NPL National Physical Laboratory

Metrology for the 2020s

This Vision for Metrology in the 2020s was developed by scientists working at NPL.

The lead authors were:

Kamal Hossain, Martin Milton, Bill Nimmo

Supported by contributions from:

Michael Adeogun, Neil Campbell, Markys Cain, Jason Crain, Alistair Forbes, Nigel Fox, Mark Gee, Patrick Gill, Ian Gilmore, Neil Harrison, JT Janssen, Steven Judge, Andrew Lewis, Graham Machin, David Nettleton, Ian Robinson, Bryan Roebuck, Max Ryadnov, Alex Shard, Graham Sims, Graham Topley, Graham Torr, Alan Turnbull, Jonathan Williams, Bajram Zeqiri.

Production and design:

Fiona Auty, the NPL Graphics Team

May 2013

National Physical Laboratory

Hampton Road
Teddington
Middlesex
TW11 0LW

Switchboard 020 8977 3222
www.npl.co.uk/contact

The National Physical Laboratory is operated on behalf of the National Measurement Office by NPL Management Limited, a wholly owned subsidiary of Serco Group plc

Metrology for the 2020s

Foreword from the Managing Director

I am delighted to present NPL's Vision for Metrology in the 2020s to you.

It is difficult to predict the future - who would have realised that the atomic clock, first built at NPL in 1955, would play such a critical part in our everyday lives providing timing for GPS, mobile phones and the internet?

Ever since NPL was established in 1900, we have sought to provide the measurement capability that underpins the UK's prosperity and quality of life. This is why we continue to develop our work on time – with our atomic clock now accurate to one second in 158 million years – and are leading the commercialisation of new materials such as graphene.

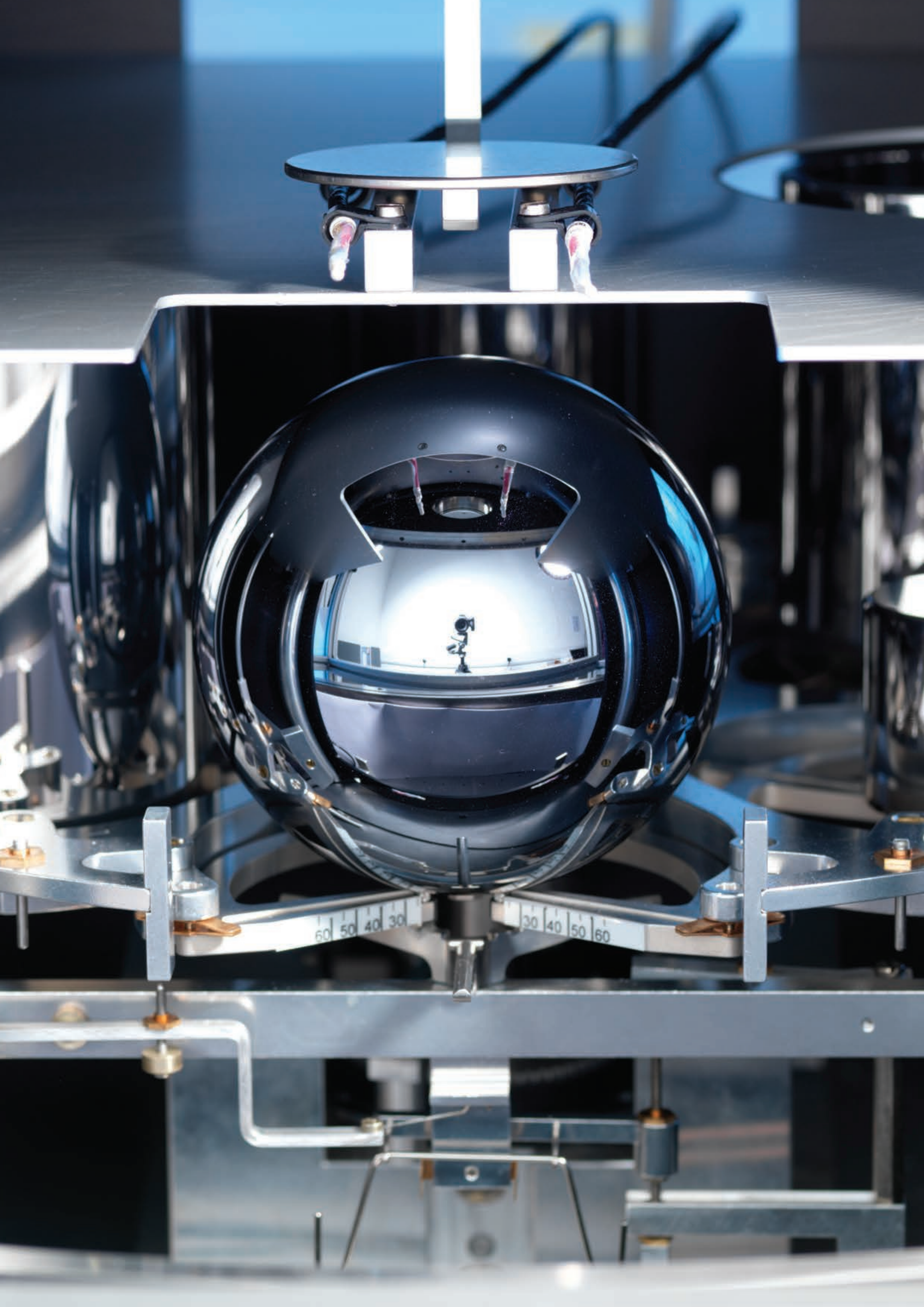
Our vision is based upon discussions amongst NPL's scientists and our partners in government, academia and industry, both within the UK and internationally, about where we expect our capabilities and knowledge base will take us in the future. It reflects our view about how innovation and invention will advance and it captures our excitement about what we believe metrology will be able to achieve in the 2020s.

