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Validation of measurement uncertainty budgets

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Deutscher Kalibrierdienst (DKD) – German Calibration Service

Since its foundation in 1977, the German Calibration Service has brought together calibration laboratories of industrial enterprises, research institutes, technical authorities, inspection and testing institutes. On 3rd May 2011, the German Calibration Service was reestablished as a *technical body* of PTB and accredited laboratories.
This body is known as *Deutscher Kalibrierdienst* (DKD for short) and is under the direction of PTB. The guidelines and guides developed by DKD represent the state of the art in the respective areas of technical expertise and can be used by the *Deutsche Akkreditierungsstelle GmbH* (the German accreditation body – DAkkS) for the accreditation of calibration laboratories.
The accredited calibration laboratories are now accredited and supervised by DAkkS as legal successor to the DKD. They carry out calibrations of measuring instruments and measuring standards for the measurands and measuring ranges defined during accreditation. The calibration certificates issued by these laboratories prove the traceability to national standards as required by the family of standards DIN EN ISO 9000 and DIN EN ISO/IEC 17025.

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Foreword

DKD guides are recommendations on technical issues arising from the practical work in accredited calibration laboratories. The guides describe procedures which may serve the accredited calibration laboratories as model for defining internal processes and regulations. DKD guides may become an essential component of quality management manuals of calibration laboratories. The implementation of the guidelines will help to incorporate the state of the art in the respective field into laboratory practice. Thus, a standardization of procedures as well as an increased efficiency in the work of calibration laboratories shall be achieved.

DKD guides should not impede the further development of calibration procedures and processes. Deviations from guidelines as well as new procedures are permitted if there are technical reasons to support this action

The present guide was prepared by the Technical Committee *Measurement Uncertainty* and approved by the Board of the DKD.

1 Purpose and scope of application

This Guide is a tool for the validation of determined measurement uncertainties.

It takes into account the determination of the smallest measurement uncertainty to be specified (best measurement uncertainty in the frame of the CMC[1]) as well as the representation of the measurement uncertainty assigned to an actual measurement, which is to be stated in test or calibration certificates.

The Guide is intended for calibration and testing laboratories as well as for people preparing measurement uncertainty documentations (management documents). It shows the information to be provided when determining measurement uncertainties. Application-specific particularities that go beyond or deviate from general metrological requirements are addressed by way of example in the checklist.

This Guide has been developed in form of a checklist to provide an opportunity for carefully examining the available information, based on the questions asked.

The validation of procedures, quality-relevant documents, work aids and software prior to their release and application is a fundamental requirement of all QM systems. Validations must be documented. The checklist provided by this Guide may constitute such a proof of validation for measurement uncertainties.

If a laboratory deals with more than one measurand, a separate checklist for each measurand according to this Guide should be available.

[1] CMC = Calibration and measurement capability, see EN ISO/IEC 17011:2017, 7.8.3 c) and EA-4/02 M: 2013, Appendix B, B2.

2 List of symbols, designations and abbreviations

Metrological symbols and formula symbols

Symbol, designation or abbreviation	**Definition**
Output quantity	Result of a measurement uncertainty budget or a calculation (of a result).
c_i	Sensitivity coefficient. In many cases, c_i is a dimensionless multiplier. However, physical units are also possible.
DAkkS	Deutsche Akkreditierungsstelle GmbH (German Accreditation Body)
Effective degrees of freedom	Formula symbol ν_{eff} (Greek: "ny"). In general, the *t*-distribution will not describe the distribution of the variable $(y - Y)/u_c(y)$ if $u_c^2(y)$ is the sum of two or more estimated variance components, even if each x_i is the estimate of a normally distributed input quantity X_i. However, the distribution of that variable may be approximated by a *t*-distribution with an effective degrees of freedom ν_{eff} obtained from the Welch-Satterthwaite formula: $$\nu_{eff} = \frac{u^4}{\sum_{i=1}^{n} \frac{u_i^4(y_i)}{\nu_i}}$$ With n being the number of uncertainty contributions considered, u_i the respective uncertainty contribution in the measurement uncertainty budget, ν_i the degrees of freedom of the respective uncertainty contribution, u (without index) the calculated measurement uncertainty of the result, without coverage factor. → JCGM 100:2008, [1],section G.4
Influence quantity	Quantity that is not the measurand but that affects the result of the measurement and whose value cannot be exactly specified. → JCGM 100:2008, [1], B.2.10 → VIM3, [2], 2.52
Sensitivity coefficient	The sensitivity coefficients show the sensitivity by which the result of a measurement will depend on an influence quantity. They result from the model equation by partial derivation according to the respective influence quantities. The sensitivity coefficient is determined as follows: $$c_i = \frac{\partial f(x)}{\partial x_i}$$ With: c_i being the sensitivity coefficient of the influence quantity x_i

