Atomic frequency standards, physical constants, and metrology

Jacques Vanier

Retired, Université de Montréal, Montréal, Canada
jacpaul.vanier@gmail.com

When we started this series of symposia on frequency standards in 1971, Helmut Hellwig and I were wandering what title we should give to it. There was another series under the control of the US Army Electronics Command, called *Annual Frequency Control Symposium*. It was and is still held yearly In 1983, IEEE became a co-sponsor. We wanted to have some independence in content relative to sponsors. Furthermore, the second, a base unit of time in the International System of Units, the SI, had just been defined in terms of the Cs ground state hyperfine frequency (1967). It was implemented by means of the Cs beam atomic frequency standard, becoming the first practical, accurate, reliable atomic clock. Length was already defined in terms of a wavelength in the krypton spectrum, and we thought that those definitions were steps opening the door to the use of frequency standards in *metrology* at large. In those days we thought also that when a measurement of a phenomenon was planned, a gain in accuracy would result if it could be transformed into a frequency or time measurement. Consequently, we associated the name frequency standards to metrology in the title. The idea went much further. It did spread to the quantity length, and in 1982, the metre was redefined in terms of the speed of light, *c*, making it a unit that depends on the base unit of time, the second. The speed of light is of course defined in terms of two other physical constants, the vacuum magnetic and electrical constants, μ_o and ε_o. A deep interest in implementing other SI base units in terms of physical constants arose. The other base SI quantities involved are mass (kilogram, kg), electric current (ampere, A), temperature (kelvin, K), light intensity (candela, cd), quantity of matter, (mole, mol). Could we not extend the idea to those other units in particular the kilogram, which was defined in terms of an artefact, a metal cylinder stored under three bell jars at BIPM? A basic discovery had been made earlier, the Josephson effect, coupling the derived unit *volt* to Planck's constant, *h*, the charge of the electron, *e*, and the second. Another discovery was later made, the quantum Hall effect, studied by von Klitzing, coupling the derived unit *ohm*, to the two same constants *h* and *e*. It made possible the determination of the ampere in terms of those constants through ohm's law. However, there was a need to couple this to the original definition of the ampere in terms of a force between two infinite wires. The unique and direct approach to do that was the use of a so-called ampere balance and the kilogram artefact in the earth's gravitational field as base standard. However, the implementation of such an instrument faces major geometrical difficulties. This was resolved by means of the so-called Kibble balance that leads to a connection of the kg artefact to Plank's constant. The presentation will outline the steps that were accomplished, which led to the determination of *h* in terms of the kilogram standard. That accomplishment led in turn to the new 2019 International System of Units, in which all the units are now defined in terms of physical constants*. Except for the mole, all SI units depend now on the unit of time defined by means of the hyperfine frequency of the ground state of Cs, thus completing the original task associated to the goal of the present symposia series, coupling frequency standards and metrology at a level we did not expect in those days.

**The presentation is based on various articles and reports, in particular those of the International Bureau of Weights and Measures, BIPM, available in open literature.*