We hope that this document will motivate discussions with colleagues, stakeholders and customers.

In the future this document and your comments will help cement the requirements for new capabilities and inform our roadmaps and strategies.

Dr Brian Bowsher

Managing Director


60 50 40 30
30 40 50 60

The future of metrology

We believe that technological progress in the 2020s will be driven and constrained by the need to achieve:

- a sustainable low-carbon economy
- scientific discovery, innovation and R&D intensive growth
- the well-being and security of the citizen

Meeting these needs will demand continued evolution as well as step-changes in metrological science and its application.

These will require developments in the whole measurement infrastructure, which involves a 'supply chain' including:

- National Metrology Institutes (NMIs) and their associated government funding agencies
- equipment and device suppliers
- standards bodies
- calibration and service providers
- universities and academic users
- industrial and regulatory stakeholders

The rate of change in metrology is driven by the need to sustain the performance of measurement standards at a level that supports users and is able to stay ahead of their requirements.

Why do we need metrology?

Metrology plays a fundamental part in sustaining a fair, efficient and technological society. To develop new products, services and processes, companies need to measure quantity, quality and performance. To trade successfully, companies utilise a regulatory framework, based upon measurement confidence, ensuring access to global markets that are fair and open and without unnecessary barriers to trade. Supporting this is an established infrastructure of traceable measurement linked seamlessly to internationally recognised standards.

"When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of meagre and unsatisfactory kind."

Lord Kelvin, Scientist 1824 - 1907

"Measurement provides structure, removes chaos, reduces waste, ensures open and fair markets, supports precision where required and saves lives, money and time."

Measurement Matters, UK National Measurement Office 2011

Shaping our vision

This vision for metrology in the 2020s has been developed by scientists at NPL, many of whom are world-leading in their fields. Their work with academics and industry gives them experience of current metrology capabilities and future requirements. In the generation of this vision, they have brought together:

- An understanding of the state of the art in the different areas of metrology and the potential for further advances.
- Projections of the technologies that will be available in that decade and an understanding of how these will enable metrology.
- The needs and expectations of end users and how these will develop as new metrology capability becomes available.
- An assessment of the interactions between the above and the metrology supply chain from the SI units through to metrology systems.

This vision is also based on the strong expectation that several important developments affecting metrology will have taken place by the 2020s, including:

- The redefinition of the SI, which will require new dissemination methods.
- Maturation of currently emerging sensor technologies - the availability of cost-effective sensors based on quantum, bio and nanotechnologies.
- Increased computing power and capability - analysis techniques and new paradigms to cope with large amounts of data and images from different sources.
- Increased adoption of multi-scale, multi-physics modelling and simulation, supported by validated data.
- More demanding end user needs and expectations for on-line and networked services.

Our vision for metrology

NPL's mission is "to provide the measurement capability that underpins the UK's prosperity and quality of life". Our vision is that metrology will develop in the 2020s within a framework defined by the four themes summarised below.

Theme 1 **The new quantum SI**

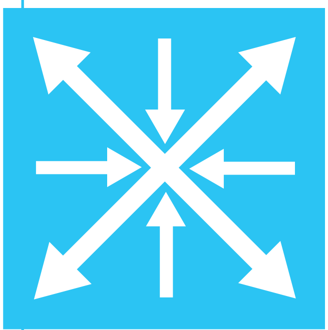
At the heart of the traceability of measurement results provided by NMIs is an unbroken series of links to the definitions of the base units. As a result of the introduction of The New Quantum SI, several of the base units will be significantly **revised and redefined** to remove the remaining physical artefacts and to take advantage of advances in quantum metrology by fixing the values of a set of carefully chosen physical and atomic constants. This will provide new opportunities to:

- Realise the base units much closer to their point of use to allow substantially shorter traceability chains.
- Support research at the frontiers of scientific and technological development.
- Provide a stable platform for progress on fundamental studies such as tests of the laws and constants of physics.

Theme 2 **Measurement at the frontiers**

Advances in science and technology push at the frontiers of what is possible for metrology. This drives the need for new capabilities to make measurements that are **beyond the boundaries** of today's measurement capability. For example:

- At a range of length scales from the atomic to the very large.
- Measuring properties and characterising behaviour at timescales ranging from attoseconds to millennia.
- In complex and harsh environments and in real-world applications.
- In the presence of interference and in rapidly changing environments.



