Bryan Kibble

The Conference on Precision Electromagnetic Measurements 2014

The Conference on Precision Electromagnetic Measurements (CPEM) brings together metrologists from all over the world to discuss improving measurement accuracy. Such is the status of CPEM that the participants often, consciously or unconsciously, endeavour to present their most significant discoveries and technical advances there. CPEM not only addresses problems of international uniformity of electrical and magnetic SI units, standards and measurements but also allows discussions of physical constants measurements, which are the base of these units. These discussions now include non-electrical constants such as the Boltzmann constant for the entirely new thermodynamic temperature scale. Also presented were measurements of ancillary quantities such as the local gravitational acceleration needed to link electrical SI units with the mechanical ones.

The CPEM convenes every two years at different locations around the world, and we met last August in Rio de Janiero, Brazil (there has to be some compensation for spending long hours of hard work in a stuffy laboratory)! Not unexpectedly, the hot topic of this 2014 conference was the continuing effort to supply the results necessary for the imminent redefinition of the kilogram by adopting a fixed value of Planck's constant h to replace the specified lump of platinum-iridium alloy locked away in a safe at the International Bureau of Weights and Measures. This 125-year-old artefact kilogram seems to have changed by 0.05 parts per million or worse, but it is impossible to know how much worse because nothing more stable exists to check against it.

For redefinition to happen, it has been suggested that the minimum requirement should be three agreeing experimental results for h derived using the old kilogram. One result should have an estimated accuracy of better than 0.02 parts per million, and it should be supported by two other results of better than 0.05 parts per million accuracy, with one measured by a quite different method. Re-definition in terms of the value of h thus determined should ensure that the redefined value of the kilogram is unchanging in time and space forever, and that a material lump representing this new unit can be obtained by anyone anywhere prepared to invest time and money in the necessary apparatus. For continuity, it should also ensure that the new kilogram is indistinguishable from the old so that no-one habitually weighing objects will notice the change.

Naturally, stipulation of these requirements was with full knowledge of what might possibly be achieved by the two experimental methods being pursued. The first method uses a Watt-balance (see my June 2014 article [1]), which equates the change of potential energy of a kilogram in the earth's gravitational field to the electrical energy of a voltage times a current in a coil suspended in a magnetic field. A result claiming an accuracy of 0.019 parts per million and another claiming 0.035 parts per million were reported at the conference [2], [3].

For the whole of the forty years' history of developing the Watt-balance to this stage of perfection, it has been assumed that very exact vertical alignment of the apparatus together with the elimination of any horizontal or rotational motions of the coil were essential. An elegant analysis supported by experimental evidence showed that this alignment is totally unnecessary and consequently a whole class of supposed systematic errors have now disappeared. Why did it take so long?

The second method involves counting the (very large) number of ^{28}Si atoms that weigh the same as the old kilogram. This is easy to suggest but in practice is very difficult to accomplish to the almost impossibly high accuracy required. An ingot, which is a perfect ^{28}Si crystal, must be prepared and from it near-perfect spheres weighing a kilogram that are cut and polished. The spacing between the atoms in the crystal and the volume of the sphere must be measured so that the number of atoms in the sphere can be calculated. There were two major problems. First, natural silicon contains three isotopes, ^{28}Si (92%), ^{29}Si (5%), and ^{30}Si (3%), that differ by about 3% in mass. Refining natural silicon does not result in perfect ^{28}Si. Therefore, very exact measurement of the remaining isotopic content is necessary. Several methods have been employed, but in some measurements, there was re-contamination of the sample of the ingot with very small amounts of natural silicon, leading to discrepancies in the results. It was reported at the conference how this was sorted out. The second problem is the presence of mono-layers of silicon oxide, water, and other possible contaminants on the surface of the sphere. These

