrology in a 'real-world' context.
- Building PGR collaborations as a springboard to future leadership.

The PGI's graduates have diverse career destinations, with around 78% moving outside academia immediately after graduation. The PGI's aims are to build on these foundations by:

- Developing sustainable investment with industry and 3rd-party collaboration.
- Extending our international reach and partnerships.
- Enhancing the PGI's relationship with our Alumni.
- Expanding the training opportunities to meet the future needs of researchers and stakeholders.

The opportunity to innovate directly and advance collaborations is an essential precursor to delivering the Roadmaps, careers and leadership in science and engineering and applying measurement science across a range of industrial sectors and in academia.

"Aside from performing exciting atomic physics, I really like that this research has close links to real world applications and has the potential to be very impactful in industry ."

Martin James Knapp
Post Graduate Researcher

Delivering high quality research

Our Roadmaps are built on a foundation of sound research governance and a healthy research culture which values respect, equality, diversity and inclusion.

Diversity and inclusion

As outlined in our Diversity and Inclusion Strategy, we believe that different persepctives make us better and are important to enable us to deliver excellent science and engineering. Inclusion is essential for success and by creating an environment where everyone can thrive, we can enhance our ability to solve real-world challenges and create extraordinary impact for all of society. We want to work with a diverse range of partners and teams, in ways that are accessible and open to all.

Research integrity

Research integrity is the bedrock for trust at NPL. Our independence, impartiality, probity and rigorous metrology means we can be relied upon for impartial advice and reproducible science. As part of our values-based approach, we are dedicated to fostering a supportive research culture where we recognise and value **how** outputs are achieved, as well as **what** is delivered. NPL is committed to the UK Concordat to Support Research Integrity and upholding the core values of honesty, rigour, transparency, care, respect and accountability. NPL's Professor Ian Gilmore is a member of the UK Committee on Research Integrity.

Research culture

People and culture sit at the heart of our vision. We aim to create an environment that is kind, fair, challenging and rewarding. We aim to:

- attract a diverse range of people into metrology and deliver solutions that meet the needs of all.
- ensure consumers, investors, policymakers and entrepreneurs can trust the work we do.
- build diversity into our collaborations to support change across the research and innovation landscape.
- facilitate responsible, sustainable innovation as we respond to national challenges.
- embed inclusive research design principles and remove potential bias from our research.
- support the development of our researchers' skills throughout their careers at NPL and beyond.

"My ten years working for NPL have been a rewarding journey, filled with lots of achievements and experiences I am proud of. The people I work with share the same passion and dedication to science as I do, which creates a supportive and engaging atmosphere. NPL has allowed me to grow and develop my own area of science in renewable energy. I enjoy thinking creatively to solve measurement challenges as the world seeks new energy solutions for the future."

Lucy Culleton
Senior Research Scientist
Gas Metrology


STANDARD

NPL's Research Roadmaps

1. The redefined kilogram
2. The redefined kelvin
3. Redefinition of the second
4. Digital metrology
5. Medical physics
6. Climate and emissions metrology
7. Net zero energy technologies
8. Advanced manufacturing and productivity
9. Biometrology and molecular imaging
10. Quantum electrical metrology
11. Quantum clocks, sensors and communications
12. Quantum computing

Glossary of general terms

AI/ML	Artificial intelligence / machine learning
BAT	Best available technology
CIPM MRA	CIPM Mutual Recognition Arrangement
CIPM	International committee for weights and measures
CMC	Calibration and measurement capability
CRM	Certified reference material
ISO	International Organisation for Standardisation
NMI	National Metrology Institute
QA	Quality assurance
RM	Reference material
PRM	Primary reference material
TRL	Technology readiness level
U	Expanded uncertainty
UKAS	United Kingdom Accreditation Service

Key to Roadmaps

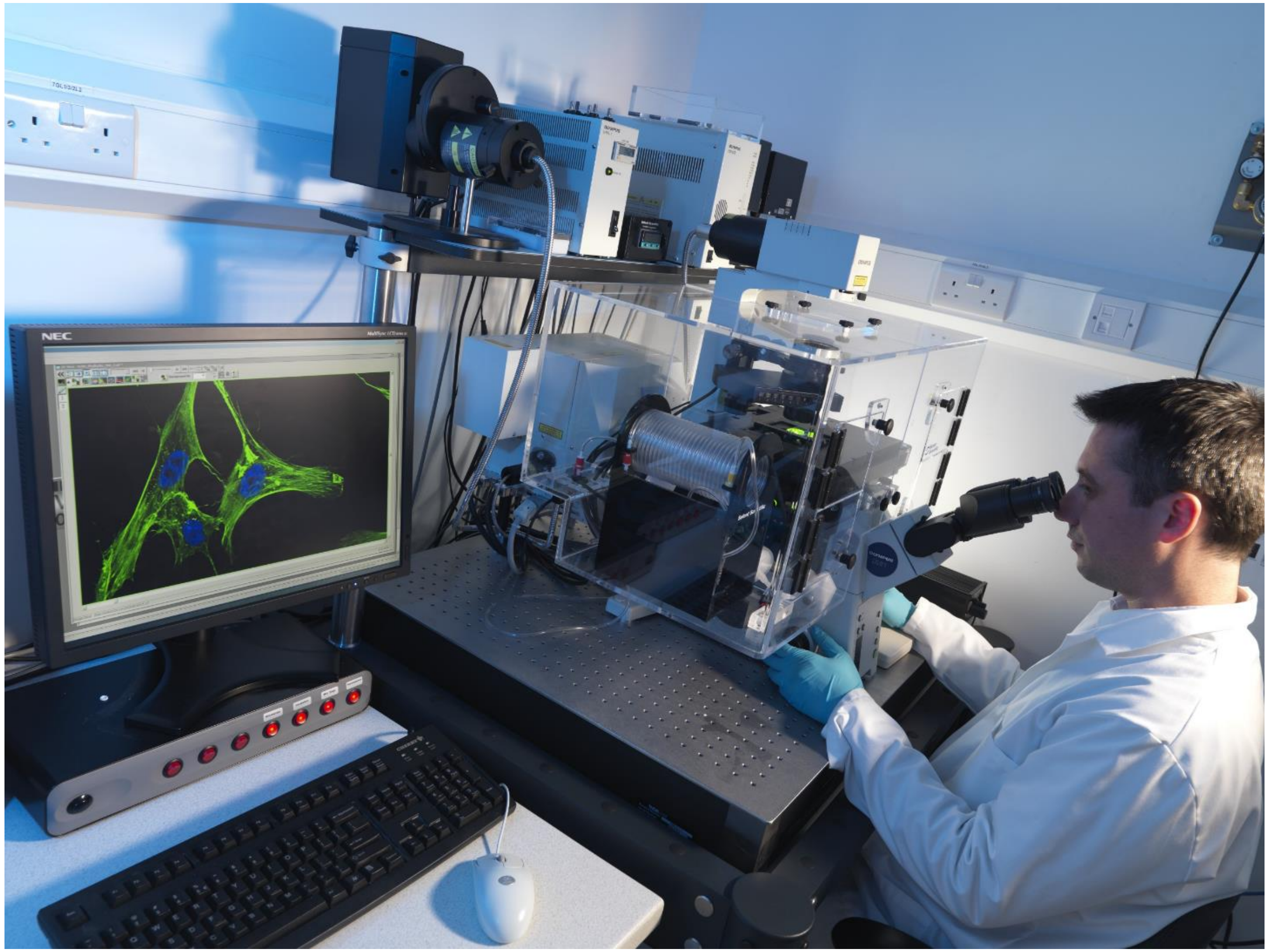
Solution exists

Solution in development

No known solution

"I chose to work at NPL as I wanted to combine my passion for engineering with science to make a change in today's world. Little did I know that I would be part of an NPL space related project to lead the electronics development for a calibration system being supplied for a European Space Agency mission! The team have worked tirelessly to deliver the huge system, throughout the pandemic."

Mayank Joshi
Higher Research Engineer
Instruments and Engineering


NEC

The redefined kilogram

The Kibble balance allows SI realisations of mass, force and torque over a range of values. By building simple, accurate Kibble balances, NPL can take a world leading position in the realisation of the kilogram and related mechanical units. The world needs a stable, robust, mass scale based on the new definition. To this end we can supply national measurement institutes with balances and collaborate with them, both to improve the balances and to generate a robust mass scale. This approach could achieve lower uncertainties than any single laboratory. We are presently collaborating with National Metrology Institute of South Africa and The Research Institute in Sweden to supply each of them with a balance which will start the process. Much of the work described in the roadmap could be carried out in collaboration with other NMIs, academia or industry.

To achieve our aims, the NPL Kibble balance must be easy to use, reliable and accurate. We must develop robust iodine-stabilised lasers, resistance standards based on Quantum Hall arrays and sub-nanovolt voltmeters based on an optimised combination of conventional and Josephson technology. It is also possible to use the NPL Kibble balance to make free-fall measurements of local gravity which would eliminate a complex, and expensive, separate gravimeter.

