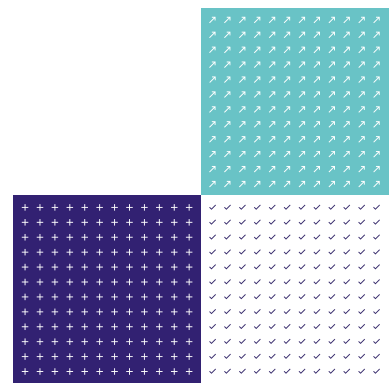


# LAB 12

Edition 4 - April 2022

## The Expression of Uncertainty in Testing



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## Changes since last edition

Minor typographic and editorial changes to refresh the document.

Section 3 revised

Section 9.2 'Special Cases' removed

Section 11 'Proficiency Testing and Measurement Audit' removed

## 1 Introduction

- 1.1 The general requirements for the estimation and reporting of uncertainty in accredited laboratories are given in ISO/IEC 17025 and in ISO 15189. Guidance on how these may be met when estimating and reporting uncertainty in testing is given in this publication. UKAS Publication M3003 provides guidance on evaluation of uncertainty.
- 1.2 The general approach to evaluating and expressing uncertainty in testing outlined here is based on the recommendations produced by the International Committee for Weights and Measures (CIPM), as described in *JCGM 100:2008 Evaluation of measurement data - Guide to the Expression of Uncertainty in Measurement* (The 'GUM').
- 1.3 In the interests of keeping to a general, descriptive format, exceptions, special cases and qualifying remarks have not been dealt with in detail and equations have not been included. The GUM should be consulted for equations and symbols, and when needing to resolve special difficulties that may arise in specific tests.



## 2 Definitions

- 2.1 Definitions of terms are given in alphabetical order in Appendix B. Defined terms are printed in bold at the first appropriate occurrence in the main body of the text. Note that these are loose definitions, given for the purpose of clarity in this document. Full and authoritative definitions of metrological terms can be found in the *International vocabulary of metrology – Basic and general concepts and associated terms* (The 'VIM').

## 3 Reporting and Evaluation of Uncertainty

- 3.1 The requirements of ISO/IEC 17025 and ISO 15189 distinguish between the need for reporting and the need for evaluation of **measurement uncertainty**.
- 3.2 Reporting is required when information on uncertainty is relevant to the validity or application of the test results, when the client requires it or when the uncertainty affects conformity with a specification limit.
- 3.3 In cases where a published test method specifies limits to the values of major sources of measurement uncertainty and specifies the form of presentation of the results the requirement to estimate measurement uncertainty can be considered to have been satisfied by following the test method and its reporting instructions. For example, when a published test method has been evaluated according to the principles of ISO 5725.
- 3.4 Not all tests result in measured quantities. Instead, many tests involve some form of examination (or inspection), sometimes referred to as a 'qualitative' test, to which the strict VIM concept of measurement uncertainty does not readily apply. For example, when the outcome is perhaps the assignment of a nominal property (e.g., colour, shape, sequence) or some other characteristic, such as position on an ordinal scale (e.g., Rockwell C, Richter, Beaufort). That isn't to say that measurement uncertainty doesn't play a role in performing such tests... in most circumstances, examinations are performed under defined conditions that, in order to verify that these are being achieved, are themselves subject to measurement and require uncertainty evaluation.

## 4 Reasons for Evaluating Uncertainty

- 4.1 Expression of the uncertainty associated with a measured value allows realistic comparison of results from different laboratories, or within a laboratory, or with reference values given in specifications or standards. This information can often prevent unnecessary repetition of tests.
- 4.2 Measurement uncertainty may need to be taken into account by a customer when interpreting data. For example, comparison of results from different batches of material may not indicate real differences in properties or performance if the observed differences could simply be accounted for by the uncertainty of the results.
- 4.3 Consideration of **uncertainty components** reveals aspects of a test to which attention should be directed to improve procedures.