Theme 3 **Smart and interconnected measurement**

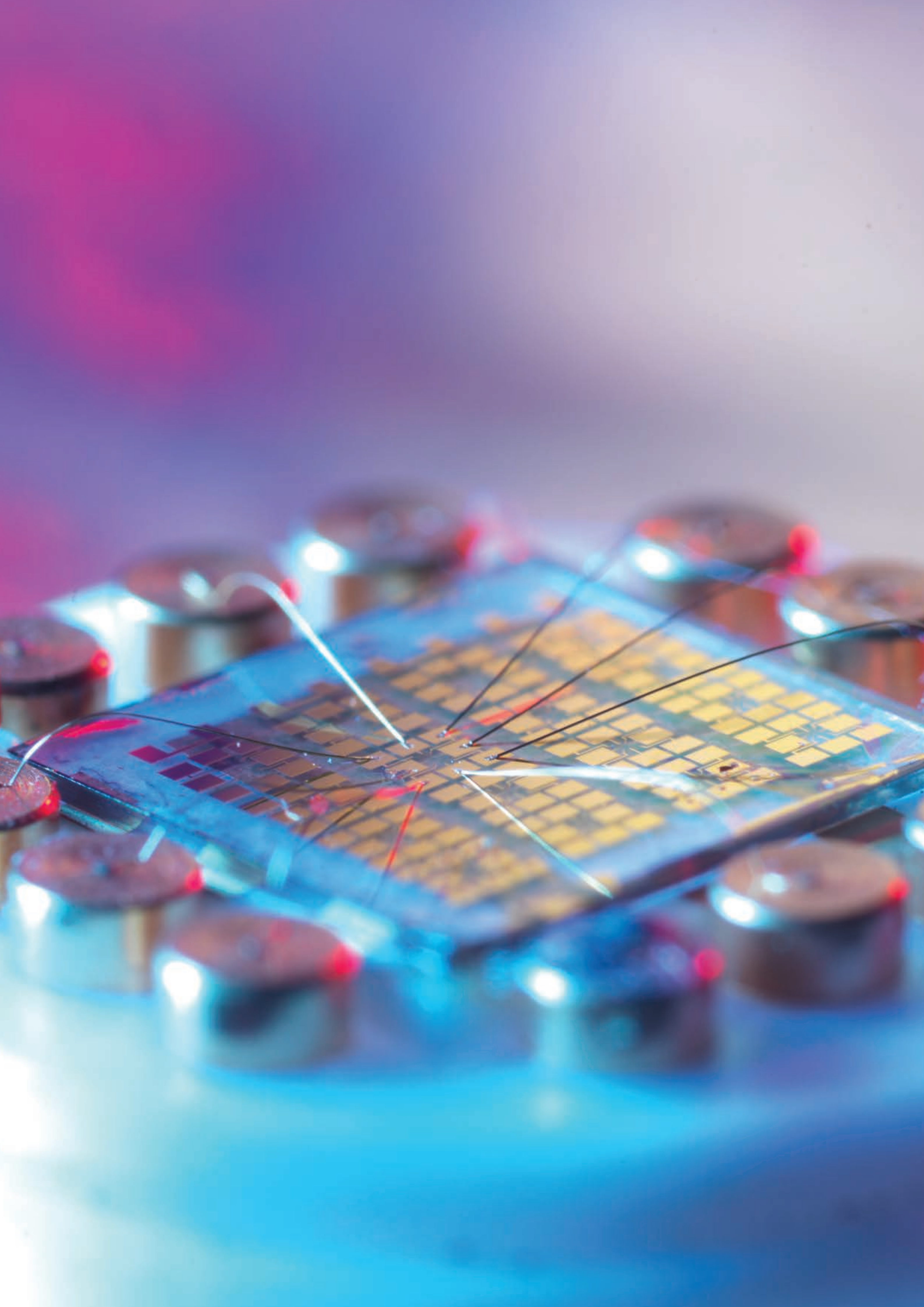
The deployment of large-scale multi-sensor, multi-measurand and multi-node systems will exploit the availability of networked information and make use of the **'internet of things'**, in which physical objects are integrated seamlessly into the global information network. It will be:

- Enabled by new capabilities in computing, software and communication technologies.
- Driven by developments in sensors based on quantum, bio and nanotechnologies integrated into measurement networks.
- Interconnected – using large numbers of sensors of different types and integrating data from different systems.
- Smart – achieving calibration across networks by fusion of data leading to a new interpretation of traceability throughout a system.

Theme 4 **Embedded and ubiquitous measurement**

Metrology capability will be embedded at the heart of products and systems exemplifying **technological convergence**, (the trend for technology-driven systems to evolve to perform similar tasks). As a result:

- Critical measurement systems will be 'always on' and 'always calibrated' in real time.
- Metrology will be embedded into machines and instruments at the design stage and accessible as part of their functionality.
- New approaches to delivery will give access to traceability directly at the point of measurement so that end users can 'build metrology' into processes, products and services.



What metrology can achieve in the 2020s - six portraits

Metrology in the 2020s will play a key role in meeting the socio-economic and scientific challenges faced by our society.

These challenges can be summarised by the need to achieve:

- a sustainable low-carbon economy
- scientific discovery, innovation and R&D intensive growth
- the well-being and security of the citizen

To show how our vision will be realised, we provide six portraits of what metrology can achieve in the 2020s.

A sustainable low-carbon economy

- monitoring the state of the planet
- energy efficiency and diversity of supply

Scientific discovery, innovation and R&D intensive growth

- the future factory
- big science

The well-being and security of the citizen

- a healthy population
- managing key resources and infrastructure

These portraits illustrate how metrology will address the challenges of the 2020s and include examples of how the four themes in our vision for metrology in the 2020s will have impact.

Monitoring the state of the planet

Our need to monitor the state of the planet will continue to drive requirements for widely-dispersed and long-term stable measurements of climate variables and the environment. A validated earth monitoring system, stable over centennial timescales, will be formed to enable: the linking of cause and effect; management of climate change through actions taken on all scales from local to global; and the prediction and avoidance of tipping points.

Monitoring essential climate variables

Global monitoring of the earth's climate system will focus on the 'Essential Climate Variables' that define the key measurands for the atmosphere, land and ocean. These will be fully SI traceable at location and time of sampling (e.g. temperature, moisture, reflectance, emittance and transmittance utilising the full electromagnetic spectrum at all spatial and temporal scales, including observations from space and *in situ*).

- The relevance of earth observation to global issues will be increased by the availability of environmental data with linkages to decision-support tools. The widest acceptance of such data will be achieved when they are underpinned by SI traceability.
- Specialised satellites will perform benchmark measurements for decadal climate studies and serve as high-accuracy calibration references to underpin other earth observation platforms.

Monitoring mitigation strategies

Embracing a low-carbon economy will require valid data about the performance of mitigation strategies.

- Emissions trading will be underpinned by traceable measurements and compliance with emission targets for carbon dioxide and other greenhouse gases will be ensured.
- Sensitive long-term methods will measure the integrity of facilities used to capture and store carbon dioxide, including low-level leak detection.
- Satellite observations will be validated and deployed around the world for quantification of estimates of carbon sequestered by natural sinks including forests.
- Proposal for international geoengineering projects will require transparent risk analysis based on globally accepted data.

Monitoring the global environment

Autonomous, self-calibrating and self-validating networks of sensors will be deployed to measure atmospheric and ocean composition as well as land and sea temperature.