Calibration of an ‘industrial’ Kibble balance can be carried out without direct access to the balance mechanism which will simplify industrial processes. However, the development of such Kibble balances for masses in the range from kilograms to 100 mg is restricted by room temperature electrical standards. Significant improvements to the accuracy of such standards would enable the production of low-cost, accurate Kibble balances and benefit many areas of science and industry. Benefits could also be obtained by using the Kibble technique to measure torque, eliminating the need for mass or length standards. In the next few years NPL will concentrate on improving our conventional, cost-effective, force measurement capability before moving on to torque measurements.

For masses below 100 mg the relative uncertainty requirements are relaxed, and existing conventional electrical standards can be used. A ‘micro’ Kibble balance has the potential to measure small masses and forces at relatively low cost, leading to applications in industry, such as pharmaceutical production processes, micro robotics and particulate mass monitoring, where current calibration facilities are a barrier to progress.

“NPL offers me the opportunity to apply electronics design skills, built up over many years, to cutting-edge physics. There is an atmosphere of mutual respect between professionals of different backgrounds and specialties, due to NPL being positioned between academia and industry. In particular, I enjoy designing from first principles, often using discrete components. Aside from the science, I love meeting colleagues from around the world, and hearing their languages.”

Greg Walsh
Senior Research Scientist
Instruments and Engineering

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Implementation of the redefined kilogram	NPL realisation of the redefined kilogram	Investigate and improve the operation of the latest Kibble balance.	Achieve a relative standard uncertainty of 20 in 10^9 or better. Participate in a Key Comparison.	Iodine stabilised diode laser, interferometer, quantum Hall array, vibration isolation.	Improved Josephson voltage measurement, mass exchanger and load lock.	Investigate improved methods of frame guidance and free fall (gravity) measurements.	Combined balance and gravimeter.
	Global mass realisation	3 collaboration balances in production.	Achieve 20 in 10^9 uncertainty per balance. 2 more in production.	Possible 9 balances in the group with 7 in 10^9 group uncertainty.	15 in 10^9 uncertainty. Possible 15 in group with 4 in 10^9 group uncertainty.	Possible 21 balances in group with 3 in 10^9 group uncertainty.	10 in 10^9 uncertainty. Possible 27 balances in group with 2 in 10^9 group uncertainty.
	Gravity (free fall acceleration)	Use a conventional gravimeter.	Take part in key comparison Inter-national Comparison of Absolute Grav-imeters 2023. NPL gravimetry CMC	Support for: NPL and industrial Kibble balances, atomic clocks, UK gravimetry, UK industry for developing quantum gravimeters.		Develop a Kibble balance-based gravimeter.	Use a Kibble balance as a gravimeter.
Industrially focused applications of Kibble balance techniques	Industrial mass from 100 mg to 1 kg	Determine the market need for Kibble balance technology over conventional masses.	A target uncertainty approaching 100 in 10^9 would require major improvements in: room temperature standards of voltage and resistance, low-cost traceable velocity measurements and low-cost determinations of free fall acceleration.			Improved design simple setup.	Better magnets/ magnetometry.
	Industrial μ- mass/force < 100 mg/1 mN	Adapt existing Kibble electronics and software to control a scale model.	Miniaturise to micro-electromechanical systems (MEMS) scale laboratory prototype.	Adapt laboratory prototype to industrial applications.	Improve low-cost, traceable, velocity measurements.	Adapt sensor for healthcare applications. Possible chip scale operation.	Adapt sensor for environmental monitoring applications.
	Force and torque				Kibble technology for primary torque measurements to 100 N·m .	Kibble technology for continuous primary force and torque.	Kibble technology for continuous primary force and torque.

The redefined kelvin

The reliable traceable measurement of temperature with low uncertainty impacts most areas of human endeavour. Examples, linked to societal challenges, include:

Health - The reliable measurement of body temperatures is essential for determining human health and assigning treatment pathways (such as for sepsis). Trustworthy fever screening is needed for pandemic containment.

Environment - Reliable temperature measurement is essential for energy generation to ensure the correct, efficient and safe operation of fuel cells (hydrogen), batteries (automotive) and nuclear reactors, so helping facilitate the transition to net zero. Temperature and humidity are essential climate variables and need reliable measurement for global health monitoring.

Resilience - The transition to traceability at the point of measurement facilitates autonomy. For example, by providing trustworthy temperature reference points in sensor networks and for controlling factories, power plants and monitoring climate change.

Prosperity - Most industry relies on thermal processing. Reliable thermometry drives energy efficiency (especially in energy intensive industries) facilitating optimum energy use, zero waste and high-quality production.

This impact is ensured by the UK having leading capability of traceability to the SI unit the kelvin. The redefinition of the kelvin in 2019 has made direct traceability to thermodynamic temperature independent of defined scales possible. We will undertake collaborative research and work through the Consultative Committee on Temperature (CCT) to effect this change. In addition, there are emerging disruptive trends to temperature traceability, particularly through self-calibration and practical primary thermometry. This Roadmap represents NPL's approach to transitioning to traceability by thermodynamic temperature and ensuring we continue to contribute to the international development of the SI unit whilst remaining global leaders in this field.

Glossary

AR	Acoustic resonator
ARRT	Active ring resonator thermometry
DBT	Doppler Broadening Thermometry
HTFP	High Temperature Fixed Point
ITS-90	International Temperature Scale of 1990
JNT	Johnson Noise Thermometry
MeP-K	*Mise en pratique* for the definition of the kelvin
MeP-K-19	The most recent version (2019) of the *MeP*-K
QSR	Quasi-spherical resonator
SPRT	Standard platinum resistance thermometer
SVS	Self-Validation Sensor
T	Thermodynamic temperature
T_{90}	Temperature on ITS-90 scale

"NPL gives me the opportunity to be part of challenging projects with universities and industry, and also learn from world-leading experts in metrology. It is rewarding for me to make a difference with my work and to develop my technical and leadership skills within a collaborative and supportive group environment. Exciting future work includes collaborations with top industries to solve measurement problems and implement the redefined kelvin, using world-class temperature measurement systems and standards."

Sofia Korniliou
Higher Research Scientist
Temperature and Humidity

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
***Mise en pratique* for the definition of the kelvin**							
***MeP*-K-19**	Replacement of ITS-90 >Ag point (1235 K)	High Temperature Fixed Points (HTFPs) constructed and validated	Suite of HTFP with international validated *T*	Realisation and dissemination of *T* >Ag point HTFPs	Accredited meas. service *T* > Ag point by HTFPs		
	Acoustic resonator (AR) AR1 ~(77 K - 323 K)	Design of low *T* AR1 for T-T_{90} & standard Pt resistance thermometry (SPRT) calibration	Construction and validation of AR1	T-T_{90} & SPRT calibration trialled ~77 K to 323 K	Trial measurement service of SPRTs to *T* ~77 K to 323 K	Accredited measurement service of SPRTs to *T* ~77 K to 323 K	
	Acoustic resonator (AR) AR2 ~(290 K -700 K)		Initial design: AR2 ~290 K to 700 K	Design complete: AR2	Construction and validation of AR2	T-T_{90} & SPRT calibration trialled ~290 K to 700 K	Supplementary measurement service SPRTs: *T* ~700 K
Input into ITS-XX	Determine T-T_{90}	Measure T- T_{90} with current QSR and/or cylindrical resonator	Publish T- T_{90} from current QSR and / or cylindrical resonator	Other T- T_{90} values to be determined by AR1 and AR2 in *MeP*-K section above			
Disruptive traceability trends (e.g. traceability at the point of measurement)							
Photonic thermometry	Doppler Broadening Thermometry (DBT)	Early desk-based feasibility studies	Small scale DBT research begun	Prototype small scale DBT demonstrated	First practical DBT; linkage to NPL *T* group (2027), field trials (2028-29)	Co-develop with industry to raise TRL	Commercially available
	Active ring resonator thermometry (ARRT)	Design of first generation ARRT underway	Fabrication and demonstration of first generation ARRT	Prototype practical ARRT; linkage to NPL *T* group	Field trials, Co-develop with industry to raise TRL	Commercially available	
Practical Johnson noise thermometer (JNT)	Practical JNT	Elevate TRL to 8/9	Commercial prototype:1000 °C	Harsh environment tested: 1000 °C	Commercially available	Prototype to 1500 °C	Commercially available
Self-validating sensors (SVS)	SVS – high temperature	High T SVS, licensed and in industry trials	High temperature SVS commercially available				
	SVS – low temperature		Develop range, miniature FPs <500 °C	Integrate with sensor, automate plateau detection	Co-develop with industry to raise TRL level	Commercially available	

Redefinition of the second

This Roadmap is closely aligned to the international roadmap for a redefinition of the second, which targets a redefinition in 2030. A key goal is that the redefinition should offer an improvement in the realisation of the definition of the second by a factor of 10 – 100 in the short-term, and potentially more in the longer term. To achieve this, we not only need to improve the estimated systematic uncertainties of our optical clocks, but also collaborate with other NMIs to validate those uncertainties through international comparisons. Within Europe such comparisons will exploit the optical fibre network linking NPL with other NMIs, but new approaches are required to compare optical clocks on different continents at a level commensurate with their performance. We also need to measure the frequencies of our optical clocks as accurately as possible in terms of the current definition of the second, to ensure that no discontinuity is introduced at the point of redefinition. The target uncertainties appearing in the roadmap correspond to those set by the CCTF as mandatory criteria to be met prior to a redefinition.

