The impact of the kelvin redefinition and recent primary thermometry on temperature measurements for meteorology and climatology.

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ABSTRACT

All calibrations of thermometers for meteorological or climatological applications are based on the *International Temperature Scale* of 1990, ITS-90. Based on the best science available in 1990, ITS-90 specifies procedures which enable cost-effective calibration of thermometers worldwide. In this paper we discuss the impact for meteorology of two recent developments: the forthcoming 2018 redefinition of the kelvin, and the emergence of techniques of primary thermometry that have revealed small errors in ITS-90.

The kelvin redefinition. Currently, the International System Units, the SI, defines the kelvin (and the degree Celsius) in terms of the temperature of the triple point of water, which is assigned the exact value of 273.16 K (0.01 °C). From 2018, the SI definitions of these units will change such that the kelvin (and the degree Celsius) will be defined in terms of the average amount of energy that the atoms and molecules of a substance possess at a given temperature. This will be achieved by specifying an exact value of the Boltzmann constant, k_B, in units of joules per kelvin. Thus after 2018, measurements of temperature will become fundamentally measurements of the energy of molecular motion. However, because thermometers will continue to be calibrated according to the procedures specified in ITS-90, this will have no immediate effect on the practice of meteorology.

Errors in ITS-90. Since 1990, the primary thermometry technique known as *acoustic thermometry* has improved to an extraordinary extent. Acoustic thermometry measurements are now capable of detecting errors in the primary thermometry used to construct ITS-90, and hence in ITS-90 itself. Over the meteorological range these errors are small but they are present in <u>*every*</u> calibrated thermometer on Earth. The errors vary approximately linearly between ≈ +0.005 K at ~ +50 °C, and ≈ -0.003 K at ~-30 °C. Errors of this magnitude are unlikely to concern meteorologists, but if there is in future a shift away from ITS-90 to a new *International Temperature Scale*, then the concomitant shifts in practical temperature calibrations may be just detectable by homogenisation algorithms used in climate studies.

1 TEMPERATURE MEASUREMENTS IN METEOROLOGY

1.1 INTRODUCTION

Temperature measurements form the experimental foundation of modern quantitative meteorology and climate science. This role arises from three features of temperature measurement.

Firstly (and most obviously) temperature is critically important for understanding the evolution of the weather, the climate, and their impact on human activity.

The second feature of temperature measurement that cements its foundational status is that extensive measurements using standardised instruments have been available for several hundred years [1]. In contrast measurements of other quantities of meteorological interest suffer from larger uncertainties, or their measurements are less spatially or historically complete.

The final feature is that measurements of temperature can be related to the thermodynamic properties of moist air [2] with low uncertainty. It is this feature that makes it important that temperature measurements can be made traceable to the definition of what we mean by one kelvin. Fortunately, despite numerous biases arising from siting, screening, representativeness, height, insolation and precipitation, meaningful uncertainties of below 1 K (~0.3% of thermodynamic temperature) are possible for meteorological temperature measurements. [3, 4]

It is this final feature, the relationship between meteorological temperature measurements and thermodynamic temperature, T, that is the topic of this paper.

In Section 2 we review the structure of the *International System of Units*, the SI and outline the rationale for the changes to the unit definitions planned for 2018. Readers only interested in temperature only may skip Section 2 and move straight to Section 3 where we detail the planned redefinition of the kelvin, and the role of the *International Temperature Scale of 1990* (ITS-90). In Section 4, we discuss the latest measurements of the errors in ITS-90.

1.2 IMPACT AND MOTIVATION

The unit redefinition planned for 2018 represents an important conceptual change of what we mean by one kelvin or one degree Celsius, and anyone involved in temperature measurement should be aware that the redefinition is about to happen, and of its consequences. In general, the consequences will initially be small. However, for meteorologists using sensors calibrated in accordance with ITS-90 it is possible to state unequivocally that you will *not* be affected by the re-definition. This is explained more fully in Sections 3.3 and 3.4

The detailed motivations for the redefinition of the SI base units are discussed in Section 2, but it may puzzle some readers that metrologists should be bothering to redefine a unit, when the immediate impact of the redefinition will be close to zero.

