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Is the revision of the SI “Getting ahead of itself”?

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Abstract

In some respect, the use of the fundamental constants for the definition of the most important measurement units of the International System, seemed at first glance to be a good solution to found it on more solid bases. From further analysis, it is found implying a number of consequences apparently under-evaluated by the BIPM, or at least not explained to the Countries signatories of the Metre Treaty. This lack of clarity will affect the implementations of the revised System in the future.

The paper is focussing on the following issues: how many are the digits that can safely be stipulated for the numerical values of the constants; why the present experimental uncertainties do not support the pretended precision of the constants; inconsistencies in some-constant 2017 database; why the CODATA LSA analysis could have been not apt or insufficient to provide the “best” numerical values of the constants; hierarchy between the constants and the base units and the new metrological pyramid; necessity to keep the former base units preserving their present magnitudes; base-units/constants relationship; use of the present top national standards in future; some significant discontinuities in the magnitude of the new units.

Keywords: constants, Planck constant, Avogadro constant, revised SI, measurement units, stipulation, metrology.

Отримано: ???

Introduction

Approaching the date when the CGPM will examine the CIPM proposal for the revision of the SI, the analyses that follow are based on the 2018 status of the structure of the revised SI, on the results of the CODATA 2017 adjustment reported in [1] and on some papers published in the same 2018 issue of *Metrologia* [2–4], and particularly on what is related to Planck constant (mass unit), h, and Avogadro constant (amount of substance unit), N_A. Paper [2] provides a deeper analysis than [1] in support of the results of the 2017 CODATA adjustment, with further details on the method used. In particular, its Figure 2 shows the 2014–2017 data for the Planck constant obtained by the CODATA. See [4–12] for further previous analyses on the revision of the SI.

Paper [3] is musing on the data for the Planck constant – one of the main reasons for the commonly-agreed urgency of the SI revision – and looks like a position paper, according to its strong assertion that CODATA analysis is exempt from problems.

Paper [4], on a different analysis of the current Planck constant numerical value, is helpful to better understand papers the 2017 data for h, with diverging conclusions.

Analysis and Comments

“Exactness” of the CODATA stipulated data

Concerning papers [1, 2], a reader informed on the SI-revision process notes that the number of digits now proposed by the CODATA for the stipulated constants, possibly with the exception of the Boltzmann one, k, is larger than previously aimed at. That is certainly due to the lowering of the experimental uncertainties – in the period since 2006 an outstanding ≈5 times – but, apparently, it is also due to a particular use of the original data and of their associated uncertainties. Table 2 shows both the CODATA proposed/stipulated values and “exactly-known values”, when affected, differently from Table 1, by an expanded uncertainty – as is common practice in science for very important issues – because its use here should be considered mandatory.

The CIPM preference expressed in [14], as that of CCU was “*for the minimum number of digits [of the stipulated value] for each defining constant* h, e, k, *and* N_A *of the revised SI that yields consistency factors equal to* 1 *within their uncertainties*”. The CODATA-proposed stipulations [1, 2] in Table 2 intends to match it, after careful critical analysis of the available data.

However, there is a principle, explicit in the CIPM/CCU rules when they talk of “consistency factors”, which must be respected in stipulation: the “continuity principle”.

Values of the “consistency factors” can be computed from the CODATA 2017 stipulated values reported in Table 2, here in Eqs. (1):

Table 1

Change in numerical value and its uncertainty u of the CODATA adjustments 2006–2017, for the new constant k, e, N_A and k involved in the revised SI definition