It is important to ensure that the new SI second is available through TAI and UTC, and that the quality of TAI improves significantly as soon as the definition is changed. This means that the robustness and reliability of our optical clocks needs to be improved, so that they can regularly contribute data to the BIPM for the computation of TAI, initially as secondary representations of the second, and later as primary frequency standards. Finally, optical clocks must be introduced into UTC(NPL), and infrastructure developed to enable the new SI second to be disseminated to a broad range of users. Partnering to develop highly accurate, yet cost-effective, ways of making optical frequency references accessible at the point of need will be key to underpinning future innovation across a broad range of sectors.

Glossary

α	Fine structure constant
ACES	Atomic Clock Ensemble in Space
AQML	Advanced Quantum Metrology Laboratory
CCTF	Consultative Committee for Time and Frequency
m_p/m_e	Proton-to-electron mass ratio
NTC	National Timing Centre
RETSI	Resilient Enhanced Time Scale Infrastructure (new geographically distributed time scale being developed as part of the NTC programme)
T&F	Time and Frequency
TAI	International Atomic Time
UTC	Coordinated Universal Time
UTC(k)	Physical realisation of UTC maintained by laboratory k
UTC(NPL)	Physical realisation of UTC maintained by NPL

"NPL is the UK's national metrology institute, where we take the most precise measurements possible today. Such precision enables us to see effects that otherwise would be lost in the noise. These effects are often unexpected, and they always offer the joyful opportunity to keep on improving our understanding of nature. This better understanding strengthens the foundations of our modern society with benefits to our wider community."

Marco Schioppo
Senior Research Scientist
Time and Frequency

Theme	Sub-theme	Time					
		2021	2023	2025	2027	2029	2031
Optical clocks	Improved stability and accuracy		High-stability composite optical clocks	Uncertainties $< 2 \times 10^{-18}$	Cryogenic optical local oscillator	Quantum-enhanced optical clocks demonstrating metrological advantage	
Optical clock comparisons	Local comparisons		Comparison v. Cs with uncertainty $< 3 \times 10^{-16}$	Local optical ratios with uncertainties $< 5 \times 10^{-18}$			
	European comparisons	Maintain London-Paris fibre link	Exploit European network linking NPL, LNE-SYRTE, PTB and INRIM	Comparisons demonstrate agreement to better than 5×10^{-18}	Increasingly sensitive tests of fundamental physics, e.g. search for oscillations in m_e/m_p and α		
	Intercontinental comparisons	First demo of intercontinental optical frequency transfer via fibre	Comparisons using satellite links & transportable clocks	Global comparisons enabled by Atomic Clock Ensemble in Space mission	Optical clock comparison over an intercontinental fibre link	Regular intercontinental comparisons via fibre links	Intercontinental frequency transfer via free space
Contributions to time scales	TAI / UTC	Local geopotential known at level required for TAI contributions	Optical clocks approved for TAI steering; periodic contributions	Time transfer over optical fibre link to another UTC(*k*) lab	Optical clocks submitting data monthly for TAI steering		Optical clocks become primary standards
	UTC(NPL)		Experimental prototype of optically steered UTC(NPL)	Optimisation of steering algorithms	Optical clocks at one RETSI site, routinely used to steer UTC(NPL)	Optical clocks at second RETSI site to improve resilience	
Dissemination to end users	Clock test and evaluation facility in the AQML	Equipment procured for new AQML facilities	Collaborative access to state-of-the-art optical frequency references	New measurement services for clock sub-components	Continually running optical clocks	New measurement services for optical clocks	Commercially available optical clocks
	UK fibre network for T&F distribution		Demonstrator link to University of Birmingham	New solutions to reduce cost of large-scale implementation	Expanding network – optical frequency references available at point of need	Link up to European research infrastructure	'Plug and play' optical frequency metrology for remote users

Digital metrology

The topic of digital metrology has become prominent in recent years. CIPM have created working groups focusing on a digital framework for the SI. Many of the CIPM consultative committees explicitly consider digital dissemination in their strategy documents and several of the Regional Metrology Organisations are undertaking coordinated activity around digitalisation. The long-term goal is to create globally agreed standards for machine-actionable metrological data, and to enable realisations of the SI units at the point of use. This Roadmap outlines the research that NPL needs to undertake to ensure that these standards meet the UK's needs. The work described here is highly collaborative. The EURAMET Working Group on 'Metrology for Digitalisation', currently chaired by NPL, has several collaborative projects with involvement of multiple NMIs addressing many of the data challenges listed and European Metrology Partnership programme proposals address some of the other challenges. We are working with sensor manufacturers and end users, such as the National Composites Centre, to ensure our solutions are usable and can be deployed at scale in future.

These standards will have a huge impact because they will define how metrological data is created, stored and described via metadata. They will accelerate innovation by giving machine-readable access to reliable data when products are in development and by reducing uncertainties through *in situ* delivery of SI units. They will support the cross-disciplinary collaboration needed to address global grand challenges, such as the climate crisis, by ensuring that data is machine-actionable, of known quality and provenance, and described in a way the end user can understand. The standards will improve confidence in data by allowing traceability and calibration information and uncertainty to travel through data processing chains, including use of advanced analytics such as machine learning, right up to the point of decision-making.

Digital metrology cuts across all science at NPL, so there are strong links and overlaps with other Roadmaps and co-operation with the international community. Tools that cut across multiple areas where metrology has an impact, such as digital twinning, data quality metrics, quantitative imaging, data sharing across disciplines, and sensor networks, have not been explicitly captured on this roadmap but are key components of the more detailed subject area Roadmaps that have informed the contents of this one.

Glossary

DCC	Digital calibration certificate
FAIR	Findable accessible interoperable re-useable

"I am privileged to be a part of the data science team where we work on a large variety of projects with other NPL departments and external collaborators. The cross-disciplinary nature of our work is reflected in many engaging discussions and great willingness to learn and transfer knowledge between domains among all team members. I learn something new every day and believe that together we are making the world a better place, bit by bit."

Marina Romanchikova
Science Area Leader
Informatics

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Direct delivery of the SI to point of use	*In situ* realisation and validation of units and self-calibrating temperature sensors		First self-calibrating temperature sensors commercially available	Lab scale prototypes for *in situ* realisations	Digital twins to monitor and validate *in situ* realisations	Industrial deployment for *in situ* realisations in 3 key applications	
	Remote calibration and delivery of units via cable.	Proof of concept development for remote calibration.	Toolbox and framework approach for remote calibration	Local sharing of realisations.	New approaches to key comparisons for remote calibrations	Analytics for correction of low-cost sensor networks in the field	Digital artefacts & synthetic data for remote testing
Digitalisation of comparisons and the MRA	Data and metadata structures for FAIR metrology		Draft domain agnostic ontology for metrology	Framework for reference databases including semantic technologies	Analytics to optimise comparison coverage for complex capabilities.	Critical assessment of information infrastructure for intercomparisons	Standardisation of data structures across metrology
Digital dissemination of SI traceability via demonstrably trustworthy workflows	Digital Calibration Certificates (DCCs)	Gap analysis of existing schema and extension prioritisation		Traceable temporal databases to support realisation of DCCs	Implementation in five priority domains	Embedded generation of DCCs into NPL realisations and instruments.	
	Metadata standardisation	Minimum FAIR metadata for uncertainty quantification & traceability in two areas	Extend existing standards by metrology metadata in two selected domains	Ontology-based metadata registries	Establish FAIR metadata standards in collaboration with international metrology community		International agreement of standards in three metrology areas
Metrology and machine actionability	Making metrology machine-actionable		Development of revised machine-friendly vocabulary	Supply of realisation experimental data in machine actionable format	Tools for end users to generate and use machine actionable data	Embedding machine actionable into measurement instruments	Develop machine actionable measurement procedures
	Making machine actions metrology-friendly: uncertainty, explainability and reporting		Capture metrology requirements and review existing methods	Extend, adapt, or design methods to meet metrology requirements	Develop standardised methods, implement an example within digital metrology	Publish good practice and implementations for examples in diverse sectors	Publish Standards and metrology guidance documents

Medical physics

The SARS-CoV-2 pandemic demonstrated the importance of NPL's primary standard realisations of the gray, becquerel and pascal and the criticality of their dissemination routes to UK hospitals and medical equipment manufacturers world-wide. Through collaborative research with clinical and industry partners, our target is to accelerate healthcare innovations to deliver better care outcomes, underpinning future resilience of healthcare delivery and, through this, saving lives and optimising deployed resources.