The answer is that the definition of a unit is part of the foundations of the SI, and the SI, like all complex structures, occasionally needs maintenance of its foundations. As with physical structures, work on foundations is often expensive and time consuming, and when completed there is little left to show for the expense. However, one is then able to build on those foundations with greater confidence knowing that in future, they will not ‘shift’ or ‘crack’ or ‘distort’. In short, the redefinition is not about solving problems we have today, but is instead building a stable foundation for centuries of future technological change.

2 The International System of Units

2.1 Introduction

The *International System of Units*, the SI [5] defines seven base units that form the foundation of measurements in the physical sciences. These consist of four 'core' units built upon the metre-kilogram-second-ampere (MKSA) system of units, and three additional units: the mole, candela and kelvin.

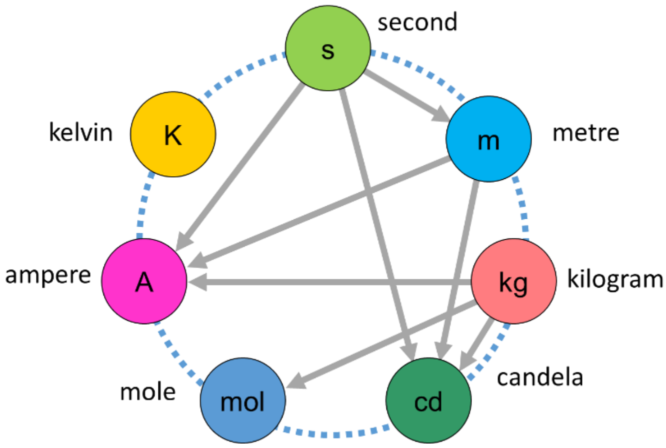


Figure 1: Representation of the links between seven base units of the *International System of Units*. Notice that the kilogram is a 'source definition', i.e. its definition affects the definition of, for example, the mole. Notice that the kelvin definition is currently not connected to the definition of any other SI base units

The SI is overseen by the *International Committee on Weights and Measures* (CIPM) and a series of consultative committees, one for each unit. The consultative committees contain measurement experts from states which are signatories of the Metre Convention (1875). Overall, the role of the CIPM is to make sure that the definitions of the units and the recommended procedures for their dissemination stay relevant to the needs of users worldwide. In recent years, CIPM has been concerned with two fundamental problems regarding the definitions of the kilogram and the ampere.

2.1.1 The kilogram problem

The 'kilogram' [6] is the basis of all mass measurements worldwide. One kilogram is defined as "the mass of the *International Prototype of the Kilogram* (the IPK)", a cylinder of platinum-iridium alloy held since 1889 in a safe at the *International Bureau of Weight and Measures* (BIPM) in Sèvres, near Paris. Nominally identical copies of the IPK were distributed to laboratories around the world and for the last 130 years have allowed mass measurements worldwide traceable to the mass of the IPK. However periodic comparisons (1889, 1948, 1989 and 2014) of the IPK with the national prototypes have shown that the national prototypes are changing mass with respect to the IPK [7].

By definition, the IPK always weighs one kilogram, but the implication of these inter-comparisons is that the mass of the IPK is also probably changing. However it is impossible even in principle to quantify the extent of this change, a state of affairs which is considered profoundly unsatisfactory.

2.1.2 The ampere problem

The 'ampere' was defined in 1961 as "the current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length"[8]. This definition implies 'realisation' of the ampere by methods involving force balances and considerable research effort was expended in order to build calculable resistors and hence derive standard resistances and voltages.

However in 1962, the Josephson Effect was discovered. In one version of this effect, when electromagnetic waves (typically microwaves) illuminate a junction between two superconductors, a DC voltage is generated across the junction. This DC voltage has a magnitude proportional to the frequency of the radiation, with a constant of proportionality known as the *Josephson Constant*, K_J. Significantly, as far as can be determined, K_J has a value equal to exactly $h/2e$ where h is the Planck constant and e is the elementary electronic charge. Numerous tests have shown that K_J has the same value independent of the material from which the junction is constructed. By illuminating arrays of such junctions with microwaves of known frequency, this discovery has enabled the generation of arbitrary (but calculable) known voltages with extremely low uncertainty.