Constant	CODATA	Numerical value*	u (k = 1)/ relative $\cdot 10^7$	Change	Total shift
Planck $h\cdot 10^{34}$	2006	6.626 0690	3.3/0.50	–	
	2010	6.626 0696	2.9/0.44	$6\cdot 10^{-7}$	
	2014 [13]	6.626 070 04[a]	0.8/0.12	$4.4\cdot 10^{-7}$	$10.4\cdot 10^{-7}$
	2017	6.626 070 15[a]	0.7/0.11	$1.1\cdot 10^{-7}$	$11.5\cdot 10^{-7}$
Electron charge $e\cdot 10^{19}$	2006	1.602 176 49	0.4/0.23	–	
	2010	1.602 176 57	0.35/0.19	$8\cdot 10^{-8}$	
	2014 [13]	1.602 176 62	0.1/0.06	$5\cdot 10^{-8}$	$1.3\cdot 10^{-7}$
	2017	1.602 176 634[b]	0.08/0.05	$1.4\cdot 10^{-8}$	$1.4_4\cdot 10^{-7}$
Avogadro $N_A\cdot 10^{-23}$	2006	6.022 1418	3.0/0.50	–	
	2010	6.022 1413	2.7/0.45	$-5\cdot 10^{-7}$	
	2014 [13]	6.022 1408[c]	0.7/0.12	$-4\cdot 10^{-7}$	$-9\cdot 10^{-7}$
	2017	6.022 140 76[c]	0.6/0.10	$+1\cdot 10^{-7}$	$-8\cdot 10^{-7}$
Boltzmann $k\cdot 10^{23}$	2006	1.380 6504[d]	24/17	–	
	2010	1.380 6488[d]	13/9.4	$-1.6\cdot 10^{-6}$	
	2014 [13]	1.380 6485	8/5.8	$-0.3\cdot 10^{-6}$	$-1.9\cdot 10^{-6}$
	2017	1.380 649[e]	5/3.6	$+0.5\cdot 10^{-6}$	$-1.4\cdot 10^{-6}$

*The CODATA reports standard uncertainty u. The smaller-case digits, taken from the CODATA two-digit uncertainty format, are *uncertain*, an issue that is relevant to the analyses in this paper.

[a] The 2014 CODATA outcome is 6.626 070 040(81), therefore the numerical value can be as low as 6.626 069 959, thus affecting also the preceding digit. Similarly for the 2017 one, the CODATA outcome is 6.626 070 150(69). Consequently, the upper bound of the 2017 interval is 6.626 070 121, and the lower bound of the 2017 interval in 6.626 070 081, *not significantly overlapping*.

[b] The 2017 CODATA outcome is 1.602 176 6341(83), therefore the numerical value can be as low as 1.602 176 6258 and as high as 1.602 176 6424, thus affecting also the preceding digit.

[c] The 2014 CODATA outcome is 6.022 140 857(74), therefore the numerical value can be between 6.022 140 783 and 6.022 140 931, thus affecting the preceding digit. The analysis is similar for the 2017 one, where the CODATA outcome is 6.022 140 758(62).

[d] Two digits are shown because the rounding affects also the preceding digit.

[e] The CODATA 2017 outcome is 1.380 649 03(51), thus the rounding does not include uncertain digits (the only occurrence in the Table). However, the numerical value can be as low as 1.380 648 50, thus in fact affecting the last digit.

Table 2

Different ways to treat the digits of the same numerical values of the four constants (for $k \approx 2$)

Constant numerical value	CODATA 2017 [1] ($k \approx 2$) [a]	CODATA–stipulated[b] [1] (relative uncertainty)	Exactly-known number[c] (from first column)
$\{h\}\cdot 10^{34}$	6.626 070 150(138) $2.1\cdot 10^{-8}$	6.626 070 15 $7.5\cdot 10^{-10}$	6.626 070 $2.3\cdot 10^{-8}$
$\{e\}\cdot 10^{19}$	1.602 176 6341(186) $1.2\cdot 10^{-8}$	1.602 176 634 $3.1\cdot 10^{-10}$	1.602 176(6) $4\cdot 10^{-7}$
$\{N_A\}\cdot 10^{-23}$	6.022 140 758(124) $2.1\cdot 10^{-8}$	6.022 140 76 $8.3\cdot 10^{-10}$	6.022 140(8) $1.3\cdot 10^{-7}$
$\{k\}\cdot 10^{23}$	1.380 649 03(102) $7.4\cdot 10^{-7}$	1.380 649 $3.6\cdot 10^{-7}$	1.380 6(5) $3.5\cdot 10^{-5}$

[a] *Three* digits are left here for uncertainty only to allow appreciating the difference with respect to the CODATA 2017 two-digit (halved) estimates.