Future activities will underpin the development of quantitative clinical imaging techniques, such as PET, MRI, SPECT and ultrasound / photoacoustics, to address earlier and more specific disease detection and stratification over modalities. This will provide robust, traceable and validated reference tools to establish confidence in decision-making. The generation of clinical data and its optimal application using AI techniques, will play a key role in benefit realisation. Research supporting the safe and optimised application of novel methods of radiotherapy treatment delivery through accurate measurement of applied dose, will accelerate take-up of proton therapy and emerging modalities such as FLASH RT. Accurate clinical thermal imaging is required to support reliable fever screening for increased national resilience to future pandemics. Work to reinstate routine reliable clinical thermometry is required to improve patient care and outcomes. These aspects are covered in the roadmap *The redefined kelvin* (on page 13).

Glossary

AI	Artificial intelligence
CCAUV	Consultative Committee on Acoustics, Ultrasound and Vibration
CoP	Codes of practice
CT	Computed Tomography
DAP	Dose area Product
DFU	Diabetic Foot Ulcer
FLASH	Novel radiotherapy technology defined as a single ultra-high dose-rate (≥ 40 Gy/s).
IPASC	International PhotoacousticsStandardisation Consortium
kQ	Beam quality correction factor
MITHRAS	Next generation Molecular Imaging and THerapy with RAdionuclideSproject.
PA	Photoacoustics
PET	Positron Emission Tomography
PRISMAP	Production of high purity isotopes by mass separation
SPECT	Single-photon emission computerized tomography
T1	MRI imaging sequence which is T1-weighted
T2	MRI imaging sequence which is T2-weighted
UP	Uncertainty propogation

"I knew about NPL long before moving to the UK. When I saw a job opportunity at NPL, that was closely related to my previous experience, I did not hesitate to apply and here I am, 10 years later. NPL is giving me the opportunity to work in the area of standardisation of preclinical dosimetry, an exciting area of research in support of better understanding of mechanism leading to new and personalised cancer treatments involving radiotherapy."

Ileana Silvestre Patallo Senior Research Scientist
Medical Radiation Physics

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Magnetic Resonance Imaging (MRI)	Imaging Data analysis, simulation	Design and initial testing of distortion and resolution phantoms	Draft uncertainty budget for T2 mapping, extension to T1	Traceable methods for iron diffusion and T1, T2	Guidance and training on low-distortion imaging	Accredited trial qualification service for T1, T2, fat, iron diffusion (imaging application specific)	Best practice guide for phantom materials
Nuclear medicine	SPECT and PET quantitative imaging (QI)	Calibration/guidelines/ validation of SPECT/CT QI systems.	Traceable calibration and UP for all SPECT QI radionuclides and F-18 PET imaging	Traceable calibration of commercial SPECT to NPL. Traceability and UP for PET-MR.	Traceable calibration and UP for whole body PET systems.	UP & traceability to support AI-based iterative reconstruction	Metrology for future whole body scanning systems
	Novel medical radionuclides	Metrology for PRISMAP (EU-CERN) and MITHRAS (UK-KCL)	Hub for UK Radiopharmaceutical R&D	Mobile station for radionuclide standardisation	Adoption of automated separations for routine measurement services		GLP for separation of medical radionuclides
Radiation dosimetry	Primary standards Air Kerma and Absorbed dose realisation (gray)	Reporting of Proton Cal Mk1 studies	Commissioning of Proton Primary Standard Mk 2	Water calorimeter. Expansion of Alanine kQ.	Commencement of Micro Calorimeter Mk 2 development	Standard for Absorbed Dose measurements of multi-mechanism contribution techniques	Combined Primary standard for combined modalities (Photon/Proton/ Electron)
		Adiabatic vs Isothermal modes of operation. UHDR detector characterisation					
Radiotherapy	Emerging technologies	kQ factors for new radiotherapy modalities	Tissue equivalent materials for protons	Development of detectors for FLASH radiotherapy	Incorporation of motion into phantoms	End-to-end Audits for novel technologies supporting clinical roll-out	Validation through adaptive pathways
Radiobiology	Pre-clinical and Microdosimetry; radiolabelling	Detectors and theoretical framework for microdosimetry; establish cross group capabilities	Tools/methodologies for international CoP. Novel phantoms for targeted radiopharmaceutical metrology	Uncertainty propagation for radiobiological modelling; standard method for targeting molecules	Consultancy for pre-clinical irradiator audits; traceability link to pre-clinical cell studies	Traceability of pre-clinical dosimetry; metrology for Auger emitters	Development of a microdosimeter primary standard
Ultrasound	Primary standards pascal realisation	New hydrophone calibration system commissioned with uncertainty of 8% at 40 MHz	Extension of hydrophone calibration up to 100 MHz	NPL-PTB bilateral high frequency calibration comparison	Lead CCAUV key comparison (100 MHz)	Primary standard accessible to users, 50-100 MHz (20% uncertainty)	Feasibility study of hydrophone calibration above 100 MHz.
	Quantitative Imaging (QI)	Characterisation of biological specimens using acoustic metrics (1 MHz to 300 MHz)	Development of photoacoustic system and validation using tissue equivalent materials	New breast imager developed capable of 500+ volunteer study	IPASC comparison of photoacoustic systems completed	Service provided to characterise photoacoustic contrast agents	IEC standards developed and published for quantitative imaging

Climate and emissions metrology

This Roadmap describes how NPL will build on existing expertise and ongoing and new collaborations (eg. The Met Office, UK Space Agency, European Space Agency, World Meterological Organisation (WMO), International Atomic Energy Agency, industry and academia) in environmental metrology, taking metrological traceability out to field, on site and satellite observations and to the information products derived from those.

The air quality activity describes NPL's work to support air quality networks. NPL expects to become the national custodian for air quality networks. The greenhouse gas (GHG) emissions and carbon stocktake activity covers NPL activities to support the monitoring and attribution of greenhouse gas emissions, as well as land use change using direct emission measurements, *in situ* networks and satellite observations. These activities underpin regulations and national and international inventories, and in support the global "stocktake", the formal UN formal process to assess progress towards the Paris Climate Agreement. NPL expects to become a globally recognised and accredited provider for GHG source measurement and attribution, and to provide quality assurance for GHG observations from space.

The Roadmap shows our ambition to support climate observations from satellites and *in situ* instruments. These activities support the pre-flight and post-launch calibration of satellite sensors, field validation of satellite data products, the establishment of reference *in situ* networks, and the development of software tools and a quality-assurance framework for environmental observation comparisons and uncertainty analysis. The UKSA-funded, NPL-led ESA satellite mission TRUTHS ~ will bring NPL's radiometric traceability chain into orbit. NPL will establish, with partners, meteorological, desert, vegetated and ocean reference sites and extend our research to new types of sensors and applications. NPL's work will support the climate science value chain and take our experience in metrology for observations and their basic processing, into data science, data assimilation and support information products for decision makers.

Glossary

A/B1/B2/C/D/E	Mission stages from concept to launch
AI/ML	Artificial intelligence / machine learning
EO S2S	Earth observation sensor to sensor
GRUAN	GCOS (Global Climate Observing System) Reference Upper Air Network
Hypernets	Hyperspectral instrument network measuring ground reflectance
ICP-MS	Inductively coupled mass spectrometry
MicroCarb	France/UK CO_2 measurement satellite
PAR	Photosynthetically active radiation
SRIPS	Spectral radiance/irradiance primary scales
TRUTHS	NPL's SI-traceable satellite "Traceable Radiometry Underpinning Terrestrial and Helio Studies"
TLS	Terrestrial laser scanner

"I find NPL a really exciting place to work as an early career scientist as the breadth of science undertaken here is huge. The research we do ranges from developing algorithms to analyse satellite data, to using drones to measure forests, to installing radiometric instruments in deserts. NPL provides a unique opportunity to work with world-leading experts across a variety of areas of science, all linked by the common purpose of underpinning the UK's measurement capabilities."

