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On non-SI units accepted for use with the SI in a digital system of units

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Abstract. There is a need to develop an unambiguous digital version of the International System of Units (SI), as required for information systems and distributed sensor networks. This leads to a reconsideration of the status of the non-SI units accepted for use with the SI. Here, the case of the non-SI units dalton (Da), neper (Np), bel (B) and decibel (dB) is considered.

1 Towards a digital system of units

Building confidence in the accuracy and global comparability of measurements requires the creation of a machine-actionable, unambiguous full digital representation of the SI. The SI has been used around the world as the preferred system of units since it was established in 1960 by a resolution of the General Conference on Weights and Measures (CGPM). The CGPM is an intergovernmental organization created by a diplomatic treaty called the Metre Convention, signed in Paris in 1875 by representatives of 17 nations. There are currently 64 member states and 36 associate states and economies. In almost all countries, the legislation on measurement units is nowadays based on the SI. Standardization bodies may specify further details for quantities, units, symbols and the rules for their application, e.g. in the ISO/IEC 80000 series of international standards. A key reference providing a list of factors to allow conversion between SI units and numerous non-SI units is the NIST *Guide for the use of the International System of Units* (Thompson and Taylor, 2008). This guide also includes rules and style conventions for unit symbols. There are also ontologies and unified codes including all units of measurement used in science, engineering, and business (e.g. Quantities, Units, Dimensions and Types (QUDT) and Unified Code for Units of Measure (UCUM)) addressing important issues related to digitalization, like symbols used, prefixes, quantities and kind of quantities, etc. The coexistence of SI units with non-SI units introduces ambiguities. The joint use for some of them has been admitted in the SI Brochure (BIPM, 2019), in principle without any time limit. The new paradigm of the digital transformation now requires considerations that were not on the agenda of decision-making levels in metrology before the recent redefinition of the SI units. Here we address a proposed guide for the use of the metadata format in metrology for communication between machines using only SI base units (Hutzschenreuter et al., 2019). An adapter denoted as "hybrid" is offered for those quantities with unrecommended units in order to integrate them by means of XML structured data into the machine-readable Digital-SI (D-SI) data model. Humans may still refer to customary non-SI units at the user interface level. The document was developed within the framework of the EU project SmartCom, ended in September 2021, with the participation of several major national metrology institutes, headed by Germany's Physikalisch-Technische Bundesanstalt (PTB) (National Physical Laboratory (NPL) of the United Kingdom, Korea Research Institute of Standards and Science (KRISS) of South Korea, National Institute of Metrology (NIM) of China, and Czech Metrology Institute (CMI) of the Czech Republic), as well as several universities and well-known industrial companies. Non-SI units accepted for use with the SI stated in the SI Brochure could be included, but only during specified transition periods. Metrological data provided by this D-SI data model are categorized into five quality classes of machine readability: platinum, gold "2030", silver "2024", bronze "2020" and "improvable". Platinum corresponds to the strongest readability. In addition to the seven SI base units, the unit “one”; the units “degree”, “minute”, and “second” for angles; and the time units “day” and “minute” are also classified as quality class platinum. SI-derived units and the following non-SI units accepted in the SI Brochure to be used together with the SI are considered quality class silver (also called 2024): hectare, litre, tonne, electronvolt, dalton, astronomical unit, neper, bel and decibel. In the next sections, we will address some issues related to the units dalton, neper, bel and decibel in the context of a digital SI.

Beyond the proposal arising from the aforementioned SmartCom project, a significant highlight is the creation within the International Committee for Weights and Measures (CIPM) of a Task Group on the SI Digital Framework. The aim is to develop and establish a world-wide, uniform, unambiguous and secure data exchange format for use in IoT (Internet of Things) networks based on the SI described in the SI Brochure. In March 2023, the CIPM decided to establish a cross-sectional Forum on Metrology and Digitalization. Its agenda now includes establishing a unique SI Reference Point (SIRP), also available through machine-actionable interfaces, thus transporting the SI Brochure into the digital world. The unique SIRP would facilitate interoperability between systems like QUDT and UCUM. Irrespective of the unit representation system, all should lead back to a fully digital representation within the unique SIRP. The concept of what a kilogram is (or what a metre is) has been changing. The symbol m (for metre) should be accompanied by a timeline in order to be machine-interpretable, because there are different definitions of the metre: metre 1889, metre 1927, metre 1983, metre 1960 and metre 2018.

