

NPL REPORT

DEM-TQD 006

**Quantum Metrology
Roadmaps — 2005**

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October 2005

Quantum Metrology Roadmaps - 2005

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DEM

ABSTRACT

We present technology roadmaps for areas relevant to the NMS Quantum Metrology Programme. These outline expected developments which will meet the challenges in the programme areas over a 15 - 20 year timescale. They will be used to encourage collaboration as well as inform the upcoming quantum programme formulation.

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Approved on behalf of the Managing Director, NPL
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1 INTRODUCTION

Technology Roadmapping is a planning process, here used to coordinate predicted industrial and societal needs with the scientific research and development necessary to meet those needs. It is allied to business roadmapping, which additionally includes market predictions and resource requirements. The techniques are now widely used in industry and government but were first used in the electronics industry where the semiconductor roadmap¹ remains the most frequently quoted as a successful example.

Our roadmaps show the technology challenges that must be met to achieve a given target, often referred to as emerging technology roadmaps in the literature. Each shows alternative routes whereby the targets can be reached by meeting different challenges, so it is not a project plan or a commitment from any party to follow a particular path, but it allows diverse organisations to set priorities for their own research and development so that the required outputs are available at the necessary time to contribute to the end goal. It also encourages collaboration between organisations on the same path in a technology chain to ensure that the challenges are met effectively and efficiently. Roadmaps present challenges rather than solutions, they are dynamic and should be being continually updated to reflect the latest opportunities so they can allow for discovery of the unexpected.

These roadmaps are high-level strategic views, more detailed roadmaps and other plans are required to specify projects or groups of projects in detail.

As an input to the formulation of the next UK National Measurement System's Quantum Metrology Programme², NPL was asked to produce:

“An International Metrology Road Map” - An analysis of the work and plans of the major NMIs in areas relevant to the Quantum Metrology Programme to set the work of the UK NMS in an international context, to examine the degree of international alignment and the scope for collaboration

adapting current practice in technology roadmapping as necessary.

A first draft of four roadmaps, along with an explanation of the process used to produce them, was published in March 2005³. The draft was circulated widely to other National Metrology Institutes (NMIs), Regional Metrology Associations (e.g. Euromet) and within the BIPM to seek comments. Structured interviews were also held with the relevant CIPM consultative committee executive secretaries to validate the roadmaps and discover if any known relevant international activity had been missed.

¹ ITRS International Technology Roadmap for Semiconductors (2004) <http://public.itrs.net/>.

² The UK National Measurement System's 'Quantum Metrology Programme' (NMS QMP) aims to provide secure long-term foundations for the whole of the National Measurement System in terms of the accuracy of the SI unit standards, the integrity of links between SI units and the ability to transfer those standards to UK industry through a coherent range of intelligence-gathering, research, development and technology transfer activities that complement the National Measurement System's Science & Technology Programmes. Further details can be found at <http://www.npl.co.uk/quantum>.

³ Flowers, J. L. A roadmap for quantum metrology. NPL Report DEM-TQD 001 (2005)

As a result of the consultation process, this report now presents revisions of the original four roadmaps and introduces two new roadmaps.

1.1 Layout of the Quantum Metrology Roadmaps

A roadmap starts with the “Triggers” — What predicted change or need in industry or society is metrology required to address? This is followed by the “Targets” — what needs to be achieved and by when? The horizontal axis is then a timeline chosen to correspond to the 15 - 20 year timescale that corresponds to the typical timeframe for a quantum metrology project or group of projects. The vertical axis then shows increasing development towards realisation - increasing development and integration of technology, from the basic science that underpins the metrological experiment to a metrological experiment itself. Each roadmap is preceded by a short background text to set the work plotted in the roadmap in context and indications of which NMIs are active in the area.

A roadmap is a picture representing possible future directions not a detailed plan, the reader should not infer more detail than intended. For example, in many cases the boxes have been shaped or positioned to fit their text or avoid overlaps; trying to read exact start and finish dates from their position would be an over-literal interpretation.

2 TIME AND FREQUENCY: BETTER CLOCKS

2.1 Background

Atomic clocks based on caesium have been the basis of the timescale and the definition of the second since the 1960's. During this time there has been significant development of the technology and their accuracy has improved by an astounding factor of 10^5 . Nowadays a number of cold atom caesium fountains are among the clocks contributing to the global timescale, with uncertainties approaching one part in 10^{15} .

Recent advances have been made in optical frequency standards using single trapped ions or alternatively neutral atoms in an optical lattice. It has also become possible to compare these new optical frequency standards to microwave standards such as caesium fountains, which provide the present definition of the second. This link can be done using femtosecond frequency combs without loss of accuracy.

This roadmap charts the future development of time and frequency metrology, based initially on improvements to microwave frequency standards, but with optical frequency standards replacing them as the ultimate frequency references during the time under consideration. Optical standards have the potential to reach a part in 10^{18} in stability. However, in order to achieve and make use of this remarkable stability other technologies such as local oscillators and frequency combs must be commensurately improved. In particular, in order to establish a timescale at enhanced accuracy, the techniques that will allow time transfer at these improved accuracies must be developed using quantum information processing techniques. The timescale will have to take account of the gravitational redshift, which shifts a clock's frequency by about a part in 10^{16} for each metre of height, so improved mapping of the gravitational field will be required. The definition of the second is based on the microwave caesium transition so a new definition would be required to take the realisation of the second to accuracies achievable with optical clocks. It is still unclear what form the new definition would take, but it would be desirable to link to fundamental constants as is being done in the proposed new definitions of the kilogram, ampere and kelvin.

The improved frequency metrology infrastructure will enable improvements in a wide range of science and technology applications such as satellite navigation, high-speed communications, secure communications, fundamental physics and fundamental constant evaluations

2.2 Major activity at NMIs and other similar institutions

Here we list NMI that are known to have significant research activity in time and frequency metrology, with highlights of their contributions. Also listed are some other organisations whose research is particularly metrologically orientated or has made significant metrological impact. Compared to the other subject areas discussed in this report time and frequency is a long standing area of recognised metrological significance hence most NMIs have activity in this area with variation in the research, either in clocks or time transfer. This list is restricted to those laboratories with

significant clock research. (See Glossary section 9 for the expansions of Laboratory name abbreviations).