Madeline Stedman
Research Scientist
Climate and Earth Observation

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Air quality	Air quality metrology	ICP-MS isotope ratio methods (non-exhaust vehicle emissions)	Research impact of hydrogen combustion	NO_2, NH_3 and HCl reference materials (U < 3 %), new standardised method	NPL custodian of national network of remotely calibrated sensors	Air pollutant emission quantification. U <25% personal exposure sensing	Underpin particle sizing & black carbon measurement. Integrate pollutant & GHG reporting.
Greenhouse gas emissions / carbon stocktake	Fundamental Greenhouse Gas (GHG) metrology	SI traceability for CO_2, CH_4 and N_2O (U=0.05 %, 0.1 % and 0.3 %)		NPL to provide traceability to the WMO CO_2 scale for Europe	Capability - CO_2 and CH_4 source attribution (WMO data quality objectives)	NPL global provider of accredited isotope ratio Reference materials (CO_2 and CH_4)	Isotope ratio no longer a traceability exception under the CIPM-MRA
	Applied GHG metrology	In situ $\delta^{13}C$ and $\delta^{2}H$ measurement (U <0.1 ‰ and <1 ‰)	Cryogen-free pre-concentration of ambient CO_2 and CH_4	CH_4, CO_2 and N_2O capability <1 kg/hr for fugitive emissions	Optical Isotope Ratio Spectroscopy applied to rare isotopologues - regional scale pollution detection	Multi-scalar emission source measurements	Near-real-time, measurement-based multi-scalar reports Multi-isotopic tracers
	GHG sources and sinks from satellites	MicroCarb satellite data quality assurance and GHG certification study	MicroCarb in-orbit validation. EO-based land-use, land-use change and forestry	GHG sensor kitemark / UN Global Stocktake data	Application to commercial missions	Certification of commercial missions and stocktake quality assurance	
Sensor development and calibration facilities	Underpinning capability	Upgrade Cryogenic Radiometer, National Reference Reflect-ometer and SRIPS	Camera Absolute Radiometric Evaluation Suite	Post-tungsten references. Camera Absolute Radiometric Evaluation Suite accredited	Transportable small-sat calibration facility	New traceability routes for radiometric scales, next generation reference standards	
	In orbit SI	TRUTHS designed	TRUTHS realised (ESA phases B2/C/D)			TRUTHS launch (phase E)	TRUTHS-2 / SI-sat
Climate observations from satellites and *in situ* networks	Fiducial reference measurements and reference networks	Drone-borne sensors for field work. Multi-angle /spectral sensors (Hypernets)	NPL research weather station Hypernets in field. TLS, PAR (U < 3 %)	Lunar ref. (U <2 %). New European ocean colour facility. GRUAN uncertainty toolbox	Vegetated super-sites with visible, IR & active capability	Above-ground biomass budget framework; Application of ocean colour facility Traceable and improved reference climate observations with attributed uncertainties	
	Fundamental data record and interoperability	Fundamental data record framework published. Software tools audited	Interoperable software tools & UK Space Agency framework	EO S2S commercial services operational Altimetry/synthetic aperture radar tools	TRUTHS data exploitation tools	TRUTHS product calibration and certification services	
Climate information / modelling	Modelling and Data Assimilation	Covariance definitions and case studies	Collaboration with Data Assimilation community	Uncertainty for AI/ML for observation. Classification maps	Uncertainty for decision making incl. expert judgement	Tools for communicating uncertainty and risk	

Net zero energy technologies

NPL is supporting the rollout of low carbon energy technologies by collaborating with key partners to develop the metrological infrastructure required to underpin and validate improvements in their performance, lifetime and safety. Generation of more reliable, reproducible and inter-comparable data provides confidence to end users, investors, regulators and consumers that the materials, components and systems will function as required, accelerating their development and deployment at scale. The Roadmap is split by the themes of energy generation, storage/distribution and consumption, and many activities are aligned with UK national challenge programmes in which NPL is leading the measurement, test and validation work packages (e.g. Faraday Battery Challenge, Hydrogen Innovation Initiative, Driving the Electric Revolution). The Roadmap highlights the priority areas, although other important work is planned in solar photovoltaics, biofuels and metrology for buildings.

Research to address these challenges involves collaboration with National Measurement System partner laboratories (e.g. National Engineering Laboratory on hydrogen, National Gear Metrology Laboratory on wind turbines), other NMIs (e.g. Physikalisch-Technische Bundesanstalt on lithium-ion batteries, Instituto Nazionale di Ricerca Metrologica on electric motors), as well as universities, research institutes and industry. Underpinning themes include:

Materials metrology

- Providing increased confidence in measurement and modelling of material properties
- Development of representative accelerated stress tests to obtain more reliable prediction of material, component and device lifetime in harsh environments
- Development of standard test protocols to enable inter-comparison of data from different laboratories and support cost effective material selection

Data science

- Applying data management tools, AI and ML techniques to the analysis of performance and lifetime data

Technology validation

- Acting as the highest point of reference for verification and validation of performance claims
- Developing novel test methods and diagnostic tools to support uptake of emerging technologies

"Working at NPL means working on research areas that will make a difference for the world, either in the near or slightly more distant future. As a scientist in the area of renewable energy, I can see my work having a direct impact in the industry and society, towards tackling climate change and transforming power generation at a worldwide level."

George Koutsourakis
Senior Research Scientist
Electronic and Magnetic Materials

Glossary

ASCC	Atmospheric Stress Corrosion Cracking	LH_2	Liquid Hydrogen
AMPP	Association for Materials Protection and Performance	NDT	Non-Destructive Testing
BMS	Battery Management System	NSO	Network Strategy and Operations
GES	Good Environmental Status	SMR	Small Modular Reactor
IEC	International Electrotechnical Commission	SS	System Strength

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Energy generation	Wind	High-speed Digital Image Correlation (DIC) for turbine blade composites; ultrasonic methods for piling	Validated noise abatement methods for offshore wind construction	Validation of low noise construction (blue piling, floating wind); validation of *in situ* DIC methods	ISO standards for NDT of composites; validated methods for cumulative ocean noise effects with uncertainty	Traceability in recycled composites; ISO standard high-speed DIC; ocean noise mapping for GES	Liquid composite moulding digital twin; validated methods for estimating effect of noise on ecosystems
	Nuclear	Establish NMI role for SMR, AMR & fusion programmes; ASCC test protocol	UKAEA support for fusion research; ASCC environmental variables analysis	R&D facility for SMR monitoring; ISO standard on ASCC testing	Tools for lifetime prediction in storage of nuclear waste; neutron standards for fusion	Services & standards for online SMR monitoring; R&D for AMR/Gen-IV	Integration of lifetime prediction and monitoring tools
	Carbon Capture, Utilisation and Storage (CCUS)	First methods & PRMs for impurities in CO_2; literature review on corrosion test methods	Test facility for solvent degradation; corrosion test capability; UK BAT amine/nitrosamine measurements	PRMs; sampling good practice & QA; draft standard corrosion test method	CMCs for impurities in CO_2; AMPP standard corrosion test; CO_2 loss quantification standard	ISO standard on testing CCUS solvents; industry specifications for material selection	ISO standard on QA of CO_2 in CCUS; integration of lifetime prediction and monitoring tools
Energy storage & distribution	Hydrogen	Fuel cell & electrolyser validation & modelling; PRMs for H_2/Natural gas blends; humidity in H_2; H_2 permeation in composites	Impact of impurities on fuel cells; PRMs; modelling apps; ISO 14687 UKAS accreditation; humidity calibration in H_2	Draft standard fuel cell & electrolyser test methods; PRMs for 100% H_2 in gas grid; humidity calibration at elevated pressure; LH_2 mechanical testing	ISO & IEC standards; high power fuel cell & electrolyser stacks; humidity traceability in H_2; H_2 leak quantification methods	Inline quality control in fuel cell & electrolyser manufacturing; 700 bar H_2 sampling rig; CMCs for humidity measurement	Next gen tech; hybridisation; systems; annual PT scheme for H_2; stable multi-component PRMs at ISO 14687 purity threshold
	Batteries	Standard test protocols, modelling tools, *in situ* & *operando* diagnostic techniques	Inline quality control in manufacturing; module testing; modelling apps	Draft standard test methods; pack testing; traceable fibre-optic thermometry	IEC standards for performance & lifetime; BMS; measurement methods for next generation materials	Systems modelling; standard methods for electrode composition determination	Next gen tech; hybridisation; system management; multi-modal techniques for electrode composition
	Electricity Grid	Measurement needs for stable integration of net zero renewables ensuring inertia, system strength and low disturbance	New inertia reference method; SS algorithms; early warning methods for non-synchronous oscillations	Inertia test beds, site & instrument verification; NSO protection; traceable condition monitoring via thermal imaging	Commercial protection solutions; data analytics to assure grid power quality for mixed-source electricity	*In situ* condition monitoring through traceable thermal imaging	
Energy consumption	Power Electronics	Intercomparison of insulation resistance testing methods in damp environments	Methods to assess power electronics reliability	Internationally agreed test method for insulation resistance in condensing environments	Internationally agreed test protocol for reliability assessment of protective coatings in power electronics	Method for complex reliability test cycles	Integrate data driven diagnostics methods to reliability test measurements
	Electric Machines & Drives	Open circuit measurement uncertainties < 1% for NdFeB/SmCo magnets in electric motors	Magnetic measurements under simulated operational conditions (high temp, mechanical stress)	AC loss techniques to assess soft magnetic materials at 10-50 kHz & under mechanical stress	Internationally agreed magnetic measure-ments during operation (up to 155 °C and non-standard geometries)	Methods under complex conditions (temp, stress, non-sinusoidal waveforms)	Accreditation under combined operational conditions (target combined *U* of 3-10%)

Advanced manufacturing and productivity

As the pace of innovation accelerates, there is a growing gap between the point when industry needs best practice in measurement and when international standards are actually available. NPL provides confidence in the adoption and innovation of materials and technologies by developing the required pre-normative research that provides UK industry with early access to best practice in measurements, and by ensuring best practice is internationally agreed. The well-established materials metrology expertise at NPL covers a wide range of properties, applications and sectors. It plays a key role in establishing and maintaining an international measurement infrastructure which is paramount to support innovation, manufacturing and trade.

