NPL
National Physical Laboratory

NPL's perspective on the future of metrology

2025 update of Technology and Measurement Foresighting

National Physical Laboratory (NPL)

NPL's perspective on the future of metrology

We are the UK's National Metrology Institute (NMI), a world-leading centre of excellence that provides cutting-edge measurement science, engineering and technology that underpins prosperity and quality of life in the UK.

Introduction from NPL’s Chief Scientist

NPL’s mission is to provide the measurement capability to underpin the UK’s prosperity and quality of life. How we do this evolves over time to support industry, research and new technologies in the most appropriate way. As the UK’s National Metrology Institute (NMI), we have a responsibility to ensure that emerging technologies are backed up by reliable measurements, so that decisions can be made based on accurate data, where we fully understand the provenance, timeliness and accuracy.

Our readiness depends on looking to the future and identifying key trends in science and society. These may be emerging or converging technologies, existing technologies used in new ways, or completely disruptive changes. NPL can then develop the metrological framework to enable research to develop into innovative products and services.

Foresighting has been part of the NPL landscape for nearly two decades, the most significant reports being: *Metrology for the 2020s* (published in 2013) and *Technology and Measurement Foresighting* (published in 2020). In addition, continuous horizon scanning is also conducted. We frequently convene and collaborate with world leaders in metrology to share our plans, consider developments from all over the world and achieve a consensus on future requirements for metrology that will enable global trade and a common approach to the most challenging technology problems.

Over the last few years, the speed of political, technological and environmental change has increased, which has impacted our metrology needs and solutions. The international metrology community has been working at pace, which has made it appropriate that we revisit and update the findings from our 2020 foresighting exercise. We are evolving the way we think about the future role of the NMI and metrology, and how we can best support industry, research and our society.

This report reviews the key challenges that metrologists are facing, recommends that all researchers need to have a “metrology mindset” and considers how the role of an NMI will evolve.

I hope our findings will motivate you to come and discuss your measurement challenges with us. NPL will be carrying out a new Foresighting exercise in 2026, and it is only by collaborating with our colleagues, customers and stakeholders from all over the world that we can deliver the measurement infrastructure which will support innovation and benefit all.

Prof. Jan-Theodoor (JT) Janssen FREng
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Metrology at a glance

Metrology, the science and application of measurement, develops internationally agreed reference points, so that measurements - from length or mass to radiation doses or biological activity - can be confidently and quantitatively compared. The role of metrology is to ensure that measurements are useful and accurate, providing the infrastructure that ensures we have confidence in data and the operation of technology. Metrology helps decision making, whereas measurement alone does not.

The International System of Units (‘the SI’) is the only globally agreed system of measurement units. The SI defines units for almost all measurements necessary to ensure that everyday life functions and that all critical technologies provide comparable and consistent outcomes worldwide.

The revision of the SI in 2018 means that all seven base units are defined according to defining constants, rather than physical artefacts, which allows more end users to be able to measure with high accuracy. This ensures the long-term stability and adaptability of the SI to scientific advancements and allows future advances in technology (such as 6G networks, quantum technologies, engineering biology and other innovations that are yet to be imagined) to be turned directly into improvements in the accuracy of measurements.

Some measurements do not fit easily within the SI, but the need for accuracy, reproducibility and uncertainty are nonetheless still important. Measurements can be indirect, of a hybrid nature or use proxies for the quantity of interest. This is particularly true in complex systems, with multiple processes or components interacting. Analysing complex systems is becoming more important as scientists try and understand climate change, biological processes and ever growing, interconnected and interdependent global infrastructure.

NPL is the UK’s National Metrology Institute and a world leading centre of research excellence, developing and applying the most accurate science to provide the measurement infrastructure to meet the needs of industry and society.

Review of Technology and Metrology Foresighting

In 2020 NPL released Technology and Metrology Foresighting which explored the implications of new technologies on how and why measurements are performed. It considered the drivers of change and the pressures that make society evolve and industry develop. **Wellbeing**, **enterprise** and **sustainability** were the drivers used to highlight which technologies were going to be significant.

These three drivers resonated with the recent strategy from the International Committee for Weights and Measures (CIPM), who promote world-wide uniformity in units of measurement and previous NPL foresighting exercises. Their continued relevance demonstrates that they have provided a strong foundation for producing accurate scenarios for the future of metrology and technology.