- 4.4 Systematic assessment of the factors influencing the result and the uncertainty (based on the understanding of the principles of the method and practical experience of its application) can be a key part of method validation.
- 4.5 Measurement uncertainty must be taken into account either directly or indirectly by the **Decision Rule** when statements of conformity are to be reported.

## 5 General Principles

- 5.1 The objective of a measurement is to determine the value of the **measurand**, i.e. the specific quantity subject to measurement. When applied to testing, the general term measurand may cover many different quantities, e.g., the strength of a material, the concentration of an analyte, the level of emissions of noise or electromagnetic radiation, the quantity of micro-organisms. A measurement begins with an appropriate specification of the measurand, the method of measurement and the specific detailed measurement procedure.
- 5.2 In general, no measurement or test is perfect, and the imperfections give rise to **errors of measurement** in the result. Consequently, the result of a measurement is only an estimate of the true value of the measurand and is only complete when accompanied by a statement of the uncertainty of that estimation.
- 5.3 Errors of measurement arise from a variety of sources which all affect the measurement uncertainty.
- 5.4 Random errors arise from random statistical variations of the observations (random effects). Every time a measurement is performed under the same conditions, random effects from various sources affect the measured value. A series of measurements produces a scatter of measured values around a mean value. A number of sources may contribute to variability each time a measurement is performed, and their influence may be continually changing. They cannot be eliminated but increasing the number of measurement observations and applying statistical analysis may reduce the uncertainty due to their effect.
- 5.5 Systematic errors arise from imperfect knowledge of measurement processes such as finite resolution or drift in the characteristics of measuring equipment. These errors remain unchanged when a measurement is repeated under the same conditions, and their effect is to introduce a displacement between the value of the measurand and the experimentally determined mean value. They cannot be eliminated but may in some cases be reduced through a better understanding of the measurement process.
- 5.6 The GUM has adopted the approach of grouping uncertainty components into two categories based on their method of evaluation. 'Type A' evaluation is done by calculation from a series of repeated observations, using statistical methods. Type B' evaluation is done by means other than that used for 'Type A'. For example, by judgement based on data in calibration certificates, previous measurement data, experience with the behaviour of the instruments, manufacturers' specifications and all other relevant information.
- 5.7 Components of uncertainty are evaluated by the appropriate method, and each is expressed as a **standard deviation** and is referred to as a **standard uncertainty**.
- 5.8 The standard uncertainty components are combined to produce an overall value of uncertainty, known as the **combined standard uncertainty**.

- 5.9 An **expanded uncertainty** is usually required to meet the needs of industrial, commercial, health and safety, or other applications. It is intended to provide a greater **coverage interval** about the result of a measurement than the standard uncertainty with, consequently, a higher probability that it encompasses the true value of the measurand. It is obtained by multiplying the combined standard uncertainty by a **coverage factor**,  $k$ . The choice of factor is based on the **coverage probability** or **level of coverage** required (see paragraph 7.4).

## 6 Sources of Uncertainty

- 6.1 There are many possible sources of uncertainty in testing, including:
- (a) Incomplete definition of the test; the requirement is not clearly described, e.g., the temperature of a test may be given as 'room temperature';
  - (b) Imperfect realisations of the test procedure - even when the test conditions are clearly defined it may not be possible to produce the required conditions;
  - (c) Sampling - the sample may not be fully representative;
  - (d) Inadequate knowledge of the effects of environmental conditions on the measurement process, or imperfect measurement of environmental conditions;
  - (e) Personal bias in reading analogue instruments;
  - (f) Instrument resolution or discrimination threshold, or errors in graduation of a scale;
  - (g) Values assigned to measurement standards (both reference and working) and reference materials;
  - (h) Changes in the characteristics or performance of a measuring instrument since the last calibration (drift);
  - (i) Values of constants and other parameters used in data evaluation;
  - (j) Approximations and assumptions incorporated in the measurement method and procedure;
  - (k) Variations in repeated observations of a measurement value made under apparently identical conditions - such random effects may be caused by, for example: short-term fluctuations in local environment, e.g., temperature, humidity and air pressure; variability in the performance of the tester.
- 6.2 These sources are not necessarily independent, and in addition, unrecognised systematic effects may exist that cannot be taken into account but contribute to error. (The existence of such effects may sometimes be evident from examination of the results of an inter-laboratory comparison programme.)