Symbol, designation or abbreviation	Definition
Coverage factor	Formula symbol k. numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty. → According to JCGM 100:2008 [1], 2.3.6
k	→ Coverage factor.
Best measurement uncertainty	Smallest uncertainty of measurement that can be expected to be achieved by a laboratory for a specific quantity within its scope of accreditation (Calibration and measurement capability, CMC) under ideal measurement conditions. → EA-4/02 M: 2013 [3], Appendix B, B2
MCS	Monte Carlo simulation
Measurement uncertainty contribution	Numerical portion of the influence of a measurement uncertainty on a measurement result within the scope of the uncertainty budget.
Uncertainty budget	Statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination. Note: An uncertainty budget should include the measurement model, estimates, and measurement uncertainties associated with the quantities in the measurement model, covariances, type of applied probability density functions, degrees of freedom, type of evaluation of measurement uncertainty, and any coverage factor. → VIM, 3rd edition, section 2.33
Influence of the measurement uncertainty	An influence causing a measurement error with statistical probability.
n/a	The abbreviation is used with two different meanings: “not applicable” or “not available”.
PDF	Probability density function. Mathematical term used to describe the possible values of the quantity characterized by this function, e. g. the measurement result.
u $u(x_i)$	Formula symbol for the standard measurement uncertainty (also: standard uncertainty) associated with the estimated value of the measurand x_i (influence quantity). Same physical unit as the measurand.

Symbol, designation or abbreviation	Definition
U $U(y)$ $U_{0,95}$	Formula symbol for the expanded measurement uncertainty associated with the estimated value of the measurand y, that is to say, the result. An index value (in this case 0.95 for 95 %) can be assigned to the formula symbol of the expanded measurement uncertainty. This index value represents the coverage probability.
Validation	The verification of the procedure for determining a measurement uncertainty has been defined in accordance with the term "*validation*" pursuant to JCGM 200:2012 (VIM) [2], 2.45. Accordingly, the validation is a verification in which a fact is checked with regard to an intended use. → JCGM 200:2012 (VIM) [2], 2.45
w $x(x_i)$	Formula symbol for the relative standard uncertainty attributed to the estimated value of the measurand x_i (influence quantity).
W $W(y)$ $W_{0,95}$	Formula symbol for the relative expanded measurement uncertainty associated with the estimated value of the measurand y, i. e. the result. An index value (in this case 0.95 for 95 %) can be assigned to the formula symbol of the expanded measurement uncertainty. This index value indicates the coverage probability (or: the degree of confidence).

Table 1: Metrological symbols and formula symbols

3 General

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3.2 Basic principles

3.2.1 Objectives

The following distinctions must be made when determining the measurement uncertainty:

- **Best measurement uncertainty:** It depends on the requirements to be fulfilled, for example, as proof of competence of the calibration or testing laboratories during accreditations. This is where the potential of the laboratory is demonstrated: the routine calibration of real, high-quality measuring instruments under optimal conditions and by applying the methods commonly used in the laboratory[2].

  →EA-4/02 M: 2013 [3], Appendix A

  The laboratory's documentation on the measurement uncertainty must be available, and fully comprehensible to outsiders.

  Checklist to be used → Section 4, "Checklist for the validation of the best measurement uncertainty", page 14

- **Measurement uncertainty attributed to an actual measurement value:** This quantity describes the measurement uncertainty to be determined within the scope of practical measurements, as stated in calibration certificates or test reports.