Laboratory	Principal related activities
LNE-SYRTE	Cs fountain, Rb/Cs dual fountain, optically pumped caesium, Sr optical fountain, transportable Cs fountain FOM, PHARAO space clock – only laboratory with more than one fountain clock
NIST	Cs fountain, Cs beams, Hg^+ , Be^+/Al^+ ions, Ca atoms, optical frequency comb, lattice clocks, PARCS space clock
PTB	Cs fountain and 4 Cs beams (these were for many years the most stable clocks and are still important as they work continuously unlike fountains), $^{171}\text{Yb}^+$ ion, Ca atom, optical frequency comb
NPL	Cs fountain, Rb fountain, Yb^+ and Sr^+ ions, hydrogen atoms, optical frequency comb
MPQ	In^+ ion, hydrogen atom, optical frequency comb
University of Tokyo, NMIJ/AIST	Lattice clocks
NMIJ	Cs fountain under development
NRC-INMS	Cs fountain under development, Ca atom, Sr^+ ion, optical frequency comb
IEN	Cs fountain
NICT	Cs fountain, Ca^+ ion
METAS/Neuchâtel	Cs fountain – novel design but not yet contributed to TAI
LKB/LNE-SYRTE	Hydrogen atom
NMI	Yb^+ ion (microwave transition)
USNO/JPL	Hg^+ ion (microwave transition)

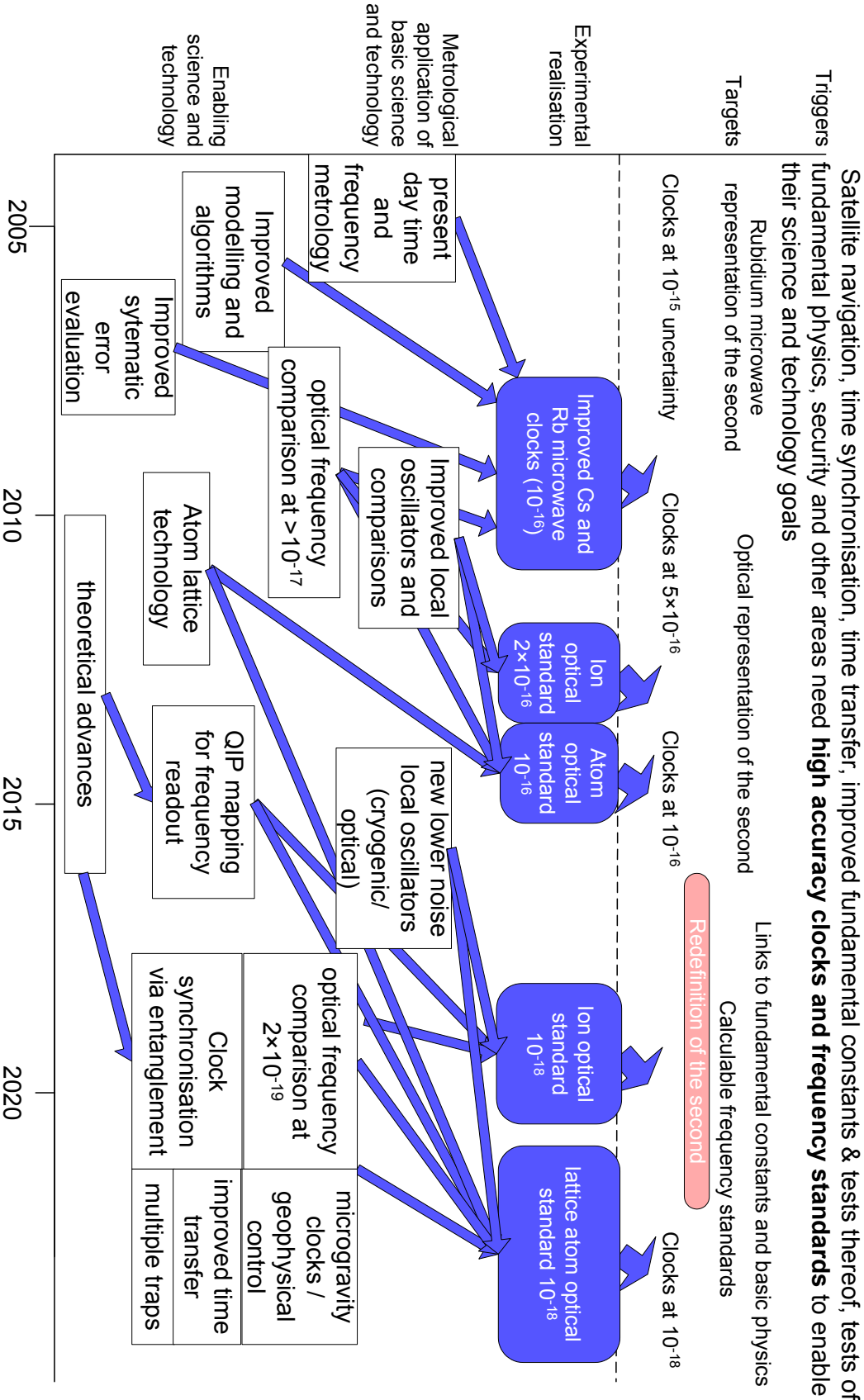
2.3 Glossary

Cs – Caesium

QIP – Quantum Information Processing

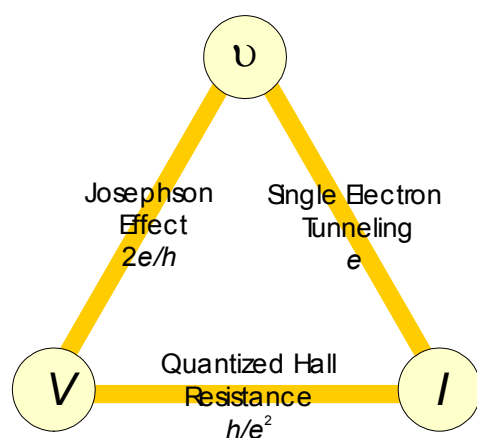
Rb – Rubidium

Time and Frequency: better clocks



3 QUANTUM ELECTRICAL STANDARDS

3.1 Background



Representation of the metrological triangle. The sides represent three quantum effects and the points the quantities related by each

Since 1990 the volt and ohm have been maintained using quantum effects, the Josephson and quantum Hall effects respectively. Two constants are introduced the Josephson constant K_J and the von Klitzing constant R_K . These constants are predicted by theory to have the following relationships to the Planck constant h and the electron charge e :

$$K_J = 2e/h \text{ and } R_K = h/e^2.$$

Experiments to date have yielded results consistent with the above relations. For the purpose of uniformity of electrical standards based on quantum effects, these two constants were given assigned exact values K_{J-90} and R_{K-90} which were chosen to be as close to the SI values as possible. This gives the volt and ohm a much greater stability than accuracy (in the SI system).

A long-standing goal of electrical metrology is to test whether the above relations are indeed identities. One approach is to test the consistency of these relationships using the 'metrological triangle'. The experiment is to compare the voltage produced by a quantised current (controlled passage of counted electrons) passing through a quantum Hall effect resistor with a Josephson voltage. To do this at a meaningful level will require a quantum standard of current accurate at about one part in 10^8 whereas the current state of the art is approaching one part in 10^7 . This roadmap explores the route for closing the metrological triangle, which would greatly enhance confidence in these quantum standards, which support voltage and resistance measurements at the highest level. It encompasses the development of a quantum current standard, which combined with other experiments, would improve knowledge of the value of the electron charge. The redefinition of the ampere presently under discussion assumes that the above relationships are correct, it is a matter of debate whether they could be used in a redefinition before their self-consistency was proven. The von Klitzing constant, R_K , is related to the fine structure constant, α , so experiments from other areas of physics designed to measure α also give information on R_K .