With increased manufacturing automation, rapid, cost-effective, in process quality control solutions are required which are verified and have well-understood uncertainties. Provision of traceability, self-calibration and robust uncertainty evaluation at the point of measurement will represent a paradigm shift in the concept of traceability, for the first-time providing SI traceability in process and in real time. This innovation is needed to facilitate flexible, autonomous and data driven production, as well as to provide 'truth points' in interconnected sensor networks to ensure confidence in data and measurement reliability. Confidence, in the form of a statement of measurement uncertainty, adds value to data, underpins digital twinning and facilitates robust decision making throughout a product's life cycle. Establishing techniques for automated data governance will create an additional layer of understanding of the needs of end users. Furthermore, building confidence in the quality and provenance of manufacturing data will create value within smarter and more data-rich supply chains.

The Roadmap describes some of our key priorities, in support of digitalisation and automation, technology innovation and complex systems metrology, in close alignment with UK Government priorities, NPL's Technology and Measurement Foresighting document and the High Value Manufacturing Catapult Integrated Metrology 10-Year Roadmap for Advanced Manufacturing (2020). NPL expects to work closely with universities, Catapults and other research technology organisations in delivery of this vision.

"For me, working for NPL is realising my professional ambition. To be part of the NMI where every voice is heard and valued, and we put the interests of UK plc at the heart of every single thing we do. As UK manufacturing is in constant change, I am excited to be part of NPL's contribution towards manufacturing measurement evolution."

John Turland
Training Delivery Manager

Glossary

TRL	Technology Readiness Level
ALM	Additive Layer Manufacturing
IoT	Internet of Things
ITER	International Thermonuclear Experimental Reactor

Theme	Sub-theme	Time: 2021	2023	2025	2027	2029	2031
Digitalisation and automation	**In process metrology driven manufacturing and digitalisation**	Build first traceable interferometric multi-target distance measurement sensor (OPTIMUM sensor)	Traceable, self-calibrating, dynamic coordinate metrology for automated process control at 10 - 1 ppm on scales < 1 m and 1 – 10 m. Machine - metrology system integration: protocols for feed-froward and feed-back control		Metrology driven, robotic manufacturing with traceable data output TRL 7. Methods for traceable, self-calibrating optical scanning at large (< 10 m), small (< 1 m) and micro-scales (<1 mm) at 10 ppm to TRL 5/6.		Traceable, self-calibrating optical area scanning technology at TRL 7
	Traceability through Digitalisation	Digitalisation of materials measurement and integration into data management systems		Digital integration of material measurement uncertainty in data frameworks		Materials data quality frameworks developed and implemented	
			New m and kg realisations. Digital traceability from BIPM through the SI realisation to measurement services to the customer				
	Force, torque				Kibble technology applied to industrial force and torque metrology (1 µN to 100 N at 1 ppm, 1 µNm – 100 Nm at 10 ppm)		
	In-situ traceable thermometry	High temp. (> 500 °C) self-validating sensors	Self-validating sensors (< 500 °C) Non-contact thermometer/hygrometer (for air temperatures). Traceable surface thermometry		No drift/self-validating sensors to facilitate industry 4.0/autonomous production. Commercialise phosphor thermometry - to provide reliable traceable surface thermometry in range of applications		
	Industrial data governance & approval		“Maps” of Industrial data exchange & governance for application within integrated supply chains		Ontologies & controlled vocabularies	Advanced verification and approval techniques for highly regulated industries)	
	Industrial uncertainty data provenance	Proof of concept industrial “dynamic” uncertainty data model	Uncertainty modelling to support IoT in control system feedback	New techniques for sharing trusted industrial data	Mapping of uncertainty generation within industrial processes	Visualisation of dynamic and complex uncertainty	End to end digital factory traceability of uncertainty
Technology innovation and complex systems	**Composites, additive layer manufactured and coatings**	Good practice guide on 3D Composites and ALM microstructural characterisation	New techniques for measurement of strain and *in situ* micro-scale testing	Cryogenic composites testing Metrology for complex thin-walled structures	Detection limits and uncertainty of resonant ultrasound spectroscopy NDE. Pre-normative methods for dynamic mechanical characterization of complex thin-walled structures		International standards for multi-material and multi-functionality measurements
	Chemistry of surfaces and interfaces	Complete XPS Key Comparison on sub-10 nm layer thickness.	Verify peak intensity ratio uncertainties for in-line Raman	Quantitative XPS sputter depth profiles with U <2 at%	Validated methods for magnitude of matrix effect in Raman	Develop standard quantitative method for surface/sub-surface chemical composition of films.	
	Magnetic materials and sensors	Low field stability (nT) and temperature control of the low field magnetometer	Methods for magnetic properties measurement in operational conditions	- ^{3}He primary magnetic field standard leading to reduced uncertainties at elevated fields - Traceability of magnetic properties at operational temp (-40 to 200 °C)		UKAS accreditation for measurements under combined operational conditions Establish fundamental limits of absolute magnetic field measurements using NMR (CERN, ITER)	
	Emerging Semiconductors	Compressed sensing sampling method in 2D imaging up to 200 mm sample size	- International agreement on calibration method of spatial resolution in confocal spectroscopy - Hyperspectral imaging platform with high spectral resolution (<5nm)		Advanced sampling techniques for multi-modal imaging	Validated hybrid metrology data analysis methods for multi-modal datasets	Real time reconstruction methods for large data hypercubes
	Health technologies	Best practice for number concentration of colloids (mass ≥ 10^{-19} kg)	Measurement of cargo load and distribution in advanced particle formulations	Data ontology standard for pharmaceutical manufacturing approval for clinical trials	Uncertainties, their propagation and impact on confidence in real-time predictive models for pharmaceutical manufacturing		Traceable measurement of administered therapeutic dose

Biometrology and molecular imaging

A healthy population is one of the nation's most important priorities. Our Roadmap aims to provide the necessary measurement infrastructure to accelerate innovation and technological advances in the UK and enable effective diagnostic and therapeutic solutions to a much wider range of disease than is currently possible. The SARS-CoV-2 pandemic has highlighted the critical role the UK's world-class pharmaceutical and biotechnology sector plays in safeguarding human health. It has also revealed how the rapid rise in demand for testing and treatments overwhelms existing infrastructures, emphasising the need for better preparedness against infectious diseases and other health conditions. We have consulted closely with the industry along with other leading research institutes to prioritise metrology needs for the next decade.

We develop molecular imaging to help improve patient outcomes via key population-level studies generating high-quality data. We lead the CRUK Grand Challenge Rosetta project creating powerful capabilities for spatial metabolomics spanning multiple length scales from organs to cells. Complementary to this are our metrology developments to reduce drug attrition, a major issue in the pharmaceutical industry. We are developing metrology in collaboration with GlaxoSmithKline and Astra Zeneca to measure drug targeting in cells and tissues and map the drug action with single cell resolution. In collaboration with biologists at the Francis Crick Institute and supported by the Wellcome Trust, we are developing new high-resolution molecular imaging technology and methods for the life-sciences.

Government policies and strategies, such as the Life Sciences Vision, call for investment in infrastructures supporting innovation by assuring confidence in the reproducibility of biomedical research. We are establishing a correlative biophysical infrastructure of the highest metrological order which covers multiple techniques. It will encompass reference materials and reference measurement procedures allowing the validation of the application of biological phenomena in a continuum of constituent properties completely and reproducibly. We are developing this infrastructure in collaboration with pharmaceutical and Artificial Intelligence companies (e.g. IBM, Evotec), instrument and device manufacturers (e.g. Oxford Instruments, Smith and Nephew) as well as the NHS. As an early impact demonstrator, we apply our developments to support innovation in advanced therapies including antimicrobial, gene and regenerative therapies.

"At NPL we bring together multi-disciplinary expertise in response to complex health, societal and environmental problems. It is a privilege to work as part of large and expert teams to innovate and deliver multi modal measurement strategies. In the Cancer Research UK Grand Challenge programme we are working with world leading biologists and clinicians to use MS and MS imaging at all stages of the patient journey."