  - If necessary, it must be possible to establish the traceability of the uncertainty determination from recordings of the measured value. The calculation methods are to be documented in a suitable place as, for example, in procedure or process descriptions.
  - It is assumed that the best measurement uncertainty for the measured variable has already been determined – or a comparable consideration is available – so that the representation of the actual measurement uncertainty only requires adjustments to the current measurement.

    The influence quantities taken into account must also be documented in a practice-oriented manner, for example by way of measurement reports or measurement data files or descriptions of the measurement setup.

    → DIN EN ISO/IEC 17025:2018 [4], 7.5.1

  - Checklist to be used → Section 5, "Checklist for the validation of the best measurement uncertainty (further requirements)", page 22.

3.2.2 Methods of evaluation

Moreover, the different methods by which the measurement uncertainty can be evaluated must be taken into account, such as:

---

[2] However, this does not exclude the possibility that a laboratory may achieve lower uncertainties by using different methods. Given that these services cannot be routinely offered to customers, they are not covered by the definition of *best measurement uncertainty* (smallest uncertainty to be specified).

- GUM Framework, according to JCGM 100:2008 [1]
- Vector/matrix form for multidimensional output quantities, as shown in JCGM 102:2009 [5]
- Monte Carlo Simulation (MCS) according to JCGM 101:2008 [6]
- Comparative investigations by means of other measuring devices and transfer to the measurement task under consideration

The questions in the checklist are kept general; this way they can be used – to a great extent – regardless of the adopted procedure. Specific requirements that differ from general metrological requirements are shown in rectangular brackets […].

3.2.3 Liability

The checklist is non-binding. It is a recommendation. However, various contents are elementary for the verifiability of the measurement uncertainty and should be available. It is usually assumed that a laboratory seeking a DAkkS[3] accreditation fulfils these requirements.

3.3 Normative principles

3.3.1 Validation

The verification of the procedure for determining a measurement uncertainty has been defined according to the term *"validation"* pursuant to JCGM 200:2012 (VIM) [2], 2.45 [4].

→ JCGM 200:2012 (VIM) [2], 2.45

→ DIN EN ISO/IEC 17025:2018 [4], 7.2

This checklist also contains cross-references to standards which do not necessarily form the basis for accreditation but are helpful when formulating certain points[5]. The checklist presented here may serve as proof of validation for measurement uncertainties.

→ DIN EN ISO/IEC 17025:2018 [4], 7.2

→ DIN EN ISO 9001:2015 [7], 8.3.4.d

3.4 Comments on how to use the checklist

The checklist is only valid for one measurand at a time. If several measured variables are to be considered, an individual evaluation for each measurand is recommended.

3.5 Example: Question concerning the general section (document header)

[3] DAkkS: Deutsche Akkreditierungsstelle GmbH (German Accreditation Body)
[4] Hence, a validation is a verification in which a given issue is checked with regard to its intended use.
[5] For instance, reference is made to the "QM standard" DIN EN ISO 9001:2008, regardless of whether a laboratory is certified according to this standard.

The document presenting the measurement uncertainty must be clearly identifiable. → DIN EN ISO/IEC 17025:2018 [4], 7.11, 8.3 → DIN EN ISO 9001 [7], 4.2.3				
Name of the document	Appendix Measurement Uncertainty concerning working instruction WI-02/22, rev. 2.2			
Designation of the measurand	Rectangularity of material measures			
Version	2.2			
Release date	1.9.2008			
Issued by (Name)	Meier, Laboratory			
Approved by (Name)	Schmitt, Head of Laboratory			
Evaluation	All necessary information available.	☺✓	😐	☹

- “Criterion fulfilled” (☺) is to be selected if the degree of compliance with the criterion does not require further improvement. The criterion does not necessarily have to be 100 % fulfilled, but the main aspects must be complied with.
- “Criterion partly fulfilled” (😐) means that, in principle, the criterion is being implemented, but potential for improvement has been identified.
- “Criterion not fulfilled” (☹) indicates that there is no compliance with the criterion.
- If an option does not apply, you can enter “not applicable” or “n/a” under “Evaluation”.
- If reworking is recommended, a corresponding recommendation can be made under “Evaluation”.