The challenge is of much wider interest than is initially apparent. This roadmap covers the development of electrical measurements at the finest scale. It concerns the control and manipulation of single electrons and therefore the ultimate limit of Moore's Law for electronics, when only a single electron is involved in an operation. The map is presented in terms of a metrological enquiry, but the outputs are the measurement capabilities to address emerging needs in the electronics industry.

Feedback from the BIPM expressed a view that in addition to items included on the roadmap, the Quantum Hall and Josephson effects still needed some background

work. While we agree that this is the case we consider that such work is outside what we consider the area encompassed by the Quantum Metrology Programme and would come under the Electrical Programme of the NMS.

3.2 Major activity at NMIs and other similar institutions

Laboratory	Principal related activities
NIST	Capacitance charging, SET pumps
PTB, NPL, Cambridge University	SET-SAW pump
LNE-LCIE	Capacitance charging, SET pumps, calculable capacitor
METAS	Electron tunnelling
BIPM/NMIA	Calculable capacitor
NIM	Calculable capacitor
NRC-INMS	SET pumps

3.3 Glossary

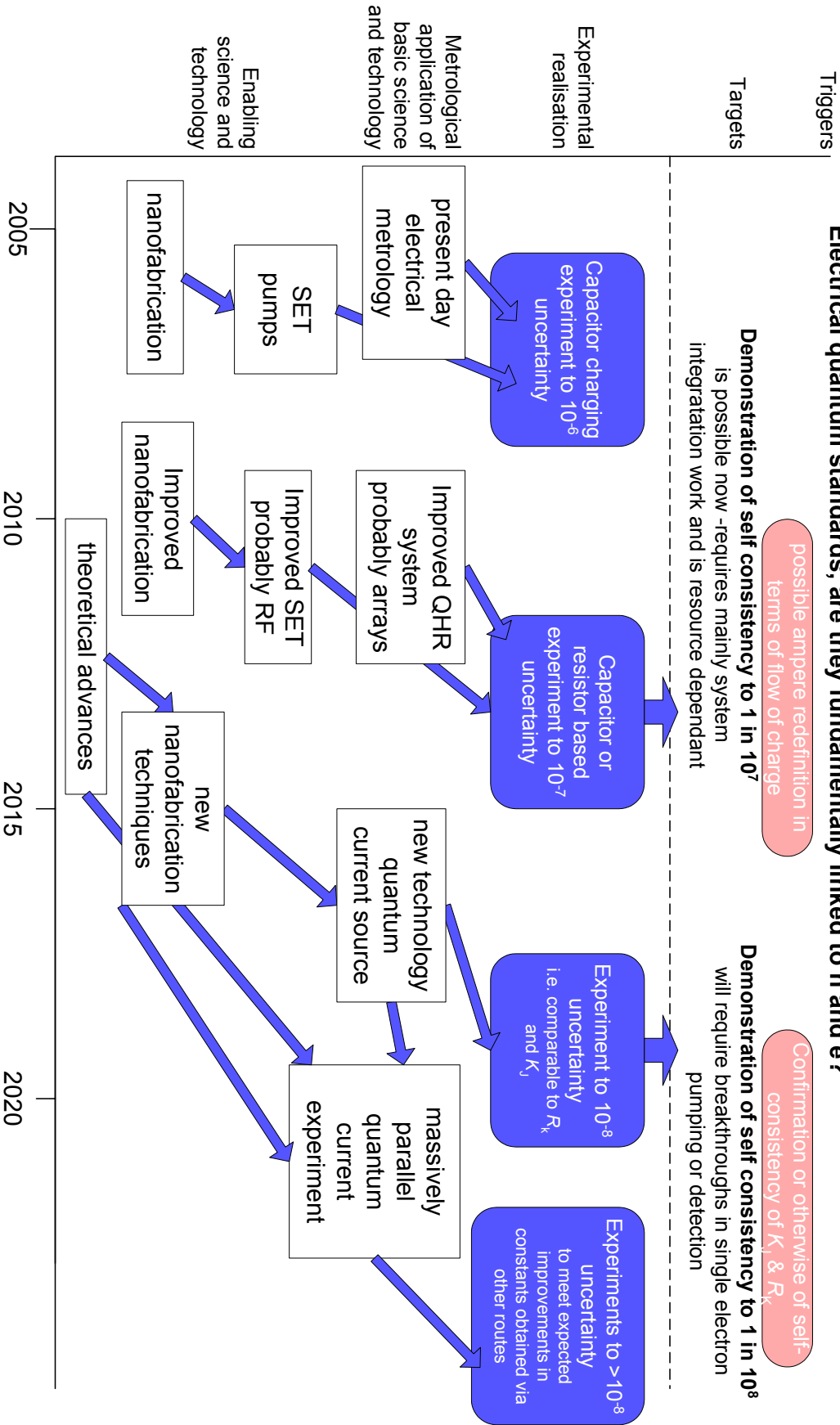
QHR – Quantum Hall Resistor / Resistance

SET – Single Electron Tunnelling / Transistor

SET-SAW – Single Electron Tunnelling-Surface Acoustic Wave

Quantum electrical standards

Need to provide high accuracy control of single electrons for future electronic devices
Electrical quantum standards, are they fundamentally linked to h and e?



4 PRIMARY MASS

4.1 Background

The replacement of the artefact prototype kilogram is a long-standing goal of quantum metrology. This would replace the last base unit of the SI system to be based on an artefact standard, eliminating concerns over the stability of the prototype kilogram. A new method would have to provide mass measurements with an uncertainty of better than a part in 10^8 before it could be considered and improvement on the present status.

Of the methods likely to enable replacement of the kilogram, the most developed is the watt balance. This works by comparing the mechanical power of a moving mass with electrical power provided by electrical standards of voltage and resistance, which have a high stability. The apparatus is a mechanical balance. It compares the force produced by a current flowing through a coil with the weight of a kilogram mass. Measurement of the voltage produced by moving the coil in the same magnetic field then allows the geometry of the coil and the magnetic flux density to be cancelled out. Precision electrical measurements, mechanical alignment and gravity measurements are needed as well as time stability of the apparatus.

An alternative approach to a new mass standard is counting atoms. In the Avogadro method the number of atoms in a single crystal sphere of silicon is determined from its volume and the measured spacing of silicon atoms in a crystal lattice. Hence the mass is determined in terms of the atomic mass. This method has run into problems due to the unknown isotopic makeup of the silicon and so the collaboration is pursuing the preparation of a crystal of pure silicon 28.

Atom counting is also being attempted by a method of ion accumulation. Here ions in a beam of known current are captured and weighed. The known current means that if all the ions can be captured and neutralised a known mass of material is produced. The method is limited at present by the small mass produced and the difficulty of collecting all the ions in the beam with high reliability. This method is at a much less developed stage than the watt balance or Avogadro method.

The uncertainties across the top of this roadmap indicate the ability to monitor the stability of a prototype kilogram at the appropriate level. The redefinition of mass is a political process, which would require approval through a number of committees of the BIPM.

