The Redefinition of the SI: Impact on Calibration Services at NIST

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Abstract: As most readers are probably at least vaguely aware, it is likely that the SI system of units will be redefined in 2018. This redefinition would fundamentally change the logical structure of the SI, with one result being a substantial change in how mass is realized and disseminated within national metrology institutes (NMI's) such as the National Institute of Standards and Technology (NIST). However, we expect that the only impact on how customers see calibration services will be small step changes that NIST will document and publicize to customers in advance. In this article, we list the main areas of calibration services at NIST, describe how for most of them there will be negligible impact, discuss the impact on mass and DC electrical calibrations, and explain our best predictions as to how we expect NIST to make a seamless transition for customers in those two areas.

1. Introduction and Motivation

As most readers know, it is likely that the system of units (SI or Système International d'Unités) will be substantially changed in 2018 [1, 2]. This change is being considered, and if adopted will be implemented by the international metrology community through a vote in the CGPM (General Conference on Weights and Measures), which is the governing body of the Treaty of the Meter [3]; we note this specifically to make the point that this change is not being mandated by NIST nor by any other individual NMI. We have heard informally that there is substantial curiosity and concern in the measurement services community as to how this likely change will impact calibrations and disseminations from NIST, and thus their businesses. This paper is an attempt to satisfy that curiosity, with the good news being that for almost all calibration services, there will be no impact.

Please see Table 1 for a list of the major calibration areas at NIST [4]. Recently, we surveyed the calibration experts at NIST in these areas, and prepared an internal report to assess the impact on the work that NIST does. For that report, we considered only calibration services and not standard reference materials; the latter are sold by NIST, typically for disseminating chemical and materials properties. Having done that work for the internal survey, it seems to us that we can use the results to inform the general metrology community as to how these impacts will appear to outside companies.

For the purposes of the calibration community, there are two important consequences to the likely redefinition. The first is that the present list of seven base units would be replaced by seven "defining constants" (seven fundamental constants with zero uncertainty) [2]. While this change is of substantial interest to the scientific community because it affords the ability to scale units over large ranges [5], the selection of the seven defining constants were chosen so as to cause no change in the experimental methods of realization and dissemination (except for the case of mass, which we discuss below). Choosing the example of length realization and dissemination, the present definition of the base unit is the meter, which is defined as the distance that light travels in a certain amount of time. In the likely redefinition, the corresponding defining constant will be the speed of light c, which means that the realization of length will still depend on the distance light travels in a certain time.

The second important consequence is that there would be a substantive impact on two areas of metrology. For DC electrical quantities such as voltage and resistance, the proposed change is to keep the same basic set of experiments, but with relative shifts in the accepted values of those standards of up to 10^{-7} (see below). For mass realization, instead of tracing mass to the International Prototype of the Kilogram (IPK, held in a safe near Paris, France), mass realizations would be based on the DC electrical quantities of resistance and voltage using the "electronic kilogram" or

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Calibration Service Area	Typical Services
Dimensional Measurements	length, angles
Electromagnetic Measurements at low frequencies	resistance, voltage, capacitance, power
Electromagnetic Measurements at high frequencies	microwave transmission characteristics, scattering parameters, antenna measurements, high-speed waveforms
Ionizing Radiation Measurements	radioactivity and dosimetry
Mechanical Measurements other than Mass	force, volume, flow
Mass	
Optical Radiation Measurements	photometry and spectral radiometry
Thermodynamic Quantities	pressure, thermocouples, resistance thermometry
Time and Frequency Measurements	broadcast and measurement services, characterization of oscillators

Table 1. The major calibration service areas at NIST (for a more detailed list, please consult http://www.nist.gov/calibrations).

"watt balance" [5, 6].[1] While this likely redefinition will result in a very substantial change in the way mass is realized and disseminated within NIST (see below), it is likely that the mass calibration service to outside calibration customers will look exactly the same to those customers (albeit with different lowest uncertainties).

We note that there have been two recent papers in *NCSLI Measure* regarding the impact of the likely redefinition on the electrical units [7] and on mass realization and dissemination [5]; both of these articles go into much more depth on the science underpinning the likely redefinition [2].

In the rest of this paper, we will i) give brief explanations of why there will be little or no impact on most of the calibration services listed in Table 1, and ii) discuss in moderate detail the impacts on the DC electrical quantities and on mass realization and dissemination.