4 Checklist for the validation of the best measurement uncertainty

4.1 Formal inspections

4.1.1 Denomination and identification of a document for calculating the measurement uncertainty

If there is a separate document for the documentation of the measurement uncertainty, it must be clearly identifiable. → DIN EN ISO/IEC 17025:2018 [4], 7.11, 8.3 → DIN EN ISO 9001 [7], A.6				
Name of the document				
Designation of the measurand				
Version				
Release date				
Issued by (Name)				
Approved by (Name)				
Evaluation		☺	😐	☹

4.1.2 Designations used

The designations used in the document must be unambiguous and must not be in contradiction to normatively regulated designations.				
Evaluation		☺	😐	☹

4.1.3 Abbreviations

All (metrological) abbreviations used must be defined in a QM-monitored document and must be easy to find.				
Evaluation		☺	😐	☹

4.1.4 Formula symbols

Physical quantities are represented by formula symbols. These must be unambiguous. In the case of self-explanatory formula symbols[6] or those explained in the text, a definition is not required. → Table 1, "Metrological symbols and formula symbols", page 8				
Evaluation		☺	😐	☹

4.2 Measurand

4.2.1 Definition of the measurand

The measurand must be clearly defined.				
Evaluation		☺	😐	☹

4.3 Measuring process

4.3.1 Description of the measuring process

The measurement process and procedure must be described in a comprehensible manner.				
Evaluation		☺	😐	☹

[6] Formula symbols are self-explanatory if it is directly and unambiguously recognisable which quantity is meant. If necessary, the unambiguity is given by the context. Example: "A time interval of t = 10 s is read". In this example, t is directly assigned to a time interval and is thus unambiguously defined.

4.3.2 Requirements concerning the measuring process

Relevant specifications under which a measurement is to be performed must be defined and documented. The specifications may be required, for example, by the client or by the laboratory itself.				
Evaluation		☺	😐	☹

4.3.3 Limitations of the measurement process

Limit values which have to be observed during measurement in order to ensure the validity of the determined measurement uncertainty must be defined at a suitable point.				
Evaluation		☺	😐	☹

4.3.4 Process equation

Before establishing the model equation, the measurement process should be considered and described in terms of its physical relationships. This should be done using a mathematical expression, using a process equation[7].				
Evaluation		☺	😐	☹

4.4 Measuring equipment

4.4.1 Requirements for measuring equipment and measuring devices

The standards, measuring equipment and auxiliary means planned for the measurement must be clearly described.				
Evaluation		☺	😐	☹

4.4.2 Metrological traceability

The metrological traceability of all measuring equipment and auxiliary means used is to be documented in a suitable place whenever it is to be assumed that they have an influence on the measurand or the measurement uncertainty.				
Evaluation		☺	😐	☹

[7] The use of a process equation is not illustrated in JCGM 100:2008. It is used to mathematically describe the measurement process. Its establishment is recommended for preparing the model equation.

4.4.3 Measuring equipment for monitoring measurement or ambient conditions

(Secondary) measuring equipment used for monitoring measurement or ambient conditions shall be subject to the same conditions as those specified in 4.4.1 and 4.4.2.				
Evaluation		☺	😐	☹

4.4.4 Validation of the software used

Software used for the determination of the measurand or the measurement uncertainty must be validated. → “Validation” in Table 1, “Metrological symbols and formula symbol”, page 8 → DIN EN ISO/IEC 17025:2018 [4], 7.2.1, 7.2.2				
Evaluation		☺	😐	☹

4.4.5 Representation of the measuring arrangement

A clear representation of the measuring arrangement in pictorial, graphic or written form must be available.				
Evaluation		☺	😐	☹

4.5 Modelling

4.5.1 Model equation

A model equation (measurement model) has to be established. In addition to the components of the process equation, the model equation contains all known influence quantities.				
Evaluation		☺	😐	☹

4.5.2 Linearization of the model

The model equation must be sufficiently linear and continuously differentiable (at least at the measuring point). If the model equation is not linear, this must be taken into account by suitable mathematical methods (keywords: linearization, Taylor series expansion, MCS).				
Evaluation		☺	😐	☹

4.5.3 Separation of the influence quantities

The model must clearly show which influence quantities are taken into account and how they contribute to the measurement result.				
Evaluation		☺	😐	☹