[b] The smaller-case digits are used here for those affected by uncertainty in the previous column, i. e. for $k \approx 2$.

[c] Here "exact" means unaffected by the original experimental uncertainty. The added smaller-case digit in parentheses is *not* exact, being affected by the CODATA uncertainty interval indicated in the previous column: e could be as high as 1.602 1767, k could be as low as 1.380 648.

$$\begin{aligned}
&[m(\mathrm{K})/(\mathrm{kg})_{\mathrm{rev}}]/1 = 1.000\,000\,001(10) && [1.2\cdot 10^{-8}] \\
&[\mu_0/(\mathrm{H\ m^{-1}})_{\mathrm{rev}}]/(4\pi\cdot 10^{-7}) = 1.000\,000\,000\,20(23) && [2.3\cdot 10^{-10}] \\
&[M(^{12}\mathrm{C})/(\mathrm{kg\ mol^{-1}})_{\mathrm{rev}}]/0.012 = 1.000\,000\,000\,37(45) && [4.5\cdot 10^{-10}] \\
&[T_{\mathrm{TPW}}/(\mathrm{K})_{\mathrm{rev}}]/273.16 = 1.000\,000\,01(37) && [5.7\cdot 10^{-7}]
\end{aligned} \tag{1}$$

These factors are based on the CODATA stipulated values obtained from the adjusted values in Table 1, and were considered to just correspond to the CIPM indicated criterion. However, there is a basic difference between a scientific context (the constants, CODATA) and a regulatory context (the SI, CIPM).

Eqs. (1) satisfy the CIPM requirement [14] that the continuity principle is satisfied within the present-SI best realisation uncertainties, but are *not* supported by the present experimental evidence, as shown in Table 1 (even worse in Table 2).

That **unresolved conflict** consists of the fact, rather obvious, that one could not stipulate a number with more digit(s) than those confirmed exact by the experiments. The fact that the uncertainty will eventually be dropped in stipulation is totally irrelevant: uncertainty means that, digit(s) affected by it could be different from the stipulated one(s).

It is a fact that the present experimental results, still do not support a firm continuity of the units' magnitudes. To get the desired continuity one is obliged to "guess" the value of the last digit(s), affected by uncertainty.

Inconsistent data and their effect

Another major issue was raised since the 2017 CCU document [15], concerning the evident inconsistency of several supplied new data for the Planck constant: "*... Notes ... that work is under way in NMIs to understand the cause for the dispersion of the experimental determinations of the Planck and Avogadro constants ...*" – as also noted by the CODATA in [1–2]. Nevertheless, the CCU concluded "*that numerical values and uncertainties for the Boltzmann constant and the Avogadro constant provided by the CODATA Task Group on Fundamental Constants in their special Least-Squares Adjustment of the experimental data provide a sufficient foundation to support the redefinition*, ..." and recommended the CIPM to proceed for the 26th CGPM in 2018. The CIPM did so in its 2017 meeting [15].

If data inconsistency is called, by default, an evidence of non-overlapping uncertainty intervals (for k = 1 in case of the CODATA) for the data, Fig. 2 in [2] shows such a case for three 2017 data, which have been considered as such by the CODATA. In the latter respect, the conclusion in [3], based on different specific statistical tools, does not support the lack of inconsistency. On the contrary, in [4] evidence for inconsistency comes from the use of another (Bayesian) method for the analysis of the 2017 – available data. Those three 2017 data are directly used in the analysis in [4] brings to important and conspicuous results: while the CODATA 2017 adjusted value for h results basically equal to NRC-17, from Figs. 3–4 in [4] (to be compared with Fig. 2 in [3]) the evidence comes of a continuing trend towards higher values of h – see also the above Table 1 – pointing rather to the IAC-17 value (not consistent with the CODATA 2017 adjusted value [2]).

The trend in 2017 is still sufficiently significant to allow the doubt that the CODATA conclusion, and the assertion in [3], are not sufficiently founded. In fact, Figs. 3–4 in [4] also show an increase of the credible interval, another reason for being cautious about the number of stipulated digits. These facts brought to the conclusion in [4] that: "*Although nothing can be concluded about a possible future development of the CODATA values for the Planck constant, their contingent change over the past decades does not encourage a redefinition of the kilogram at present*".

