SHORT COMMUNICATION • **OPEN ACCESS**

What is measurement uncertainty? A discussion*

To cite this article: Luca Mari *et al* 2025 *Metrologia* **62** 062101

OPEN ACCESS
IOP Publishing | Bureau International des Poids et Mesures
Metrologia
Metrologia 62 (2025) 062101 (6pp)
https://doi.org/10.1088/1681-7575/ae1f1e

Short Communication

What is measurement uncertainty? A discussion*

Luca Mari[1,], Richard J C Brown[2], Claudio Narduzzi[3], Gunnar Nordin[4], Stefanie Trapmann[5] and Daniel Varela Magalhães[6]**

[1] Cattaneo University LIUC, Corso G Matteotti 22, Castellanza, Italy
[2] National Physical Laboratory, Hampton Road, Teddington TW11 0LW, United Kingdom
[3] Department of Information Engineering, University of Padova, I-35131 Padua, Italy
[4] Equalis AB, Uppsala, Sweden
[5] European Commission, Joint Research Centre, Geel, Belgium
[6] University of São Paulo, São Carlos Institute of Physics, São Carlos, Brazil

E-mail: lmari@liuc.it

Received 10 September 2025, revised 11 November 2025
Accepted for publication 13 November 2025
Published 5 December 2025

Abstract

In 1993, the *Guide to the Expression of Uncertainty in Measurement* (GUM) defined measurement uncertainty as a parameter, and therefore a mathematical entity. In the following 30 years this definition has been maintained as a reference, although it has increasingly proven to be too narrow in its scope. In 2023, the *Introduction to GUM* introduced a different definition, which implied three radical changes to the well-established and widely adopted conceptual framework of the GUM, as adopted by the *International Vocabulary of Metrology* (VIM). These involved treating measurement uncertainty as (i) a psychological entity instead of a mathematical one, (ii) related to the doubt about a theoretical true value instead of to an operational dispersion of measured values, and (iii) only applicable to single-valued measurands instead of the more general and more useful case of measurands with non-zero definitional uncertainty. Since the same changes are now proposed for inclusion in the next edition of the VIM it is appropriate to carefully analyze them. Our conclusion is that there are no sufficient reasons for radically changing the fundamental concept of measurement uncertainty. Instead, the definition of the GUM should rather be generalized to make it more widely applicable.

Supplementary material for this article is available online

Keywords: measurement uncertainty, *International Vocabulary of Metrology*, *Guide to the Expression of Uncertainty in Measurement*, definitions, conceptual framework

* While authored by members of JCGM-WG2:VIM, what is written here does not represent any official position of the Working Group.
** Author to whom any correspondence should be addressed.

1. Introduction

'What is measurement uncertainty?' and therefore 'How should the concept of measurement uncertainty be defined?' These questions have often been heard and discussed lately (including in an open webinar organized by the BIPM on behalf of the Joint Committee for Guides in Metrology (JCGM) on 2 July 2025; www.bipm.org/en/committees/jc/jcgm/wg/jcgm-webinar/2025-07-02), generating some different—sometimes markedly different—answers. A key reason for these discussions is that in 1993 the *Guide to the Expression of Uncertainty in Measurement* (GUM) [1] defined measurement uncertainty as a parameter, and therefore a mathematical entity. In the following 30 years this definition has been maintained as a reference, first of all by the *International Vocabulary of Metrology* (VIM) [2], although it has increasingly proven to be too narrow in its scope. In 2023, the *Introduction to GUM* (GUM-1) [3] introduced a radically different definition, which is now proposed for inclusion in the next edition of the VIM.

But what is the actual content of the above questions? Given that measurement is a designed process, not one that happens in nature, measurement uncertainty is also not a natural entity, 'something out there' that exists independently of us and our understanding. Accordingly, there is nothing like an intrinsic meaning of the term "measurement uncertainty" that we can discover and then define accordingly. Hence, how to define 'measurement uncertainty' (and 'measurement result' and 'measurement' itself) is a matter for our decision. Does it imply that such a definition is completely arbitrary? No, because the principles and rules of terminology need to be maintained and they set the boundary conditions.

After a short recap about some basics of terminology, in section 2 we summarize the GUM position on measurement uncertainty, considered to be the *received view* (i.e. both the widely accepted view of theories and the established consensus), given the acknowledged pivotal role that the GUM has had on this subject. Section 3 is then devoted to discussing the definition introduced in the GUM-1, by highlighting three radical changes to the definition in the GUM that it implies. In the final two sections we provide some comments on this situation, and offer some options for solving the acknowledged issues of the GUM definition that do not require any change in the nature of measurement uncertainty.