- Personal exposure to chemical pollutants in urban and indoor air will be monitored in real time, with an emphasis on accurate values for agents posing short- and long-term health risks. Personal exposure to emissions will be monitored with networked personal wireless devices to ensure the safety of the population.
- Statistical models will be capable of trend analysis exploiting spatio-temporal correlation in data and will support the validation of environmental monitoring networks.
- Data fusion will be possible across multi-modal sensor networks (for example, acoustic, electro-chemical and earth observation).
- Traceable measurement of key soil parameters will be made to assess the effect of climate change and the importance of soil as a carbon sink.

Examples of metrology in the 2020s applied to
Monitoring the state of the planet

The new quantum SI	Direct traceability for Earth observation systems at uncertainties of 0.01% for incoming and 0.3% for reflected radiation to enable detection of decadal climate change.
Measurements at the frontiers	Sensitive and accurate methods developed to measure the long-term integrity of carbon capture and storage facilities, for example by monitoring carbon dioxide at ambient levels with ppb accuracy.
Smart and interconnected measurement	Networks of self-calibrating sensors monitoring chemical species in the atmosphere. Such networks will make use of new mathematical strategies that exploit the 'internet of things' to provide real-time data verification and quality assurance.
Embedded and ubiquitous measurement	Traceable environmental data publicly accessible in real time from sensors embedded in vehicles and mobile devices. For example, providing data for citizens to minimise their personal exposure.

Energy efficiency and diversity of supply

Ambitious targets to reduce carbon emissions, together with the need to maintain security of supply, are setting enormous challenges to every sector of energy generation, supply, use and regulation. The solutions will involve diversification, improved efficiency and an emphasis on sustainability. Metrology will, by ensuring the reliability, performance and benefits of the innovation in the energy infrastructures, systems, and technologies, give confidence in the investment decisions necessary to bring about a step-change in security of supply and consumption.

Diversified power generation

New methods for materials characterisation, performance evaluation and systems management will facilitate the introduction of novel power generation technologies.

- Materials performance will be measured in extreme operating conditions, for example, those encountered by offshore wind and wave energy generation projects.
- Novel measurement capability will facilitate the management of load and sustain power quality in a decentralised integrated set of networks enabling optimisation at local, national and international scales.
- Better characterisation and simulation of the durability of fusion containment materials under the influence of high energy neutron bombardment will require plasma temperature characterisation.
- Traceable measurement will be needed for the key parameters associated with new generation fission power plants, in the area of materials, temperature and neutron fluence.

Intelligent and efficient transport systems

Step changes in the efficiency of transport require intelligent control systems and the effective implementation of new materials technologies.

- Data fusion methods will link ambient measurements, traffic information and save live data enabling the use of automatic feedback control of transport networks.
- Measurement capability and new standards will be needed for purity, monitoring and metering, to support the hydrogen economy.
- New sensing methods for aero-engine hot-zone temperature measurement will allow optimum fuel efficiency and emissions control.
- Metrology will enable the design of ultra-low friction bearing surface materials, such as nano coatings for longer life.
- The characterisation of micro-nano scaled coatings over large areas will quantify improvements in aerodynamic efficiency.
- Metrology will support the development of a new generation of stronger and tougher lightweight materials that reduce fuel and total energy usage.

Towards a sustainable energy supply

The development of the energy economy will be informed by data from measurement standards for sustainability.

- Energy production and consumption standards will support policy setting that enables 'green' growth as a response to the current economic recession.
- Proving the technical and economic feasibility of Carbon Capture and Storage through better traceability of calculated emissions, direct measurement of mass emissions of carbon dioxide and metrology to prove the design, and standards to give confidence in the use of high pressure and large volume systems for storage and transport.
- New approaches will be needed to the quantification of the energy performance of building stock using non-contact techniques operating independently of surface emissivity.
- Characterisation of the spatial and temporal properties of ultra-high powered lasers will be needed for inertial-confinement fusion.
- Future upscaling of photovoltaic technologies will require accurate data on full lifetime net energy yields.

Examples of metrology in the 2020s applied to

Energy efficiency and diversity of supply

The new quantum SI	Dissemination of derived SI units providing improved confidence in performance data, enabling optimisation of the long-term performance of the global energy system.
Measurements at the frontiers	Structural health monitoring and analysis techniques that identify micro-scale and chemical changes, and give confidence in the integrity of structures.
Smart and interconnected measurement	Traceability of the computational science systems and validation of the protocols that enable critical disruptive decision making (for example, controlling traffic flow) in systems where the metrology and intelligence are one.
Embedded and ubiquitous measurement	Integrated calibration and checking of sensors in critical components in power and propulsion generation systems to minimise negative environmental effects.

The future factory

The future factory will be a smart facility where design and manufacture are integrated into a single engineering process that enables 'right first time' every time fabrication of bespoke products. Metrology will be used to assess and guarantee the fit, performance and functionality of every part and supporting the targets of zero waste and a carbon neutral outcome. Metrology will support the interconnection of these new factories to form an industrial base that is independent of the scale of production and combining R&D with production whilst achieving the lowest energy consumption and impact on the environment.

Smart design and on-demand manufacturing

Low waste and 'right first time' prototyping will require validated data and modelling methods.

- SI traceable measurements for intelligent design of products will match human perceptual demands, coupled with sensors deployed in manufacturing to ensure production quality is achieved.
- Application-specific engineering materials will enable major improvements in durability through measurement-inspired micro-structural design of materials and surfaces.
- Automated self-scan systems will enable reverse engineering of critical components such that 3D CAD data are automatically generated and fed to machining centred or 3D print systems for automatic manufacture.
- Surface engineering will assess the durability and performance of surface coatings and treatments designed for control of wear and reduction of friction such as low-friction carbon coatings and nanostructured surfaces.
- 3D chemical and structural analysis will provide performance data for the use of organic electronics in displays, photovoltaics and multi-layer films.