CODATA treatment of inconsistent data

In [1] is said: "*... To achieve consistency, multiplicative expansion factors were applied to the uncertainties ... The uncertainties of these input data are multiplied by a factor of* 1.7. *With this expansion of the uncertainties of the eight data, five have relative standard uncertainties* u_r *at or below* $50 \cdot 10^{-9}$, *with two at or below* $20 \cdot 10^{-9}$ ..." (facts also indicated in [2]), where only [2] specifies: "*It is note worthy that even after applying an expansion factor of* 1.7 *to the uncertainties of all ... data, thereby bringing them into agreement, the relative uncertainties of the first five values of h ... are, in parts in* 10^9, *only* 15, 20, 23, 34, *and* 42, *respectively*".

The reported uncertainty lowering is strictly a feature of the *consistency-checking* LSA method. Here, it also shows its weakness in cases like this.

Actually, it is certainly not the first time that the uncertainty of a constant is reduced thanks to the connections that the LSA method establishes between all the elements of the dataset. In this case, it might indicate that the effect of the dispersion of the 2017 values for h, after having been assigned a 1.7-larger uncertainty, becomes almost irrelevant for the general consistency-degree of the whole dataset (Note that here consistency has a different meaning with respect to the data consistency, as discussed in [3, 4] by using specific statistical tools different from the CODATA one). However, since here the uncertainty lowering does not reflect onto the experimental findings, it should be considered as a LSA artefact, and the conclusions reported in [4] looks valid.

Further, the CODATA method of increasing the data uncertainty to eliminate the inconsistencies is common in metrology: however, it should be considered as a better-than-nothing solution, since the discrepancy could be, in reality, not due to an underestimate of the uncertainty, but to a bias of the provided value. In the present case, too, it is not without inconveniences. The fact that the uncertainty after the uncertainty "expansion" remains nearly the same of that in 2014 is not necessarily good news, but it may indicate instead that the 2017 values were brought to have an irrelevant effect. The numerical value could become impaired by the small sensitivity of the constant's subset with respect to the overall dataset. As a consequence, it may happen that the value is adjusted more or less than correctly.

Insufficient overall analysis of 2017 final database

In conclusion, the confidence/degree-of-believe on future stability of the numerical values of h could be considered insufficient. A deeper discussion of the evident inconsistencies of several data should be provided.

The analyses in [2–4], contrasting with each other, are presently insufficient to draw the conclusion of sufficiency about such an important subject matter. In particular, the CODATA 2017 value of h is not supported by all presently-published analyses. Considering the extraordinary effort made by several NMIs for supplying more data in order to support the decisions that must be taken about the numerical values to assign to the constants, one would expect that deeper analyses are made available in support to the results of the 2017 CODATA adjustment, and, beyond it, to the available dataset — which should possibly be increased.

The importance of the result of the SI revision, not only for the metrologists but for the entire Community of scientists, should prompt a broad number of competent and independent analyses, using different methods. In this respect, also analyses independent on the CODATA one should be included.

In general, the LSA method allows checking only *consistency* of the dataset, because the measured values are changed ("adjusted") to optimise the standard deviation of the set. This method, sound for many scientific applications, looks unsuitable when, as for the SI, the *numerical values* of the constants are instead the unique goal: the values supplied by CODATA are *relative to the constraints* chosen to make determined LSA relational-equation set — strictly speaking, the LSA is not a statistical method for obtaining "best" mean values of the dataset.

The advantage would be to mitigate the otherwise un-confronted effect of the somewhat-biased values and reduction of uncertainty levels caused by the CODATA use of the LSA, so leading to better evidence about the digits needed and allowed to express the numerical values of the constants and the Planck one in particular. In turn, that would offer higher confidence to the process of stipulation of "exact" numerical values. A combined "best value", and its associated uncertainty, should be obtained by using several diverse methods.

Is a hierarchy between countries now established, or are the present top national standards still valid after the SI revision?

This issue, non-scientific but basic in the SI regulatory context, is fully discussed in [12]. Here only some conclusions are reported.