1094-6969/15/$25.00©2015IEEE

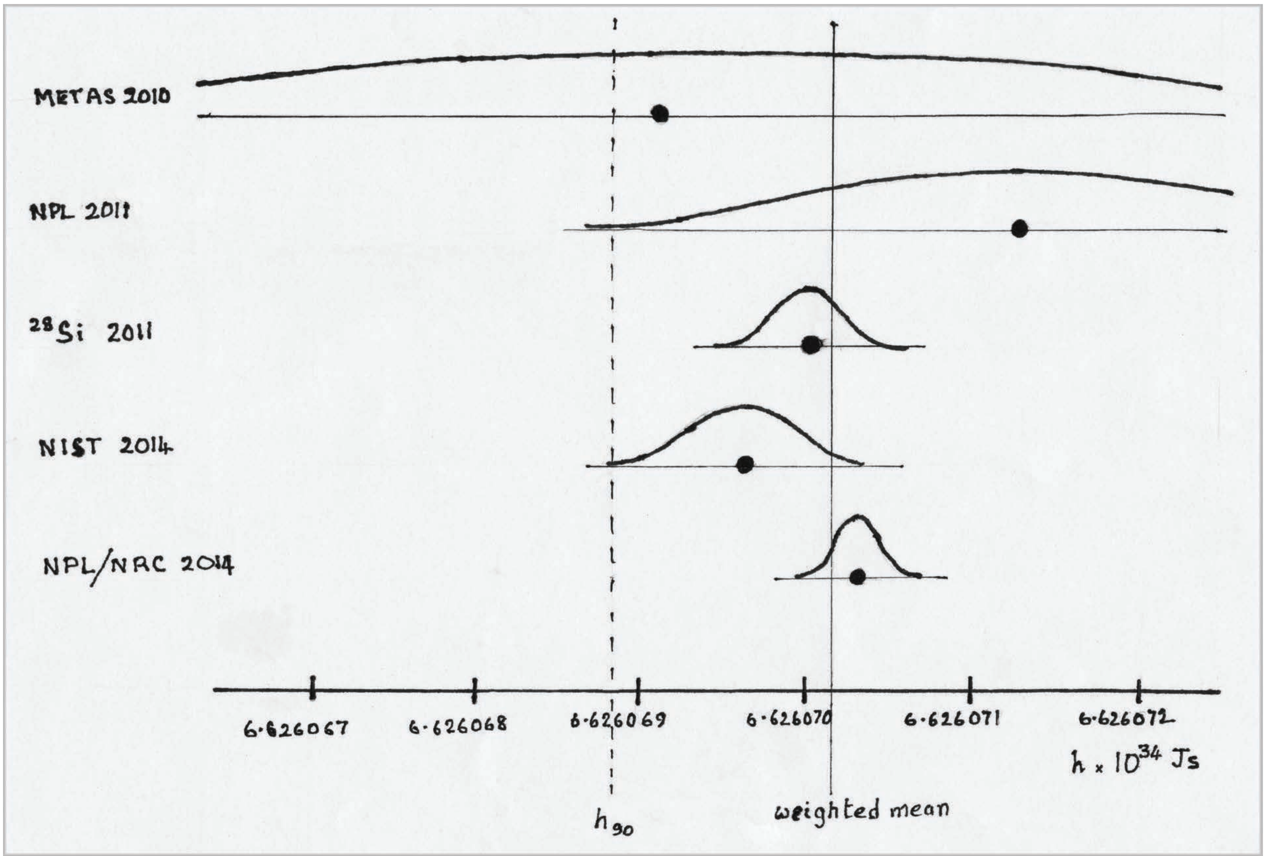

Fig. 1. Four-watt balance and one-^{28}Si measurements of *h* as of May 2014 showing their associated Gaussian error curves. The METAS is the Swiss National Measurement Laboratory, the NPL is British, the NRC is Canadian, and the NIST belongs to the USA. h_{90} is the value of *h* based on results previous to 1990.

films have been measured and the appropriate corrections made. From well-established relationships amongst physical constants, the result can be expressed with negligible loss of accuracy as a value of *h* [3]. It is consistent with the two Watt-balance results, as the figure shows.