The underlying purpose of this short communication is to propose—along the lines of the GUM—that measurement uncertainty can be properly defined, modeled and dealt with with no explicit reference to true values of the relevant measurand. Vice versa, it is not our purpose here to discuss the very existence of true values of quantities, and measurands in particular, nor to take a stance about what conditions justify the hypothesis that true values are unique.

This short communication also includes three appendices provided as supplementary information. The first discusses the justifications for the change in the GUM-1 proposed by the only two papers we are aware of [4, 5], referring to a guidance document [6] and a previous paper [7] as their starting point. The second and third appendices outline two simple examples, inspired by an analogous example in Annex D of the GUM, aimed at showing that the GUM definition, possibly in a suitably generalized version, remains appropriate to describe measurement and its results.

A recap about terminology

These questions are also related to terminology. Since perhaps not all readers are familiar with the basics of terminology, a recap could be helpful, in reference to ISO terminology standards such as ISO 1087 *Terminology Work and Terminology Science—Vocabulary* [8] (the following quotes are simplified rephrasing of the originals):

- we use language to talk about *objects*, i.e. 'anything perceivable or conceivable' (3.1.1),
- and to this purpose we create *concepts*, i.e. 'units of knowledge' (3.2.7),
- and then *definitions*, i.e. 'representations of concepts by an expression that describes them and differentiates them from related concepts' (3.3.1),
- and *terms*, i.e. 'representations of concepts by a sign which denotes them by linguistic means' (3.4.1 and 3.4.2).

Hence, by following the notational convention about delimiters, measurement uncertainty (no delimiters) is an object, of which we have some knowledge and therefore a concept, 'measurement uncertainty' (single quotes), designated in English by a term "measurement uncertainty" (double quotes). Hence, what is defined here is the concept 'measurement uncertainty', not the object measurement uncertainty and not the term "measurement uncertainty". While different people could have non-identical concepts, for example due to their different knowledge of probability theory, a good definition helps them to refer to the same object when they use the term "measurement uncertainty".

In the context of this terminological framework let us take a look at the issue of what measurement uncertainty is.

2. The received view

The history is known, and summarily told in the Foreword of the GUM:

> *In 1977, recognizing the lack of international consensus on the expression of uncertainty in measurement, the world's highest authority in metrology, the Comité International des Poids et Mesures (CIPM), requested the Bureau International des Poids et Mesures (BIPM) to address the problem in conjunction with the national standards laboratories and to make a recommendation.*

The GUM is the offspring of this endeavor, as a document which ‘establishes general rules for evaluating and expressing uncertainty in measurement’ (1. Scope).

Plausibly, with the consideration that for ‘evaluating and expressing’ something we have to share at least some basic information about that something, the GUM went on and

- wrote about ‘the concept of uncertainty as a quantifiable attribute’ (0.2) (suggesting that uncertainty is quantifiable, and therefore not already a quantity as such),
- established conditions on the ‘quantity used to express uncertainty’ (0.4) (suggesting again that uncertainty can be expressed by a quantity), and also
- included a section of definitions (2).

Paragraph 2.2.1 of that section deserves full quotation and careful reading.

> *The word “uncertainty” means doubt, and thus in its broadest sense “uncertainty of measurement” means doubt about the validity of the result of a measurement. Because of the lack of different words for this general concept of uncertainty and the specific quantities that provide quantitative measures of the concept, for example, the standard deviation, it is necessary to use the word “uncertainty” in these two different senses.*

Two aspects should be noted.

First, while “result of a measurement” means here the ‘value attributed to a measurand, obtained by measurement’ (B.2.11), in the meantime it has been acknowledged that a measurement is aimed at producing more than just a value—precisely because some information on measurement uncertainty is required—and therefore the term for this concept has been changed to “measured value” (‘quantity value representing a measurement result’ in VIM, 2.10). Hence, the sentence above would be written today ‘… in its broadest sense “uncertainty of measurement” means doubt about the validity of the measured value …’.

Second, paragraph 2.2.1 is terminologically problematic, as it mingles concepts and objects by stating

- that a term (“uncertainty”) stands for both a concept (the general concept of uncertainty) and some objects (some specific quantities), and
- that a concept, and not an object, can be measured.