Then in 1980, the Quantum Hall Effect (QHE) was discovered, in which the electrical resistance of a semiconductor could be stabilised in integer multiples of h/e^2. The equivalence of the resistance values has again been tested extensively in different materials. This discovery has enabled the realisation of electrical resistances in terms of a 'natural' unit of electrical resistance.

The Josephson Effect and the QHE have transformed electrical metrology, allowing realisations of the ampere, volt, and ohm with uncertainties at least 10 times better than conventional 'force-based' metrology [8]. So since 1990, electrical metrology worldwide has been based on these two quantum mechanical effects using our best estimates of h and e. Again this state of affairs is considered unsatisfactory because the unit as disseminated does not arise directly from the definition of the unit.

2.1.3 Solution to the kilogram problem

The solution to the kilogram problem has taken a long time to emerge and has required the development of two extraordinary projects.

In the first, known as the International Avogadro Project [9], artefacts have been created with a predictable mass but not based a relationship to the IPK. The artefacts created are extremely perfect single crystal spheres of isotopically-pure silicon-28 and their mass is determined by measurements of the shape and size of the spheres; their chemical and isotopic purity; and the lattice constant of the silicon crystal. Their mass is expressed in terms of a multiple of the atomic mass of ^{28}Si and the Avogadro constant, N_A This endeavour has involved laboratories around the world, and the artefacts created have demonstrated that it is possible in practice to create a known macroscopic mass from first principles. This could allow for the creation of a small number of these extremely expensive artefacts that could in principle be re-made periodically to check for slow changes in mass.

The second project involved the construction of devices previously known as Watt Balances [10], but now referred to as Kibble Balances. The naming is given in honour of Bryan Kibble who invented the principle of the Watt Balance and built the first working model. Kibble Balances allow measurement of mass in terms of the electrical power required to lift a mass at a known speed in a gravitational field. The balances look like conventional equal-arm balances with an unknown weight on one pan. The other pan is linked to a coil of wire that can either (a) fall through a magnetic field and generate a voltage or (b) be lifted through the same magnetic field by passing a current through the coil. Combining these two modes of operation with measurements of the speed of rising and falling allows the unknown mass to be determined in terms of electrical forces rather than as a comparison with the IPK.

Recently these techniques have reached a degree of perfection in which multiple Kibble Balances and Avogadro artefacts have been inter-compared and found to be in agreement at the level of 20 parts per billion i.e. they agree on the weight of a kilogram to within 20 micrograms. This level of agreement was judged sufficient by CIPM such that using these new technologies would avoid any disruption to the stability of mass measurements around the world. It is this advance in metrology that has opened the door to a redefinition a kilogram.

2.1.4 Summary of the motives for redefinition

Stimulated by the need to find a solution to the kilogram problem, and mindful of the need to refine the ampere, the CIPM have looked more widely at all the SI base units to look for consequences of the redefinitions, and possible further improvements.

Many options were available, but after lengthy consideration, it has been decided to step back from 'old style' definitions which create a unit definition in terms of the best technology available at a particular time, and instead create definitions based on the most stable things we know: the physical constants of the natural world. [11]

2.2 Definitions and Realisations

The main lesson to be learned from the 'kilogram problem' and the 'ampere problem' is that in order to avoid a series of repeated re-definitions of the SI units, with each definition chasing some unanticipated technological development, a new type of unit definition is required. We require definitions of units in which we separate what we mean by a unit (its definition), from the method in which copies of that unit are made in practice (its realisation).

Historically we have favoured unit definitions which are the opposite of this. We have preferred a form in which the definition of the unit also implies how copies of the unit should be realised. So for example, the kilogram definition implies that what we mean by 'one kilogram' is something with identical mass to the IPK. So in order to 'realise' a copy of the kilogram one needs to make an object of equal mass and check this equality on a balance.

Similarly definitions of lengths were historically made in terms of exquisitely-manufactured length artefacts. This historically defined 'what we meant by 1 metre' as being something of equal length to a standard bar.