The setting up of an SI thermodynamic temperature scale by defining a fixed value of Boltzmann's constant *k* is a very poor relation of the kilogram redefinition. At present, temperatures are measured on a scale having two fixed points, *absolute* zero, which is the temperature (0 K) at which a system has no energy whatever, and the water triple point (273.16 K) where isolated liquid water, water vapor, and ice exist together in equilibrium. A few other melting temperatures of pure elements are thermodynamically related to these by practical gas thermometry, corrected to what would be obtained from an *ideal* gas, but intermediate temperatures have unfortunately to be obtained by assuming simple non-linear relationships, for example, between the temperature and the resistance of a platinum wire thermometer. The proposal for redefinition is to have a new scale for all temperatures based on the heat energy *kT* of an *ideal* system, with the value of *k* chosen for continuity to match the present 273.16 K water triple point. Gas thermometry measurements of this triple point have yielded a value of *k* of sub-part-per-million accuracy, but methods for measuring other temperatures in terms of the defined *k* value are lacking. In principle, this need can be met by Johnson noise thermometry because the statistical mean square electrical voltage noise *V* generated across a resistance *R* at a temperature *T* in a frequency bandwidth d*f* is given by

$$\mathrm{d}\left(\overline{V}^2\right) = 4hfR\left[1/2 + 1/\left\{\exp\left(hf/kT\right) - 1\right\}\right]\mathrm{d}f.$$

The approximate formula $k = \overline{V}^2/4RT\Delta f$ usually quoted is accurate enough except at very low temperatures. Unfortunately, noise thermometry is technically difficult because *V* is so small, but steady progress was reported, and the method could well be viable at higher temperatures for setting up a truly thermodynamic scale for promulgation by national measurement laboratories.

There was much news from various laboratories about the new generation of Thompson-Lampard calculable capacitors, which are nearing completion and operation. These instruments obtain the mean capacitance between two opposing pairs of columnar round electrodes with their ends at the corners of equal squares. The mean capacitance is a simple function of a portion of the length of the columns only and is on the order of a picofarad. It can be scaled up and converted to SI capacitance, inductance, or AC resistance standards by appropriate coaxial AC bridges. The expected accuracy of these improved capacitors is about 0.01 parts in a million. Alternatively, impedance standards can be derived to an accuracy of about 0.01 parts in a million from ac measurements of the quantum Hall effect if small errors arising from the lossy capacitances of an actual quantum Hall device are accounted for. A quantum Hall device is a thin layer of millimetre dimensions in which the orbital motion of free electrons subjected to a strong perpendicular magnetic field is confined in a plane. The ratio of the voltage generated at right angles to a current passed through it is $(h/e^2)/i$, where e is the electronic charge and i is a small integer. The SI value of h/e^2 is available from measurements of the spectrum of atomic hydrogen, to an accuracy of 0.3 parts in a *billion*. The first ac measurements of a graphene quantum Hall device were reported at the conference. The results were in good agreement with previous gallium arsenide devices and indicated that graphene could offer the substantial advantages of lower field strengths and smaller lossy capacitances.

These limited impressions of the conference strongly reflect my (own) personal interests and do no justice to other advances such as the concepts of smart energy distribution grids and metering or higher frequency metrology up to optical frequencies, which were also presented. The conference was simply too comprehensive to cover in a short article, but I hope a correct impression has been created of rapidly advancing fields of metrology. Roll on CPEM16 in Ottawa, Canada!

Bryan's bio is at http://ieee-ims.org/publications/im-magazine.

References

[1] B. Kibble, "The measuring stick came before the wheel," *Instrum. Meas. Magazine*, vol. 17, no. 3, pp. 28-29, 2014.

[2] I. A. Robinson (Ed.), *Metrologia*, vol. 51, 2014.

[3] B. Andreas, et al., "Determination of the Avogadro constant by counting the atoms in a ^{28}Si crystal," *Phys. Rev. Lett.*, vol. 106, 03080, 2011.