Title: Novel techniques for traceable temperature dissemination

Abstract

Temperature influences almost every physical, chemical, and biological process. It determines the efficiency of thermal engines and industrial processes, the speed of chemical reactions and the reproduction of living cell etc. Temperature is one of the most frequently and widely measured parameters and its accurate and traceable measurement is critical for ensuring reproducible processes.

The International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale of 2000 (PLTS-2000) are currently the only internationally agreed mechanisms for approximating the kelvin in accordance with the International System of Units (SI). However the ITS-90 has limitations and can be improved, thus leading to increased longevity for the scale. There is a need to develop new measurement techniques and improve the performance of novel temperature sensors to provide practical methods for disseminating the kelvin in the most efficient way to support its wider and simpler dissemination to users.

Keywords

Applied thermometry, Mise en Pratique for the kelvin, thermodynamic temperature, International Temperature Scale of 1990, ITS-90, PLTS-2000, novel sensors, fixed points, standard platinum resistance thermometers, radiation thermometers

Background to the Metrological Challenges

The International Temperature Scale of 1990 (ITS-90) and the Provisional Low Temperature Scale of 2000 (PLTS-2000) [1] are currently the only internationally agreed mechanisms for approximating the kelvin in accordance with the International System of Units (SI). In particular, below the silver point (961.78 ºC) most realisation and dissemination of temperature will continue to occur via the ITS-90 [2-4] because no 'thermodynamic' thermometer (i.e. one which measures a quantity that can be related to temperature via basic physics) has achieved the necessary repeatability and reproducibility. However the ITS-90 has limitations [5, 6] and can be improved, thus leading to increased longevity for the scale [5]. Recent research, for example in the EMRP project SIB10 NOTED 'Novel techniques for traceable temperature dissemination', has addressed a number of limitations of ITS-90 but further improvements are required. Improvements to the lifespan of the ITS-90 would benefit industry and other end users as any changes in the scale definition can have a profound practical and economic impact. For example, when the IPTS-68 was changed to ITS-90 some users noted that the corresponding 5 mK change at 20 °C was sufficient to influence precision dimensional metrology.

At present the traceability of temperature measurements to the kelvin is ensured at a practical level by means of calibrated SPRTs and radiation thermometers. The best attainable uncertainties are of the order of tenths of a millikelvin close to the triple point of water (0.01 °C) and up to the order of a millikelvin or more at the freezing point of silver (961.78 °C) in contact thermometry, rising to hundreds of millikelvin in radiation thermometry.

In Europe several NMIs have developed limited capabilities to assemble and study fixed point cells for the calibration of thermometers, but no attempt has been made to establish a distributed, coherent and comprehensive European capability to design, produce and fully characterise fixed point cells. The establishment of such a capability would contribute to the improvement of the ITS-90 and would prepare the ground for the future ITS-XX. Several procedures for construction of fixed point cells have been developed, and significant advances made in understanding the influence of thermal and impurity effects on the practical realisation of the fixed points. Modelling and numerical studies have improved the ability to handle the complexity of phase transition behaviour, interaction with the surroundings, and other parameters (furnace profiles, initiation techniques, self-heating, etc.). These advances mean that it is now appropriate for a joint European effort towards establishing a coordinated capability for the construction of a new generation of comprehensively characterised fixed point cell standards.

There is an increasing need for low measurement uncertainties for secondary thermometers, i.e thermometers that are not interpolating instruments of the ITS-90, over specific ranges and for very specific purposes. For example, in some cases it is necessary to achieve sub-millikelvin uncertainties for calibration by comparison at temperatures close to ambient temperature (20 ºC) for dimensional calibrations in nanometrology, in ionising radiation metrology (water calorimeters at 4 ºC) or in oceanography to investigate the warming of deep ocean. Due to their designs these secondary thermometers cannot be calibrated using conventional fixed point cells according to the ITS-90 so specific calibration facilities and procedures are required. Procedures for calibrating secondary standard thermometers are well established but the best uncertainties currently attainable in the medium temperature range (-50 ºC up to 275 ºC) are typically several millikelvin. In the cryogenic range (0.5 K up to 25 K) the Rh-Fe resistance thermometer is the instrument of choice for dissemination of the kelvin, however it must be calibrated by comparison as it is not an ITS-90 interpolating instrument. Uncertainties of the order of millikelvin can be achieved but only by using a large number of calibration points with the resultant associated cost and time.

Several novel temperature sensors, which show considerable promise and are highly accurate and simple in use, have been developed and/or characterised recently, but require further improvements to their performance or to the associated instrumentation to improve the resolution and stability. Considerable progress has been made on a sapphire-based whispering gallery mode thermometer which can attain a resolution of better than 1 mK and stability at 0 °C of better than 3 mK. Acoustic thermometers, both resonator-based and using waveguides, have shown sensitivity comparable with a platinum resistance thermometer, but at much lower cost. Further research is required to achieve lower uncertainties and to develop user friendly devices. Other sensors, such as the Au/Pt thermocouple, could transform dissemination of ITS-90 between 660.323 °C (Al freezing point) and 961.78 °C (Ag freezing point), as these sensors constructed with currently available materials are competitive and simpler alternatives to the complicated high temperature platinum resistance thermometer. These sensors however require a detailed evaluation of their stability in comparison with the high-temperature standard platinum resistance thermometer, together with a better understanding of the relationships between thermoelectric homogeneity and deviation from the reference function and between heat treatment and thermoelectric homogeneity.