Although these types of definitions are simple to understand and have good short-term reproducibility, they inevitably run into problems in the long term because every human artefact decays or changes in some way. Additionally artefact-based definitions are not truly international since there can only be one unique realisation of each artefact.

CIPM's radical proposal is to avoid using objects created by humans as standards. Instead they propose to use features of the natural world – the constants of nature – as the basis for all measurements. Their motivation is that the constants of nature are the most stable things we know. For example, the kilogram artefact (the IPK) is likely to be changing mass at a rate of approximately 1 part in 10^{10} every year. In contrast, recent measurements of a combination of fundamental constants known as the fine structure constant ($\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$) have been shown to be changing at rate of less than 2 parts in 10^{17} per year: at least one million times more stable than the kilogram [12, 13, 14].

So if we create a system of measurement defined in terms of constants of nature, then the concept of what we mean by a unit should remain unchanged, subject only to the constancy of the laws of physics.

The benefit of this is that these definitions can be exact, with no uncertainty, and they should remain unchanged even in the face of unanticipated technological developments. We should then be able to take advantage of developments in science and technology to improve the perfection with which we *realise* the unit definitions, and hence gradually improve practical metrology.

2.3 Making the Change

This kind of change has been done before. In 1983 the definition of the metre was changed to define a metre in terms of the speed of light in a vacuum, c, a quantity which we believe is universally constant and unchanging [15]. The procedure for making this change involved many years research to measure the speed of light (in metres per second) in terms of the previous definition of one metre and one second. When research groups independently measured c and their results agreed within the estimated uncertainty Δc at a low enough level, then the switch was made to the new definition.

Before the switch, the metre was defined as an exact length, specified as an exact number of wavelengths of light of a specified origin, and the speed of light c expressed in terms of this metre definition had an uncertainty Δc. After the re-definition, the speed of light c was considered to have an ***exact*** value with no uncertainty, and it now became our measurement standard. The metre was then defined as ***exactly*** the distance travelled in vacuum by light during the time $1/c$ seconds.

The uncertainty of measurement now arises from our ability to realise this exact definition in practice. As had been anticipated, over the relatively short period of 34 years since the redefinition, our concept of the speed of light in vacuum has not changed, and so neither has our definition of one metre. However, even over that relatively short period, our ability to *realise* that definition in practice has improved significantly due to developments in technology.

The plan for the 2018 re-definitions is similar. Since 2007 measurement scientists from around the world have been re-measuring fundamental constants, particularly the Planck constant h and the Boltzmann constant k_B. Measurements will continue until July 2017, but already (in 2016) measurements have reached a level of agreement and with low enough uncertainty to allow the redefinition to go ahead with negligible disturbance to the worldwide measurement system.

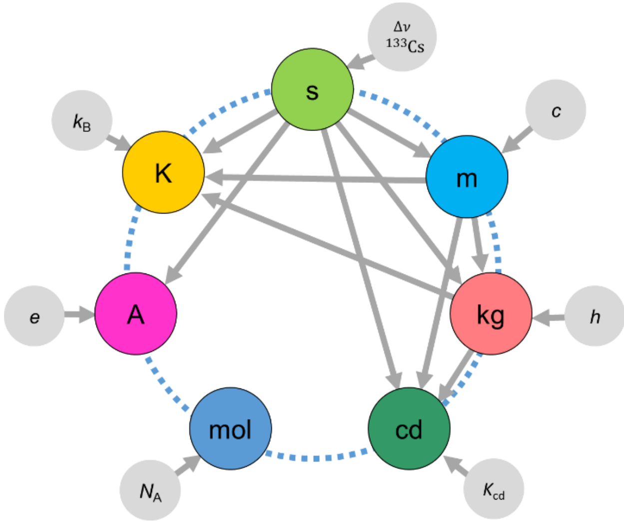
The SI will then define the measurements units by stating the exact value of constants of nature in this system of measurement [11]. Specifically, the SI, is the system of units in which:

- the unperturbed ground state hyperfine splitting frequency of the caesium 133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz,
- the speed of light in vacuum c is 299 792 458 m/s,
- the Planck constant h is $6.626\,070\,040 \times 10^{-34}$ J s,
- the elementary charge e is $1.602\,176\,620\,8 \times 10^{-19}$ C,
- the Boltzmann constant k_B is $1.380\,648\,52 \times 10^{-23}$ J/K,
- the Avogadro constant N_A is $6.022\,140\,857 \times 10^{23}$ mol^{-1} ,
- the luminous efficacy K_{cd} of monochromatic radiation of frequency 540×10^{12} hertz is 683 lm/W

and the numerical values of these seven defining constants have no uncertainty. Note: These numerical values are from the 2014 CODATA evaluation [16] and will be revised using the latest results in 2017. [11]

The values of these constants are sufficient to allow us to realise the base units of the SI: the second, metre, kilogram, ampere, kelvin, mole and lumen. The latest techniques for realising the measurement units will be describing a series of accompanying documents known as '*Mise en Pratique'*s

Figure 2: Representation of the links between seven base units of the *International System of Units* after the 2018 re-definition. Notice that the kelvin definition is now connected to the definition of three SI base units: the second, the metre and the kilogram, that together define the unit of energy, the joule.



3 The kelvin re-definition

3.1 The existing Definition

Having looked at the general rationale for redefining the units in Section 2, let us see how this affects the definition of the kelvin and degree Celsius, and how this will in turn affect temperature measurement outside of calibration laboratories.

Since 1948, the kelvin has been defined as the "the fraction 1/273.16 of the temperature of the triple point of pure water" [5]. The definition was refined in 2005 to state that the isotopic composition of what was meant by 'pure water' was that of Vienna Standard Mean Ocean Water [17].

Using the temperature of the triple point of water, T_{TPW}, as a reference temperature is preferable to using the melting or freezing temperature of water because T_{TPW} does not depend upon atmospheric pressure. The triple-point is created inside a sealed glass cell containing only pure water from which all air has been removed. Under these conditions the melting/freezing process takes place under the natural vapour pressure of water/ice, ~611 Pa.

Inter-comparisons amongst national measurement institutes [18] have shown that the temperature of the triple point of water, T_{TPW}, is reproducible at the level of better than 0.1 mK. For measurements in the meteorological range, this is completely adequate.

3.2 The New Definition

Using the current definition, T_{TPW} is considered to be exactly 273.16 K (0.01 °C). As the only exactly-known temperature, calibration at T_{TPW} is the starting point for the calibration of every high-quality thermometer. Indeed, because of this definition, ultimately *every* temperature measurement is a comparison of the temperature of an object being measured with T_{TPW}.

After the re-definition the kelvin will be defined such that the Boltzmann constant k_B has the exact value 1.380 648 52 ×10$^{−23}$ J K^{-1}. This number has been chosen to ensure that T_{TPW} still has the same value (273.16 K) but it now has an associated measurement uncertainty. Instead of being 273.160 000 000 … K exactly, T_{TPW} will in future be considered to be 273.160 000 K ± 0.000 156 K. This actual uncertainty value may change slightly depending on measurement results in the coming year.

The uncertainty in T_{TPW} arises because T_{TPW} no longer defines what we mean by one degree. Instead it is now merely a convenient reproducible temperature. Temperatures measured according to the new definition are ultimately comparisons of the average level of molecular energy with the SI unit of energy, the joule (i.e. one kilogram metre second^{-2}).

3.3 The International Temperature Scale of 1990

All calibrations of thermometers for meteorological or climatological applications are based on the *International Temperature Scale* of 1990, ITS-90 [19, 20].

Calibration according to ITS-90 involves two components: 'fixed-points' and 'interpolating devices'. A 'fixed-point' is a cell containing a pure substance which melts or freezes at a reproducible temperature. The values of these melting or freezing temperatures in ITS-90 are based on the best information available prior to 1990 based on experiments described in Section 4. The values assigned to the fixed points most commonly used for meteorological calibrations are shown in Table 1.

Table 1: Fixed Points of ITS-90 used for meteorological calibrations. The table shows the assigned temperatures and resistance ratios of pure strain-free platinum at the melting temperature of gallium and the triple point of mercury.