Waste and energy reduction

The future of manufacturing will be based on reduced energy consumption and waste.

- New metrology tools will help understand local reaction kinetics and rates of mass transport enabling the development of low carbon chemistries to improve the energy efficiency and carbon footprint in the manufacture of large-scale assets.
- Reduced scrap rates will result from the use of 'virtual tools', used to predict machine performance in manufacturing processes and to inform designers.
- Real-time sorting of waste streams will be based on smart composition detection and be achieved using sensing methods with in-situ calibration.
- Emerging pollutants and other emission products from recycling processes will be monitored automatically.

Processing and production

Metrology assisted manufacture and assembly will become reality. This will enable production to be accurately focused on user requirements.

- Whole-factory sensor technology (for example, indoor GPS and metrology-assisted robotics) will allow fully automated, deterministic manufacture and assembly.
- Machine tools will calibrate themselves periodically and be used as in-situ metrology devices.
- Metrology-assisted assembly will improve surface-to-surface jointing and overall structural accuracy.
- Compact interferometer systems using diode lasers locked to quantum standards will be built into machines providing accurate and traceable metrology on the shop floor.
- Quantification of chemical engineering parameters with in-situ traceable sensors will support bio-processing and bio-reactor plants.
- On-line monitoring of surface chemistry during production will optimise yields in roll-to-roll processing.

Examples of metrology in the 2020s applied to

The future factory

The new quantum SI	The 'quantum shop floor'. Small, low cost interferometer systems using diode lasers locked to quantum standards embedded in machines providing 'NMI accuracy' and traceable metrology on the shop floor.
Measurements at the frontiers	On-line tools for rapid and large area (>100 cm^2) assessment (>20 m/min) of thickness, structure, composition, activity and defect detection during processing. 3D chemical imaging of soft materials to quantify the interaction of products and devices on skin and hair.
Smart and interconnected measurement	Machine tools that calibrate themselves with traceability to the SI and which can be used as *in-situ* metrology devices. Distributed self-calibrating temperature sensors enabling continuous optimum process control.
Embedded and ubiquitous measurement	Machine tools with absolute distance measuring capability, coupled with whole-factory sensor technology. Factories inter-connected producing parts in parallel controlled from the customer's design department.

Big science

Measurement science faces some of its most exacting challenges in making measurements at the frontiers of science and technology to deliver society's most ambitious 'big science' projects. Metrology will be essential to the successful delivery of the outcomes of large scale or high investment scientific R&D by providing measurement capabilities to monitor and design systems, and validate the results.

The laws of physics can be tested using atomic clocks in space that take advantage of variable gravitational fields, larger distances, higher velocities and lower accelerations. For example, a grand unified theory combining the standard model of particle physics and gravity should lead to violations of the underlying separate theories.

- The Einstein Equivalence Principle (EEP), the basis behind our understanding of the curvature of space and time. Violations of EEP should be observable through tests of relativity theory with high-accuracy clocks.
- Special relativity can be challenged by studying time dilation and the independence of the speed of light with the velocity of the source. (The latter can be investigated by comparing very stable laser frequencies against an optical clock as a function of changes in the direction of the laser axis.)
- General Relativity including the universality of the gravitational red shift. This can be monitored by comparing the frequencies of atomic clocks in different gravitational potentials.
- Quantum mechanics. Experiments can determine whether there is a preferred direction for quantum mechanics and observe the collapse of the wave packet.

Exploring the universe will require access to highly-precise measurements.

- Synchronisation of telescope elements in large telescope arrays (for example, the Square Kilometer Array) and instrumentation in particle accelerators using accurate time signals from atomic clocks.
- Ultra-stable interferometry for the Laser Interferometer Space Antenna (LISA) and other gravitational wave observatories capable of measuring, for example, micro-radian phase shifts (picometre changes to 5 million km interferometer arm lengths) to achieve strain sensitivity of parts in 10^{21}.
- Recalibration of the universe length scale by linking astrophysical photometric based standards (for example, Vega) to known ultra-precise radiometric standards (for example, known high temperature fixed points). This would enable closer constraints for the cosmological constant and astrophysical based determinations of the fine structure constant.

The wave-like nature of matter leads to properties not observed in the classical world and many new disruptive technologies are being developed under the common term 'Quantum Information Processing and Communication' (QIPC). At the same time quantum physics allows for measurement precision that goes beyond that allowed by classical methods. Other behaviour in the quantum domain that will lead to new applications including spin transport electronics or 'spintronics'.

- Self-calibrating quantum devices using triggered entangled photons and true single-photon sources providing a new foundation for absolute photometric metrology.
- The fundamental properties of nano-magnetic systems will be harnessed, opening up spintronics as a new paradigm for information processing.
- Challenging the 'end of Moore's Law' will require the extension of nanometrology to address measures of size, material properties, speed, storage density and heat management to meet the continued drive towards ever more powerful computers.
- Relating atomic-scale processes to macroscopic observables remains a grand challenge in materials science, and metrology has a significant role to play in elucidating this, for example, in developing ab-initio models to characterise fundamental scaling limits of multi-functional materials.
- Quantum sensors and standards based on the counting of individual quanta photons, electrons, spin and phonons including, for example, the challenge to produce single electrons at the level of one part in 10^8 equivalent to the other two quantum electrical standards.

Examples of metrology in the 2020s applied to

Big science

The new quantum SI	Tests of the laws of physics based on high precision experimentation, for example, the determination of the rate of change of the fine-structure constant to better than parts in 10^{18} per year.
Measurements at the frontiers	Accurate navigation in deep space using clocks stable to better than parts in 10^{17} to ensure that high-cost mission reach their intended targets safely.
Smart and interconnected measurement	Through the use of single-photon measurement technologies enable quantum key distribution over existing fibre networks that will provide the ultimate in secure communications.
Embedded and ubiquitous measurement	A new generation of quantum electrical standards operating at room temperature will be integrated into high-performance calibration equipment and in large-scale scientific experiments.