2. Negligible Impact on Most Calibration Areas

As discussed in Section 3, it is likely that all of the low-frequency electrical standards will undergo relative step changes in the reported values that are of order 1×10^{-7} (see Table 2). For all of the calibration services listed in this section, it appears likely that the most significant potential impact on these services due to the proposed definition will be from those step changes. As we will see, the reported uncertainty of all of the calibration services in this section are much larger than the size of the likely step changes in voltage, resistance, etc., so that there will be negligible impact on those services.

2.1 Dimensional Measurements

These services span the gamut from length (over the range from nanometers to kilometers) to diameter and roundness and measurements of angle. They all originate from a length standard realized by measuring the wavelength of laser light (i.e., the distance light travels in a specified amount of time). As discussed above, the likely change from base unit to defining constant would not affect this realization and dissemination, and thus the calibration services would remain the same.

[1] We note that NIST, and many of the world's NMI's, are likely to use the electronic kilogram experiment as the primary realization of the kilogram after the redefinition; however, it appears likely that at least one NMI will use an alternative primary realization based on the mass of a nearly perfect Si sphere (the Avogadro project) [5].

2.2 Electromagnetic Measurements at High Frequencies

These services include power and electric field measurements from the RF to millimeter-range, scattering parameters and antenna measurements, and high-speed voltage waveform measurements. They are all essentially based on the low-frequency and DC electric standards (discussed in Section 3). The basic science of these high-frequency measurements will be unchanged; however, it is possible that the shifts in the DC electrical quantities could affect the exact values disseminated. However, the lowest relative uncertainty in any of these calibration services is about 10^{-3}, which means that there will be negligible impact.

2.3 Ionizing Radiation Measurements

One calibration service measures α, β (electrons), or γ radiation from gaseous, liquid or solid sources, with a total range from 1 Bq to 100 MBq. The other service calibrates dosimeters for neutrons, x-rays, γ rays, and electrons. Radiation measurements are essentially based on the reciprocal second, so no changes (other than perhaps documentation) are anticipated. Dosimetry is similar to radioactivity; the smallest relative uncertainty is about 10^{-2}.

2.4 Mechanical Measurements other than Mass

Mechanical calibrations at NIST range from volume to flow and airspeed, force and vibration standards. As examples, force measurements span the range from 0.5 kN to 50 MN based in part on gravitational force, while airspeeds from 0.15 m/s to 40 m/s are measured in a wind tunnel whose temperature, pressure, and humidity are monitored. Similar to the above, the basic science of the measurement will be unchanged. The smallest relative uncertainty is 5×10^{-6} for calibrations of forces between 400 N and 4 MN, and thus there will be negligible impact.

2.5 Optical Radiation Measurements

These tests range from photometry and spectroradiometry (lamp intensity in units of the candela from the IR to the UV) to surface color and optical properties of materials. Similar to the above, the basic science of the measurements will be unchanged. The smallest relative uncertainty (in radiometry) is about 10^{-4}.

Quantity	Formula for SI Unit	Relative Change
voltage	$V = V_{90} [1 - (100 \times 10^{-9})]$	-100 ppb
resistance	$\Omega = \Omega_{90} [1 - (17 \times 10^{-9})]$	-17 ppb
current	$A = A_{90} [1 - (83 \times 10^{-9})]$	-83 ppb
charge	$C = C_{90} [1 - (83 \times 10^{-9})]$	-83 ppb
power	$W = W_{90} [1 - (183 \times 10^{-9})]$	-183 ppb
capacitance	$F = F_{90} [1 + (17 \times 10^{-9})]$	17 ppb
inductance	$H = H_{90} [1 - (17 \times 10^{-9})]$	-17 ppb

Table 2. Likely shifts in the values of the SI electrical units with respect to those based on the 1990 values. Note that the shift in capacitance unit (F) will only occur for impedance disseminated from the quantum electrical standards; capacitances that come from the calculable capacitor will be unchanged. "ppb" denotes 10^{-9}.

2.6 Thermodynamic Quantities

2.6.1 Quantities other than Temperature

Calibration services include pressure/vacuum (typical range from 10^{-7} to 10^{8} Pa, or 10^{-8} Torr to thousands of atm), leak rate, and humidity measurements. In this wide range, the calibrations depend on a number of different physical quantities ranging from the density of mercury (pressure) to mole fraction (humidity). Similar to the above, the basic science of the measurements will be unchanged. By far the smallest relative uncertainty is in pressure measurements, with an uncertainty of about 5×10^{-6}.