Fixed Point	ITS-90 temperature	Reference Resistance Ratio
Triple Point of Mercury	-38.8344 °C	0.844 142 11
Triple Point of Water	0.01 °C	1.000 000 00
Melting Temperature of Gallium	29.7646 °C	1.118 138 89

The 'interpolating device' in this temperature range is the standard platinum resistance thermometer (SPRT) which works like a normal PRT but uses ultra-pure platinum wires suspended on a strain-relieved frame. SPRTs are much more delicate than a conventional PRTs and generally unsuitable for use outside of a calibration laboratory.

The resistance ratio, $W(T)$, is defined as the ratio of the electrical resistance at a temperature T to that at T_{TPW}. ITS-90 specifies a reference polynomial which describes the temperature-dependence of the resistance ratio $W_{ref}(T)$ of an 'ideal' SPRT in between the fixed-points.

Calibration in ITS-90 consists of measuring the resistance ratio of an SPRT at one or more fixed points. After this measurement has been carried out, the W values for a particular thermometer are compared with the 'reference ratios', W_{ref}, and the small differences $W – W_{ref}$, are used to produce a small correction to the reference polynomial that applies to that particular thermometer.

Uncertainties in ITS-90 temperature assigned to an SPRT are typically less than 0.001 °C over the meteorological range. SPRTs calibrated in this way would normally be used in calibration laboratories to calibrate more practical thermometers (thermistors, industrial quality Pt-100 devices, or thermocouples) at a convenient set of temperatures. The final uncertainty for these practical devices can be as low as 0.01 °C, and completely sufficient for meteorological applications.

3.4 Impact of the kelvin redefinition on ITS-90

Examination of the précis of ITS-90 calibration procedures in Section 3.3 makes it clear that because the redefinition of the kelvin leaves the value of the triple point of water unchanged, the redefinition will have no effect on calibrations carried out according to ITS-90.

Thus despite its profound philosophical significance, the immediate practical impact of the redefinition for meteorology will be exactly zero.

The lack of any immediate impact is deliberate: the value of the Boltzmann constant in the redefinition has been chosen so as keep the temperature of the triple point of water – and hence calibrations according to ITS-90 – unchanged.

Although the initial impact on meteorology will be zero, the redefinition will have an immediate impact on temperature measurements at temperature extremes, typically below 20 K and above 1000 °C. It does this by eliminating the need to make a direct comparison of a thermometer reading with its equivalent reading at T_{TPW}.

4 Errors in ITS-90

4.1 The foundations of ITS-90

The temperatures assigned to the fixed points in ITS-90 (Table 1) and the temperature dependence of the resistance an ideal SPRT were decided by consensus in 1990 based on the best primary measurements at the time.

A primary measurement of temperature is one which uses basic physics to infer the temperature. In the meteorological temperature range, the most common technique of primary thermometry used before 1990 was the constant volume gas thermometer (CVGT). In this technique, a measured amount of gas (*n* molecules) is placed in a container of known volume, *V*. The pressure, *P*, of this gas is measured at T_{TPW} and at unknown temperatures such as the melting temperature of gallium T_{Ga}. Assuming ideal gas behaviour:

$$P = \frac{n}{V} k_{\mathrm{B}} T$$

the ratio of pressures at these temperatures ($P_{\mathrm{Ga}}/P_{\mathrm{TPW}}$) could be used to infer the ratio of their absolute temperatures ($T_{\mathrm{Ga}}/T_{\mathrm{TPW}}$).

$$T_{Ga} = \left[\frac{P(Ga)}{P(TPW)}\right] T_{TPW}$$

In order to achieve temperature estimates with uncertainties of a few thousandths of a degree, this technique requires high-resolution pressure measurements, and the accurate assessment of many small corrections. The most significant corrections arise from the fact that experimental gases such as helium or argon do not behave like an ideal gas. To account for this, the temperatures are inferred from the limiting ratio of pressures as the density of the gas (*n*/*V*) in the container is lowered.

Primary measurements are extremely difficult and time-consuming. Typically a CVGT would take several years to construct, and might take several weeks to measure a single temperature. This is clearly not the kind of instrument that could be used to calibrate a customer's thermometer in a matter of minutes and hours.