Hence, the following rephrasing can be proposed, in which the references to concepts are left implicit, to make the message more correct and clearer:

> *The term “uncertainty“ means ‘doubt’, and thus in its broadest sense “uncertainty of measurement” means ‘doubt about the validity of the measured value’. Because of the lack of different terms for referring to the doubt about the validity of the measured value and to the mathematical entities that provide quantitative information on such a doubt, for example, standard deviation, the word “uncertainty2 is used with these two meanings.*

On this basis we can read ‘the formal definition […] developed for use’ in the GUM (2.2.3):

> *uncertainty (of measurement): parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand*

and again update it as:

> *parameter, associated with the measured value, that characterizes the dispersion of the values that could reasonably be attributed to the measurand*

In short, the GUM started by maintaining a distinction between uncertainty and the ‘quantit[ies] used to express’ it. It then acknowledged that with the term “uncertainty” we refer both to a psychological entity (doubt) and several mathematical entities (such as standard deviation). Finally, it adopted a sentence about the latter as its ‘formal definition’. While a more explicit justification of the definition might have been desirable, the underlying intent is clear: given that “measurement uncertainty” does not have anything like a ‘true’ meaning, and that in fact some different meanings are possible, the GUM opted to use “measurement uncertainty” as a term referring to a mathematical entity, and specifically a parameter.

It is also important to consider a second decision embedded in this definition. Measurement uncertainty is meant to be about the validity of the measured value, and therefore ‘the values that could reasonably be attributed to the measurand’. Consider here the principled distinction between

- *the measured value*, that is chosen and reported as resulting from the measurement and as such is known, and
- *the true value of the measurand*, that is inferred or estimated by means of the measurement but, with possible exceptions, remains only uncertainly known.

A value that is chosen can estimate a true value but cannot be a true value, because truth is given, not chosen. Hence, the phrase ‘values that could reasonably be attributed to the measurand’ in the GUM definition refers to measured values, not to true values. This implies that the GUM opted to maintain an encompassing and operational standpoint that avoids any explicit mention of true values in the definition of ‘measurement uncertainty’. As a consequence

- those who consider the reference to the true value (or the ‘essentially unique’ true value, or a true value) of the measurand as a necessary component of a correct description of a measurement could interpret the doubt about the validity of the measured value as implicitly related to its ‘closeness’ to

the true value, and could also interpret 'reasonable attribution' as a matter of parameter estimation or something similar, whereas
- those who endorse a position according to which measurements and their results can be described without any reference to true values, or even deny the existence of true values, could interpret both the validity of the measured value and 'reasonable attribution', for example, as a matter of knowledge elicitation and quality of the information acquired by means of the measurement.

Given the acknowledged authoritative position of the GUM in the last 30+ years, as also endorsed by the VIM, this standpoint, i.e. that according to the definition of the GUM measurement uncertainty

- is a mathematical entity (and not a psychological one, such as doubt) and
- is about operationally known measured values (and not necessarily related to the true value of the measurand),

can be safely considered to be *the received view* on measurement uncertainty.

3. What is at stake now

The GUM-1 was published in 2023 and includes the following statement (3.4):

> *Measurement uncertainty is the doubt about the true value of the measurand that remains after making a measurement.*

Though not presented as a formal definition, it is hard to doubt that it is intended as such. The analysis above highlights the radical switch from the received view. Primarily this is because it refuses any multiplicity of meanings of the term "measurement uncertainty" by stating that measurement uncertainty is one entity (doubt), whereas, as we have seen, the GUM provides only one definition but acknowledges a plurality of meanings, thus guaranteeing its wider applicability and acceptability.

There are three explicit contradictions between the GUM-1 and the GUM, which are labeled here as 'radical changes'.

First radical change. Measurement uncertainty is stated to be a doubt and therefore is interpreted as a *psychological entity* (a doubt) instead of a *mathematical* one (a parameter). One may wonder how and for what purpose metrologists would ever concretely refer to a psychological entity in their jobs when they are focused on 'evaluating and expressing uncertainty in measurement'. As an example, would any metrologist really feel the need to write uncertainty budgets as lists of doubts, perhaps to be analyzed by a psychologist, instead of lists of standard deviations?

Second radical change. Measurement uncertainty is related to the doubt about the *true value of the measurand* instead of the dispersion of the values that could reasonably be attributed to the measurand. This is a major conceptual and operational change, from doubt about the validity of something we produce and therefore we know (a measured value) to doubt about a truth we generally do not know (the true value). This would need a careful justification, also remembering the decades of open-ended discussions about 'true value'. The parameters of probabilistic models do have, unproblematically, true values. However, what we measure are empirical properties of objects, not parameters of mathematical models.