2.6.2 Temperature with respect to the SI kelvin

The case of temperature realization and dissemination has been somewhat different from most other calibration services. For many decades, temperature realization and dissemination has been based on a set of fixed point cells which provide the temperature at a single discrete value. The set of 17 fixed points was codified in 1990 in the International Temperature Scale (ITS-90) for temperatures between approximately 1 and 1235 K [8]. The present definition of the SI kelvin (K) is based on the triple point of water (TPW), and the TPW is also one of the fixed points in the ITS-90; thus, temperatures disseminated from the ITS-90 are compatible with the realization of K. We can ask the question: Why should temperature realization and dissemination be based on fixed points? The answer is that most of the other calibrated physical quantities are extensive quantities, but temperature is an intensive quantity. To give an example, a distance of 200 m can be thought of as adding end to end two distances of 100 m each, but a temperature of 200 K cannot be thought of as adding together two solids that are each at a temperature of 100 K.

If the redefinition is adopted, instead of K being based on a fixed point (the TPW), the SI kelvin will realize thermodynamic temperature through the defining Boltzmann constant *k*. This obviously raises the question: What do we mean by the thermodynamic temperature? As many of us learned back in the days of undergraduate thermodynamics, temperature is inherently based on the statistics of a large number of atoms, and is the quantity which is equal when two set of atoms are in thermodynamic equilibrium. As we may have also learned in statistical mechanics, temperature is the constant of proportionality between number of degrees of freedom and energy; the classic example is $E = 3/2\ kT$ per atom, for a monatomic ideal gas.

Modern-day measurements of thermodynamic temperature T_{thermo} (e.g., acoustic thermometry, Johnson noise thermometry, etc.) are based on a combination of fundamental thermodynamic prediction of T_{thermo} for an ideal system (e.g. an ideal gas), and careful experimentation to compare the temperature of the ideal system to that of the ITS-90 fixed point(s). The consequence of this can be viewed from the point of view of the useful quantity $k\ T_{\text{TPW}}$; at present, T_{TPW} is a defining constant with zero uncertainty and *k* is an experimentally determined value with nonzero uncertainty; if the redefinition is adopted, T_{TPW} will be a measured quantity with nonzero uncertainty and *k* will be a defining constant.

As determined primarily by acoustic thermometry (at present, the most accurate way to determine the thermodynamic SI kelvin), the offset between the accepted values of the various fixed points and the SI kelvin is as follows: the relative offset $(T_{\text{thermo}} - T_{\text{ITS-90}}) / T_{\text{thermo}}$ is as large as $+70 \times 10^{-6}$ at 100 K and -35×10^{-6} at 650 K [9]. There have been repeated discussions of this topic amongst the experts in the field of temperature metrology at their regular meetings, and there is consensus agreement that this situation is satisfactory. Thus, we expect that the ITS-90 will remain the basis of thermometry calibration services whether or not the redefinition occurs.

2.6.3 Thermocouple Calibrations

Measuring temperatures with thermocouples is perhaps the most direct example of the impact of shifts in the values of the electrical quantities (in particular, voltage) on a dissemination of a non-electrical quantity. At present, we expect that for most calibrations, the reported calibration uncertainty will be much larger than the shift due to the shift in voltage calibrations. For example, we estimate the following for Au/Pt thermocouples, which is where we expect the largest shift to occur: In that case, we estimate that the shift in V will result in an equivalent temperature change at least 100 times smaller than the temperature uncertainty reported for those thermocouples.

2.7 Time and Frequency Measurements

NIST time and frequency measurement services include such measurements as characterization of GPS receivers for precision timing applications, characterization of the frequency of oscillators and atomic frequency standards, and a range of precision phase noise measurements. All of these services are referenced to the SI definition of the second based on the microwave hyperfine transition in cesium-133 atoms as realized by the NIST-F1 and

NIST-F2 primary frequency standards. Since the realization and dissemination of the second will not be changed in any proposed SI redefinition, there will be no impact on any NIST time and frequency measurement service.