Instead, such primary thermometers are used to characterise the temperature-dependence of the electrical resistivity of platinum, and to determine the temperatures of fixed-points. The results of primary studies world-wide are then collated by the Consultative Committee on Thermometry (CCT) of the CIPM and recommended procedures for temperature calibration are then intermittently produced. ITS-90, for example, replaced the *International Practical Temperature Scale* of 1968 (IPTS-68) [21].

ITS-90 has been extremely successful and inter-comparisons shows that high quality thermometers calibrated completely independently agree to better than one thousandth of a degree, and thus allow temperature measurements made around the world to be truly comparable.

However, in the years since 1990, it has become clear that some of the primary thermometry used in establishing ITS-90 was subject to systematic errors that were not appreciated at the time. These errors have been revealed by improvements in primary acoustic thermometry

4.2 Acoustic Thermometry

Acoustic thermometry is currently the most accurate technique of primary thermometry, with uncertainties almost 10 times smaller than those associated with CVGT. [22]

The technique exploits the fact the speed of sound in a gas is closely related to the average speed of the molecules within the gas. In practice a gas is held in a spherical resonator whose dimensions are known with low uncertainty and the frequency of a series of acoustic resonances is recorded. From the frequencies of the resonances and the known dimensions of the resonator, the speed of sound can be deduced.

Importantly, many small corrections affect different resonances to different extents, and so by measuring several resonances, the technique provides a powerful self-checking mechanism. For example in NPL's acoustic gas thermometer, measurements of the speed of sound inferred from six difference resonances covering a factor 10 in frequency had a spread characterised by just 90 parts per billion.

The speed of sound, *u*, is related to the absolute temperature by:

$$u_0^2 = \frac{\gamma k_B T}{m}$$

where γ is the adiabatic index of the gas, and *m* the average molecular mass. In this equation u_0^2 is the speed of sound squared, u^2, in the limit of low density, which is estimated from the pressure dependence of $u^2(P)$.

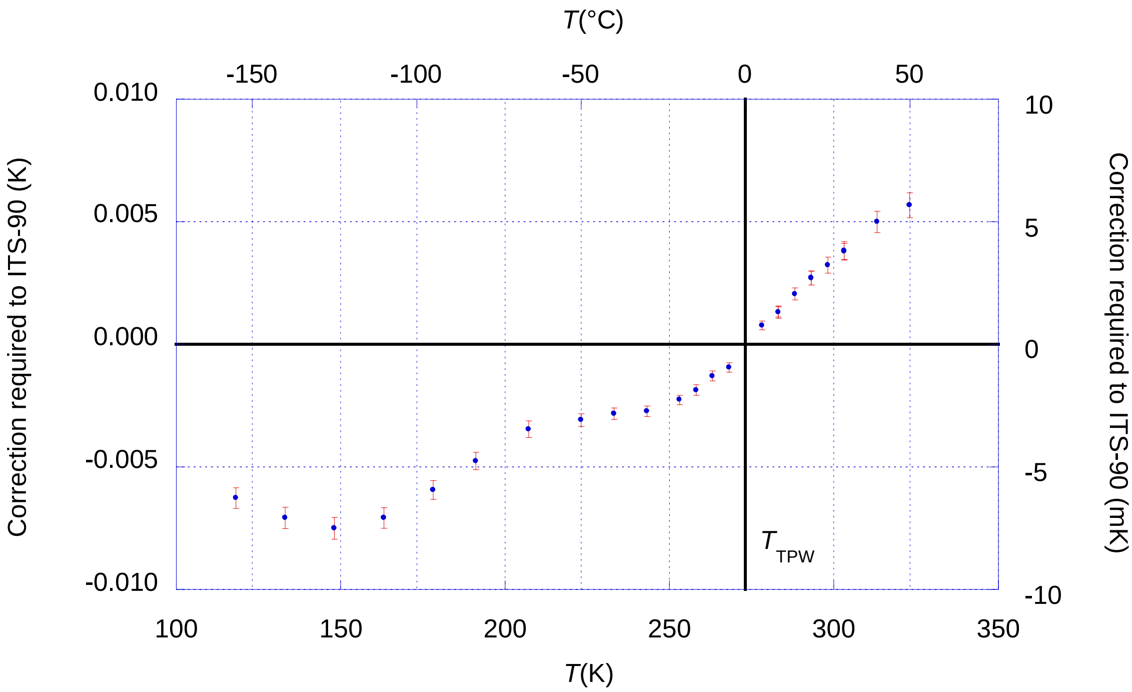
An unknown temperature such as the melting temperature of gallium T_{Ga} is then inferred from the ratio ($u_0^2(Ga)/u_0^2(TPW)$:

$$T_{Ga} = \left[\frac{u_0^2(Ga)}{u_0^2(TPW)}\right] T_{TPW}$$

4.3 Acoustic Thermometry

Estimates of the errors in ITS-90 based on work at NPL are shown in Figure 3 [23]. Above the triple point of water, ITS-90 underestimates the true temperature by up to approximately 0.005 °C at 50 °C, with the error varying approximately linearly with temperature. The linear trend continues for approximately 30 °C below the triple-point of water, but then flattens off reaching an error of approximately -0.005 °C at the extreme low end of the meteorological range at -90 °C.

Figure 3: The graph shows the estimated correction required to ITS-90 to bring it into agreement with thermodynamic temperature. The estimates are based on acoustic thermometry at NPL [23]. The horizontal axis shows the temperature in kelvin below the graph and in degrees Celsius above the graph. The difference between the true (thermodynamic) temperature and the ITS-90 temperature is shown on the left-hand axis in kelvin and on the right-hand axis as millikelvin. Above the temperature of the triple point of water, temperatures estimated by ITS-90 are slightly lower than the true temperature and the correction shown should be added to the ITS-90 temperature to achieve an estimate of the true temperature within the uncertainty shown.



The main consequence of these errors is that temperatures reported by thermometers calibrated according to ITS-90 have a small temperature-dependent error. In meteorological terms, this error is smaller than other influencing factors, such as siting, or the height of the sensor above the ground. Nonetheless, it applies to every sensor on Earth, and is worth bearing in mind.

From a broad meteorological perspective these errors are obviously negligible but there are in fact two places in which these errors may show up, albeit at the very limits of meteorological relevance.

The first concerns the slope of the errors. The data indicate that around T_{TPW} a change of +1 °C as estimated in ITS-90 is smaller than the true degree by approximately 1.5 parts in 10^4. As a consequence, thermodynamic functions (such as the heat capacity of water or air) based on measurements using thermometers calibrated according to ITS-90, are all in error by the same factor.

The second concerns any possible future revision of ITS-90, tentatively known as ITS-20XX. It is not clear yet whether such a revision will take place, but if it does, then the current errors will certainly be removed and the temperatures estimated according to ITS-20XX will be likely to be much closer to true (i.e. thermodynamic) temperature *T* than at the moment.

Consider a weather station with a mean annual temperature of 20.000 °C reported with sensors calibrated according to ITS-90. From Figure 3 we can see that at 20 °C, ITS-90 underestimates the true temperature by approximately 0.002 °C. Thus, if the sensors from this station were recalibrated under a hypothetical ITS-20XX, its average temperature would be reported as approximately 20.002 °C. Although small, it is conceivable that such a shift might be just detectable in homogenisation procedures using annual or decadal means.

5 Conclusions

As part of a wider re-definition of SI units and a re-framing of concepts within the SI, the kelvin and degree Celsius will be re-defined in 2018. Although philosophically significant, and of immediate benefit to users measuring at temperature extremes, there will be no immediate impact on meteorological measurements because all such measurements are calibrated using the ITS-90 which will not be affected by this re-definition.

However, work on acoustic thermometry leading up to the re-definition has revealed small errors in ITS-90 which are near the limit of detection in a meteorological context.

Additionally, stimulated by developments leading up to the re-definition of the kelvin, researchers have begun making direct measurements of the thermodynamic temperature of air in the free-field [24, 25]. Such measurements are unlikely to achieve the low uncertainty of the measurement reported in [23], but the speed of measurement and the simultaneous, non-contact measurement of temperature and humidity may become meteorologically relevant in some applications.

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