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The European Metrology Programme for Innovation and Research project: Implementing the new kelvin 2 (InK2)

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Abstract. The International System of Units (SI) is to be redefined with implementation set to be on World Metrology Day (20th May 2019). Under the auspices of the Consultative Committee of Thermometry (CCT) the world thermometry community has been working together to ensure a smooth and effective redefinition of the kelvin. A large part of that activity has been coordinated through the European Metrology Programme for Innovation and Research: “Implementing the new kelvin” projects. This paper describes the InK2 project contribution.

1. Introduction

The SI is currently defined through a heterogeneous mix of classical and fundamental constant approaches [1]. When the SI redefinition comes into force that will change and the SI will be based on a defined set of fundamental constants [2, 3]. This makes a complete separation of the unit definition from the realization meaning that the definition can remain unchanged whilst the realisation can evolve with technological advances.

The kelvin, currently based on a defined value of the water triple point [1], will in future be based on a defined value of the Boltzmann constant [4, 5]. The redefined kelvin will be implemented and regulated through a document prepared by the Consultative Committee of Thermometry (CCT), the *mise en pratique* for the definition of the kelvin (*MeP-K-19*) [6]. The *MeP-K-19* describes primary thermometry methods suitable for a direct realization of the redefined kelvin and also includes the text of the two current defined temperature scales, the International Temperature Scale of 1990 (ITS-90) [7] and the Provisional Low Temperature Scale of 2000 (PLTS-2000) [8].

Since 2012 much of the background research necessary to ensure an effective kelvin redefinition has been performed through the “Implementing the new kelvin” (InK) projects. The results of the InK1 project, completed in 2015, were summarized in [9, 10]. The InK2 project has been underway since June 2016 and has focused on four main activities:

1. To undertake thermodynamic temperature measurement in the range ~430 K to ~1358 K
2. To undertake thermodynamic temperature measurement in the range ~5 K to ~200 K
3. To develop and use three novel primary thermometry methods
4. To improve low temperature thermodynamic thermometry between 0.9 mK – 1 K

In this short paper it is impossible to give technical details of the various primary thermometry approaches pursued in InK2, the interested reader is referred to [9, 11, 12]. Progress with the InK2 project can also be followed through the InK2 website [13]. Here we briefly describe progress made in the four areas of research. This is initially focused on establishing capability to measure $T-T_{90}$ (activities 1 and 2) and $T-T_{2000}$ ¹ (activity 4) and to establish the novel thermometry approaches (activity 3). The paper concludes with an outlook to project completion and ongoing research requirements are outlined.

¹ The quantities $T-T_{90}$ and $T-T_{2000}$ represent the difference between the temperatures realised using thermodynamic approaches and temperatures realised using the defined scales (ITS-90 or PLTS-2000)



2. Thermodynamic temperature measurements in the range ~430 K to ~1358 K using high temperature acoustic and low temperature radiometric thermometry

The thermodynamic thermometry approaches used here are high temperature acoustic gas thermometry (AGT) [14], which measures temperature through determining the speed of sound in a gas such as Ar, and low temperature primary radiometry [15], which measures temperature by determining the spectral radiance emitted by a blackbody. The ITS-90 values [7] will be realised from calibrated long stem standard platinum resistance thermometers (SPRTs), gold-platinum (Au/Pt) thermocouples or via fixed points. The temperature range investigated in these measurements is between the freezing point of In (~430 K) and the freezing point of Cu (~1358 K). Measurements will be performed by LNE-CNAM, PTB, CEM², NIM³ and NPL.

The low temperature primary radiometry measurements will be performed from the Sn freezing point (~505 K) to the Cu freezing point using radiometers calibrated directly or indirectly to optical power (see for e.g. [15] which describes the radiometer used by NPL). The blackbodies are of two types:

- A set of high performance fixed-point blackbody sources (Sn, Zn (~693 K), Al (~933 K), Ag (~1235 K) and Cu) will be used to compare the ITS-90 defined temperatures to new evaluations of the thermodynamic temperatures of the fixed points. Some initial results have already been obtained.
- A range of heat-pipe based variable temperature blackbody sources [16, 17], whose ITS-90 temperature is determined by long stem SPRTs (or Au/Pt thermocouples), will be measured by the radiometers operating at different wavelengths to give thermodynamic temperatures. These measurements will be used to determine $T-T_{90}$ over a range of temperatures.