4.2 Major activity at NMIs and other similar institutions

Since the original NPL work two watt balance experiments have reported results, those at NPL and NIST including a very recent result by NIST (Oct 2005). Other laboratories (METAS, LNE and BIPM) have watt balance experiments working or under construction but are yet to produce results. There are other watt balance experiments planned.

The Avogadro method is being pursued by the International Avogadro Coordination (IAC). Because of the scale of the project, a single measurement is being performed

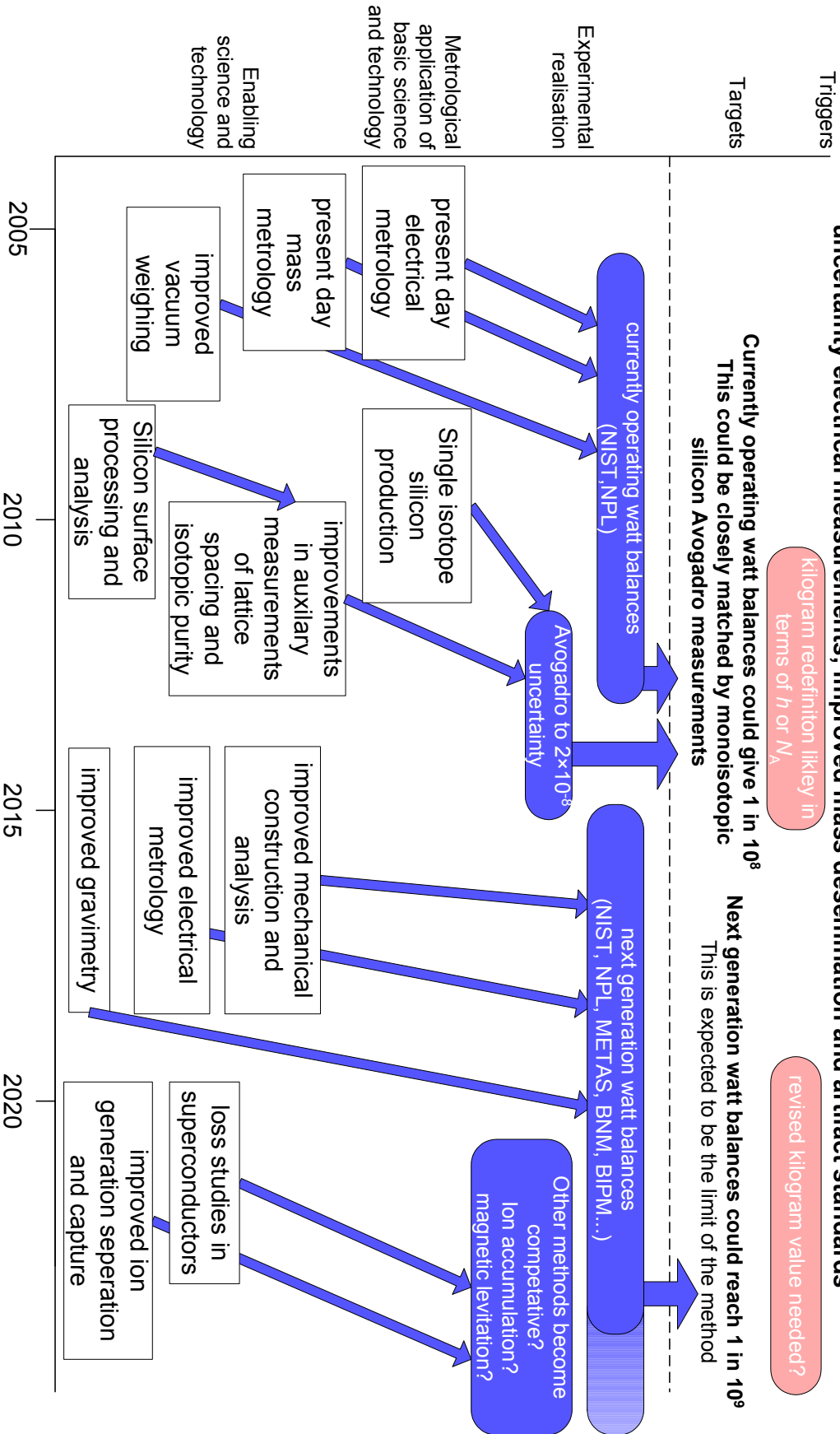
by an International cooperation of PTB, IRNM, NMIJ, IMGC, NPL, BIPM, CSIRA, NIST (& Harvard University) with single isotope production by the Institut für Kristallzüchtung in Berlin using Russian facilities in St Petersburg.

PTB is the only laboratory we know of to be undertaking an ion accumulation experiment but this is still at a ‘proof of principle’ stage, far from the uncertainty achieved by the other methods.

A MIKAS/VNIIM collaboration is planning a magnetic levitation measurement of the Planck constant.

Primary mass

Replacement of the artefact kilogram to give higher stability mass measurements and lower uncertainty electrical measurements; improved mass dissemination and artifact standards



5 TEMPERATURE: DEFINITION OF THE KELVIN

5.1 Background

The current definition of the kelvin in terms of the triple-point of water is ultimately limited by the properties of a material substance. The limiting uncertainty in its realisation is likely to be in the region of 1 part in 10^7 due to isotopic and impurity effects. It has become interesting to consider the uncertainty with which it may be possible to determine the Boltzmann constant k , consistent with the unit as currently defined. Clearly, if it can be done to 1 part in 10^7 , the kelvin could be redefined by fixing the value of k without any noticeable discontinuity from the previous definition, and at the same time freeing the unit from a link to any particular temperature value or state of matter or measurement method.

In reality, a determination of k will be limited by thermodynamic uncertainties, rather than by the uncertainty in the realisation of the triple point of water. The current value, which dates from 1988, has an uncertainty of 1.8 parts in 10^6 , and while this is sufficient for present thermodynamic requirements, it is highly desirable that new determinations are undertaken at the level of 1 or 2 parts in 10^6 to confirm and improve on it before a redefinition of the kelvin takes place.

The consequence for practical thermometry of a change in definition to a value of k with an uncertainty of 1 or 2 parts in 10^6 would be that, in the fullness of time, it may be found that the triple-point of water, which becomes subject to experimental determination, is not 273.16 K exactly but perhaps up to 0.0005 K different from this. But the triple-point of water would no longer be a special case, and much larger errors are known to exist in the thermodynamic values of other 'fixed points'. An evaluation and adjustment of all temperature values will be required prior to a revision of the International Temperature Scale, and is still several years away. Meanwhile practical thermometry can continue to be based on the ITS-90, with its excellent precision and reproducibility.

Since temperature always enters physics (in this context, thermodynamics and statistical mechanics) as the product kT , an experiment for determining k or T can in principle be based on any fundamental law governing the statistical properties of an ensemble of particles at equilibrium, or on an equivalent time-series measurement. Candidate systems are atoms in a gas, electrons in metals, photons in a cavity and ions in excited states, all of which have already been exploited in thermometry. No plausible ideas for harnessing more exotic particles have yet been advanced.