Over the past few years, the world has experienced a once-in-a-generation pandemic, increased political stability, cost-of-living pressures, fluctuations in the global energy markets and financial shocks. The ability to be resilient by controlling and protecting critical assets, supply chains and resources has become increasingly important. This means that **security** is now considered an additional driver of change.

NPL has updated its Foresighting through the lens of these four drivers to assess the challenges facing metrology in the future.

Wellbeing: The health, security and safety of a growing population with evolving social attitudes and values

Promoting independent and healthy lives in an increasingly ageing population is putting serious demands on the healthcare system. Access to healthcare will become more decentralised and advances in wearable and implantable bioelectronics will allow collection and secure sharing of personal data. Personalised medicine will allow tailored medical treatment for individual patients based on many factors including their disease risk, genetic makeup, lifestyle and environment. Predictive and preventative medicine will become a high priority as people increasingly manage their own health, costs are controlled and future pandemics are tackled. Digital frameworks will support physical and mental health in co-ordinated and innovative ways.

Enterprise: Digital innovation to increase prosperity, productivity and growth and also to enable equality and fairness

Manufacturing systems will increasingly rely on digital solutions and intelligent data driven tools coupled with trusted automation and autonomous sensing systems. They will become responsive and agile through innovative production techniques which will rely on continuous measurement and product verification through digital and virtual methods. AI and data science will make manufacturing more efficient and sustainable. Digitalisation of supply chains and sustainable resource management will become increasingly complex, international and interdependent. New materials which are sustainable and have advanced functionalities will become widespread, particularly for semiconductors, quantum technology, biomanufacturing, plastic replacements and nanotechnology. Quantum, advanced communications and timing technologies will both enable and require advanced manufacturing systems.

Sustainability: Reduced human impact on the climate and management of natural resources

Electricity will play a larger role in the overall energy mix, with demand increasing from transport, artificial intelligence (AI) and the data and communication infrastructure. The electricity network will become decentralised and distributed to take advantage of renewable technology. The resulting complexity from intermittency of supply, supply-demand matching and current market structures system will require updates in the technology and the metrology, including quantum solutions. The decentralised electricity network will likely feature small modular reactors which have significant manufacturing and assembly issues for *in situ* metrology. Building consensus on climate and Earth information is vital to monitor pollution, environmental change and limit human impact. This needs reliable technology, measurement frameworks and understanding the factors we have to measure, as well as quantifying the effect of mitigation measures. Healthier, wealthier societies will require sustainable growth, such as efficient manufacturing, decarbonisation and packaging and waste reduction. Managing recycling and re-use of limited global resources such as land, energy, water and materials will be vital.

Security: The ability to control and protect critical assets, supply chains and resources to maintain competitive advantage

Critical National Infrastructure refers to essential systems, assets and services whose loss or damage would impact public safety, the economy or national security, including energy, defence, transport, water and the digital infrastructure. The security and reliability of these systems, devices and data relies on establishing and maintaining measurement standards and techniques, and applying them to assess and enhance security measures. For example, security of supply chains will also rely on traceability, digital passports, and blockchain. Metrology helps to guarantee the security, confidentiality and integrity of data exchanged in networks and embedded systems. This requires measurement methods to detect and prevent unauthorised access, modification or disclosure of sensitive information. AI, ML and automation increasingly call for developments to be safe and trustworthy, which requires agreed definitions and standards, inclusion of meta data, and the careful pre- and post-processing of raw data., particularly for cybersecurity and to protect digital information from attacks by future quantum computers. The principles of FAIR data: findability, accessibility, interoperability and reusability, also remain important. Critical technologies such as quantum and advanced materials require non-traditional metrology, often not traceable directly to an SI unit, but providing confidence in data through traceability to agreed documentary standards detailing performance criteria and technology assessment methods. However, achieving technical consensus in fast developing and intellectual property-rich areas is not always amenable to agreement or openness.

The future of metrology

The four drivers – wellbeing, enterprise, sustainability and security – enable an understanding of the pressures and technologies which are shaping society. In addition, science is become increasingly multidisciplinary as scientists and engineers with widely differing expertise and technical languages work together. Metrology must be integrated into this mix so that it is being developed and employed in parallel with the technology.