A healthy population

Healthcare systems in the future will provide personalised medicine tailored to the needs, lifestyle and living environment of the individual that will increase well-being throughout their life using point of care diagnostics, better-targeted therapies, and 24/7 assessment of critical patient parameters and health indicators. New measurement techniques will be essential discovery tools that provide the knowledge that is critical to develop personalised diagnostics and therapies that are economically viable and clinically effective.

Point of care testing and diagnosis

Consistency and reliability of in-vitro measurements of diagnostics and biomarkers will be achievable, where needed to the SI, cascading down to robust and fit-for-purpose standardisation of point of care measurements.

- Sensitive and stable 'breath testing' will enable rapid diagnosis 'at home' of a range of disease states and will support a safe and independent lifestyle for the ageing population.
- Novel methods for traceable sub 100 µg mass and force measurement on aero gels and tissues will enable applications such as those required for precise drug-dose control, for example, self-controlled pain relief and long-term medical dosing, without hospital intervention.
- Rapid and accurate diagnostics will measure biomarkers for robust and detailed diagnosis, ideally at the point of care. Novel affinity reagents for diagnostics will overcome the limitations of antibody-based systems.

Synthetic and systems biology

Some of the greatest research challenges in the life sciences, with requirements for quantitative measurements and descriptions, will be in synthetic and systems biology.

- Traceable measurements of biomolecular structure in the cellular environment and with atomistic detail, correlating spectroscopy and imaging methods for their application to structure-function-activity determinations and the understanding of the origins and development of disease.
- Chemical characterisation at the single molecule level (in-singulo vs. in-multiplo) to understand 'molecular individualism' and the behaviour of complex molecules in bulk.
- Non-invasive imaging methods with high resolution that provide chemical and structural information on cells and tissues.

Advanced therapies and drug delivery

By the 2020s, radiotherapy treatments will become increasingly personalised and, when combined with novel drug delivery modalities, will form the basis for targeted therapies. Quantitative differential diagnostics and imaging, together with data provided by other monitoring modalities, will be used to track treatment progress.

- Novel therapeutic applications of non-ionising radiation, including the use of ultrasound and the targeted use of micro-bubbles, will continue to develop. To exploit the potential of such methods, treatment planning methods must be developed and validated, underpinned by advances in modelling, the knowledge of tissue properties, and accurate in-vivo and in-vitro dosimetry.
- The performance ex-vivo and in-vivo of biocompatible and biodegradable controlled release devices will be measured. This will lead to quantification of the dependence of their structural and interfacial profiles on specific cell and tissue responses.
- Accurate biological interaction data will be combined with new insights into ionisation and energy deposition at the nano- and micro-metre scale to support the increasing application of proton and light ion beams aimed at improving cancer survival rates.
- The performance of responsive and 'intelligent' implants (sub-cellular to tissue scales) will be measured, supporting their application to disruptive therapies (regenerative medicine scaffolds, cell transplants, molecular therapy vectors) and to supportive therapies (blood and skin substitutes).
- Improved tomographic methods for real-time temperature measurement will support active therapies such as focused ultrasound tumour ablation.
- Reference measurement methods and vector materials will support systemic use and clinical trials of gene transfer medicines. Quantitative methods will be required to measure the activity of vectors to support traceable gene and drug delivery.
- Three-dimensional dosimetry will enable per-patient dosing of targeted radionuclide and complex external-beam therapies.

Examples of metrology in the 2020s applied to

A healthy population

The new quantum SI	In vivo traceability to the SI will increase confidence in the measurement of critical parameters (temperature, blood pressure, blood glucose, bone density, etc.) that are key health indicators and predictors.
Measurements at the frontiers	Non-linear spectroscopies achieving label-free imaging with resolution down to 1 nm in fixed cells and 20 nm in living cells for the development of patient-specific therapies.
Smart and interconnected measurement	Calibrated diagnostic devices connected directly to knowledge databases and treatment plans to deliver therapeutic interventions.
Embedded and ubiquitous measurement	Accurate and reliable implantable multi-analyte sensors with operating lives of years rather than weeks.

Managing key resources and infrastructure

By 2025, the global population is expected to have grown to 8 billion; this, combined with a changing climate, growing consumerism and increasing energy demand, presents significant challenges for sustaining resources and extending the lifetime of infrastructure. Metrology will therefore support the transition to a sustainable economy by enabling the extension of the lifetime of infrastructure, validation of trading protocols for carbon, and monitoring of the status of key resources, such as soil and water.

Meeting our needs for food and water

The security and quality of water and food supplies is a growing issue for governments and industry, with estimates suggesting that by 2030, there will a 50 % increase in global demand for food. Despite this, up to 40 % of food harvested is presently lost in processing, storage and transport.

- Accurate instrumentation for monitoring and control of soil pollution and groundwater will reduce contamination of food and drinking water supplies.
- The modification of crop materials will produce 'functional foods' and 'nutraceuticals' that will require validation during the research and development phases against regulatory standards.
- Measurements to enable rational design and tuning of the microstructure of processed foods will reduce wastage and increase shelf life.
- Reduction of food waste will be facilitated by measurement of contamination in food, packing and the production environment, including microbial sensing and detection.
- Smart packaging will include measurement and sensing functions, such as moisture transport and temperature history, to enable the implementation of a safe 'fit to eat' system.

Sustainable resource management

As raw materials become increasingly scarce, particularly those needed for the manufacture of high-value added products such as electronic devices, the need to transition to a more sustainable use of material resources becomes essential.

- Improved recycling of strategically important materials will be facilitated by *in situ* identification and cleanliness assessment of secondary materials.
- The increased use of near-net shaping techniques through validated modelling of processes (such as additive manufacture) will reduce dependence on rare or depleted resources.
- Support for the technical aspects of standards will be required for life cycle analysis that can focus on the resources rather than individual products and services.