The use of infrared radiation thermometers has become increasingly widespread in recent years and will continue to increase in the future. The measurement of temperature via non-contact methods is easier, quicker and, in some cases, the only possibility. A novel prototype of a tuneable (from 1.2 nm to 1.8 µm) near infrared (NIR) radiation thermometer has recently been developed with very promising performance (wavelength tuneability about 600 nm, wavelength accuracy about 0.01 nm, stability over 24 h about 0.1 %, optical detectivity about 100 fW @ 1 Hz) and with a relative standard uncertainty of the calibrated spectral radiance responsivity of about 0.1 %, which is comparable to the uncertainties achievable with the highest metrological level non-imaging filter radiometers operating at this wavelength. However, further metrological characterisation and absolute calibration together with the validation of the associated multi-spectral techniques for the temperature determination is required. These recent achievements have demonstrated that the absolute, detector based radiometric calibration (i.e. directly to the thermodynamic temperature) of infrared radiation thermometers is feasible but in order to assess temperatures below 500 °C using radiation thermometry it is necessary to extend and increase this capability to longer wavelengths and to different detector-based devices.

Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the protocol.

The JRP shall focus on practical methods for disseminating the kelvin through a joint distributed temperature metrology network, to support its wider and simpler dissemination to users.

The specific objectives are

1. To develop a distributed capability for the construction of a new generation of fully characterised fixed point cell standards, in the range from -110 ºC up to 420 ºC, to improve and harmonise the dissemination of the kelvin in Europe. This objective includes the establishment of clear reference procedures, standardised chemical characterisation of the

impurities in fixed point materials, isotopic composition, and thermal characterisation, i.e. interaction with different interface morphologies arising from the cell's thermal environment, geometry, and impurities, including thermodynamic and numerical modelling.

2. To develop improved and new calibration procedures and facilities for secondary contact thermometers, i.e. thermometers that are not defined as interpolating instruments of the International Temperature Scale of 1990 (ITS-90), with target uncertainties at the millikelvin level and below for specific needs or applications (e.g. resistance thermometers used in length metrology, ionising radiation metrology, oceanography, etc.), or temperature ranges (e.g. the Rh-Fe thermometer from 2 K to 24 K).
3. To develop and/or perform the metrological characterisation of novel temperature sensors or measurement principles which, while maintaining the accuracy of an ITS-90 interpolating instrument and the precision of fixed points, could be highly simplified in its use (e.g. whispering gallery mode thermometer, Au/Pt thermocouples, nanothermometers and acoustic thermometry).
4. To develop and improve the absolute calibration and measurement capabilities for radiation temperature in the infrared range. This objective is twofold: to establish a distributed infrastructure allowing the combined radiometric / fixed point based calibration of infrared radiation thermometers in the mid-infrared (MIR) wavelength range (from 2 µm up to 5 µm) and to perform the metrological validation and absolute radiometric calibration (i.e. calibration in terms of thermodynamic temperature) of novel, tuneable near infrared (NIR) wavelength radiation thermometers and the evaluation of the associated multi-spectral techniques for the temperature determination and dissemination.
5. To facilitate the take up of the technology and measurement infrastructure developed by the project by the measurement supply chain (other NMIs, accredited laboratories, instrument manufacturers etc).

These objectives will require large-scale approaches that are beyond the capabilities of single National Metrology Institutes and Designated Institutes. To enhance the impact of the research work, the involvement of the larger community of metrology R&D resources outside Europe is recommended. A strong industry involvement is expected in order to align the project with their needs and guarantee an efficient knowledge transfer into industry.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this. In particular, proposers should outline the achievements of the EMRP project SIB10 NOTED and how their proposal will build on those.

EURAMET expects the average EU Contribution for the selected JRPs in this TP to be 1.8 M€, and has defined an upper limit of 2.1 M€ for this project.

EURAMET also expects the EU Contribution to the external funded partners to not exceed 21 % of the total EU Contribution to the project. Any deviation from this must be justified.

Any industrial partners that will receive significant benefit from the results of the proposed project are expected to be unfunded partners.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links to the "end user" community, describing how the project partners will engage with relevant communities during the project to facilitate knowledge transfer and accelerate the uptake of project outputs. Evidence of support from the "end user" community (e.g. letters of support) is also encouraged.

You should detail how your JRP results are going to:

- Address the SRT objectives and deliver solutions to the documented needs,
- Feed into the development of urgent documentary standards through appropriate standards bodies,
- Transfer knowledge to temperature instrumentation manufacturers, calibration and testing laboratories and the manufacturing sector.

You should detail other impacts of your proposed JRP as specified in the document "Guide 4: Writing Joint Research Projects (JRPs)"

You should also detail how your approach to realising the objectives will further the aim of EMPIR to develop a coherent approach at the European level in the field of metrology and include the best available contributions from across the metrology community. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of EURAMET Member States whose metrology programmes are at an early stage of development to be increased
- organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of up to 3 years duration.

Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] http://www.bipm.org/en/committees/cc/cct/publications-cc.html#kelvin-and-temperature-scales

[2] CCT Workshop "Toward the ITS-XX", Chicago, 25 October 2002, CCT Document CCT/03-01

[3] Report of the CCT 24th meeting (22 –23 May 2008) to the International Committee for Weights and Measures. http://www.bipm.org/utils/common/pdf/CC/CCT/CCT24.pdf.

[4] New Kelvin dissemination workshop held at NPL on 27-28 October 2010. G. Machin et al. Metrologia 40 (2011) 68-69.

[5] Uncertainties in the SPRT Subranges of ITS-90: Topics for further research. D. R. White et al. Int. J. Thermophys. (2010) 31:1749-1761.

[6] Uncertainties in the Realisation of the SPRT Subranges of the ITS-90. CCT/08-19/rev. http://www.bipm.org/cc/CCT/Allowed/24/D19_rev_WG3_Doc_rev_10July2009.pdf.