The role of time and frequency metrology inside the new definitions of SI quantities

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Abstract. There is an on-going discussion, initiated in 2011, which proposes several changes to the official definitions of the base units of the International System of Units (SI). This will also entail changes in the relationships between the primary quantities of SI and some universal constants. One result of this process points in the direction of giving greater importance and centrality to unit of time (s), increasing the practical importance of the realization of the quantities frequency and time. So, it is strongly recommended that the metrological maintenance of these quantities, in Brazil, be done in the Campus of INMETRO.

1. Introduction
The CGPM (Conférence Générale des Poids et Mesures) adopted a Resolution and encouraged communication and debate on the possible future revision of the SI (Système International de Unites) during its 24th meeting in October 2011. In order to disseminate the discussion it was given universal access at BIPM (Bureau International des Poids et Mesures) site to key documents on the redefinition of certain SI units, which are currently at draft stage and will be amended in the coming years [1].

In the "New SI", four of the seven SI base units, namely the kilogram, the ampere, the kelvin and the mole, will be redefined in terms of invariants of nature [2]. This new definitions will be based on fixed numerical values of the Planck constant (h), the elementary charge (e), the Boltzmann constant (k), and the Avogadro constant (N_A), respectively. Some different constants were evaluated [3], namely the Compton Length (λ_e), the magnetic constant (permeability of the vacuum - μ_0), the constant of Rydberg (R_∞) and the mass of electron (m_e), but they did not created a complete set to form a unit basis.

The choice for these four numerical constants was made based on the algebra associated with units´ exponents which was used both to display the relationships between different sets of units and to provide simple tests of whether a particular set of constants provides combinations of units that forms a complete set [3]. This approach gave rise to defining units in a quantum based SI, about which all NMIs (National Metrology Institutes) should be aware.

In the "New SI" the definitions of all seven base units will also be uniformly expressed using the explicit-constant formulation, and specific mises en pratique (practical realizations) will be drawn up to explain the realizations of the definitions of the base units in a practical way.

Sometimes making predictions and forecasts are only mental exercises about different future scenarios that should not be taken so seriously into account due to the ephemeral aspect of the future.
itself, but the redefinition of the SI is not from the same futurology studies: it is imminent and is already technically discussed in consultative committees in BIPM. Of course a major diplomatic discussion is still to be made at CIPM (Comité International des Poids et Mesures) because there are several economic and technological aspects of these redefinitions that should be addressed before the change take place and a world consensus be achieved, but the change is coming.

2. Time Definition
The redefinition of SI will not change the definition of time (and frequency) because this quantity is already explicitly connected to a constant of nature or fundamental constant, $\nu_{Cs}$ - the frequency of the transition between the two hyperfine levels of the Cesium ground state.

The proposed definition - “The second, s, is the unit of time; its magnitude is set by fixing the numerical value of the ground state hyperfine splitting frequency of the cesium 133 atom, at rest and at a temperature of 0 K, to be equal to exactly 9 192 631 770 when it is expressed in the unit s$^{-1}$, which is equal to Hz” - changes the words without changing the sense of the previous definition: “The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom”.

All other SI units will be redefined in order to be explicitly linked to a fundamental constant. The constants of nature linked to them will be:

- the ground state hyperfine splitting frequency of the cesium 133 atom $\nu_{Cs}$ is exactly 9 192 631 770 hertz, Hz, s$^{-1}$,
- the speed of light in vacuum $c$ is exactly 299 792 458 meter per second, m s$^{-1}$,
- the Planck constant $\hbar$ is exactly 6.626 06X $\times 10^{-34}$ joule second, J s,
- the elementary charge $e$ is exactly 1.602 17X $\times 10^{-19}$ coulomb, C,
- the Boltzmann constant $k$ is exactly 1.380 65X $\times 10^{-23}$ joule per kelvin, J K$^{-1}$,
- the Avogadro constant $N_A$ is exactly 6.022 14X $\times 10^{23}$ reciprocal mole, mol$^{-1}$,
- the luminous efficacy $K_{cd}$ of monochromatic radiation of frequency 540 $\times 10^{12}$ hertz is exactly 683 lumen per watt, lm W$^{-1}$.

With the seven base units it is possible to describe all the derived quantities because they are chosen to form a complete set.

Using the BIPM recommendations expressed at the 8th edition of SI-International System of Units [4][5], we could easily describe the dimension of a derived quantity $Q$ as expressed in Equation 1,

$$\text{Im} \ Q = T^\alpha I^\beta M^\gamma I^\delta \theta^\epsilon N^\zeta j^\eta$$

(1)

where the exponents $\alpha, \beta, \gamma, \delta, \epsilon, \zeta, \text{and } \eta$ are small integer numbers, positive, negative or null, and are called dimensional exponents.

In this work, to make easier to recall the quantities involved in the algebraic formalism, we will express the derived quantity directly by its unit symbol and the dimensional analysis will be made using matrix formalism.

One can describe the SI units defined in the 8th edition of SI [4] using the constants described there, where the mass, electric current, thermodynamic temperature and amount of substance are related to the mass of IPK (International Prototype of Kilogram), the magnetic permeability constant, the temperature of triple point of water and the mass of isotope 12 of carbon. Table 1 presents the dimensional exponents for each fundamental constant as stated in 2006 – SI Brochure, and Table 2 presents the same content as proposed in 2011 for discussion.
When comparing both tables one can realize that the previous definition of mass and temperature were related to material artifacts and in the redefinition these quantities are now related to frequency definitions. Only the amount of substance definition is independent of the frequency realization.

Time and frequency standardizations by using the frequency of the cesium atom has become a strategic technology and a very important metrological knowledge in order to assure the practical realization of six from the seven SI units according to the new definition.

### 3. Time and Frequency Standards at Inmetro

LAORT, one of the laboratories of Dmtic at Inmetro, through the measurement of the Local Time Scale at Campus Xerém, participates in the BIPM Circular T since October 2012. This monthly report presents the results of a time and frequency continuous key comparison. They can be used to demonstrate the degree of equivalence between all NMIs clocks (~400 clocks at 68 laboratories and 13 primary standards at 8 laboratories).

The name chosen for the Local Time Scale at the Campus of Inmetro in Xerém is INXE (INmetro XErém) and it is available for dissemination inside the Campus. The Universal Coordinated Time - UTC(INXE) - has the technical recognition because it is validated by the key intercomparison but it did not have any CMC (Calibration and Measurement Capability) assigned to this effort.

At the moment Inmetro’s Time Scale UTC(INXE) is composed by a commercial Cesium clock and it will be expanded in the near future to two commercial Cesium clocks and one research Cesium primary frequency standard employing a thermal beam and optical laser pumping.

The behavior of the availability of UTC(INXE), compared to the UTC, can be seen in Figure 1.
4. Conclusions
Some of the efforts to create an infrastructure for time and frequency metrology at Inmetro are now giving rise to more fruitful possibilities in developing and realizing other SI units’ standardizations.

The availability of the Local Time Scale, as can be seen in the Figure 1, is almost in the range of $3\sigma$, with some episodes of $2\sigma$ month availability due to power failure and flood.

Some of the discussions presented here should help to trace new routes for time and frequency metrology at the Campus of Inmetro.

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6. References
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