2 We live with two units of mass accepted in the SI

Since 20 May 2019, all SI units are now defined in terms of seven defining constants. The redefinition of the SI ended the decades-long coexistence of two systems of electrical units by fixing the values of the Planck constant, h, and the elementary charge, e, to the definitions of the kilogram and the ampere, respectively. But we continue to live with two units of mass. For historical and technical reasons, the dalton (Da) is still used in atomic mass measurements instead of the kilogram. The dalton and the unified atomic mass unit (u) are alternative names for the same unit, equal to $1/12$ of the mass of a free carbon-12 atom, at rest and in its ground state. The consequences of revising the SI for measurements in chemistry were analysed in advance by IUPAC (International Union of Pure and Applied Chemistry). From a IUPAC technical report published in 2017 (Marquardt et al., 2017), it can be concluded that since the masses of the nuclides are reported in the unified atomic mass unit, in the case of fixing the values of the Planck constant h and the Avogadro number N_A (as really occurred), the Atomic Mass Evaluations published at regular intervals by IUPAC would remain unaffected. In other words, there was no intention to replace the dalton with the kilogram.

The kilogram is now reaching the dalton (Da)

The redefinition of the SI opened up improvements and new possibilities across the whole mass scale, especially in the range of atomic masses. With the kilogram defined in terms of the Planck constant, the realization of mass can be achieved at any desired scale level without the need to trace the measurements to a 1 kg mass. Employing atom interferometry, the measurement of the recoil velocity of an atom of mass m that absorbs a photon of momentum $\hbar k$ yields the ratio h/m (where $\hbar = h/2\pi$, $k = 2\pi/\lambda$, and λ is a laser wavelength). Because the value of the Planck constant h has been fixed in the new SI, the ratio h/m_u ensures the realization of the kilogram at the atomic scale (Cladé et al., 2016). Furthermore, as the Avogadro constant has also been fixed and the carbon molar mass $M(^{12}\mathrm{C})$ is no longer equal to 12 g per mol, it is now determined from m_u. Before the redefinition of the SI, the accuracy of atomic masses expressed in kilogram (kg) was of the order of 10^{-8}, well above the minor uncertainties reached in terms of the dalton. The last value recommended by CODATA (Committee on Data for Science and Technology) at that time for the equivalence between kilogram and dalton was $1\,\mathrm{Da} = 1.660539040 \times 10^{-27}\,\mathrm{kg}$, with a relative standard uncertainty of 1.2×10^{-8}. From the value of the ratio h/m_u, the uncertainty in the ratio dalton to kilogram just after fixing h was reduced to more than 1 order of magnitude. Shortly after the new SI came into force, some considerations on the future of the SI were already published (Valdés, 2019), including data showing how $h/m(X)$ measurements using atom interferometry were evolving from 2002, as recorded by CODATA. X may be $^{87}\mathrm{Rb}$ atoms, as determined at the Laboratoire Kastler Brossel (LKB) in Paris, or $^{133}\mathrm{Cs}$ atoms, as determined in the University of California in Berkeley.

Table 1 shows the evolution of h/m values, including now the last value obtained at LKB in Paris in December 2020 (Morel et al., 2020). This value for $m(^{87}\mathrm{Rb})$ is the most accurate atomic mass measurement, reducing the uncertainty in the equivalence between kilogram and dalton below the 10^{-10} level. Therefore, the removal of the non-SI unit dalton, opening the way for the use of the kilogram also on the atomic mass scale, would not have such a high negative impact as before the redefinition of the SI (Valdés, 2023); the experimental uncertainties achieved in the most precise cases are very similar now. Holger Müller’s group at the University of California, Berkeley, is also working on improvements, intending to produce new $h/m(^{133}\mathrm{Cs})$ results with uncertainties below 10^{-10} in the near future. Only some of the most precise atomic and ion relative masses are known at the 10^{-11} level (Wang et al., 2021). Other relative masses are also being measured with an unprecedented precision at the

Table 1. Evolution of the relative standard uncertainties of $h/m(^{133}\mathrm{Cs})$ and $h/m(^{88}\mathrm{Rb})$.