Josephine Bunch
NPL Fellow
The National Centre of Excellence in Mass Spectrometry Imaging

Glossary

AP LDI	Atmospheric pressure laser desorption ionisation
CRM	Certified reference materials
DESI	Desorption electrospray ionisation
FFPE	Formalin fixed paraffin embedded
JCTLM	Joint committee for traceability in laboratory medicine
Log P	Logarithm of partition coefficient in non-polar solvent and water
MSI	Mass spectrometry imaging
OrbiSIMS	Orbitrap Secondary ion mass spectrometry
qSAR	quantitative Structure Activity Relationships
REIMS	Rapid evaporative inlet mass spectrometry

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Biomolecular metrology	SI-traceable reference measurements	Bio-calibration for high-resolution imaging (2-15 nm, *U* < 10 %)	Agree SI-traceability route for differential diagnostics (2-10 nm, *U* < 10 %)	CRMs for biomolecular imaging *in situ* (1-5 nm)	CRMs for gene transfer (mg/g, *U* (w_A) ~5%)	Protocols for biopolymer synthesis ($10^{3\text{-}4}$-mer)	Establish digital qSAR description of functional biologic materials
	SI-traceable CRMs for biosystems	Internal standards for biospecimen analysis (<10 nm, *U* < 10 %)	qSAR activity calibrants for drug screening (mass, µM per cell)	Response stability calibrants *in situ* and *in cellulo* (X/dT, *U* ~10%)	Reference scaffolds for 3D culture (2 mg/mL)		
Metrology for drug discovery	Drug at target, right pharmacology, right phenotype, molecular pharmacology	Compound (Log P > 3) identification and localisation < 5 µm (dehydrated)	Initiate improved detection methods in Orbitrap MS to increase sensitivity	Cryo OrbiSIMS-sensitivity increase of drug (-2 < Log P < 7) in hydrated state.	3D native state imaging at 1 µm *X*, *Y* and 10 nm *Z* resolution,	Improved detection in Orbitrap for single ion sensitivity	3D native state imaging (drug, metabolite) at 500 nm *X*, *Y* resolution,
		AP LDI + post ionisation small molecules from tissue	Variable wavelength LDI-post ionisation for optimal analysis of different sample forms	MSI resolution of ~ 1 µm for atmospheric pressure FFPE / fresh hydrated tissue	Detection of all metabolite and lipid classes with AP LDI post ionisation		High throughput single-cell AP LDI cryo-MSI with broad metabolic pathway coverage
	MSI metrology for multi-modal MSI		Optimal DESI solvent composition for broad metabolite coverage	Understanding of ionisation mechanisms and matrix effects	Trusted algorithms for pre-processing signal (Poisson processes)		Multi-compound quantitative imaging
	Drug-target engagement	Crystallisation screening protocols for biologics	Protein sensitivity comparison ambient MS modalities	Reproducible *in situ* native protein MSI	Crystallisation screening protocols for drug-target complexes		*In situ* competitive binding assays
	SI-traceable high-content phenotypic single-cell screening		bacteria (10 drugs per 3 cell lines) at a single cell level over minutes to hours	human (2 drugs per 2 cell lines) and co-cultured cells (10^5 cells)		Define SI-traceable drug screening	
Biophysical metrology of the cell & tissue	Quantitative correlative cell and tissue measurements	Multi-modal high-, super-resolution, SRS & MS imaging methods (2 -100 nm; 1-10^5 cells)	Functional 3D mapping of cell-laden biosystems (nm – cm)	Tissue phantoms for biomedical imaging (diffusion MRI, mean diffusivity)	Validated database of matrix effect in Raman spectroscopy	Bio-calibrants for traceable imaging across modalities, (length & time)	Demonstrate SI-traceable extra-intra-intercellular drug trafficking
International metrology	Toolbox and standards	ISO technical specification for bio-calibrants	Toolbox of CRMs for industry (length and mass, first 3 CRMs)	JCTLM-like depository of qSAR CRMs (3 CRMs)	ISO technical standards for biological CRMs		Agree biological-SI for qSAR internationally
	Reference materials for mass spectrometry imaging (MSI)	Define protocol for lateral resolution inter-laboratory study	Single modality lateral resolution test device for MSI		Interlaboratory multimodal evaluation of single lateral resolution test device		Traceable bio-MSI reference standard 20 nm – 50 µm

Quantum electrical metrology

The 2019 redefinition of the SI units linked the definition of three electrical units, ampere, volt and ohm, to the fixed values of fundamental constants *e* the elementary charge and *h* the Planck constant. While the volt and ohm are realised by the quantum Hall effect and the Josephson effect, respectively, the ampere does not have practical methods of realisation. The development of primary ampere standards by single-electron transfer would enable the quantum metrological triangle experiment, which would test the consistency of three electrical standards, and would form the basis of a robust system of electrical metrology. Expanding the areas of application of primary electrical standards, such as higher frequency, higher temperature and smaller signal level, would enable and improve the traceability of electrical measurements in more situations, including networked sensing, space applications or cryogenic electronics.

NPL is also carrying out research on local primary standards that can be used outside NMIs. This includes on the factory floor, on space satellites and in applications which require transporting equipment from site to site. They may not require the ultimate accuracies that NMI primary standards offer, so relaxations in their operating conditions (cryogenic temperature, vibration and size) may be possible. This roadmap develops the essential metrology for future local quantum current, Josephson voltage and Quantum Hall resistance primary standards operating at 77 K. In the longer term we also aim to create single-electron pumps that can achieve a current > 100 nA with 0.001 ppm accuracy.

NPL recognises that the field of quantum electrical metrology has been developed and maintained through international collaborations and continues to do so. Overcoming the challenges identified in this roadmap will require collaboration with other NMIs and research institutes. NPL will continue to contribute to international collaborative efforts in the development of this field and will strive to play a leading role in this community.

Glossary

HOM	Hong-Ou-Mandel (two-particle interaction effect)
MZI	Mach-Zehnder interferometer (single-particle interferometry)
PJVS	Programmable Josephson voltage standard

“I joined NPL to make an impact on RF and microwave metrology. NPL, as the leading metrology institute in the world with its influence on the future of metrology, provides me with a unique opportunity to grow my career in RF and microwave metrology. It is amazing to work in a very helpful and creative team on highly challenging national and international projects using world-class facilities.”

Murat Celep
Senior Research Scientist
Electromagnetic Measurements

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Science of single-particle technologies	Single-electron pump	Multiplexed single-electron pumps	Achieve 1 nA current	Achieve 0.1 ppm accuracy with 1 nA current.	Perform Quantum metrological triangle experiments with 0.1 ppm accuracy	Scaling up pump current to 10 nA with 0.01 ppm accuracy	Performing Quantum metrological triangle experiments with 0.01 ppm accuracy
	Interferometry	Emission control and detection of single/multiple electron excitations	Demonstration of single-electron MZI	Demonstration of HOM effect	GHz electric field sensing	GHz magnetic field sensing	Entangled particle interference
	Photonics	Two-dimensional lateral P-N junction	On-demand generation of multi-photon pulse		On-demand generation of single photon	Electron spin measurements	
Quantum electrical standards	Current	Blind-test protocol	Validating alternative Quantum current standard technologies		Demonstration of 1 nA 0.1 ppm Quantum current standard	International comparison at 1 nA Quantum current standard	10 nA 0.01 ppm Quantum current standard
	Voltage	Cryogen-free operation of DC Josephson voltage standard	Demonstration of 1 kHz 1 ppm AC Josephson voltage standard	Demonstration of pulse-driven Josephson voltage standard	Demonstration of 1 MHz 1 ppm AC Josephson voltage standard	AC Josephson voltage standard international comparison	GHz voltage waveform at 1000 ppm
	Resistance	Cryogen-free cryogenic current comparator	Table-top Quantum Hall resistance + Cryogenic current comparator	High turn ratio cryogenic current comparator			
Dissemination	Primary electrical standards in measurement service	Table-top Quantum Hall resistance primary standard	Cryogen-free table-top Quantum Hall resistance + Cryogenic current comparator	Cryogen-free 1 kHz AC Josephson voltage standard	Cryogen-free high turn ratio cryogenic current comparator	Cryogen-free 1 MHz AC Josephson voltage standard, 0.1 ppm integrated Quantum metrological triangle	

Quantum clocks, sensors and communications

This Roadmap reflects NPL's role in supporting the priorities of the National Quantum Technology Programme and addressing related national challenges in resilience, energy and space. It is organised according to the main themes of the National Quantum Technologies Programme: timing, sensing, imaging, and communications.

The atomic clock is historically the first quantum 2.0 technology relying on superposition of quantum states and is also the most mature and impactful. The main challenges addressed by this Roadmap are miniaturisation and portability of the optical and microwave clocks alongside their enabling infrastructure, such as frequency combs and ultra-stable cavities.