## 7 Evaluation of Uncertainty

### 7.1 General Approach

- 7.1.1 This section describes the basic stages in the evaluation of uncertainty. Where available, sector-specific Standards, Guides or other publications may provide more detailed guidance.
- 7.1.2 The measurement uncertainty is a combination of a number of uncertainty components. Even a single instrument reading may be influenced by several factors. Careful consideration of each measurement involved in the test is required to identify all the factors that contribute to the overall uncertainty. This is a very important step and requires a good understanding of the measuring equipment, the principles and practice of the test and the influence of environment.
- 7.1.3 The next step is to quantify uncertainty components by appropriate means. An initial approximate quantification may be valuable in enabling some to be shown to be negligible and not worthy of more rigorous evaluation. In most cases, a practical rule would be that an uncertainty component is negligible if it is not more than a fifth of the magnitude of the largest component <sup>1</sup>. Some uncertainty components may be quantified by calculation of the standard deviation from a set of repeated measurements (Type A) as detailed in the GUM. Quantification of others will require the exercise of judgement, using all relevant information on the possible variability of each factor (Type B). For 'Type B' estimations, the pool of information may include:
- (a) Previous measurement data;
  - (b) Published uncertainty associated with validated methods;
  - (c) Data provided in calibration certificates;
  - (d) Uncertainty assigned to reference data taken from handbooks;
  - (e) Experience with or general knowledge of the behaviour and properties of relevant materials and instruments;
  - (f) Manufacturer's specifications.
- 7.1.4 Subsequent calculations may be made simpler if, wherever possible, all components are expressed in the same way, e.g., either as a proportion (percent, parts per million, etc.) or in the same units as used for the reported result.
- 7.1.5 It is essential to keep good records that support the uncertainty estimate. These should explain in detail how the evaluation is performed, they should provide references to source of data such as calibration certificate numbers, reference sources, data files and procedures for processing data.

### 7.2 Standard Uncertainty

- 7.2.1 The standard uncertainty is simply the measurement uncertainty expressed as a standard deviation. The potential for mistakes at a later stage of the evaluation may be minimised by expressing all uncertainty components as a standard deviation. This may require adjustment of some uncertainty values, such as those obtained from calibration certificates and other sources,

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<sup>1</sup> Note that the one-fifth rule applies to uncertainties relating to the measurand, not to uncertainties relating to the input or influence quantities. For instance, an influence quantity may be temperature expressed in degrees Celsius and the measurand may be mass expressed in say kg. The one-fifth rule applies to the mass values, i.e. *after* applying a sensitivity coefficient to the temperature contribution to determine the associated component of uncertainty in the measurand.

which often will have been expressed as an expanded uncertainty, involving a multiple of the associated standard deviation.

### 7.3 Combined Standard Uncertainty

7.3.1 Uncertainty components are combined to produce an overall uncertainty using the procedure set out in the GUM. In most cases, this reduces to taking the square root of the sum of the squares of the standard uncertainties (the root sum square method). However, some components may be interdependent and could, for example, cancel each other out or could reinforce each other. In many cases this is easily seen and the associated uncertainty components may be added algebraically to give a net value. However, in more complex cases more rigorous mathematical methods may be required for such 'correlated' components and the GUM should be consulted.

### 7.4 Expanded Uncertainty

7.4.1 It is usually necessary to quote an expanded uncertainty and the combined standard uncertainty therefore needs to be multiplied by the appropriate coverage factor ( $k$ ). The choice of coverage factor reflects the **level of confidence** required and is dictated by the details of the **probability distribution**, characterised by the measurement result and its combined standard uncertainty. In many cases, an approximation is acceptable, viz. that the probability distribution can be assumed to be normal and that a value of  $k = 2$  defines an interval having a coverage probability of approximately 95 %. For more critical applications, a value of  $k = 3$  defines an interval having a coverage probability of approximately 99.7 %.