There are recurring questions that crop up from the drivers and in multiple situations:

- How can a robust chain of traceability be ensured for digitally enabled measurements?
- If sensors are self-calibrating or measure *in-situ* then what does traceability actually mean?
- Will increasingly complex measurements without SI traceability require new, sophisticated methods to assess equivalence?
- Will devices and techniques producing large quantities of data need fundamentally different types of measurement?
- Will quantum devices require different standards?
- How can model systems in the laboratory reflect the increased complexity when measurements are made in a real environment?
- Will AI require new approaches to traceability?
- How is trustworthy data generated for the performance and demonstration of reliability for innovative technologies?
- Will new sensor technologies and digitalisation change the role of traceability and NMIs?
- How will metrological services and the quality infrastructure change in future?

These questions can be summarised by the three main trends for the future of metrology, which NPL identified in the 2020 Technology and Measurement Foresighting.

1. Metrology will support a digitally-enabled global measurement infrastructure

Since 2018, the definitions of the SI base units, and consequently the SI derived units, have enabled easier and wider access. New digital knowledge management and dissemination tools are bringing primary standards closer to the end user, shortening the traceability chain and reducing uncertainty. Traceability, which will be embedded directly into some measuring instruments, involves more than just calibration, and the digital approaches will need to adapt to include other relevant information.

Digital and machine-readable calibration certificates held on globally accessible ledgers will become commonplace and enable *in-situ* calibration of sensors and local standards. This will improve the provenance of measurements, at the same time providing instant proof of authoritative calibration data and traceability back to primary measurement standards. These developments are also likely to impact other parts of the quality infrastructure, driving it to become more agile, digitally-driven and efficient.

In some areas, (an example being quantum electrical standards) end user devices will become sufficiently stable and precise, so that periods between calibrations or verifications are likely to increase significantly. Nonetheless, the requirement for assurance, often via formal accreditation, will remain in order to verify the proper operation of such devices.

Despite the move towards quantum standards, there are some areas (notably in chemistry, biology and ionising radiation) that will depend on physical reference materials for traceability for the foreseeable future. Here the thrust of future metrology will be towards miniaturisation, reducing uncertainties and providing end users with data services to validate the local implementation of the reference materials provided to them by NMIs. Some aspects of centralisation also remain essential, such as for maintaining the global timescale, or organisationally expedient, in the case of ionising radiation and aspects of climate monitoring. In these areas, the future emphasis will be on improved resilience, digitalisation, and fair and equitable access for end users.

2. Metrology will improve understanding of complex systems

Complex systems are increasingly dominating our everyday lives. Understanding and influencing them form part of the solution to many of society's biggest challenges. Climate and the Earth system, cell structure, quantum computing, advanced materials, sensor networks and AI are all examples of complex systems. They need trustworthy, stable and comparable measurements (both of system inputs and outputs) to improve their description and understand the sensitivity of their behaviour to varying inputs.

There is rarely a simple solution for understanding a complex system that will allow a single measurement to provide the necessary information for confident decision making. Instead, applying metrology can help to reduce a complex system to one that is more manageable, and within the scope of analysis. Metrology enables researchers to focus on measurements being repeatable and reproducible, as well as identifying areas where the accuracy, uncertainty or traceability of measurement is the limiting factor.

To develop and operate large, multi-scale and multi-level models for complex systems, assured measurement and agreement on new documentary standards are important. Having assured and appropriate metadata, with agreed cross-disciplinary vocabulary for measurements associated with complex systems, is vital to allow different methods of re-analysis and interrogation.

By applying metrological principles, complex systems can be appropriately analysed even if many of the measurements involved sit outside the SI. In the future, the seamless and secure sharing of data, combined with increased computation power, needs to be overseen by sound metrology. This will lead to better decision making and the application of AI and ML to new areas, therefore accelerating the use of data in a safe and reliable way.

3. Metrology will give confidence in decision making

Confidence in data is vital to make informed, trustworthy and eventually even automated decisions, especially in safety critical situations. Currently the role of traceability and uncertainty in compliance assessment (for instance, against limit values) is well understood.

Proxy, indirect or 'method defined' measurements allow the property being measured to be mapped on to that which is of interest, for instance using ex-vivo medical tests to represent the in-vivo realities. These are becoming an increasingly important part of the scientific method in several disciplines, not least in complex systems, but can result in decisions being unreliable or poorly understood.

Whilst stability and comparability for such measurements is achieved via agreed documentary standards, metrology must help to determine how well these proxies replicate the desired measurement and how sensitive the results are to different input parameters.