In summary, the first part of the road-map suggests that various experiments may lead to a value of k with an acceptable uncertainty by 2011, the date currently envisaged for changes to the kilogram and electrical units. The second part of the road-map projects improved uncertainties in thermodynamic temperature over a wide range, in order to provide the fundamental basis of a future ITS, and hence to provide science, technology and industry with a reliable substitute for difficult thermodynamic measurements. The ultimate objective of thermometry is to establish *practical thermodynamic* thermometry with uncertainties sufficient to meet the requirements of all users. In this situation, the ITS becomes redundant.

5.2 Major activity at NMIs and other similar institutions

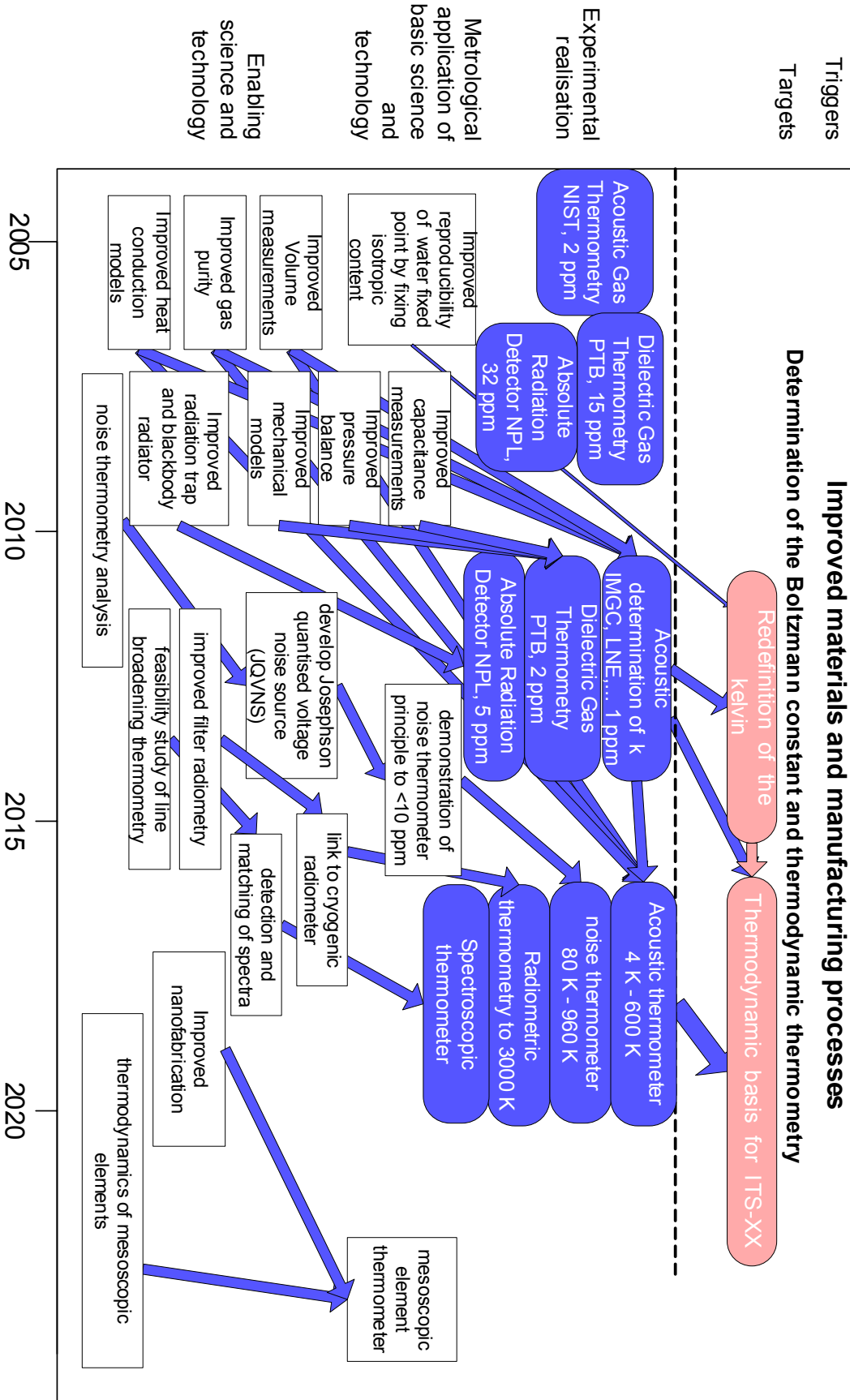
A joint iMERA project entitled 'New Determinations of the Boltzmann Constant' is proposed by LNE-INM/CNAM, University Paris North (FR), IEN/IMGC, NPL, PTB and NIST to study a number of promising methods to improve the Boltzmann constant determination and hence prepare the ground for a kelvin redefinition in terms of a fixed Boltzmann constant. The partners will use different methods, such as acoustic or dielectric constant gas thermometry, or spectroscopic and optical methods.

NPL continues to work on the Stefan-Boltzman constant, which is related to the Boltzman constant by a number of well-known factors.

The various laboratories work is labelled on the roadmap. For further information see the NPL study report 'Review of methods for a re-determination of the Boltzmann constant'⁴.

⁴ Rusby, R., de Podesta, M. & Williams, J. *Review of methods for a re-determination of the Boltzmann constant*, NPL Report DEPC TH 006 (2005).

Temperature: definition of the kelvin and thermodynamic thermometry



6 QUANTUM INFORMATION PROCESSING AND COMMUNICATION

6.1 Background

Quantum Information Processing and Communication (QIPC) has the potential to revolutionize many areas of science and technology. It exploits fundamentally new modes of computation and communication, because it is based on the physical laws of quantum mechanics instead of classical physics. It holds the promise of immense computing power beyond the capabilities of any classical computer, it guarantees absolutely secure communication, and directly leads to enhanced precision in a wide range of metrology applications such as standards and sensors.

In terms of exploitation potential, optical systems for implementing quantum cryptography are closest to market with a number of companies already providing systems for short-range secure communication. However, none of these commercial systems use true single-photon sources. The role of metrology will be to develop single-photon measurement capability and eventually certify such systems. The longer-term goal is to develop systems for long-distance secure communication based on either optical fibre or through free space. The availability of high-quality single-photon sources and the use of entanglement lead to a number of interesting applications in precision metrology, e.g. brightness standards, timing and positioning, precision spectroscopy. The applications of quantum computing are much further in the future and the medium-term aim will be to develop systems comprising a modest number of qubits systems with applications to quantum repeaters necessary for long-range quantum communication. A quantum computer consisting of approximately 30 qubits could solve non-trivial problems that are beyond the reach of any foreseeable classical machine.

The development of QIPC technologies goes hand in hand with the development of quantum enhanced metrology (QEM) techniques. For example, the optical clocks based on trapped single ions form ideal qubit systems with extremely long decoherence times. At the same time the development of entangled qubits based on trapped ions could lead to improvements in the precision and miniaturization of optical clocks. A similar relation exists for the quantum electrical standards and the development of systems based on Josephson and electron type qubits, with most technologies being generic to both fields.