4.5.4 Requirements for the application of sub-models

In principle, the use of sub-models is permitted. However, it must be checked and ensured that there are no correlations of influence quantities in different sub-models.				
Evaluation		☺	😐	☹

4.6 Sensitivity coefficients

4.6.1 Determination of the sensitivity coefficients

Where sensitivity coefficients have been determined by partial derivation, the correctness of the derivation has to be confirmed. If sensitivity coefficients have been determined by other numerical methods (e. g. approximations or estimates), the validity of the determination method must be checked.					
Method used	◻ Partial derivation	◻ Numerical approximation	◻ Does not apply (e. g. in case of the Monte Carlo Simulation)		
Evaluation			☺	😐	☹

4.7 Analysis of the measurement uncertainty

4.7.1 Relevant influences

All relevant uncertainty influences must be recorded. Known or neglected influences must be named and the reasons for not being taken into account must be stated. → DIN EN ISO/IEC 17025:2018 [4], 7.6.1				
Evaluation		☺	😐	☹

4.7.2 Probability density function

Assigning the probability density function (PDF[8]) to an influence quantity must be plausible.				
Evaluation		☺	😐	☹

4.7.3 Assumptions on influencing quantities

Estimates of influence quantities must be based on reasonable assumptions and documented.				
Evaluation		☺	😐	☹

4.7.4 Properties of the device under test

The properties of the device under test are to be taken into account when establishing the model equation.				
Evaluation		☺	😐	☹

4.7.5 External evaluations

If the evaluation of influence quantities is based on external opinions (e. g. expert opinions), the source of information must be stated.				
Evaluation		☺	😐	☹

4.7.6 Conversion factors and constants

Conversion factors and constants must be considered as possible influence quantities.				
Evaluation		☺	😐	☹

[8] In English, the probability density function is abbreviated as PDF.

4.8 Correlations

4.8.1 Determination of correlations

If there is reason to suspect that there is a correlation between influence quantities, the correlation is to be determined and included in the uncertainty budget. Even if no correlations are found, it is useful to indicate that the matter has been examined.				
Are there any correlations?	☐ Yes / ☐ No			
Evaluation		☺	😐	☹

4.9 Creation of the measurement uncertainty budget

4.9.1 Contributions with correct units

The measurement uncertainty budget must be physically and mathematically correct.				
Evaluation		☺	😐	☹

4.9.2 Presentation of the uncertainty budget in tabular form

Where the entries in the uncertainty budget are not self-explanatory, a clear description of the contents is required. The calculation steps used must unambiguous, leaving no room for interpretation.				
Evaluation		☺	😐	☹

4.9.3 Use of the units

The measurement uncertainty is stated either in relation to the measurand or in the unit of the measurand. The use of the SI or of legally regulated units is recommended. → Units and Time Act (law on units in metrology) [8] → Regulation on units [9]				
Evaluation		☺	😐	☹

4.10 Verification of the effective degrees of freedom

4.10.1 Verifying the effective degrees of freedom

If the determined measurement uncertainty has an effective degrees of freedom greater than fifty, the coverage factor k = 2 can be applied without further testing to achieve a coverage probability of approximately 95 %. Otherwise, a larger coverage factor must be applied according to the Student Table (*t*-distribution, see Appendix E in EA-4/02 M: 2013). [**MCS:** *Not applicable when using Monte Carlo simulation*.]				
Have the degrees of freedom been determined?	◻ Yes / ◻ No			
Effective degrees of freedom higher than 50?	◻ Yes / ◻ No			
Evaluation		☺	😐	☹

4.11 Presentation of results

4.11.1 Presentation of the result

The expanded uncertainty is to be indicated as a positive quantity value with an associated coverage factor and a coverage probability. *Usually, the expanded uncertainty is rounded to two significant digits.*				
Evaluation		☺	😐	☹

4.11.2 Quantity equations instead of numerical value equations

Where measurement uncertainties are expressed by equations, quantity equations instead of numerical equations are to be used.				
Evaluation		☺	😐	☹

5 Checklist for the validation of the measurement uncertainty of an actual measurement (further requirements)

5.1 Formal examinations

5.1.1 Designation and identification

The determination of the measurement uncertainty is described in the following document. Alternatively, a validated and traceable spreadsheet (or similar) can be named. → DIN EN ISO/IEC 17025:2018 [4], 7.11, 8.3 → DIN EN ISO 9001 [7], 4.2.3				
Name of the document or file				
Designation of the measurand				
Version				
Release date				
Issued by				
Approved by (Name)				
Evaluation		☺	😐	☹

5.2 Measurand

The questions concerning the best measurement uncertainty apply.