7.4.2 Exceptions to these cases would need to be dealt with on an individual basis by consulting more detailed guidance to determine the appropriate value of  $k$ . Such an exceptional case would be characterised by one or more of the following:

- (a) A random contribution to uncertainty that is relatively large compared with other contributions and based upon only a small number of repeat readings. In this case there is the possibility that the probability distribution will not be normal in form and a value of  $k = 2$  will give a level of coverage of less than 95 %. [This would not usually arise if the uncertainty assessment involved only one Type A evaluation, and the number of readings is greater than 2, and the combined standard uncertainty is more than twice the Type A uncertainty] (see M3003 Appendix B).
- (b) The absence of a significant number of uncertainty components having well-behaved probability distributions, such as normal and rectangular (see M3003 Appendix C);
- (c) Domination of the combined value by one uncertainty component with non-normal probability distribution. There is not a clear-cut definition of such a dominant component, but a practical guide would be where one component was more than five times greater than any other (see M3003 Appendix C).

## 8 Summary of the Steps in Evaluating Uncertainty

- 8.1 The following is a short, simplified summary of the general route to evaluation of uncertainty and is applicable in many circumstances. For certain types of chemical and biological testing however, the 'top-down' interpretation of the GUM provided by *EURACHEM/CITAC Guide CG4: Quantifying Uncertainty in Analytical Measurement* may be of more relevance.
- 8.2 The identification of sources of uncertainty is the most important part of the process. Quantification of uncertainty in testing normally involves a large element of estimation of Type B components. Consequently, suitably experienced personnel who apply their knowledge in a critical manner and base their estimates on quantitative data to the maximum extent should do this.
- 8.3 The steps involved are as follows (see the GUM or M3003 for more detail):
- (a) Identify all factors that may influence the measured values;
  - (b) Estimate the values that are to be attributed to each source. Express the associated uncertainty component in the same units at the one standard deviation level (see paragraph 7.1.4 and Sub-section 7.2);
  - (c) Consider the uncertainty components and decide which, if any, are correlated (i.e. interdependent) and whether a dominant component exists;
  - (d) Add any correlated uncertainty components arithmetically, i.e., take account of whether they act in unison or in opposition and thereby derive a net value (see sub-section 7.3);
  - (e) Take the independent uncertainty components and the value(s) of any derived net components and, in the absence of a dominant component, calculate the square root of the sum of their squares to produce a combined standard uncertainty (see sub-section 7.3);
  - (f) Except when only the standard uncertainty (i.e., one standard deviation) is required, multiply the combined standard uncertainty by a coverage factor  $k$ , selected on the basis of the level of coverage required, to produce an expanded uncertainty. In the absence of a particular level of coverage being specified in the standard or by the client, the coverage factor should normally be  $k = 2$ , giving a coverage probability of approximately 95 % (see sub-section 7.4).



## 9 Method of Stating Results

### 9.1 General Approach

9.1.1 The general requirements covering the extent of the information given when reporting the result of a test and its uncertainty are stated in ISO/IEC 17025 and in ISO 15189. Reporting should also be related to the requirements of the client, the specification and the intended use of the result. The methods used to calculate the result and its uncertainty should be available either in the report or in the records of the test including:

- (a) Sufficient documentation of the steps and calculations in the data analysis to enable a repetition of the calculation if necessary;
- (b) All corrections and constants used in the analysis, and their sources;
- (c) Sufficient documentation to show how the uncertainty is calculated.

9.1.2 When reporting the result and its uncertainty, the use of excessive numbers of digits should be avoided. In most cases the uncertainty need be expressed to no more than two significant figures (although at least one more figure should be used during the stages of estimation and combination of uncertainty components in order to minimise rounding errors).

9.1.3 Unless otherwise specified, the result of the measurement should be reported, together with the expanded uncertainty appropriate to the 95 % level of coverage, as in the following example:

Measured value	100.10 (units)
Measurement uncertainty	0.11 (units)

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor of  $k = 2$ , providing a level of coverage of approximately 95 %.