Quantum communications is another rapidly maturing technology. For example, quantum key distribution (QKD) and quantum random number generators (QRNGs) have matured to the point where commercial products are now available. NPL has developed a suite of measurement capabilities to characterise single-photon sources and detectors, as well as components used in specific implementations of QKD. The Roadmap reflects progress towards characterisation at the system level and more sophisticated quantum protocols. In addition, test and measurement capability will be developed to support the UK's 5G telecommunications infrastructure, and its successor, 6G. The main challenges will be the exploitation of broader bandwidths and higher (i.e. terahertz) frequencies.

Quantum sensors is a broad field which emerges to exploit a variety of quantum effects. NPL research on sensing will be focusing on detection of various physical fields, position and orientation, as well as trace gas detectors. These technologies will benefit from NPL's long-standing expertise in frequency stabilised lasers, atomic interferometry, scalable ion traps and solid-state quantum technologies.

Glossary

AOAC	All optical atom chips;
BEC	Bose-Einstein condensate
HCF	Hollow-core fibre;
MIR	mid infrared;
NICE-OHMS	Noise immune cavity enhanced optical heterodyne molecular spectroscopy
QKD	Quantum key distribution
QRNG	Quantum random number generation
SPDC	Spontaneous parametric down-conversion
SQUID	Superconducting quantum interference device

"After almost a decade working at NPL, I have yet to repeat one day. Every day has something new to it, making the experience of working at NPL so dynamic that it is always an exciting new challenge."

Héctor Corte-León
Senior Research Scientist
Quantum Materials and Sensors

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Clocks	Compact clocks		Compact Yb+ microwave physics package	Transportable Yb+ microwave clock, target accuracy 10^{-14}; trapped ion space optical clock; mini fountains	Compact optical clock demonstration, target accuracy 5 x 10^{-18}	Microwave ion clock demonstrator in harsh environment	Portable optical ion clock with integrated microcomb - performance verified in international comparison
	Clock components	Octave spanning microcombs; UK laser supply chains	Self-referenced microcomb; NPL cavity TRL6	Cubic cavity in orbit demonstrator; pump laser/ comb on same chip	Co-ordinate with large scale space integrator for space clocks /cavities	Cubic cavity on next generation gravity mission.	
Sensing	Field sensors	Scanning NV magnetometry ($< 1\ \mu T/\sqrt{Hz}$ with < 50 nm resolution) and nanoscale thermometry	Nano-SQUID microwave receivers for fundamental physics (axion dark matter $<10^{-23}$ W, neutrino mass cyclotron frequency of single electron at 27 GHz to 1 ppm)	Heisenberg-limited spectroscopy in NPL ion microtraps	Quantum measurement with entangled ions: 10^{-18} stability, 100 times faster than a single ion		Chip-based field sensors at 10^{-18} (B, E, gravity)
	Gas sensors	IR NICE-OHMS/ hollow core fibre laser stability	Transportable & MIR NICE-OHMS	Field deployable; drone based hollow core fibre	Dual microcomb prototype; hollow core fibre for space	MIR commercial NICE-OHMS	Dual microcomb commercial unit
	Rotation sensors / atom interferometers	Optical rib waveguide; Rb chip magneto-optical trap	AOAC cold atom in waveguide; Bragg BS; Rb gravimeter	Michelson AOAC; BEC absolute gravimeter	Mach-Zehnder AOAC & tests; U-shaped MZ; min. rel. gravimeter	Sagnac AOAC and miniaturisation of all systems	Arrays of AOAC for navigation; gravity imaging & quantum computing
Communications	Quantum technologies	Discrete Variable components testing, QRNG test methodology	Authentication of device-dependent optical QRNG, service to characterise single-photon sources and detectors	UK fibre QKD test facility (joint facility); Combined quantum services, e.g. quantum-secured time signals	UK satellite QKD test facility (joint facility), UK randomness beacon	Testing secure communication protocols based on entanglement	Testing new applications (e.g. based on entanglement distribution)
	5G / 6G technologies	Passive and active load-pull metrology. Millimetre-wave antenna testing for 5G protocols (in accordance with 3GPP).	Establish fully equipped facilities for testing 5G OTA, electronic and photonic systems.	Extend OTA MIMO facilities to provide full mm-wave coverage for 5G+.	Extension of other active devices to provide full mm-wave waveform coverage for 5G+	Launch THz comms capabilities using both photonics and electronics platforms for 6G protocols (in accordance with ITU-R).	Refurbish facilities to coincide with roll out of national 6G networks. Traceability to quantum references.

Quantum computing

Quantum computing (QC) has the potential to unlock unprecedented parallel processing, creating a step change in computing power. By harnessing and exploiting this capability the UK has an ambition to become the world's first quantum-ready nation. NPL helps realise this ambitious goal by working with partners in the National Quantum Technology Programme, in particular the Quantum Computing and Simulation Hub and the newly established National Quantum Computing Centre (NQCC).

The NPL Metrology Roadmap for quantum computing closely aligns with the NQCC technology Roadmap. The initial focus will be on superconducting and trapped ion qubit platforms as these are currently the most mature. NPL has built expertise in software and hardware testing of quantum devices over many years. At this stage NPL will play a major role in the development of metrics and benchmarks for quantum processors, understanding and mitigation for noise and decoherence in quantum circuits, analysis of quantum materials and fabrication processes, calibration of microwave cryo-electronics and integrated optics supporting the growth in scale of quantum processors. As the technology matures from the present 'noisy intermediate scale quantum' (NISQ) stage through Quantum Advantage towards universal fault tolerant quantum computing, the demand from the wider economy for complex independent test and evaluation is also expected to increase. This evolution requires development of metrology for complex quantum systems at the physical, logical and application levels.

The Roadmap also describes the metrology support for alternative computing and low-loss electronics. While strictly speaking not quantum computing *per se*, alternative computing paradigms, such as neuromorphic architectures inspired by the human brain, also offer significant parallelisation of information processing and energy efficiency, particularly when implemented on spintronics platforms. This strand is aligned with relevant parts of the Royce Institute Roadmap 'Materials for the Energy Transition'. There is a need to develop methods for validation and testing of technology, and in particular benchmarking different materials, devices and architectures with respect to specific figures of merit. We will build on our recognised expertise in nanomagnetism and materials characterisation from atomic to macroscopic scale.

Glossary

HW or SW	Hardware or software
IOD	In-orbit demonstrator
LLE	Low-loss electronics
NISQ	Noisy intermediate-scale quantum
SC	Superconducting
TBC	Testing, benchmarking & calibration
T&E	Test and evaluation

"I like working at NPL as it allows me to work with many bright scientists and engineers. It closely resembles my past research career at Cambridge University. I'm allowed to be creative and find solutions to complex problems often at short notice. One such example was to develop GHz electronics to assist in the integrity of Quantum Key Distribution as used in secure communications."

Pravin Patel
Senior Research Engineer
Instruments and Engineering

		Time					
Theme	**Sub-theme**	**2021**	**2023**	**2025**	**2027**	**2029**	**2031**
Computing	Superconducting circuits	Metrology of cryo RF components at mK temperature; microwave power meter, paramp modelling and testing	Advanced measurement capability for SC qubits (up to 5)	T&E services for NISQ processors	Multi-qubit metrology & integration of SW and HW for benchmarking quantum processors	Dual and complementary SC electronics	T&E services for QC subsystems, integrated with SW and HW standards
	Ion microtrap	Testbed for microtrap system subcomponents	Hi-Fidelity entanglement (2 qubits)	Hi-Fidelity entanglement (multiple qubits)		Testbed for microtrap devices and QC metrics	
	Quantum software	TBC of small-scale noisy intermediate scale NISQ computers.	ML based automated TBC for 50-100 qubit noisy intermediate scale QC			Explainable & trustworthy ML TBC for 100+ qubit NISQ computers, & for fault tolerant devices with few logical qubits	Explainable & trustworthy ML based automated TBC for large scale logical-qubit fault tolerant devices
	Low-loss	Topological magnetic phases for LLE with skyrmions and artificial spin ice.	Testbed for magnetic measurements for neuromorphic computing	Energy efficiency and performance of antiferromagnetic memory and logic (<0.18 pJ/bit)	Methods for imaging energy dissipation in operating nanoscale devices	Energy efficiency and performance of probabilistic and neuromorphic computing (<10 fJ/bit, 10^6 neurons and synapses)	T&E services for spin-based LLE
Materials for quantum technologies		Basic T&E services for quantum materials	Quantitative microscopy of deterministic atomic defects for qubits	Hyperspectral functional imaging at the atomic / meso / macro scale	Instrumentation for coherent nanoscale characterisation of SC quantum processors; quantum scanning probe microscope	ML algorithms for multiscale, hyperspectral functional imaging	Advanced automated T&E services for quantum materials

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"I love working at NPL because of the brilliant diversity and culture that resonates throughout the staff. There are so many rewarding aspects to being a scientist at NPL, but the one that stands out above all is knowing what a massive impact the work we are doing is making around the world!"

Katie Obee
Junior Science Apprentice
Dimensional Metrology

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