Source	$h/m(^{133}\mathrm{Cs})$	$h/m(^{88}\mathrm{Rb})$	h/m_u
CODATA 2002	1.5×10^{-8}		6.7×10^{-9}
CODATA 2006	1.5×10^{-8}	1.3×10^{-8}	1.4×10^{-9}
CODATA 2010	1.5×10^{-8}	1.2×10^{-9}	7.0×10^{-10}
CODATA 2014	1.5×10^{-8}	1.2×10^{-9}	4.5×10^{-10}
UC Berkeley 2018	4.0×10^{-10}		
LKB Paris 2020		1.4×10^{-10}	$\sim5\times10^{-11}$

10^{-11} level, like the proton–electron mass ratio with about 20 ppt (parts per trillion) (Patra et al., 2022).

3 We live with different logarithmic ratio quantities having the same unit

The SI Brochure refers to quantities defined as the ratio of two quantities of the same kind, e.g. refractive index. Such quantities are considered simply numbers, and the associated unit is the unit one, symbol 1. Of this large number of ratio quantities with the same unit (the number one), some additionally receive special names. Among them, let us now consider the logarithmic ratio quantities with units neper (Np), bel (B) and decibel (dB). The neper is based on the use of the neperian logarithm, while bel and decibel are based on the use of the decadic logarithm. They are currently considered in the SI Brochure as non-SI units accepted for use with the SI. In 1999, during the 21st General Conference on Weights and Measures (CGPM), a resolution was considered, proposing that the neper rather than the bel should be adopted as the coherent derived SI unit, mainly for mathematical reasons. In view of the doubts expressed, the matter remained open and was later approved in the 2001 CIPM meeting, with one abstention and one vote against (the latter by the author of this paper). After publishing further arguments (Valdés, 2002), the discussion was reopened. The CIPM then decided that both the neper and the bel remained as they were, maintaining until now the status quo of non-SI units accepted for use with the SI. The CIPM Consultative Committee for Acoustics, Ultrasound and Vibration took note that the industrial acoustical community was very happy to know that the neper would not be preferred over the bel. And 20 years after those discussions, the issue may now reappear, motivated by the digital transformation. In order to eliminate ambiguities as required by a Digital SI, the previously mentioned guide, D-SI, proposes to consider both the neper and the bel as silver class units, and with it also the decibel. This supposes to be allowed for the exchange of metrological data only for a limited transition period. The name silver "2024" suggests that this should happen rather soon.

With respect to the units neper, bel and decibel, the SI Brochure additionally includes the following explanatory note: "In using these units it is important that the nature of the quantity be specified and that any reference value used be specified". In the field of acoustics, the decibel may be used with different power and field quantities that must be also specified. For instance, when we measure pressure levels in decibel (dB) relative to the SI unit pascal (Pa) and we measure pressure levels in decibel (dB) relative to 20 µPa, the smallest value to which human hearing is sensitive, a confusing situation arises if the reference level is not specified. And the confusion may be even greater, because the unit decibel is assigned to a variety of dimensionless quantities. It may be used with different power and field quantities, specified in technical standards, such as dB(mW), dB(W), dB(0.775 V), dB(V), dB(mA), dB(µV m^{-1}), dB(W m^{-2}), dB(W (4 kHz)$^{-1}$), dB(W K^{-1}), dB(W m^{-2} kHz^{-1}), dB(kHz), dB(Pa V^{-1}), dB(mV Pa^{-1}) and dB(K^{-1}). The question then arises of how to indicate in a digital SI as many specifications as those mentioned when the name of the unit is the same, decibel in this case. In accordance with ISO 80000-1, any attachment to the unit symbol as a means of giving information about the special nature of the quantity or context of measurement under consideration is not permitted. Furthermore, if specific frequency and time weightings, as specified in IEC 61672-1, or specific frequency bands or time duration are applied, this should be indicated by appropriate subscripts to the quantity symbol. So we can say in general that, to prevent machines from being confused by these issues, the corresponding specifications may appear in the component "label" of the corresponding metadata model structure recommended in the mentioned guide for the use of the metadata format used in metrology. However, these specifications are seldom written by humans, leading to problems in fully understanding the type of decibel in question.