Micro-and nanotechnology are underpinning many of the crucial developments in QIPC, particularly in the field of single photon sources and detectors and the solid-state type of qubits. Also, to enable scaling of ion and atom based qubit systems precision engineering and micro fabrication techniques will start to play an important role. Finally, theory plays a leading role in guiding and supporting experimental developments. Examples are, formulation of a quantum information theory with new quantum algorithms, new computational models, a deeper understanding of entanglement, decoherence, & error correction.

6.2 Major activity at NMIs and other similar institutions

Unlike the metrology areas described above this is a recent field for NMI activity. There is a considerable research activity in the area, but most research is still undertaken at universities and does not specifically address metrology needs. A more detailed NPL study report ‘Applications of Quantum Entanglement to Metrology’⁵ lists the many laboratories with major effort in this area which includes NIST and NPL.

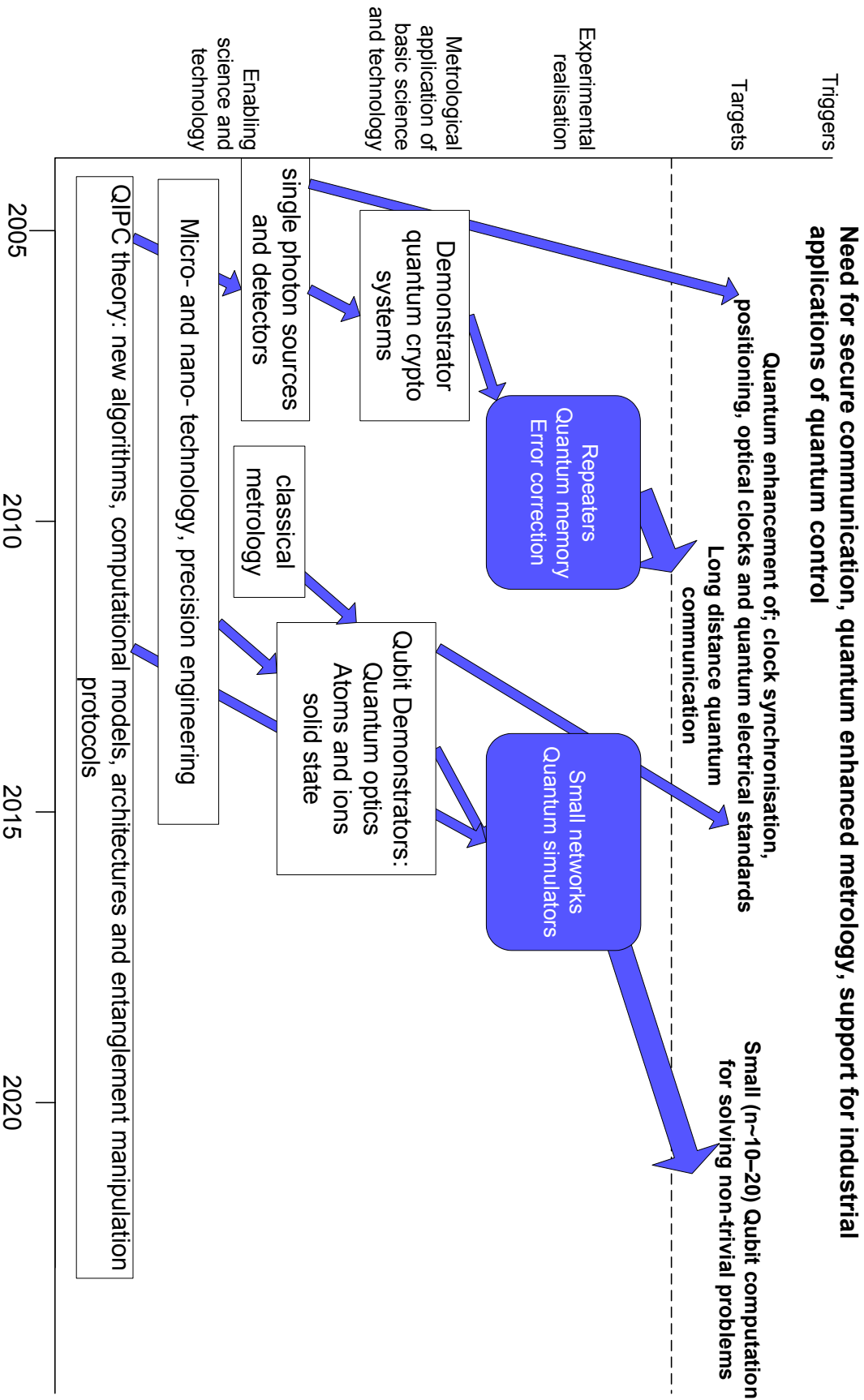
6.3 Glossary

QIPC – Quantum Information Processing and Communication

QEM – Quantum Enhanced Metrology

⁵ Lea, S. N., Webster, C. H., Sinclair, A. G. & Tzalenchuk, A. Ya. *Applications of quantum entanglement to metrology*. NPL Report DEM-TQD 005 (2005)

Metrological needs for quantum information processing and communication



7 QUANTUM DETECTION

7.1 Background

Quantum phenomena are by no means the preserve of atomic physics (as is traditionally concerned with the properties of rarefied atoms in a vacuum). Indeed, structures and devices made from condensed matter, and thus comprising billions of closely and strongly interacting atoms, can display robust quantum effects of extreme sensitivity, reproducibility, and accuracy. Though now well established, the Josephson voltage standard serves, in this context, as testimony to the potentially disruptive impact of such quantum effects within metrology.

Until recently, quantum phenomena in condensed matter could only be observed in either wholly bulk specimens or meso/micro-structured devices made through either mechanical processing or thin-film deposition and optical lithography. Here, the spatial regularity/homogeneity of the device's underlying atomic constituents supported, at a given temperature, the desired quantum order parameter and/or quasi-particle, e.g. the superconducting phase or spin-polarization field. Rapid progress in the synthesis, (self-)assembly and manipulation of condensed matter now enables the fabrication of hitherto unrealisable devices, whose three-dimensional structure at the nano or even atomic level can be deliberately engineered to promote and control quantum phenomena at relatively high operating temperatures. Air-bridges, nanowires, and targeted linker molecules are but three enabling structural themes in this context. NPL's activities within the topic area of 'Quantum Detection' aim to identify, capture, direct and exploit the potential of these quantum-engineered devices within metrology, particularly for use as functionalised probes or reference standards supporting what today are classified as the sensors, semiconductor, and information-technology industries. The principal targets are capabilities to prepare and detect (i) nuclear/electronic spin, (ii) superconducting phase, and (iii) elastomechanical vibration (i.e. 'phonons') at the level of individual quanta and, subsequently, to control the interactions between such quanta.

7.2 Major activity at NMIs and other similar institutions

The situation for this activity is similar to that of QIPC considered in the previous section: most research is undertaken at universities and does not specifically address metrological needs. Again, an NPL study report 'Metrological challenges of nanomagnetism'⁶ has addressed this in more detail (in one selected area). The principal NMIs involved are NIST, NPL and PTB, but again relevant activities elsewhere are extremely widespread and large scale.