Third radical change. Even admitting that true values exist, the term "*the* true value of the measurand" in the GUM-1 definition assumes that measurement uncertainty applies only to measurands having a unique value, and therefore to measurands whose definitional uncertainty is zero. Since in most situations in daily life this is not the case, as most measurands have non-zero definitional uncertainty (GUM calls it "intrinsic uncertainty", D.3.4), this definition has a much narrower scope than the GUM one.

In summary, the GUM-1 considers measurement uncertainty

- as a psychological entity instead of a mathematical one,
- as related to a theoretical doubt about a true value instead of an operational doubt about the validity of a measured value, and
- only applicable to single-valued measurands instead of to the more general and much more useful case of measurands with possibly non-zero definitional uncertainty.

One more quote from the GUM (E.5.1) allows us to appreciate this paradigmatic change: 'The focus of this Guide is on the measurement result and its evaluated uncertainty rather than on the unknowable quantities "true" value and error. By taking the operational views that the result of a measurement is simply the value attributed to the measurand and that the uncertainty of that result is a measure of the dispersion of the values that could reasonably be attributed to the measurand, this Guide in effect uncouples the often confusing connection between uncertainty and the unknowable quantities "true" value and error.'

Somewhat surprisingly, given how radically different they are from the received view over many years, the changes in the GUM-1 are provided as a matter of fact, with limited explanation or justification and without clear evidence that the current definition causes any difficulties for the (vast majority of the) user community.

4. Some simple reflections

Since, as already emphasized, there is nothing like an intrinsically 'true' meaning of "measurement uncertainty", the three radical changes mentioned above should be explained, to provide a justification for the break they cause with the received view. Since the GUM-1 does not include any such explanation, the reflections that follow are, again, only inferential.

Considering the first radical change, the decision to define 'measurement uncertainty' as 'doubt …' was perhaps made with the purpose of emphasizing the claim that a subjective aspect in the evaluation of measurement uncertainty is unavoidable. There is nothing controversial in this, as GUM already acknowledges that 'a Type B standard uncertainty is obtained from an assumed probability density function based on the degree of belief that an event will occur' (3.3.5), where degrees of belief are clearly subjective entities. But this is about the way measurement uncertainty *is evaluated*, not what it *is*. In this perspective, the definition in the GUM-1 seems to be based on confusing 'is' and 'is evaluated by'. The continuity with the GUM would be maintained by changing 'measurement uncertainty is the doubt …' to 'measurement uncertainty can be evaluated by taking doubt into account …', which could be the content of a note to the definition.

Another possible reason for the first radical change is the objective to clarify the distinction between *what is* measurement uncertainty (a doubt) and *how it can be expressed* (as a standard deviation, a coverage interval, etc). This is not controversial, but it implies in fact a radical change with respect to the GUM and VIM perspective, which maintain the distinction between measurement uncertainty *as a mathematical entity* (a parameter: a position that would require a generalization) and *the way in which it is evaluated* (first of all 'Type A' or 'Type B' evaluations). Why the new distinction should be better than the current one is unclear and unjustified.

Considering the second and the third radical changes, the reason for them is unclear and, since it is not declared, can only be inferred. Since estimation theory typically assumes that an entity to be estimated has a (true) value and that value is unique, measurands are required to have a unique true value for making estimation theory applicable to their evaluation.

However, the measurands we deal with in most situations in daily life are not defined so as to have a unique true value, nor is requiring to redefine them for this purpose usually appropriate. Hence, it seems that such a strategy inverts the priorities: we should adapt our tools to the relevant knowledge we have of the world, and develop new tools when appropriate, not vice versa. Concretely, since most measurands have non-zero definitional uncertainty we should adopt or develop mathematical tools that are able to deal with this condition, and not restrict the application of a fundamental concept such as measurement uncertainty to the ideal cases of single-valued measurands.

5. Conclusion

These suggestions do not imply that, as a foundational document, the GUM is free from mistakes and cannot be improved (in fact, some updates have already been proposed above). Vice versa, it is clear that in these last 30+ years we have learned quite a lot about measurement uncertainty, including that considering measurement uncertainty as a parameter is definitely too narrow, for several different reasons that need not be discussed in detail here (as an example, we also want measurement uncertainty to be evaluated when non-parametric distributions are at stake, for multivariate measurands, and so on). But the importance of conceptual continuity should not be underestimated, particularly for a body of knowledge such as metrology, grounded on stability and long-standing convention: if a definition is agreed to be too specific the first way to go is to make it more generic, which in our case could be realized, for example, by defining 'measurement uncertainty' as a mathematical entity, of which a parameter is a specific case. This would maintain the compatibility with the past and avoid imposing a change of the nature of the entity itself —from a mathematical entity to a psychological one—which would imply a clear message that everyone who endorsed the previous definition was wrong (during the mentioned JCGM webinar it was said that the GUM-1 definition is a generalization of the one in GUM, which is not the case).