Infrastructure protection and lifetime maximisation

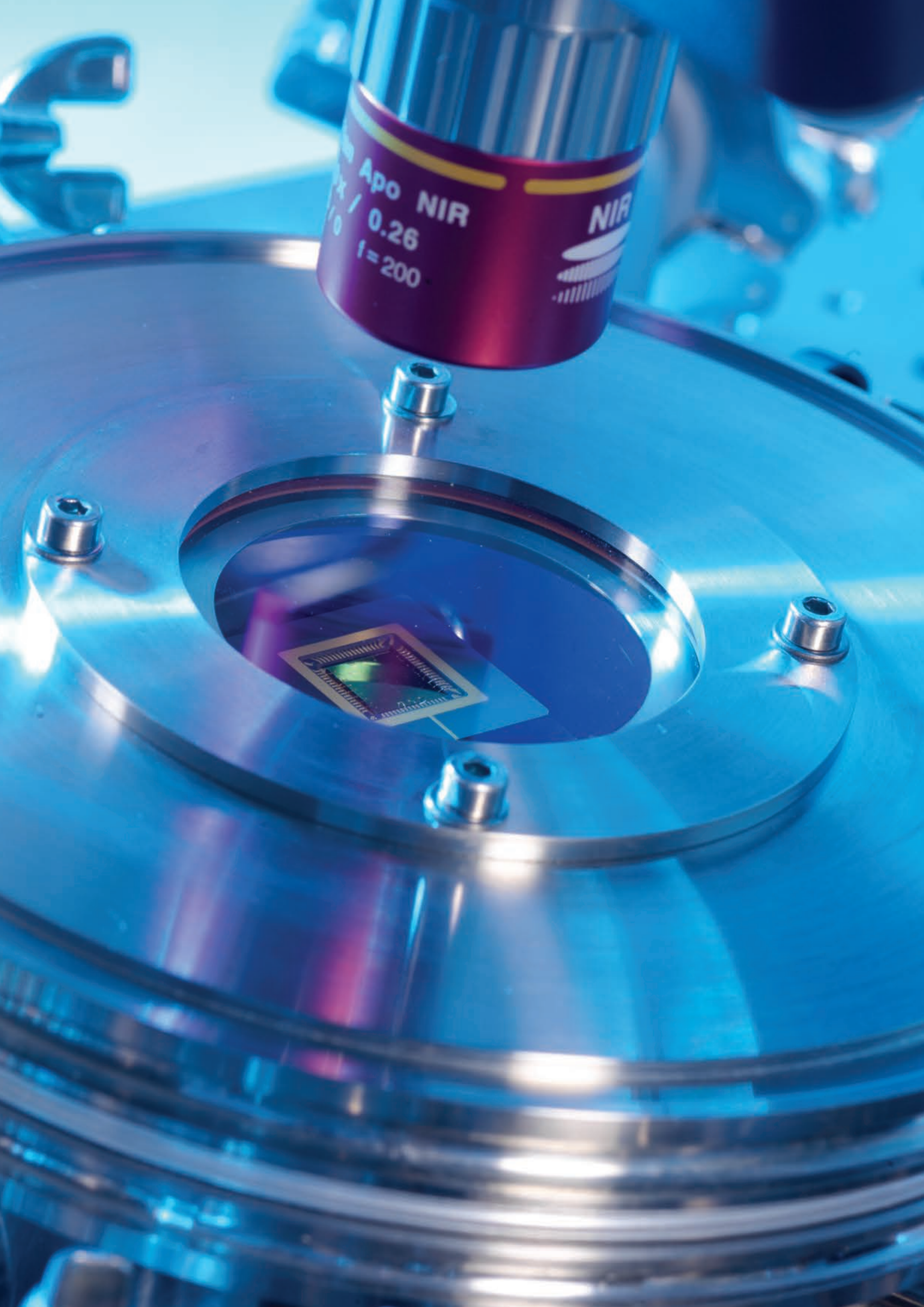
Transport infrastructure (including roads, railways, airports and ports), as well as the legacy building stock, will become increasingly costly to adapt and maintain. Innovative technology based solutions to these challenges will become increasingly attractive.

- Simulation and prediction of materials and structural performance will enable the integration of the design of material with the definition of the structure from fundamental principles.
- 3D nano and micro-structural assessment of materials integrated with modeling will allow the long-term integrity of infrastructure under aggressive conditions of wear, corrosion, fatigue and impact to be assessed.
- Structures will become 'intelligent' through the use of embedded micro-sensors providing real-time observations of integrity that will enable efficient maintenance and optimised lifetimes.
- An essential piece of infrastructure is the global information network, which will continue to need careful protection from cyber-attack. Such protection will rely on globally-agreed standards for cyber security.
- The structural integrity of critical industrial infrastructure (such as fission reactors, chemical plant and nuclear waste silos) will require long-term monitoring. For example, multiple dimensional measurements will monitor long-term deformation and changes due to seismic activity. Measurement capability will assess and monitor the performance of static and mobile wireless sensor networks *in situ*.
- Long-term temperature and environmental sensing will contribute to the monitoring of the health of nuclear waste stores. This will use drift free methods that are stable over centuries and need no recalibration.
- Validation methodologies based on ultra-low-level standards will be used to ensure the accuracy of systems used to detect nuclear material at borders and of detectors used for remote sensing of nuclear events.

Examples of metrology in the 2020s applied to

Managing key resources and infrastructure

The new quantum SI	Measurements of key resources that are traceable to the SI and can therefore be related to one another accurately despite being distributed around the world and made over different timescales.
Measurements at the frontiers	*In-situ* measurement of microstructural changes and complex hostile environments at high stresses and strain rates (10 GPa and 10^5 s^{-1}) enabling improved materials design.
Smart and interconnected measurement	Integration of measurements over wide areas of soil fertility, carbon content, biodiversity, water retention capacity, and contaminants with quality of water and air to mitigate the linked risk of food shortages and climate change.
Embedded and ubiquitous measurement	Microbial and temperature sensors in food packaging using remote data acquisition to accurately assess food quality and shelf life.