→ Section 4.2, page 15

5.3 Measuring process

5.3.1 Exceeding limit values

If limit values originally defined for the measurement process are exceeded, the effects of exceeding the limit values must be investigated and, if necessary, adequately considered as part of the measurement uncertainty budget.				
Evaluation		☺	😐	☹

5.4 Measuring equipment

5.4.1 Requirements for measuring equipment and devices

It is assumed that all standards, measuring devices and auxiliary means intended to be used for the measuring process have actually been used. Should this not be the case, it must be examined whether the change of measuring equipment affects the measurement uncertainty and if so, whether this must be taken into account.				
Evaluation		☺	😐	☹

5.5 Modelling

Actual measurements do not require a new model, provided that the model from the determination of best measurement uncertainty (→ Section 4.5, page 17) can be adopted and that this model is referred to.				
Evaluation		☺	😐	☹

5.6 Sensitivity coefficients

→ Section 4.6 applies accordingly.

5.7 Analysis of the measurement uncertainty

It has to be checked whether the model used to determine the best measurement uncertainty can also be used for an actually determined measurement uncertainty. Deviations between the two models are to be examined.				
Evaluation		☺	😐	☹

5.8 Correlations

The question in → Section 4.8.1, “Determination of correlations”, page 20, applies accordingly. The references mentioned there are also referred to.

5.9 Creation of the measurement uncertainty budget

Not required for actual measurements because usually reference can be made to the budget best measurement uncertainty for this measurand according to → Section 4.9, page 20. Otherwise, a new uncertainty budget has to be prepared.				
Evaluation		☺	😐	☹

5.10 Verifying the effective degrees of freedom

If the determined measurement uncertainty has an effective degrees of freedom greater than fifty, the coverage factor $k = 2$ can be applied without further testing to achieve a coverage probability of approximately 95 %. Otherwise, a larger coverage factor must be applied according to the Student Table (*t*-distribution, see Appendix E in EA-4/02 M: 2013). [***GUM Framework:*** *If the modelling of the task allows to rule out in advance the possibility that the degrees of freedom of a result can be assumed to be in the order of* $\nu_{eff} = 50$ *or smaller, there is no need for verification*] [***MCS:*** *Not applicable when using Monte Carlo simulation.*]				
Have the degrees of freedom been determined?	☐ Yes / ☐ Non			
Degrees of freedom higher than 50?	☐ Yes / ☐ No			
Evaluation		☺	😐	☹

5.11 Verification of the stated uncertainty

5.11.1 Complete presentation of results

When presenting measurement results, they must be stated in full, i. e. including the associated measurement uncertainty.				
Evaluation		☺	😐	☹

5.11.2 Reference to the calculation basis

When stating measurement uncertainties, an indication as to where information on the determination of these values can be found.				
Evaluation		☺	😐	☹

5.11.3 Recording of readings

The readings used to determine the measurement uncertainty (determined numerical values) must be documented as raw data. → DIN EN ISO/IEC 17025:2018 [4], 7.5.1				
Evaluation		☺	😐	☹

5.11.4 Validated calculations

The software used must be validated. Proof of validation must be provided and documented as required by the QM system. → Entry and definition “Validation” in Table 1,”Metrological symbols and formula symbol”, page 8 → DIN EN ISO 9001:2008 [7], 7.5.2 → DIN EN ISO/IEC 17025:2018 [4], 7.2, 7.11				
Evaluation		☺	😐	☹

5.11.5 Reference to the best measurement uncertainty

If the laboratory is accredited for the measurand, the stated uncertainty must not be smaller than the best measurement uncertainty. → EA-4/02 M: 2013 Appendix A [3]				
Evaluation		☺	😐	☹

6 Appendix

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