⁶ Kazakova, O., Webster, C. & Tzalenchuk, A. *Metrological challenges of nanomagnetism* NPL Report DEM-TQD 002 (2005).

7.3 Glossary

SQUID – Superconducting quantum interference device

THz – Terahertz; technologies for generating and detecting electromagnetic radiation at frequencies around 10^{12} Hz

MTJ – Magnetic tunnel junction

NMR – Nuclear Magnetic Resonance

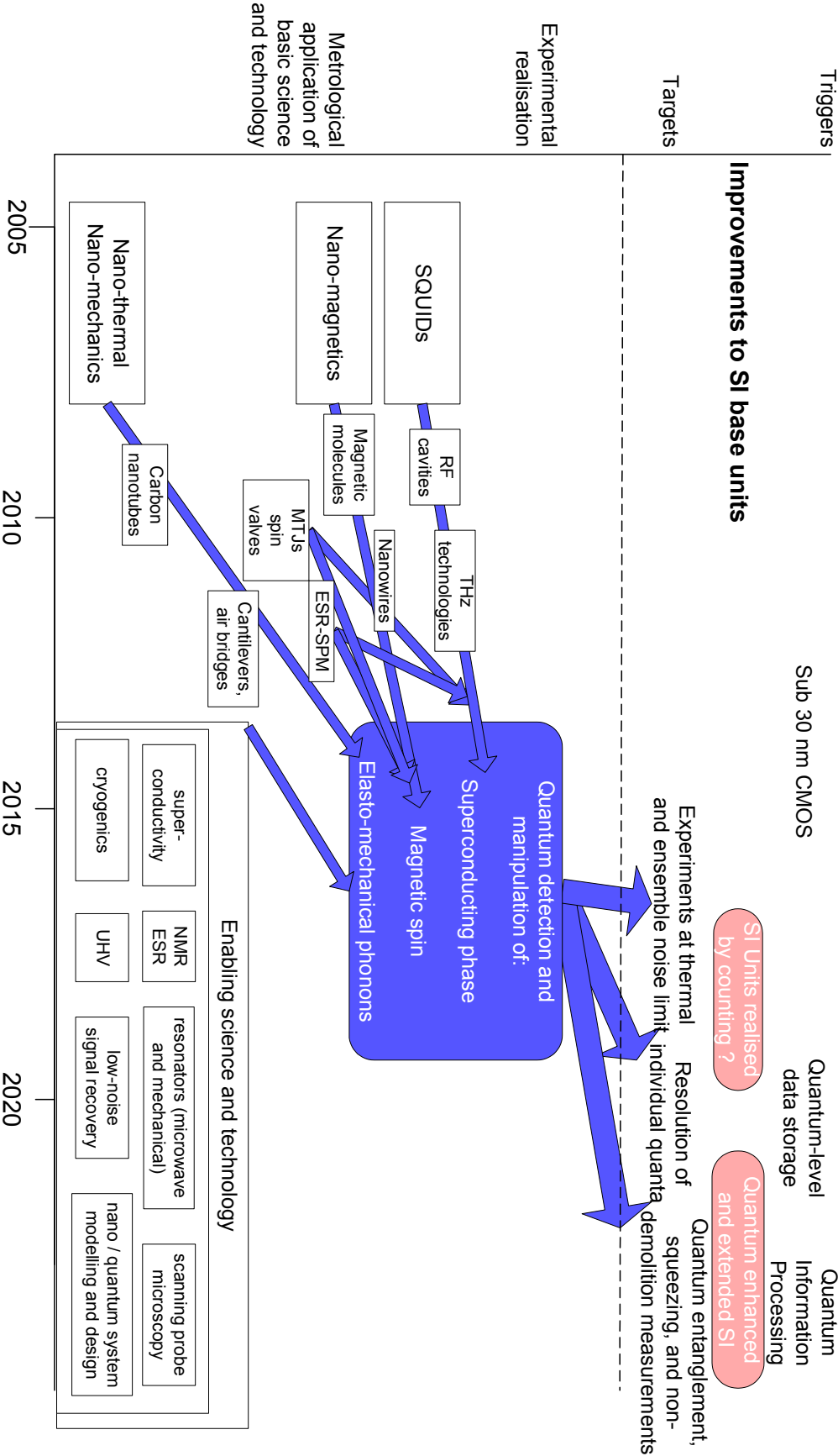
ESR – Electron Spin Resonance

SPM – Scanning-Probe Microscopy

UHV – Ultra high vacuum

Quantum Detection

Support of Sensor Semiconductor and IT industries : Continuation of Moore's Law



8 SUMMARY AND CONCLUSIONS

The draft roadmaps elicited a significant response from those that received them. Not in detailed amendments (although the temperature roadmap has changed significantly following discussions at BIPM), but rather in a desire to undertake similar activities and prepare metrology roadmaps for other areas. The Consultative Committee Executive Secretaries at BIPM have been tasked with preparing roadmaps for their areas of responsibility. The Technical Chairs in Euromet have a similar task under the iMERA project⁷, and independently NIST have started a significant project to collate and prepare roadmaps⁸.

Our work was limited to collating information to inform the formulation of the next NMS Quantum Metrology Programme and this document represents that input. We believe the true value of the exercise lies in the process that has been undertaken, the discussions that have been held across disciplines within NPL and with other organisations. The roadmaps presented in this document will only give a superficial overview to the new reader, but those that have taken part in the process have gained valuable insight into how the international aspirations in these fields could be coordinated more efficiently and will use that in their proposals for the next programme. More detailed roadmaps expanding on particular areas of the overview roadmaps presented in this document are included in a number of study reports that have been produced as part of the present Quantum Metrology Programme.

We recommend that these roadmaps should be kept under review during the next quantum metrology programme, along with all the other roadmapping activity outlined above, and that a revised document should be published every three years to coincide with the start of formulation.

Although it was the initial intention to produce a single chart as the “International Metrology Road Map”, early in the process it was realised that this was impractical as the detail required would overwhelm a single chart presentation. However, following a number of requests for a single view we have produced a summary roadmap by extracting highlights from the roadmaps above. To avoid the detail overwhelming the overview, each of the boxes on the diagram must represent a large body of work. Hence the warning, in the introduction, of not reading too much into the diagrams is particularly applicable in this case. The summary lacks the detail to allow the coordination of international activities at the project level but the roadmaps are hierarchical, so an item from the summary roadmap may be explored in more detail by referring back to a roadmap in the body of the report.

