A European roadmap for thermometry

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Abstract

A technical roadmap for thermometry has been constructed by the EURAMET Technical Committee for Thermometry (TC-T). The roadmap first identifies the key **triggers** that need to be addressed; these included societal grand challenges and the essential scientific metrology to ensure the continued fitness and relevance of the SI unit, the kelvin. In addition triggers focusing on innovation to support industrial competitiveness such as improvement in product quality and energy efficiency were considered. Clear targets to help address the triggers were formulated; these in turn provide clear direction to the required temperature measurement research until about 2025. Although constructed by EURAMET TC-T the identified societal grand challenges are common, that is they are also challenges that are facing the world community, hence the roadmap has wider applicability beyond the EURAMET region.

1. Introduction

In 2006 the EURAMET TC-T produced roadmaps for thermometry [1] and humidity and moisture [2]. This exercise formed part of a larger process undertaken by the EURAMET metrology technical committees to roadmap their technical areas. The findings of this work went on to inform, in part, the EMRP research programme 2008 [3]. Those roadmaps were meant to be active documents and so in 2010 the EURAMET TC-T Strategy Group, with the agreement of the EURAMET TC-T, took the decision to revise the roadmaps. In the event an extensive revision took place, particularly of the temperature roadmap, and the decision was made to construct a new roadmap for thermophysical properties (quantities). The roadmap for humidity and moisture was also revised at this time. A workshop was organised by and held at NPL on 30th March 2011 to roadmap these three areas. Eleven thermometry experts from Europe, mainly from the EURAMET TC-T, were invited to participate in formulating the roadmap of the thermometry area; a similar number were invited to the other two areas that were considered. The roadmaps themselves were constructed by the experts first by identifying the societal grand challenges and other high level drivers that set the context for the work (the triggers). This led to the formulation of concrete targets where the thermometry community could contribute to help address these challenges. Finally the temperature metrology and the background science required to meet the targets was identified.

The outcome of the roadmap sessions were presented to the EURAMET TC-T at its plenary meeting at NPL on 31st March/1st April 2011 and the provisional findings were endorsed by that committee. These were then completed and endorsed by the EURAMET TC-T at their plenary meeting in Istanbul on 18/19th April 2012. The roadmaps, and in particular the accompanying text, on instruction from the EURAMET TC-T, have been subsequently revised in the light of the emerging requirements from the EMPIR[1] and also those of the EURAMET 2020 strategy.

The objective of the temperature roadmap presented here is to inform the direction of temperature measurement research in the EURAMET area and inform high level research requirements in the forthcoming EMPIR programme. Roadmaps for thermophysical properties (quantities) and humidity and moisture are described elsewhere [4, 5]. This paper will describe the background to and explanation of the temperature roadmap.

2. Grand challenges: The Triggers

[1] EMPIR: European Metrology Programme for Innovation and Research

There are a common set of grand challenges that mankind faces. The group of experts had to first identify on which of these the temperature community could have the greatest impact. The grand challenges had two loci; societal needs and industrial needs and it was recognised that both were underpinned by basic metrology research into improving the realisation and dissemination of the kelvin (with particular emphasis on shrinking the traceability gap between the NMI and the user). Four triggers in particular were identified:

- Global warming - aiming to reduce carbon dioxide emissions, transition to a low carbon economy whilst in the short to medium term improve monitoring measures including establishing traceability for data series
- High value manufacturing – in particular enhancing competitiveness through optimum use of resources (raw materials and energy) and improving process control to facilitate "zero waste" manufacture and improved product quality, lifetime, and user benefits
- Energy (supply and security) – through supporting sustainable generation, increasing the amount of renewables and low carbon dioxide generation methods (eg nuclear, carbon capture storage [CCS]) in the energy mix and supporting energy efficiency measures through improved thermal efficiency and utilisation of energy
- Health, safety and security – advanced traceable temperature measurements for example in hospitals for safe active thermal therapies (eg cancer ablation) and in ports of access (buildings and boarders) for pandemic control

The development of the SI unit the kelvin itself is an underpinning foundation to helping solve these challenges. This means that <u>basic scientific metrology</u> required for <u>the development, realisation and dissemination of the SI unit the kelvin is an essential underpinning tool supporting the solution to all of the above triggers.</u>

On a practical level it is clear that the thermometry community has a lot to contribute to both understanding and addressing these grand challenges. For example improved thermometry (therefore optimising energy use), particularly by facilitating *in-situ* traceability and calibration will directly help achieve the EU's 20-20-20 goals (20% increase in energy efficiency, 20% reduction in carbon emissions and 20% renewables by 2020). While more generally it is clear that temperature is the fundamental quantity involved in a wide range of climate change investigations both identifying causes and formulating mitigation actions.

Whilst it is clear that some of these triggers are interlinked it is also clear that these are distinct challenges and need to be addressed not just by Europe but also by many nations in the coming decade/s.

