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Ambiguities in the Use of Unit Names

Chester H. Page

The volt as maintained in the United States was decreased by 8.4 ppm (1 January 1969), with no change in the ohm; should previously published values of the gyromagnetic ratio be increased or decreased for comparison with later measurements?

Experimental determinations of physical constants are usually reported in the literature in accepted units, such as SI (*1*). The actual measurements are *not* made in terms of the reported units, but in terms of the units maintained by a standards laboratory. This lack of precise identification of the results leads to ambiguities in comparing the data from different countries, and in adjusting constants to make a most consistent set.

For example, when a determination of the gyromagnetic ratio of the proton is reported, there is not only an experimental uncertainty associated with the calibration of the equipment, but usually also a semantic uncertainty associated with the meaning of the names of the units given. For example, if the gyromagnetic ratio is reported as 42.5764 MHz/T, what is really meant by "tesla"?

The ambiguity surfaces when an attempt is made to compare results given before and after the 1969 adjustment to the volt as maintained by national laboratories. The tesla is proportional to the volt by

$$T = V \cdot s/m^2$$

but also inversely proportional by

$$T = kg \cdot \Omega/s^2V$$

Theoretical Units and Actual Measurement Units

The SI base units of mechanics and electromagnetism are the kg, m, s, and A. In actual measurements, however, a laboratory uses units disseminated by national laboratories via a calibration process. For the scope of this discussion, let us assume that the "local" kg, m, and s are essentially perfect, and that they are used for measuring mass, length, and time. Measurements of force, and of electric quantities, are made by comparison with imperfect standards. Let us denote the local units maintained by these imperfect standards by $\hat{N}$, $\hat{V}$, $\hat{\Omega}$, $\hat{F}$; these are approximations to the true newton, volt, ohm, and farad. The three electrical units are established by calibrations of cells, resistors, and capacitors, and are algebraically and physically independent. The laboratory newton is usually real-

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ized in terms of the weight of a mass $\{\hat{g}^{-1}\}$ kg, where $\hat{g}$ is the accepted (not always precise) value of g at the laboratory, and $\{\hat{g}\}$ is the numerical value of the dimensioned quantity $\hat{g}$. The four base units of theory have been replaced, in practice, by seven independent units: kg, m, s, $\hat{\mathrm{N}}$, $\hat{\mathrm{V}}$, $\hat{\Omega}$, $\hat{\mathrm{F}}$.

The corresponding seven theoretical units are related by redundancy

$$\mathrm{N} = \mathrm{m} \cdot \mathrm{kg/s^2}$$

$$\Omega = \mathrm{V^2 s/(m \cdot N)}$$

$$\mathrm{F} = \mathrm{m \cdot N/V^2}$$

(Since the volt, not the ampere, is disseminated and maintained, it is convenient to express the above relations in terms of V.)

The local measurement units therefore satisfy the approximate relations

$$\hat{\mathrm{N}} \doteq \mathrm{m} \cdot \mathrm{kg/s^2}$$

$$\hat{\Omega} \doteq \hat{\mathrm{V}}^2\mathrm{s}/(\mathrm{m} \cdot \hat{\mathrm{N}})$$

$$\hat{\mathrm{F}} \doteq \mathrm{m} \cdot \hat{\mathrm{N}}/\hat{\mathrm{V}}^2$$

Quantities and Numerical Values

A *physical quantity* is invariant under changes of units or measurement systems. It can be expressed as the product of a *unit* and a *numerical value*, or *measure*. Thus the quantity x can be expressed as

$$x = \{x\}\,[x]$$

where $[x]$ is the unit and $\{x\}$ is the corresponding numerical value. Any change of unit entails a reciprocal change in the numerical value of the quantity.

The final result of the measurement of a physical constant is a *quantity*, not a *number*. If this quantity is properly reported, its numerical value can be readily determined in terms of any set of units. Similarly, any adjustment of a unit system leads to a simple adjustment of the numerical value.

Gyromagnetic Ratio as Specific Example

The gyromagnetic ratio of the proton is the ratio of its precession frequency to the ambient magnetic flux density

$$\gamma = \omega/B$$

or, more conveniently,

$$\frac{\gamma}{2\pi} = \nu/B$$

In the weak-field determination, the experiment is done in the magnetic field of a carefully constructed solenoid

$$B \propto \mu_0 I/l$$

In the strong-field determination, the flux density of an electromagnet is measured in terms of the force on a current-carrying wire:

$$B = F/Il$$

Note the inverse positions of I in these expressions.