Apo NIR
0.26
f=200
NIR

Realising this vision

The development of the four themes presented in our vision for metrology in the 2020s will drive the convergence of laboratory measurements with *in situ* measurements and metrology will become more strongly connected to its applications. This will lead to fundamental changes in the way the research and capability developed at NMIs reaches users.

- NMIs will develop a new role as operators of national facilities that individual end-user organisations or service providers would have insufficient resources or technical capability to operate.
- Services delivered from NMIs will gradually be superseded by self-calibrating portable standards; facilitating *in situ* traceability. NMI services will become focused on providing support to end users that are seeking to achieve traceable measurements in difficult situations. This will involve a shift from a traditional 'traceability' based model towards a problem solving approach that will exploit the applied measurement know-how of staff.
- Many metrology 'products' will be derived from the assimilation of low-level sensor information into complex models. Metrological concepts will be extended so that traceability can be applied to the products of such models (taking into account their uncertainties) and not only the individual sensors.

The National Physical Laboratory

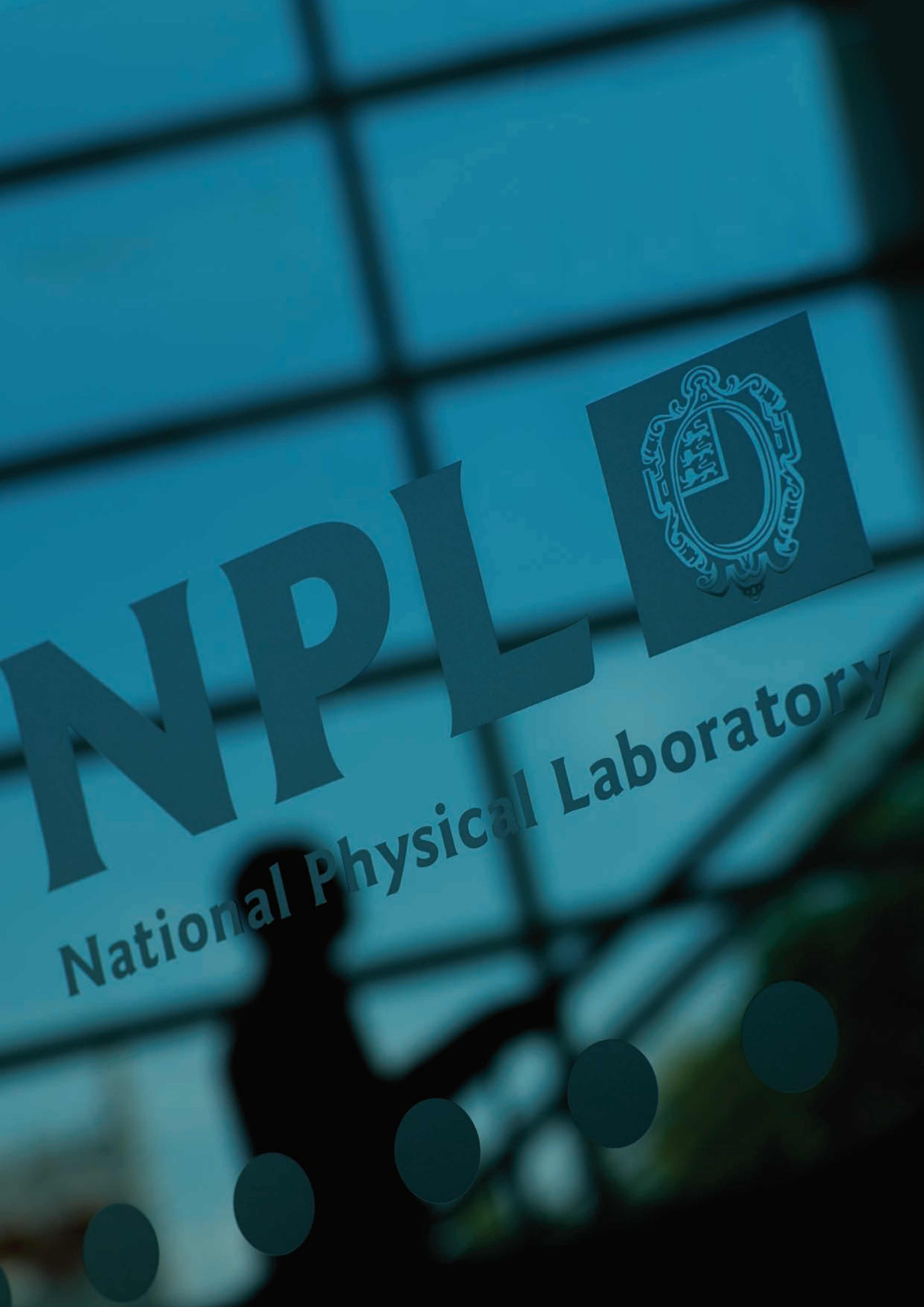
NPL's vision is to be a National Science and Technology Laboratory for Government and Business undertaking work in the national interest to deliver social and economic impact through world-class measurement science, innovative applied research and knowledge services.

This vision is inspired by NPL's mission and its NMI partners to make underpinning measurements and to provide the associated traceability that will support the UK, Europe and the world with these challenges in the 2020s.

For more than a century NPL has developed and maintained the nation's primary measurement standards as the UK's National Measurement Institute. These standards underpin the National Measurement System infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement.

Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and enabling companies to innovate. Support in areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all.

Our mission is to provide the measurement capability that underpins the UK's prosperity and quality of life.


NPL
National Physical Laboratory

10458/SEA/1K/0513