Confronting logic expressions behind ratio quantities

Logarithmic ratio quantities are framed within a more general logic, let's call it logic A, which considers the ratio of two quantities as a new quantity. Another logic could also be conceived, let's call it logic B, according to which dividing one quantity by another of the same kind merely expresses the number of times that one quantity fits into the other, resulting in just a number. This number may simply be called a coefficient, a factor or a ratio. Logic A or logic B? It's a matter of choice (Valdés, 2005). Other authors also addressed the question of choosing between what we call logic A or logic B. One of the critics of logic A (Emerson, 2004) wrote: "All dimensionless quantities now find themselves saddled with meaningless and unnecessary 'units'. Their units are all of the same name 1, *one*". For Johansson, the unit one is in relation to relative quantities superfluous as a true metric unit, since the so-called dimensionless quantities are not in fact dimensionless; the adequate name should be "unitless quantities" (Johansson, 2010). Within the philosophy of the new SI based on defining constants, the number 1 could also have been seen as a constant, and not a unit. In fact, if there is something here that cannot vary it is the number 1; it is immutable (Valdés, 2019). However, the prevailing logic is to consider the number 1 as a unit. Its possible adoption in the new SI as a constant was never formally discussed at the decision-making levels. These underlying logic expressions in the question of quantities and units are now beginning to be semantically reviewed due to the need to accommodate everything to be machine actionable. Today the entire metrological community is urged to reformulate conceptual terms in relation to quantities and units. A new edition (VIM4) of the *International Vocabulary of Metrology* is being discussed these days. A new definition of quantity could be the following: a property for which comparability by ratio, by difference, or by order applies. Ratio quantities would be properties that can be compared by ratio (such that, for example, one length may be twice another length). The base units would then be units corresponding to ratio quantities as length or mass. Refractive index and mass fraction could be then considered as ratios of ratio quantities. In the transition under discussion, from the current version VIM3 to the new one VIM4, it is perceived that some core metrological terms may remain without consensus among humans for quite some time. Concerning the so-called "quantities with unit one", it is explicitly acknowledged that changes in the term or the definition are possible in the future.

4 Conclusions

Here we refer to a guide for the digital transfer of metrological data. It includes a medal system that categorizes metrological data into different quality classes of machine-readability. The ambiguity of accepting non-SI units for use with the SI is one of the problems to be resolved in order to avoid confusion in a highly machine-readable data representation. The referred guide proposes a change from units that are familiarly used by humans towards a communication using only SI-base units, supported by a transition period. Although the non-SI units dalton, neper, bel and decibel are all categorized as silver "2024" in that guide, we conclude that the transition period should not be the same for the dalton as for the other three. The removal of the non-SI unit dalton, opening the way to the kilogram also on the atomic mass scale, would not have a negative impact as before the redefinition of the SI, since the experimental uncertainties achieved in the most precise cases are now very close. Changing the current status of the logarithmic ratio quantities in the SI Brochure would also require considerably more time, until a digital version of the SI Brochure as a Unique SI Reference Point would be approved. Furthermore, in the transition under discussion from the current version VIM3 of the *International Vocabulary of Metrology* to the new one VIM4, it is perceived that some core metrological terms may remain without consensus among humans for quite some time. This determines to some extent different periods for achieving machine-interpretable objectives in metrological terms, aiming for a time when machines can put the provided information into context and understand the meaning (semantics). Even when language consensus is achieved in written documents, facilitating understanding by machines, there are still issues to be resolved that have been standardized but humans usually do not respect. An example of this lies in the additional specifications that must be included with some logarithmic ratio quantities. For instance, indications of pressure levels, or different power and field quantities related to the unit decibel, as mentioned above in item 3, are properly specified in written technical standards but usually overlooked by humans. Machines have the capacity to include this information in machine-readable format, but it is humans who should provide it to avoid confusion between one decibel and another.

Data availability. The data that support the findings of this study are available upon request to the author if required.

Competing interests. The author has declared that there are no competing interests.

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