<u>3. Addressing the societal challenges (triggers): Targets</u>

With the triggers clearly identified targets needed to be identified that could address, these challenges. It is necessary to say at the outset that the thermometry community cannot address these challenges alone but, together with other disciplines, would form part of the solution to these challenges.

Specific targets were identified these were:

- Improved thermal measurements for meteorology – this includes air and sea (surface) temperature, radiometric temperature (including space based radiometry) and also humidity and moisture measurement [4, 6]. The focus of this target is on addressing the Global Warming trigger.
- Improving process efficiency – the loci of this target was on optimising process control. Its focus was on a) High Value Manufacturing where improved temperature measurement will have an impact on the competitiveness of European industry, particularly those which are

energy intensive (eg iron and steel, carbon-carbon composite manufacture, ceramics and glass) and b) the target also contributes to improving the efficiency of energy production and utilisation, for example in producing nuclear fuel and improved temperature measurement in electrical generation turbines. This target also has an impact on Global Warming for example promoting efficient (optimum) use of energy and so reduces carbon dioxide emissions eg through facilitating the optimum design and running of aerospace engines.

- Increased use of traceable temperature measurement – it was felt that all the triggers could benefit from this target. Better monitoring of Global Warming would be effected through strengthening traceability links to national standards [7]. Better Healthcare could be implemented particularly through developing new robust means of delivering traceability to the kelvin in active therapies such as high intensity focused ultrasound. High value manufacturing and energy production and in particular use would be improved if there were better links to traceable temperatures – in particular if *in-situ* traceability was widely implemented.
- Improved security at access points – This addresses particularly the Safety and Security trigger where better monitoring of human temperatures could inhibit or even prevent the spread of diseases in pandemic situations. This includes at airports, but also access to critical installations such as security facilities.
- Fast response multipurpose dynamic measurements – real time dynamic temperature sensing would further facilitate process efficiency and can be seen as the next step in the "Improved process efficiency" target – supporting the triggers of Global Warming, High Value Manufacturing and Energy.
- In the longer term increasing computer power (through quantum computing) – this is a potential growth industry in the future requiring accurate temperature measurement at very low temperatures and so supports the High Value Manufacturing trigger.
- Finally underpinning all these targets is the proposed redefinition of the kelvin in 2015, and subsequent deployment of the *mise en pratique* for the definition of the kelvin (*MeP*-K) [represented by a bar in the roadmap]. Continued research is essential to ensure the continuing fitness of the basic metrology infrastructure concerning the realisation and dissemination of the kelvin, and for maintaining the international competitiveness of the EURAMET TC-T community. Also it is required to prepare EURAMET TC-T for any possible new temperature scale anticipated in the 2020's. In addition capacity building support will be provided to ensure that regional temperature metrology requirements are met in an efficient manner.

4. Experimental realisation: meeting the targets

After identifying a set of generic societal and specific targets the roadmapping group then focused on more technical matters seeking to identify what specific experimental realisations were required to meet the targets. In addition background documents informed the discussion relating to the outputs of a workshop that considered the implications of the kelvin redefinition [8] and the *mise en pratique* for the definition of the kelvin [9, 10].

Specific experimental realisations that were identified were:

- Thermometry aimed specifically at meteorology applications. This includes the development of new calibration methods, equipment and good practice guidance. Procedures will be developed specifically for the climate community to facilitate the establishment of reference sites and networks for the generation of data completely characterised in terms of traceability and uncertainty. Self-validation will be included as large scale sensor re-calibration for remote stations and instrumented buoys is not practical.
- Addressing the targets for improved process control, increasing use of traceable temperatures and dynamic measurements with the development of specific temperature

metrology tools requiring stable sensors (or reliable remote (ie non-contact thermometry)) in harsh environments. This would be complemented by developing the means for *in-situ* traceability including novel means of self-validation for contact thermometers and correcting for emissivity and reflected radiation in non-contact thermometry [11] and also for distributed thermometry where temperature measurement information over large areas, or a large number of sensors was measured.

- The targets for improved security at ports of access requires *in-situ* traceability for the temperature sensors and thermal imagers used to monitor the passage of individuals. A pre-requisite of this is a rigorous understanding of the traceable calibration of thermal imagers *per se* which is currently a poorly understood process.
- The target focused on the step change in computing power envisaged by the advent of truly quantum computing requires reliable small scale thermometry. In addition new industries based on nano-technology will require reliable thermometry at the small scale.
- The measurement of heat is difficult to perform reliably and work needs to be undertaken to improve this situation particularly for improving efficient use of energy (eg in district heating and cooling networks) and health care.

A new temperature scale beyond 2020 may well be required and research in the latter part of this decade will be necessary to support such a requirement. However for now it is clear that the defined scales, together with the primary thermometry methods accessed through the mechanism of the *MeP*-K adequately serve the needs of the user community, at least in terms of basic scale realisation and dissemination.