In the strong-field experiment

$$\frac{\gamma_s}{2\pi} = \nu/B = \nu Il/F$$

so that the *numerical value* obtained for $\gamma_s/2\pi$ is

$$\left\{\frac{\gamma_s}{2\pi}\right\} = \frac{\nu Il}{F}\,\frac{[F]}{[\nu Il]}$$

Since the *quantities* v, I, l, F, and so on, are invariant to choices of units

$$\left\{\frac{\gamma_s}{2\pi}\right\} \propto [F]\,/\,[\nu Il]$$

The *quantity* reported as a result of the experiment is strictly

$$\frac{\gamma_s}{2\pi} = \left\{\frac{\gamma_s}{2\pi}\right\} [\nu]\,[I]\,[l]\,/\,[F]$$

$$= \left\{\frac{\gamma_s}{2\pi}\right\} \mathrm{Hz} \cdot \mathrm{m} \cdot \hat{\mathrm{A}}/\hat{\mathrm{N}}$$

$$= \left\{\frac{\gamma_s}{2\pi}\right\} \mathrm{Hz} \cdot \mathrm{m} \cdot \hat{\mathrm{V}}/\hat{\mathrm{N}} \cdot \hat{\Omega}$$

instead of

$$\left\{\frac{\gamma_s}{2\pi}\right\} \mathrm{Hz/T}$$

as given.

Similarly, the weak-field experiment gives

$$\frac{\gamma_w}{2\pi} = \left\{\frac{\gamma_w}{2\pi}\right\} [\mu_0]^{-1}\,\mathrm{Hz} \cdot \mathrm{m}/\hat{\mathrm{A}}$$

$$= \left\{\frac{\gamma_w}{2\pi}\right\} [\mu_0]^{-1}\,\mathrm{Hz} \cdot \mathrm{m} \cdot \hat{\Omega}/\hat{\mathrm{V}}$$

$$= \left\{\frac{\gamma_w}{2\pi}\right\} \mathrm{Hz} \cdot \mathrm{m^2} \cdot \hat{\Omega}/(\hat{\mathrm{V}} \cdot \mathrm{H})$$

On 1 January 1969, the volt as disseminated was *decreased* by 8.4 ppm, and the disseminated ohm was left unchanged. To keep the *quantities* $\gamma_s/2\pi$ and $\gamma_w/2\pi$ invariant, previously published values of $\{\gamma_s/2\pi\}$ must be *increased* by 8.4 ppm, and $\{\gamma_w/2\pi\}$ *decreased* by 8.4 ppm to express the gyromagnetic ratio in terms of the new legal units.

If an improved measurement of g should become available, what adjustments to the data would be needed? Since the local newton is the weight $g\{\hat{g}^{-1}\}$ kg, we have

$$\hat{\mathrm{N}} = g\,\{\hat{g}^{-1}\}\,\mathrm{kg} = \{g\}\,\{\hat{g}^{-1}\}\,\mathrm{kg \cdot m/s^2}$$

$$= \{g/\hat{g}\}\,\mathrm{N}$$

$$\hat{\mathrm{N}} \propto \{\hat{g}\}^{-1}$$

An increase in the numerical value of $\hat{g}$ would entail a decrease in $\hat{\mathrm{N}}$, and a decrease in $\{\gamma_s/2\pi\}$; $\{\gamma_w/2\pi\}$ would be unaffected.

Recommendations

The importance of the fundamental physical constants and their relationships leads to periodic adjustments of "best values." This requires that input data be expressed in common units, with adjustments for changes made in various national standards. Such adjustments would be easy and unambiguous if published determinations were expressed in terms of the *actual units* involved, instead of using unmodified names of theoretical units.

For example, a result could be reported as 42.5764 MHz/$\hat{\mathrm{T}}$, with the local tesla being identified by

$$\hat{\mathrm{T}} = \hat{\mathrm{N}} \cdot \hat{\Omega}/(\hat{\mathrm{V}} \cdot \mathrm{m})$$

or by

$$\hat{\mathrm{T}} = \mathrm{H} \cdot \hat{\mathrm{V}}/(\hat{\Omega} \cdot \mathrm{m^2})$$

as appropriate.

If, for example, the weak-field determination were made in terms of a local realization of the ampere instead of in terms of calibrated cells and resistors, the subsidiary equation would read

$$\hat{\mathrm{T}} = \mathrm{H} \cdot \hat{\mathrm{A}}/\mathrm{m^2}$$

One of the founders of the science of adjusting physical constants, R. T. Birge, encountered this problem in an extreme form. I quote from "A Survey of the Systematic Evaluation of the Universal Physical Constants" (Nuovo Cimento, 1957):

> It may be noted, incidentally, at this point that the closely related equation
>
> $$h\nu = Ve$$
>
> as used in connection with measured excitation and ionization potentials, furnishes the illustration of an inconsistency mentioned earlier, namely the use of two *different* values of c in the *same* equation. Thus the frequency $\nu(\mathrm{s^{-1}})$ is obtained from the measured wave number ($\mathrm{cm^{-1}}$) by multiplication by c. Similarly the potential V (esu) is obtained from the measured voltage by multiplication by $10^8/c$. Thus the factor c^2 enters the actual working equation.
>
> But when I was writing my 1929 paper I discovered that it was only too customary for the best available value of c to be

used in obtaining actual frequency, but for 300 to be used in place of the correct $c/10^8$ in the voltage transformation. Aside from this glaring inconsistency, the latter approximation introduces an error of 0.07 percent, which was by no means negligible even in 1929. But although I emphasized this point in my paper [15], the same error has actually occurred, even many years later and in connection with work of the highest precision.

If investigators would only write an expression for any result, *explicitly* in terms of the quantities actually measured (which in the foregoing illustration would lead to the explicit appearance of the factor c^2), inconsistencies and unjustified approximations would be far less likely to occur.