In future, metrology will support the growing prevalence of indirect, hybrid and proxy measurements. It will also help combine data of different quality, provenance and time periods to add value, using new data analysis techniques. This will be particularly relevant in life sciences, climate and earth observation, biology, materials science, quantum technology and more generally in the study of complex systems. It is important to present metrology data and the associated uncertainties in a form that decision makers can readily interpret, so they can understand the implications of the uncertainty for their decisions.

What this means in practice

1. Championing the “metrology mindset”

The rapid pace of change can lead to new measurement technologies being developed and employed without proper validation or quality assurance. In addition, measurement technology is generating larger and more complex datasets. Software often stands between the raw data and the user, and in many cases “black box” algorithms are used for processing and analysing data. Tracking and quantifying the reliability and uncertainty of outputs can therefore be difficult, if not impossible, and researchers must question the data and decisions, not just accept numbers at face value.

The solution to these problems is to encourage a “metrology mindset” for all researchers whether they are working in universities, research establishments, companies or NMIs,

The “metrology mindset” refers:

- Developing validated and traceable measurement methods
- Seeking independent comparison of results
- Ensuring that measurements are accompanied by an uncertainty or statement of confidence in the results
- Understanding the importance of the quality infrastructure and established best practice solutions in producing reliable measurements
- Approaching complexity in a rigorous way, seeing the measurement as part of a larger system
- Understanding which factors affect a measurement and how to control them
- Developing a mutual understanding, nomenclature and language for unambiguous communication within and across scientific disciplines

These are essential characteristics of all scientists and engineers, not just metrologists. If all researchers adopt best metrological practice, the effectiveness and efficiency of research will improve. Accelerating innovation will allow the benefits of new technologies to be realised sooner and increase trust in science and evidence-based policy.

Researchers at NMIs are in a strong position to ensure a “metrology mindset” is being applied to all measurements, whether or not they are being developed in an NMI. All researchers should take full advantage of their NMIs and the wider quality infrastructure to assure the quality of their measurements.

NPL ensures that the “metrology mindset” is woven into scientific training at all levels, from apprentices to post graduate researchers. It is central to the role of all scientists at NPL, and is coupled with agile thinking, open mindedness, an innovative mindset and the powerful framework of metrology.

2. Evolving the role of the NMI

A key responsibility of the NMI is to prepare for the future, whether that means traceability to the SI or preparing for new science. Digitalisation and an increased emphasis on the trustworthy communication of data have seen changes to how the NMI role is delivered over the last 10 years, with the emerging digital infrastructure needing new thinking. In addition, there is a need for dynamic, measurement-related decision making which needs, standards, references and metrological approaches for increasingly complex systems.

NMIs must adapt to decentralised measurement systems and continue to act as the highest point of reference for national measurement standards in a country. Their differentiator will continue to be to provide solutions in situations where the accuracy, traceability or uncertainty of measurement is the factor limiting progress. Even while some of the calibration responsibilities shift to the end user community, there will be a new role for NMIs in providing independent and authoritative intercomparison and proficiency testing schemes for these end users.

With the increased digitalisation and complexity of metrology services, it is likely that NMIs will provide an increased number of calibrations and in many cases provide these directly to the point of use, thereby improving uncertainties for end users by reducing the number of comparison links in the traditional traceability chain. NMIs will act as expert “validators” where organisations are required to use their own *in situ* metrology. In areas where standards are rapidly changing or non-existent for complex datasets (for instance biological or sociological) NMIs must develop the measurement practices to allow timely decision making. They have a unique opportunity to lead innovation, set standards, and ensure trust in new technologies.

Looking forward, NPL needs to understand which new technologies will impact how and why measurements will be taken and be quick to adapt. NPL is constantly scanning the horizons for new technologies so whether it is supporting computational workflows, self-calibrating instruments or new technologies that are yet to be identified.

Conclusion

As the pace of change increases and problems become more complex, NMIs will be at the forefront of helping to unravel complex interconnected systems, such as disease pathways, quantum technologies, weather and climate.

Innovation in measurement science and agile thinking will enable future scenarios and challenges to be tackled with confidence. Researchers with a “metrology mindset” and a toolbox of approaches will have the skills and preparedness to innovate and develop new approaches where needed.

Metrologists have a responsibility to ensure their data is being used with integrity and impartiality and to champion the “metrology mindset” amongst the wider scientific community to ensure that science benefits the lives of individuals and improves the functioning of society.

Useful background reading

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Providing the measurement capability that underpins the UK's prosperity and quality of life

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