## 10 Assessment of Conformity with Specification

10.1 When the client or a specification requires a statement of conformity, measurement uncertainty must be taken into account, either directly or indirectly. (See ILAC G8 and UKAS LAB 48).

10.1.1 The simplest case is where the specification clearly states that the measured value, extended by the uncertainty at a given level of coverage, shall not fall outside a defined tolerance limit (or limits). In these cases, assessment of conformity would be straightforward.

10.1.2 More often, the specification requires a conformity statement in the certificate or report but makes no reference to taking into account the effect of uncertainty on the assessment of conformity. In such cases it may be appropriate for the user to make a judgement of conformity, based on whether the measured value is within the specified tolerance limits (sometimes called Simple Acceptance). In this case the allowable limits on the measurement uncertainty must be agreed in a Decision Rule before conformity can be decided. This is an example of indirect account for measurement uncertainty.

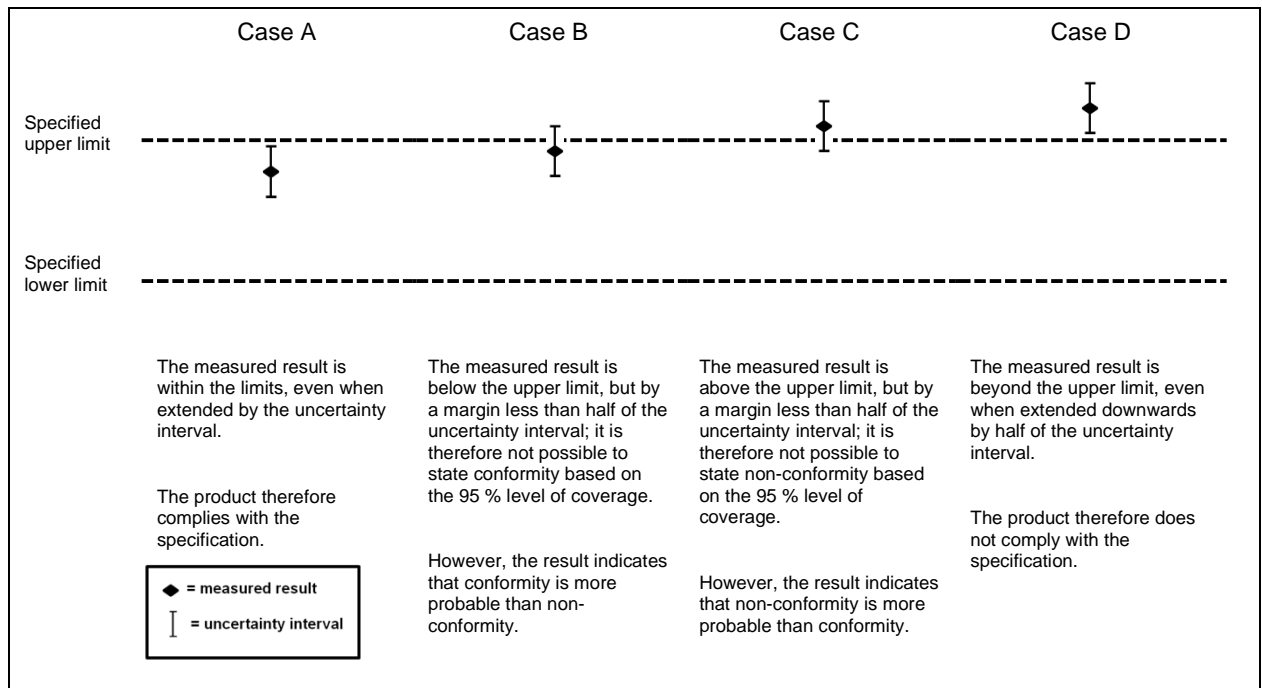
10.1.3 In the absence of any specified criteria, eg sector-specific guides, test specifications, client's requirements, or codes of practice, the following approach can be taken:

- (a) If the limits are not breached by the measurement result, extended by the uncertainty interval at a level of coverage of 95 %, then conformity with the specification can be stated, (Case A, Figure 1 and Case E, Figure 2);
- (b) Where an upper specification limit is exceeded by the measurement result even when it is decreased by half of the uncertainty interval, then nonconformity with the specification can be stated, (Case D, Figure 1);
- (c) If a lower specification limit is breached even when the measurement result is extended upwards by half of the uncertainty interval, then non-conformity with the specification can be stated (Case H, Figure 2);
- (d) If the measurement result falls sufficiently close to a limit such that the uncertainty interval overlaps the limit, it is not possible to confirm conformity or non-conformity at the stated level of coverage. The test result and expanded uncertainty should be reported together with a statement indicating that conformity was not demonstrated. A suitable statement to cover these situations (Cases B and C, Figure 1 and Cases F and G, Figure 2) would be, for example:

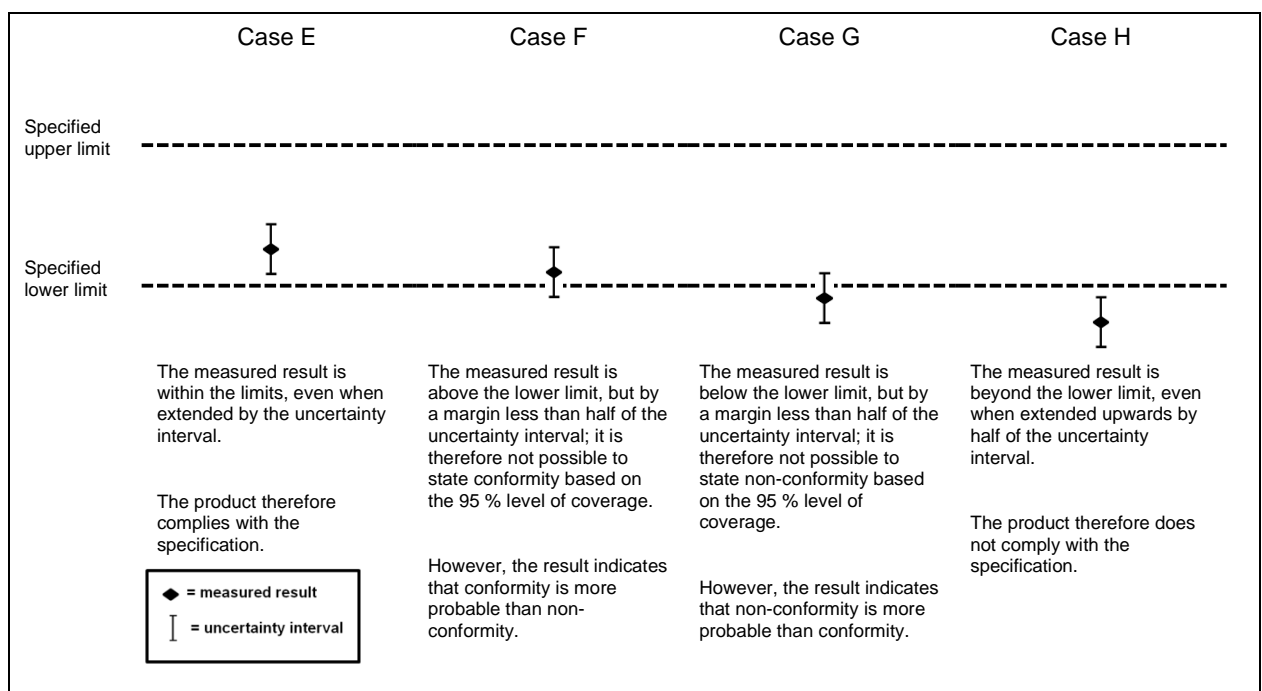
*The measured result is above (below) the specification limit by a margin less than the expanded measurement uncertainty; it is therefore not possible to state conformity based on the 95 % level of coverage. However, the result indicates that conformity (non-conformity) is more probable than non-conformity (conformity) with the specification limit.*

Note: In these circumstances if a coverage limit of less than 95 % is acceptable, a statement of conformity/non-conformity may be possible.