5. Metrological application of basic science and enabling science and technologies

The last two parts of the roadmap, “metrological application of basic science” and “enabling science and technologies” are here considered together.

New primary thermometry and in particular practical primary thermometry was seen as an important objective for the proper implementation of the *MeP*-K. Priorities for primary thermometry are summarised in [8] and methods such as radiometry, dielectric constant, acoustic, Doppler broadening, electrical noise are all possibilities. One example is the requirement to assign thermodynamic temperatures to a set of high temperature (metal-carbon eutectic) fixed points to facilitate improved high temperature primary thermometry above the silver point, both by contact and non-contact thermometry. An example of a requirement for practical primary thermometry is where long term monitoring of temperatures over decades or even longer (eg in a nuclear waste store) where stability is essential but retrieval of sensors for recalibration is impractical. Practical primary thermometry is also an important strand of technology that will address the requirement for *in-situ* traceability.

Following on from that, new thermometers, that are robust, stable and/or capable of self-validation are all required if the targets are ever to be properly addressed. These could include robust forms of pure thermoelement thermocouples; thermocouples or resistance thermometers with incorporated fixed point references; self-calibration of radiation thermometers (and thermal imagers) through the advent of *in-situ* [ie within the industrial setting itself] stable and traceable temperature references. New technologies mean that new temperature sensors (eg new thermocouples) may be developed that will need characterising and reference functions developing.

Underpinning technologies are incremental improvements to the current fixed points for the ITS-90, for example understanding the effects of impurities, eg by traceable analytical chemistry, and of thermal conditions leading to optimal realisations. Improved thermal environments for calibrating and characterising the new sensors; possible replacements for current sensors such as the problematic high temperature platinum resistance thermometer with for eg an optimised Au/Pt thermocouple, new fixed points based on for eg metal-metal eutectics may have significant contributions to make to improving thermometry and calibrations in the future.

Developments in parallel fields are also essential to drive forward the dissemination of these projected improvements for example high temperature emissivity measurement capability and rugged electronics capable of operating in harsh [eg high temperature] environments (such as in or close to aerospace engines), whilst miniaturisation and widespread use of wireless technology is required to facilitate distributed thermometry.

By the routine use of atomic force microscopes, scanning tunnelling microscopes and the like in the future small scale micro and nano thermometry methods are likely to grow in importance. Possible thermometry methods are for eg raman scattering in solids, micro-fluorescence, advanced thermal microscopy are all in use/under development but the issue of traceably on the small scale has yet to be addressed. More conventional thermometry methods at lower temperatures still needing development are for eg. magnetic and noise thermometry. At the very small scale in low particle number systems, where equipartition may not have taken place, careful thought will have to be given to ensure that the concept of temperature itself still applies.

6. Comparison with previous roadmap

It is useful to compare the new temperature roadmap with the old ones. This roadmap was constructed in the light of experience gathered from the previous roadmapping exercise and also in formulating EMRP proposals. When the comparison is made several issues are worth noting:

- In the previous roadmapping exercise Thermal Properties (Quantities) were included on the same map as Temperature, this led to two roadmaps being formed. This time Thermal Properties (Quantities) experts undertook a separate roadmapping exercise. Because of this the temperature experts were able to focus specifically on the future needs of the temperature measurement community and as a result only one roadmap was needed to cover the technical field.
- The first roadmap sometimes had an optimistic view regarding timescales of the scientific and technological advances that would be achieved to enable the required improvements in thermal metrology. For example issues concerning isotopic and impurity problems in fixed points: traceability in chemistry was supposed to be solved around 2010 but it is still an on-going problem with little likelihood of a complete solution in the near future. Knowledge that the community was too optimistic in some cases last time enabled more realistic timescales to be set on the new roadmap. Saying that some objectives were achieved broadly on time; determination of the Boltzmann constant with an uncertainty of ~1ppm is still on track for 2012, and by acoustic thermometry has already been achieved. Consequently, work to determine the Boltzmann constant devoted to the redefinition of the kelvin is no longer included in this roadmap.
- Generally the temperature measurement community has a greater awareness of societal needs than it had during the previous roadmapping process. This is partly due to the experience of participating in bidding for and running EMRP projects. This is also obtained through an increasing liaison with relevant bodies, committees, scientific communities operating in areas such as Industry, Energy, Health and Environment. As a result this roadmap seeks to address those societal needs more directly than the previous ones. So despite the triggers being substantially the same, the targets are now clearer, less vague and more "useful" in the sense that they are in most cases, focused more on “applied” rather than “pure” metrology.

7. Conclusions

Roadmaps are only ever a snap shot of requirements which is why they are in need of regular revision. This exercise indicates that significant research and development is required on a broad front by the thermometry community if it is to play its part in meeting the grand challenges that society faces now and in the future. It is envisaged that the research areas identified by this roadmapping exercise will inform and guide the direction of thermometry research in the EURAMET NMIs over the next decade.

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