The high temperature acoustic gas thermometry will cover the temperature range from the In freezing point to the Al freezing point. NPL and NIM are undertaking these measurements. At NPL an air bath thermostat has been constructed and the measurement artefact will be a cylindrical resonator, initially made from Al and then for the higher temperatures from Inconel. The air bath thermostat has already been constructed and measurements begun with the initial research focused on quantifying corrections such as the effect of temperature gradients on the acoustic waveguides.

It is anticipated that the primary acoustic thermometry may achieve uncertainties of order ~0.005 K⁴, whereas the primary radiometry uncertainties are likely to be ~4x higher.

3. Thermodynamic temperature measurement in the range ~5 K to ~200 K using low temperature acoustic, dielectric constant and refractive index thermometry

The thermodynamic thermometry approaches used here are; dielectric constant gas thermometry (DCGT) [18] over the sub-ranges ~40-80 K and ~140-200 K, AGT [14, 19] and Refractive-Index Gas Thermometry (RIGT) [20]. In the temperature range ~5 K and ~200 K. Measurements will be performed by the LNE-CNAM, PTB (DCGT) and INRIM⁵. In addition the TIPC-CAS⁶ will also undertake primary RIGT [20]. The ITS-90 values [7] will be realised using calibrated capsule (c-)SPRTs.

For DCGT the first measurement campaign between ~40-80 K is underway using He and Ne as working gases. For RIGT, INRIM, LNE-CNAM and TIPC-CAS are in the process of establishing their apparatus for the measurements. The equipment at LNE-CNAM has the additional sophistication in that it will perform primary thermometry using RIGT and AGT in the same apparatus allowing for the rigorous assessment of systematic sources of uncertainty in both approaches. Finally LNE-CNAM is in the process of modifying its current AGT apparatus to perform absolute primary thermodynamic temperature measurements with a primary pressure standard (piston gauge) to ensure the lowest uncertainties possible. The target uncertainties for these measurements are 0.5 mK and the RIGT and AGT measurements will be undertaken in 2018.

4. Develop three novel primary thermometry methods (Doppler Broadening and Double Wavelength Thermometry and Radiation Thermometry Traceable to Synchrotron Radiation)

This part of the project focuses on establishing three novel primary thermometry approaches to measure thermodynamic temperature and $T-T_{90}$ using electromagnetic radiation. The methods being developed

² CEM, the Centro Español de Metrología, Madrid, is the Spanish National Metrology Institute

³ NIM, the National Institute of Metrology, Beijing, is the Chinese National Metrology Institute

⁴ Uncertainties are given in coverage factor one i.e. $k=1$.

⁵ INRIM the Istituto nazionale di ricerca metrologica, Turin is the Italian National Metrology Institute

⁶ The Technical Institute of Physics and Chemistry-Chinese Academy of Sciences, Beijing

are; Doppler broadening thermometry (DBT) [21], double wavelength radiation thermometry (DWT) [11] and radiation thermometry traceable to synchrotron radiation (RTSR) [12]. The institutes involved are; PTB, LNE-CNAM, INRIM, TUBITAK⁷, UniCampania⁸, UP13⁹ and VNIIOFI¹⁰.

Primary DBT will be realised, for the first time, from the Hg triple point (~234 K) to the In freezing point (~430 K). UniCampania is optimising a comb-calibrated dual-laser absorption spectrometer, operating at 1.4 μm and probing a C_2H_2 line-doublet. UP13 is planning to use mid-infrared spectroscopic apparatus based upon a quantum cascade laser to probe the shape of an isolated NH_3 line. In both experiments, the Doppler width and, consequently the thermodynamic temperature of the gas, is retrieved as a result of a sophisticated spectral analysis procedure [21].

DWT [11] will measure temperatures in the range from the Cu freezing point (~1358 K) to the Re-C melting point (~2747 K). The main (potential) advantage of DWT is that its results are independent of absolute optical power measurements, whereas those of classical filter radiometry are not. The method uses the ratio of irradiances (at two different temperatures and measured with two filter radiometers of different central wavelengths) to determine thermodynamic temperature. LNE-CNAM and TUBITAK will each develop a DWT instrument, with the LNE-CNAM device using an acousto-optic tunable filter.

Finally RTSR [12] is being developed by PTB. A four-wavelength ratio filter radiometer with one common precision aperture has been constructed and preliminary measurements underway at the metrology light source in Berlin. The objective is to take advantage of the fact that the emission from a blackbody and synchrotron are calculable and use the latter to determine the temperature of a high temperature black body source (in this experiment a large area Re-C fixed point).