3. Effect on Electromagnetic Measurements at DC and Low Frequencies

As discussed in detail in a previous paper in *NCSLI Measure* [7], if the SI redefinition occurs, the realization of the electrical units will be primarily based on the two quantum electrical standards, the Josephson voltage and quantum Hall resistance standards. Very briefly, the Josephson voltage standard yields voltages typically of order 1 to 10 V by combining a large number of superconducting Josephson tunnel junctions which are exposed to microwave radiation at frequency f; the fundamental voltage that develops is given by $V_J = nhf / 2e$, where n is an integer proportional to the number of junctions, h is the Planck constant, and e is the charge of the electron. Similarly, the quantum Hall resistance standard yields a resistance of order 26 kΩ by measuring the transverse voltage in a resistor fabricated in a high-electron mobility material such as GaAs or graphene; the resistance is given by $R_K = h / ne^2$, where n is a small integer. We note that, if the SI is redefined, h and e will be two of the defining constants with zero uncertainty.

Without going into the details [7], we note that the best accepted values for the fundamental constants, including those that determine the absolute values of voltage and resistance in the two quantum electric standards, are set periodically by the Committee on Data for Science and Technology (CODATA) Task Group on Fundamental Constants [10]. We also note that, for the past 25 years, most industrial countries have based their electrical disseminations on accepted values of the two quantum electric standards which were set in 1990. Since then, the best accepted values for the fundamental constants as stated by CODATA have shifted by small amounts from the values accepted in 1990. Table 2 shows the likely approximate shifts, in both magnitude and direction, for both the DC voltage and resistance which will come directly from the quantum electric standards, as well as many other units which are realized and disseminated from or related to those two standards.

In general, the effect of these shifts will be simply that, for the same physical standard [e.g., a solid-state Zener reference (10 V)], the value reported by a calibration at NIST right after the change would be about 1 μV smaller than the value reported from a calibration done right before the change. This "step change" for any other electrical quantity can be read directly from Table 2. In general, NIST expects to deal with the impact on calibration customers of all of these step changes by a program of documentation and education similar to that done for the introduction in 1990 of the previous accepted values [11].

3.1 Resistance Calibrations at NIST

The smallest relative uncertainty reported for any resistance calibration at NIST is that for Test 51130C, done for Thomas-type 1 Ω resistors; the relative expanded (k = 2) uncertainty is 4×10^{-8}. For all other routine resistance calibrations at NIST, the stated relative uncertainty is at least a factor of five larger. Thus, for most of our calibration services, the effect of the 2×10^{-8} step change in resistance due to the likely SI redefinition will be negligible; for Test 51130C, we expect that NIST will provide the documentation and education closer to the time of redefinition.

3.2 Voltage Calibrations at NIST

The smallest relative uncertainty reported for any voltage calibration at NIST is that for Josephson calibrations of primary cells (1.018 V), with an expanded uncertainty of 4×10^{-8}; the most common calibrations (53160C) of solid-state Zener references have reported expanded uncertainties at or above 2×10^{-7}. Thus, given the likely relative step change (Table 2) in voltage of 1×10^{-7}, it is likely that there will be a moderate step change for a number of calibrations. As with resistance calibrations, NIST will provide the documentation and education closer to the time of redefinition.

In addition, we note that NIST sells programmable Josephson voltage standard systems (SRI 6000) [12]. We expect that, at the appropriate time, an update to the system software will be offered, so that reported voltages will be correct before and after any step change in V.

3.3 Capacitance Calibrations at NIST

At present, all capacitance calibrations at NIST are realized and disseminated from our "calculable capacitor" [3], which is based not on the quantum electrical standards but rather on a direct conversion from length measurement to capacitance. Because of this fact plus the lack of impact on dimensional measurements, we do not expect that any of our present calibrations will be affected by the likely SI redefinition. As an aside, we note that, in the future, NIST may choose to perform some high value calibrations (above 10 μF) based on an impedance dissemination from resistance; however, the likely relative uncertainty of such a calibration (10^{-3} or larger) means that the redefinition would have a negligible impact on this possible future service.

4. Mass Realization and Dissemination

One of the major motivations of the proposed redefinition of the SI is to remove the last of the "artifactual" standards, specifically the mass standard embodied in the IPK, a piece of Pt-Ir metal kept in a safe near Paris, France. The obvious implication of that is, in contrast to all of the likely impacts discussed above, the impact on mass realization and dissemination of this change will be substantial.