The metrological **traceability** pyramid of the standards is changed by the revised SI, as shown in Table 3: "definitional methods" do not stand anymore, but "primary methods", *not* to be included in the *mise en pratique* as CCU still does, should be identified, now replacing them. For the standards below the latter level nothing changes.

In addition, while at present, the implementation of the SI according to the Metre Treaty, in particular by the NMIs, never implies that they must resort to another NMI/Country, so that a user might decide to resort to another NMI/Country only on its *own choice*, with the revised SI definition, traceability to the definition requires the demonstration that the defined values are *determined* by the NMIs. This is *affordable only by a few Countries*, unless reference to the constants becomes only a *check*, not ***the*** SI *definition*, dif-

Table 3

Metrological traceability chain for the SI (*example: length*). (from [7])

Traceability Level	Present-SI	Revised SI
Top	Definitional method Method using "distance" and "time interval"[a]	No definitional method. "Condition": to reproduce the stipulated constant(s) value
–1	Mise en pratique. Other method(s): using frequency and period	Primary methods: c_0 *and t explicit in the model*
–2	Secondary methods. Other method(s): stabilised laser	Mise en pratique. Other method(s): using frequency and period
–3	Workshop methods. Gauge blocks	Secondary methods Other method(s): stabilised laser
–4	Lower ranks	Workshop methods: *gauge blocks*, ...

[a] This requirement is so far not always respected in the traceability chain.

ferently from the presently proposed definition. If this change will not be implemented, a **hierarchy** between Countries will necessarily be established between those who will experimentally determine the whole set of constants and the rest – the vast majority.

On the other hand, for the present standards at the top of the traceability chain, which were used to *determine the numerical values* of the constants used in the new SI definition, a different approach can be considered, still being a controversial possibility.

It is a fact, as said hereinbefore, that the numerical values of the constants are those obtained by using the units of the present-SI. Therefore, since new and old units are made *indistinguishable in magnitude* (with the two exceptions below), one could ask why the present standards, having provided the numerical values to the constants, up to top metrological level, should not be anymore permitted after promulgation of the revision. Should, e. g., the deadline moved to, say, 2020, they would continue to provide new data: so, at least for a "short period of time" [16] – i. e. under "repeatability conditions" [16] – after revision, stable standards should entitled to be used for *further valid realizations* of the constants (note, *not* providing a different numerical value). Therefore, those same numerical values – now no more in the definitions and thus uncertain – remain *by definition consistent* with the new condition set by the use of the constants for a "short period of time" [16], here meaning until evidence will become available in future, from new experiments or theoretical reasons, that the present units were actually not consistent with each other.

Immediately after the change of definition, they still *ensure the consistency* ("metrological compatibility" [16]) of the old with the new units. This means respecting the "principle of continuity", obviously within the uncertainties associated to the results obtained with the present-SI. It is an *intrinsic property of the previous standards* that is still valid and should be preserved by a clear indication in the BIPM texts.

Base units – Constants relationship

The issue is fully discussed in [8, 10]. Here only some conclusions are reported.

The SI revision is considered by the proposers to produce a scientific revolution in Kuhn's sense, so requiring a brand new approach to accommodate the changes in the SI. However, not all these changes are correctly identified in the current BIPM documents. They would be less dramatic than estimated and could be accommodated without such revolution provided that its *conceptual structure* has enough flexibility: (i) with *constants* based on the principles and tools of and contents of fundamental physics, and thus in particular on the currently accepted system of quantities and the set of fundamental constants: (ii) with (not optional) *base units* linked to the current SI so that the principle of continuity is fulfilled.

A conceptual roadmap that satisfies both these requirements, can be obtained by construing a system of units according to an explicit *two-stage structure* – explicit but not implemented in the present document – including (i) a *fundamental* system and (ii) a *conventional* one:

(i) both a system of quantities and a set of constants corresponding to the dimensions of the base of the system are assumed; this is the *fundamental* system where the *numerical value of each constant is* 1;

(ii) a *conventional* system is then considered linked to the above fundamental system, where it is admitted that the numerical values of the constants can have values different from 1, assigned according to the best available *present* knowledge, so that in changing to the new system the units maintain their values as expected according to the principle of continuity.