5. Improve low temperature thermodynamic thermometry methods at low temperatures to resolve issues with the background data of PLTS-2000 (down to 0.9 mK)

Research activities are being performed in the ultra-low thermometer regime from 0.9 mK to 1 K with the two fold purpose of; a) demonstrating that primary low temperature thermometers are able to directly disseminate thermodynamic temperature and b) ascertaining the relationship between thermodynamic temperature and the PLTS-2000, and so resolving the discrepancy in the PLTS-2000 background data. The institutes involved in this work are; PTB, VTT-MIKES¹¹ and the low-temperature research groups at Aalto University, Royal Holloway University of London and Lancaster University.

Three different primary low-temperature thermometers are being developed and improved, namely two SQUID-based noise thermometers, the current sensing noise thermometer (CSNT) [22] and the primary magnetic field fluctuation thermometer (pMFFT) [23], as well as the Coulomb blockade thermometer (CBT) [24], which is based on a completely different working principle. All these thermometers have been shown to consistently measure thermodynamic temperatures with uncertainties of less than 1% in the temperature range from 1 K down to 20 mK. The current research focuses on the temperature range from 20 mK to 0.9 mK where the PLTS-2000 background data diverges by up to 6%. At these ultra-low temperatures factors such as parasitic heat input from the environment, influences of external electromagnetic fields, and increasing thermal resistance between the thermometer and measurement object become increasingly significant, and need careful investigation to ensure the correct temperature is being measured.

The results will be made available to all stakeholders by providing international guidelines for realising thermodynamic temperatures with the developed techniques¹².

6. Outcomes and future research requirements

Good progress has been made in the preparation for the measurement phase of the InK2 project. Significant new or modified apparatus has been constructed and measurements will begin in earnest in Spring 2018, with the expectation that diverse data sets of $T-T_{90}$ and $T-T_{2000}$ will have been determined by early 2019. In spring 2019 a high level meeting will be held describing the project and its outcomes. This will be followed by a CCT workshop where the framework for developing revised consensus

⁷ Turkiye Bilimsel ve Teknolojik Arastirma Kurumu, is the Turkish National Metrology Institute

⁸ Universita degli Studi della Campania Luigi Vanvitelli

⁹ Université Paris 13, France

¹⁰ Federal Unitary Enterprise "All Russian Research Institute for Optical and Physical Measurements"

¹¹ VTT-MIKES is the Metrology Institute of Finland

¹² This research is supported by European manufacturers of cryogenic equipment such as Oxford Instruments NanoScience (UK), Bluefors (Finland), Magnicon (Germany) and Aivon Oy (Finland).

values of $T-T_{90}$ and $T-T_{2000}$ from all the new measurements will be agreed. It is anticipated that these new consensus values will be prepared in the period leading up to the next CCT in March 2020.

After the implementation of the SI redefinition in May 2019 the thermometry community will focus its research on realization and dissemination activities arising from the *MeP-K-19*. Although significant effort has been expended in the redefinition of the kelvin, the redefinition itself is just the start of the larger realization and dissemination phase. Significant research effort is anticipated in the following:

- In the primary thermometry section of the *MeP-K-19* to establish the means of realizing and disseminating the redefined unit. This is especially pertinent at high (>Ag point) and low temperatures (initially <1 K (i.e. the PLTS-2000 regime) and in the medium term up to the Ne triple point (~25 K)).
- In undertaking research to extend the life of the ITS-90 to give opportunity for the primary thermometry methods (in the *MeP-K-19*) to develop and mature. One significant research activity will be to find an alternative to the Hg triple point (~234 K). This is because the use of Hg in the medium term may be banned by international convention.
- In undertaking research in preparation for a possible successor scale to ITS-90, the so-called ITS-XX. In the longer term (late 2020s) it may be found that primary thermometry will not achieve the performance required by industry, science and research. If that is the case then a successor scale, the ITS-XX, may be needed. The requirements for such a scale have already been outlined in [25]. It is likely that such a scale will have a limited range being restricted to the “middle” temperature range with high and low temperatures served by primary thermometry linked directly to the redefined kelvin.

Summary to ensure that temperature realization and dissemination remains fit for purpose into the 2020s and beyond, a large research effort is required to bring the redefinition and explicitly the thermodynamic parts of the *MeP-K-19* to life.

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