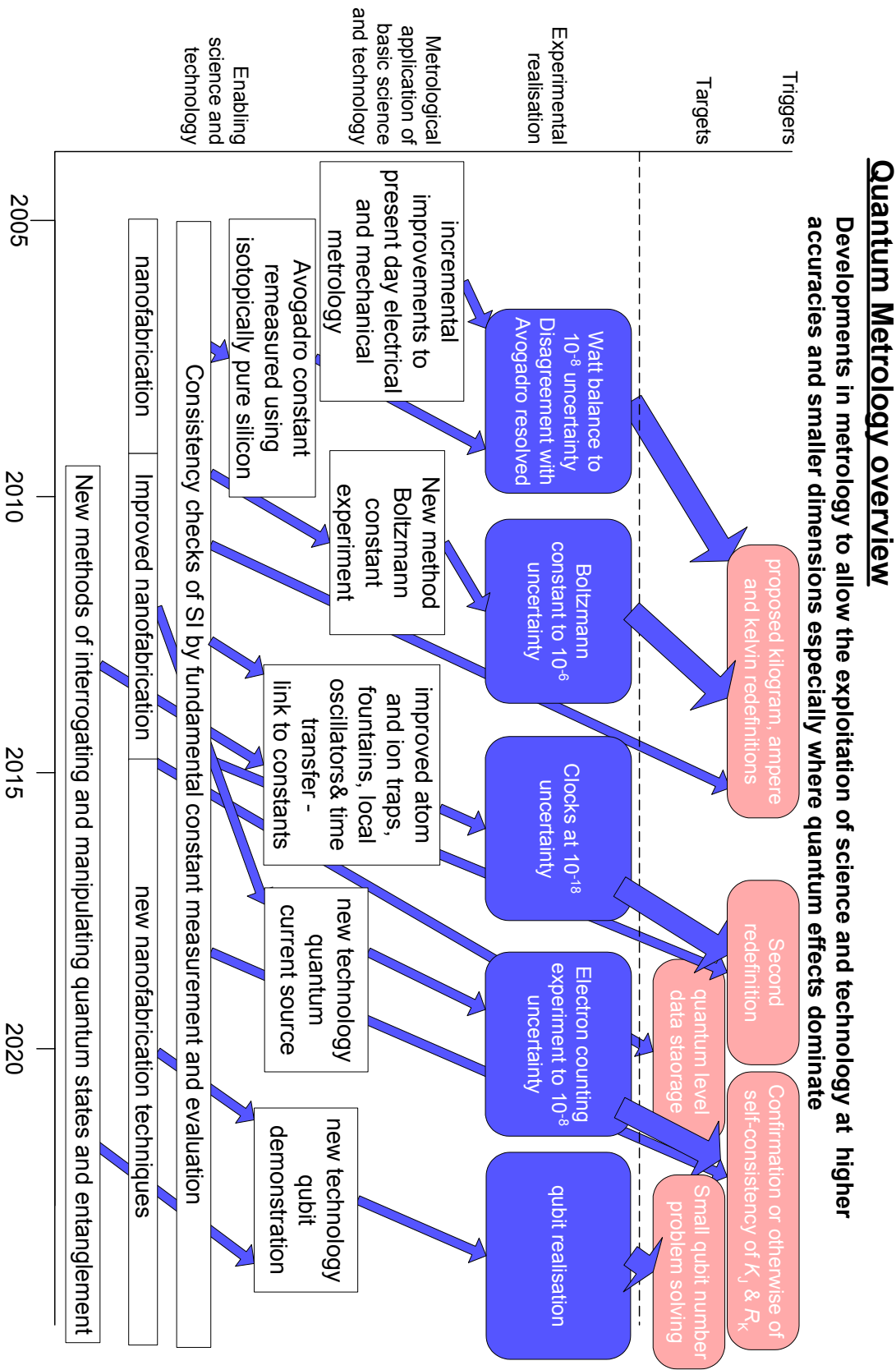
Redefinitions of the units is a political process but is subject to scientific advice. The authority for the SI is the BIPM. Decisions on changes to the SI will be taken by the CGPM advised by the CIPM which is in turn advised by the various consultative committees in deferent subject areas. At present it is proposed that the kilogram be redefined by the CGPM at their meeting in 2011, however this assumes that the present discrepancy between the watt balance and Avogadro methods will have been

⁷ <http://www.euromet.org/projects/imera/index.html>

⁸ <http://usms.nist.gov/>

satisfactorily resolved by then. If that is the case, then it is very likely that the ampere and kelvin will be redefined at the same time, even if there has been little experimental progress in those areas in the meantime. The ampere definition would be based on the assumption that the von Klitzing and Josephson relationships are correct, but this would remain unproven. If, however, establishing the value to be adopted for the kilogram remains unresolved, then the whole process will most probably be delayed at least until the next CGPM. Later conferences are expected to redefine the second following progress in optical clock technology beyond the uncertainties associated with caesium fountains. Further changes to the SI, perhaps adopting units for quantum variables for example, are more speculative.

8.1 Programme summary roadmap



9 LABORATORIES GLOSSARY

BIPM – Bureau International des Poids et Mesures

<http://www.bipm.fr/>

IEN – Istituto Elettrotecnico Nazionale “Galileo Ferraris”, Italy
Time and frequency, electrical, photometry, acoustics.

<http://www.iem.it/index.shtml>

IMGC – Istituto di Metrologia "Gustavo Colonnetti", Italy
Thermal and mechanical metrology

<http://www.imgc.to.cnr.it/english/default.asp>

JPL Jet Propulsion Laboratory, NASA, USA

<http://www.jpl.nasa.gov/>

LKB – Laboratoire Kastler Brossel, France

http://www.lne.fr/index_en.html

LNE – Laboratoire National de Métrologie et d'Essais, France
(recently changed from BNM)

LNE-INM (Institut national de métrologie)

<http://www.cnam.fr/instituts/inm>

mass, length, radiometry, thermometry

LNE (Laboratoire national de métrologie)

mechanical, thermal, optical, chemical and electrical quantities

http://www.lne.fr/index_en.html

LNE-SYRTE (Systèmes de référence Temps-Espace)

timescale maintenance, cold atom clocks

<http://opdaf1.obspm.fr>

METAS – Swiss Federal Office of Metrology and Accreditation

<http://www.metas.ch/en/index.html>

MIKES Mittatekniikan Keskus/Centre for Metrology and
Accreditation, Finland

<http://www.mikes.fi/>

MPQ – Max Planck Institut für Quantenoptik in Garching near Munich, Germany

<http://www.mpq.mpg.de/>

NICT – Japan National Institute of Information and Communications Technology

<http://www.nict.go.jp/overview/>

NIST – National Institute of Standards and Technology, USA

<http://www.nist.gov/>

NMIA – National Measurement Institute Australia

<http://www.measurement.gov.au/>

NMIJ – National Metrology Institute of Japan (was NRLM)

Part of AIST – Advanced Industrial Science and Technology

<http://www.nmij.jp/newenglish/index.html>

NRC-INMS – NRC Institute for National Measurement Standards, Canada

Part of NRC – the National Research Council Canada

http://inms-ienm.nrc-cnrc.gc.ca/main_e.html

PTB – Physikalisch-Technische Bundesanstalt, Germany

http://www.ptb.de/index_en.html

USNO – United States Naval Observatory, USA

<http://tycho.usno.navy.mil>

VNIIM – D.I. Mendeleyev Institute for Metrology, Rostekhnregulirovaniye
of Russia, Russian Fed.

<http://www.vniim.ru/>