In this section, we wish to lay out our best predictions for the impact on mass realization and dissemination for workers both inside NIST (substantial) and on calibration customers outside of NIST (moderate at most). However, we first note the following significant caveat – at this time, although the decision to redefine the SI appears likely, the formal legal decision has not been made. In addition, there is a roadmap with a timeline for reaching consensus on changing the definition of the kilogram; since this roadmap contains many interdependent elements, rather than stating the status at this moment we simply refer interested readers to the document [13]. Specifically, the roadmap indicates that the agreement to modify the treaty of the meter is scheduled to occur towards the end of 2018.

4.1 Mass Realization and Dissemination within NIST – Our Plan

The "watt balance" or "electronic kilogram" is a very clever way to achieve the "linchpin connection" between the electrical and mechanical quantities [5]. This connection is crucial in the SI system of units, because it ensures the equivalence of, for instance, 1 W of power derived electrically and 1 W derived mechanically. Described very briefly, in the watt balance this equivalence is determined by moving an electrical coil in a magnetic field, and separately comparing the force on the coil, when held fixed, to the gravitational force on a test mass. At the moment, it appears likely that mass realization inside NIST would occur as follows: The current in and voltage across the coil would be determined with respect to the Josephson voltage and quantum Hall resistance standards; in this way, the primary mass standard would depend on the quantum electrical standards (and hence the rubric "electronic kilogram").

Some of us have recently demonstrated a portion of this likely dissemination [14]. We calibrated a stainless steel 1 kg mass based on the watt balance, and achieved encouraging results: a relative uncertainty of 6×10^{-8} with a relative offset from a mass comparison (traceable to the IPK) of 3×10^{-8}. We thus have a progression path to offering a routine calibration service for mass.

We note that the present (fourth) version of the watt balance at NIST is in a vacuum chamber, primarily to avoid effects arising from the index of refraction of air and the concomitant effect on length measurements, which will otherwise change the apparent mass of the test mass. However, routine mass comparisons are done in air, and in particular customers wish their standards to be calibrated in air, because that is how they use them in their own laboratories. The obvious implication of these two facts is that we must develop the ability, in our internal dissemination chain, to compare two standard masses with one being in vacuum and the other being in air. NIST is developing such an ability using magnetic levitation [15]. We expect that at the end of this chain we will have standard masses within NIST that can be used for mass comparisons with customer's standards in air.

4.2 Mass Calibrations for NIST Customers – Our Best Prediction

We emphasize that there are major unknown aspects of the future of mass realization and dissemination in all the industrialized countries, and particularly at NIST. However, with that caveat, our best prediction is that the progression path described above will result in calibrations of customer's test masses which will be quite similar if not identical to the calibrations offered now.

A note about ultimate uncertainties: At present, NIST provides mass calibration services, with a lowest uncertainty of about 50 µg ($k = 2$) at 1 kg. At this time, it appears likely that, after the redefinition, the smallest relative uncertainty for calibrations at 1 kg will be between 70 and 80 µg ($k = 2$). We note some context for this likely increase in uncertainty: The International Organization of Legal Metrology (OIML) has defined a set of mass standard classes embodied in international recommendation *R 111* which are the most commonly used definitions throughout the world [16]. The most accurate class is E1, which defines mass standards with an uncertainty of 167 µg ($k = 2$) at 1 kg. In addition, there is the possibility in the future of an uncertainty half the size of E1 [17]; if this class is indeed implemented, then the lowest uncertainty of NIST calibrations would be significant for this class.

5. Conclusions

The possible redefinition of the SI is exciting for many metrologists, especially those in NMI's and in academia, for several reasons. As we have discussed above, a pragmatic one is the strong desire to remove the last artifactual standard, the IPK. A more fundamental reason for the excitement is that the redefinition will strengthen the conceptual underpinning of experimental ability to measure the same physical quantity over many orders of magnitude. In this regard, a particularly noteworthy possibility is to measure the mass of items ranging in size "from atoms to apples" [5] (using in one case scattering of photons by atoms, and in the other case the electronic kilogram).

However, with this major redefinition of the SI, it is likely that some people in the calibration community are curious or concerned (or both) about how this fundamental redefinition will affect their ability to continue their work. We hope that we have clearly and convincingly i) explained what impacts flow from the redefinition; ii) demonstrated that, for most areas of calibration, there will be no or negligible impact; and iii) showed how NIST plans to make the transition as seamless as possible, and to educate our customers, in the two areas where there is non-negligible impact.

We suspect that there will be many people for whom this article does not fully answer all of their questions. We encourage those people to ask questions of the various NIST workers who oversee particular calibration services, or to ask any of the authors.

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