A precursor of this paper was discussed by the Comité Consultatif des Unités. The result of the discussion was the following recommendation, subsequently approved by the Comité International des Poids et Mesures (1971) (*2*):

The Consultative Committee for Units, RECOMMENDS that reports on measurements of high precision, in particular on the experimental determination of physical constants, contain precise information on the manner in which the obtained results depend upon the values assigned to the starting-point standards and to other constants and parameters used, so that the results can be readjusted if need be.

The problem is threefold: (i) to educate experimentalists in the nuances of the relations between their local units and the SI names, (ii) to develop a simple unambiguous notation and terminology for precise reporting of important data, and (iii) to convince journal editors and reviewers of the importance of the problem.

Notes

1. Symbols and abbreviations: SI, Système International d'Unités (the modern metric system, see NBS Special Publication 330 for an official description of the International System of Units); Hz, hertz (cycle per second); M, mega, prefix for 10^6; T, tesla, SI unit for magnetic flux density; V, volt; s, second; m, meter; kg, kilogram; Ω, ohm; F, farad; N, newton, the SI unit of force; g, acceleration of gravity; γ, (gamma) gyromagnetic ratio of the proton; subscript w, weak; subscript s, strong; ω, angular frequency; B, magnetic flux density; ν, (nu) frequency; I, electric current; l, length; μ_0, magnetic constant (of the system of units), sometimes called "permeability of vacuum"; F, force; H, henry; h, Planck constant; e, elementary charge (charge of positron); c, speed of light; esu, electrostatic system of units; ppm, parts per million.
2. The original wording is as follows.
   Le Comité Consultatif des Unités, RECOMMANDE que les rapports sur les mesures de haute précision, en particulier sur la détermination expérimentale de constantes physiques, contiennent les renseignements précisant la façon dont les résultats obtenus dépendent des valeurs attribuées aux étalons de départ et aux autres constantes ou paramètres utilisés, afin que ces résultats puissent être réajustés en cas de besoin.

NEWS AND COMMENT

Technology Assessment: Congress Develops a Hybrid

Parliamentary hares, who hoped that Congress's new Office of Technology Assessment (OTA) would be operating soon enough to give it some help in sprinting past the President on current issues such as the energy crisis, are in for a disappointment. The OTA is unlikely to receive any of its authorized $5-million budget before 1 July, and therefore won't be operating until the summer. Like the proverbial tortoise, OTA is off to a slow start—but one which its proponents say indicates reliability rather than feebleness.

In the meantime, the scientific job market in Washington must be very tight, because the several Capitol Hill offices concerned with setting up OTA have on file an estimated 500 job applications, letters of recommendations, and solicitations for contract awards. Once the new director starts hiring for his 30-odd slots he will literally have crowds to choose from.

Hill procedures have been holding up the establishment of OTA. The bill creating OTA was signed last October, or months after Congress had passed the fiscal 1973 authorization for its own offices. The fiscal 1974 bill won't be voted until May or June. Interim funds could be drawn from the general fund which finances all congressional committees, but OTA isn't a committee, technically, and so cannot use those funds. Thus the office won't be able to pay a director or staff before the start of fiscal 1974 on 1 July 1973.

Although still in the planning stages, OTA is shaping up to be quite different from what academic proponents of technology assessment may have expected. A staffer to Senator Edward M. Kennedy (D–Mass.) (Kennedy is chairman of the board for the OTA's first term) pointed out last week that the office will be more of a general technical consulting service for Congress and congressmen. "Any material or advice we can give to Congress to help it make better decisions we will do. This is why we won't only do the precise, academic, technical analyses. That sort of thing is limited in what it can do for Congress," he said.

As an organizational beast, OTA will be composed of different parts drawn from various administrative animals. The board of OTA will be, in effect, a joint committee of Congress. Members from the Senate will be: Kennedy, Hubert H. Humphrey (D–Minn.), Ernest F. Hollings (D–S.C.), Peter H. Dominick (R–Colo.), Clifford P. Case (R–N.J.), and Richard S. Schweiker (R–Pa.). House members will be John W. Davis (D–Ga.), Olin E. Teague (D–Tex.), Morris K. Udall (D–Ariz.), Charles A. Mosher (R–Calif.), and James Harvey (R–Mich.).

[Mike McCormack (D–Wash.), the first scientist in Congress in recent years, was appointed to the OTA board last winter. But McCormack, who is on the House Committee on Science and Astronautics, has now obtained a seat on the Joint Committee on Atomic Energy instead.]

The OTA will be officially nonpartisan—but being nonpartisan usually means that the counting of Republicans and Democrats is considered more solemnly than the number of teeth in the medieval horse's mouth. A few months ago, Mosher, who is an active member of the House science committee and was then a senior Republican candidate for the new board, was arguing that it might benefit the OTA's nonpartisan image to have a Republican as the vice chairman of the board. But, Davis and others now think a Democrat would be more effective with the Democratic machinery of the House during the office's maiden year. Staffers now say that Davis will probably be vice chairman.

The horse trading continues. The only