With this view, let us consider again the GUM stance that (as commented above) 'in its broadest sense "uncertainty of measurement" means doubt about the validity of the measured value'. What is the actual meaning of the key expression 'validity of the measured value'? It may refer to the condition that

- the measured value is actually the true value, or one of the true values, of the measurand, or
- the measured value appropriately conveys the information acquired through the measurement, or
- no mistakes have been made in obtaining and recording the measured value, or
- possibly even something else.

Depending on the context, but also the cultural background of the measurer, each of them could be an acceptable interpretation, and this flexibility has the great strategic value of defining a concept that can be really foundational as it can be endorsed by different people with different purposes and different cultural backgrounds. Of course, this multiplicity also implies that the concept is generic. In a transitional stage like the one measurement science is in, is not encompassing genericity better than contentious specificity?

Accordingly, definitions such as

> *mathematical entity characterizing the dispersion of the values that could reasonably be attributed to a measurand after measurement*

(as updated version of the definition in the GUM and the VIM, that also has the merit of being explicitly inspired to the VIM definition of 'measurement'—the 'process of experimentally obtaining one or more values that can reasonably be attributed to a quantity'—so highlighting the fundamental connection between measurement and measurement uncertainty), or possibly

> *mathematical entity conveying information concerning the doubt about the validity of the measured value*

(as an updated version of the general characterization given by GUM) allow multiple interpretations and therefore are more easily widely endorsed. These maintain the continuity with 30+ years of the conceptual and operational tradition inaugurated by the GUM, according to which measurement uncertainty is a mathematical, not a psychological, entity, while remaining open to an evolutionary path. Moreover, they are consistent with the principle that the tools we use to deal with some entities must fit the concepts we have of those entities, and not vice versa. Finally, such a broad understanding of the fundamental concept of measurement uncertainty does not limit the scope of metrology to the top laboratories, which can perhaps afford to operate only with single-valued measurands, and instead maintains measurement uncertainty compatible with cases of non-zero definitional uncertainty.

The idea that measurement uncertainty is only applicable when there is something like 'the true value of the measurand' (supposedly a real number with infinitely many significant digits and a unit?) seems to be an unjustified return to a past that the GUM and then the VIM contributed to overcome.

Acknowledgment

This discussion paper is an outcome of several open discussions with many colleagues in different contexts: we thank in particular Chuck Ehrlich and Alessandro Giordani.

ORCID iDs

Luca Mari 0000-0002-7128-3453
Richard J C Brown 0000-0001-6106-0996

References

[1] JCGM 100:2008 2008 *Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement (GUM), GUM 1995 with Minor Corrections* (Joint Committee for Guides in Metrology (JCGM)) (https://doi.org/10.59161/JCGM100-2008E)

[2] JCGM 200:2008 2012 *International Vocabulary of Metrology—Basic and General Concepts and Associated Terms (VIM) 3rd ed, 2008 Version with Minor Corrections* (Joint Committee for Guides in Metrology (JCGM)) (https://doi.org/10.59161/JCGM200-2012)

[3] JCGM GUM-1:2023 2023 *Guide to the Expression of Uncertainty in Measurement—Part 1: Introduction* (Joint Committee for Guides in Metrology (JCGM)) (https://doi.org/10.59161/JCGMGUM-1-2023)

[4] Bich W 2023 A proposed new definition of measurement uncertainty *Ukr. Metrol. J.* **2** 3–6

[5] Possolo A 2025 Measurement uncertainty redefined *Metrologia* **62** 042101

[6] Bell S 1999 A beginner's guide to uncertainty of measurement (measurement good practice guide) vol 11 (National Physical Laboratory) (available at: www.npl.co.uk/resources/gpgs/beginners-guide-measurement-uncertainty-gpg11)

[7] Thompson M 2011 What *exactly* is uncertainty? *Accred. Qual. Assur.* **17** 93–94

[8] ISO 1087:2019 2019 *Terminology Work and Terminology Science—Vocabulary* (International Organization for Standardization (ISO))