Discontinuities occur in the magnitude of some of the new measurement units

At present, two units will show a magnitude discontinuity of the order of 10^{-7} relative, quite significant, in the revised SI:

- the volt, for which a cause is not presently explained in any publication, but probably arises from the imperfect "closure" of the "quantum triangle";
- the dalton with respect to the mole, arising from the fact that in the revised SI the Dalton is now affected by an uncertainty [17] while the mole is defined exact.

Чи є перегляд SI “забіганням уперед”?

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Анотація

Використання фундаментальних сталих для визначення найбільш важливих одиниць (кілограма, ампера, кельвіна і моля) Міжнародної системи одиниць (SI) на перший погляд здалося доцільним рішенням для отримання значень цих одиниць на більш надійній основі. Передбачається, що нові визначення ґрунтуватимуться на фіксованих чисельних значеннях сталої Планка, елементарного електричного заряду, сталої Больцмана і сталої Авогадро, відповідно. Усім цим величинам будуть приписані точні значення, що ґрунтуються на найбільш достовірних результатах вимірювань, рекомендованих Комітетом з даних для науки і техніки (CODATA).

Проводиться аналіз, що дозволяє з’ясувати ряд наслідків прийняття перегляду SI, які, ймовірно, недостатньо оцінені BIPM або, певною мірою, не пояснені країнам, що підписали Метричну конвенцію. Ця відсутність ясності вплине на реалізацію переглянутої SI у майбутньому.

Основна увага приділяється таким питанням: скільки цифр можна безпечно встановлювати для числових значень сталих; чому нинішні експериментальні невизначеності не підтримують так звану прецизійність сталих; неузгодженості у базі даних певних сталих за 2017 р.; чому аналіз методом найменших квадратів міг бути недоцільним або недостатнім для забезпечення “кращих” числових значень сталих; ієрархія щодо сталих та основних одиниць, нова метрологічна піраміда; необхідність збереження колишніх основних одиниць зі збереженням їх нинішніх числових значень; відношення основних одиниць/сталих; використання найкращих сучасних національних еталонів у майбутньому; деякі значні розриви у числових значеннях нових одиниць.

Ключові слова: сталі, стала Планка, стала Авогадро, переглянута SI, одиниці вимірювання, обмеження, метрологія.

Является ли пересмотр SI “забеганием вперед”?

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Аннотация

Использование фундаментальных постоянных для определения наиболее важных единиц (килограмма, ампера, кельвина и моля) Международной системы единиц (SI) на первый взгляд показалось целесообразным решением для получения значений данных единиц на более надежной основе. Предполагается, что новые определения будут основываться на фиксированных числовых значениях постоянной Планка, элементарного электрического заряда, постоянной Больцмана и постоянной Авогадро, соответственно. Всем этим величинам будут приписаны точные значения, основанные на наиболее достоверных результатах измерений, рекомендованных Комитетом по данным для науки и техники (CODATA).

Проводится анализ, позволяющий выяснить ряд последствий принятия пересмотра SI, которые, по-видимому, недостаточно оценены BIPM или, по крайней мере, не объяснены странам, подписавшим Метрическую конвенцию. Это отсутствие ясности повлияет на реализацию пересмотренной SI в будущем.

Основное внимание уделяется следующим вопросам: сколько цифр можно безопасно устанавливать для числовых значений постоянных; почему нынешние экспериментальные неопределенности не поддерживают так называемую прецизионность постоянных; несогласованности в базе данных некоторых постоянных за 2017 г.; почему анализ методом наименьших квадратов мог быть нецелесообразным или недостаточным для обеспечения “лучших” числовых значений постоянных; иерархия относительно постоянных и основных единиц, новая метрологическая пирамида; необходимость сохранения прежних основных единиц с сохранением их нынешних числовых значений; отношение основных единиц/постоянных; использование лучших современных национальных эталонов в будущем; некоторые значительные разрывы в числовых значениях новых единиц.

Ключевые слова: постоянные, постоянная Планка, постоянная Авогадро, пересмотренная SI, единицы измерения, ограничение, метрология.

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