**Figure 1 - Assessing conformity where the result is close to an upper limit**



**Figure 2 - Assessing conformity where the result is close to a lower limit**



## Appendix A - Bibliography

BS EN ISO/IEC 17025:2017

*General requirements for the competence of testing and calibration laboratories*

BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, OIML

*Evaluation of measurement data – Guide to the expression of uncertainty in measurement*

Joint committee for guides in metrology, JCGM 100:2008

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*International vocabulary of metrology – Basic and general concepts and associated terms*

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(Often referred to as 'VIM')

M H Ramsey and S L R Ellison (Eds)

*Eurachem/EUROLAB/CITAC/Nordtest/AMC Guide: Measurement uncertainty arising from sampling: a guide to methods and approaches Eurachem (2007)*

ISBN 978 0 948926 26 6

S L R Ellison and A Williams (Eds)

*Eurachem/CITAC Guide: Quantifying Uncertainty in Analytical Measurement*

Third edition, (2012), ISBN 978-0-948926-30-3

United Kingdom Accreditation Service

*The Expression of Uncertainty and Confidence in Measurement, M3003*

Edition 4, 2019

United Kingdom Accreditation Service

*Decision Rules and Statements of Conformity, LAB 48*

Edition 4, 2022

ILAC

*Guidelines on Decision Rules and Statements of Conformity, G8:09/2019*



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## Appendix B - Definitions of Terms

Note that these are rather informal definitions, given for the purpose of clarity in this document.

Full and authoritative definitions can be found in the International vocabulary of metrology – Basic and general concepts and associated terms (VIM).

### Combined standard uncertainty

The result of the combination of standard uncertainty components.

(See VIM 2.31)

### Coverage factor

A number that, when multiplied by the combined standard uncertainty to produce an expanded uncertainty, can be used to estimate a coverage interval.

(See VIM 2.38)

### Coverage interval

Range about the measurement result that may be expected to encompass a large, specified fraction (e.g., 95 %) of the distribution of values that could be reasonably attributed to the measurand.

(See VIM 2.36)

### Coverage probability

The probability that the value of the measurand lies within the quoted coverage interval.

See also 'Level of Confidence'.

(See VIM, 2.37)

### Decision Rule

A rule that describes how measurement uncertainty is accounted for when stating conformity with a specified requirement.

(See ISO/IEC 17025:2017, 3.1)

### Error of measurement

The value of a measurement result minus the value of some reference quantity.

(See VIM, 2.16)

### Expanded uncertainty

Obtained by multiplying the combined standard uncertainty by a coverage factor.

(See VIM, 2.35)

**Level of confidence** (See also Coverage probability)

Coverage probability.

Note that *VIM* does not define the term ‘level of confidence’. It does however note that ‘The coverage probability is also termed “level of confidence” in the GUM’. In this document (LAB 12) the two expressions are used interchangeably.

**Measurand**

The quantity of interest.

(See *VIM*, 2.3)

**Measurement result**

The value that is assigned to the measurand and its associated uncertainty.

(See *VIM*, 2.9)

**Probability distribution**

A means of describing the available knowledge about the likely values of a quantity. Usually characterized by a mean (or expectation) and standard deviation.

**Standard deviation**

The positive square root of the variance.

Variance is a measure of the dispersion of a set of measurements; the sum of the squared deviations of the observations from their average, divided by one less than the number of observations.

**Standard uncertainty**

Measurement uncertainty expressed as a standard deviation.

(See *VIM*, 2.30)

**Measurement uncertainty**

A non-negative parameter, associated with the result of a measurement, which characterises the dispersion of the values that could reasonably be attributed to the measurand.

(See *VIM*, 2.26)

**Uncertainty components**

Elements of the uncertainty evaluation that are combined to determine the uncertainty associated with the measurand. Care should be taken to avoid confusing ‘uncertainty components’ (which relate to the measurand) with uncertainties associated with the influence quantities from which they are calculated.