

Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipments —

**Part 2: Guide to the estimation of
uncertainty in GPS measurement, in
calibration of measuring equipment
and in product verification**

ICS 17.040.01

National foreword

This Draft for Development is the UK implementation of ENV ISO 14253-2:2001. It is identical with ISO/TS 14253-2:1999, incorporating corrigendum October 2007.

The start and finish of text introduced or altered by corrigendum is indicated in the text by tags. Text altered by ISO corrigendum October 2007 is indicated in the text by AC1 AC1.

This publication is not to be regarded as a British Standard.

It is being issued in the Draft for Development series of publications and is of a provisional nature because the concepts it embodies are relatively new to technical product specification and verification with the result that assimilation into general working practices, will require some time. It should be applied on this provisional basis, so that information and experience of its practical application may be obtained.

Comments arising from the use of this Draft for Development are requested so that UK experience can be reported to the European organization responsible for its conversion into a European Standard. A review of this publication will be initiated 2 years after its publication by the European organization so that a decision can be taken on its status at the end of its three-year life. The commencement of the review period will be notified by an announcement in *Update Standards*.

According to the replies received by the end of the review period, the responsible BSI Committee will decide whether to support the conversion into a European Standard, to extend the life of the prestandard or to withdraw it. Comments should be sent in writing to the Secretary of BSI Technical Committee TDW/4, Technical product realization, at 389 Chiswick High Road, London W4 4AL, giving the document reference and clause number and proposing, where possible, an appropriate revision of the text.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Geometrical Product Specifications (GPS) - Inspection by
measurement of workpieces and measuring equipments - Part
2: Guide to the estimation of uncertainty in GPS measurement,
in calibration of measuring equipment and in product verification
(ISO/TS 14253-2:1999)

Spécification géométrique des produits (GPS) - Vérification
par la mesure des pièces et des équipements de mesure -
Partie 2: Guide pour l'estimation de l'incertitude dans les
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Geometrische Produktspezifikationen (GPS) - Prüfung von
Werkstücken und Messgeräten durch Messungen - Teil 2:
Leitfaden zur Schätzung der Unsicherheit von GPS-
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This European Prestandard (ENV) was approved by CEN on 20 January 2001 as a prospective standard for provisional application.

The period of validity of this ENV is limited initially to three years. After two years the members of CEN will be requested to submit their comments, particularly on the question whether the ENV can be converted into a European Standard.

CEN members are required to announce the existence of this ENV in the same way as for an EN and to make the ENV available promptly at national level in an appropriate form. It is permissible to keep conflicting national standards in force (in parallel to the ENV) until the final decision about the possible conversion of the ENV into an EN is reached.

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Foreword

The text of the Technical Specification from Technical Committee ISO/TC 213 "Dimensional and geometrical product specifications and verification" of the International Organization for Standardization (ISO) has been taken over as a European Prestandard by Technical Committee CEN/TC 290 "Dimensional and geometrical product specification and verification", the secretariat of which is held by AFNOR.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to announce this European Prestandard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

Endorsement notice

The text of the International Technical Specification ISO/TS 14253-2:1999 has been approved by CEN as a European Prestandard without any modifications.

NOTE Normative references to International Standards are listed in annex ZA (normative). In other circumstances, particularly when there is an urgent market requirement for such documents, a technical committee may decide to publish other types of normative document:

- an ISO Publicly Available Specification (ISO/PAS) represents an agreement between technical experts in an ISO working group and is accepted for publication if it is approved by more than 50 % of the members of the parent committee casting a vote;
- an ISO Technical Specification (ISO/TS) represents an agreement between the members of a technical committee and is accepted for publication if it is approved by 2/3 of the members of the committee casting a vote.

An ISO/PAS or ISO/TS is reviewed every three years with a view to deciding whether it can be transformed into an International Standard.

Attention is drawn to the possibility that some of the elements of this Technical Specification may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TS 14253-2 was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification*.

ISO 14253 consists of the following parts, under the general title, Geometrical product specifications (GPS) – Inspection by measurement of workpieces and measuring equipment:

- Part 1: Decision rules for proving conformance or non-conformance with specification
- Part 2: Guide to the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification [Technical Specification]
- Part 3: Procedures for evaluating the integrity of uncertainty in measurement values

Annexes A to D of this Technical Specification are for information only.

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Introduction

This Technical Specification is a global GPS technical report (see ISO/TR 14638:1995). This global GPS Technical Report influences chain link 4, 5 and 6 in all chains of standards.

For more detailed information of the relation of this report to other standards and the GPS matrix model, see annex D.

This Technical Specification is developed to support ISO 14253-1. This Technical Specification establishes a simplified, iterative procedure of the concept and the way to evaluate and determine uncertainty (standard uncertainty and expanded uncertainty) of measurement, and the recommendations of the format to document and report the uncertainty of measurement information as given in "*Guide to the expression of uncertainty in measurement*" (GUM). In most cases only very limited resources are necessary to estimate uncertainty of measurement by this simplified, iterative procedure, but the procedure may lead to a slight overestimation of the uncertainty of measurement. If a more accurate estimation of the uncertainty of measurement is needed, the more elaborated procedures of the GUM must be applied.

This simplified, iterative procedure of the GUM methods is intended for GPS measurements, but may be used in other areas of industrial (applied) metrology.

Uncertainty of measurement and the concept of handling uncertainty of measurement being of importance to all the technical functions in a company, this Technical Specification relates to e.g. management function, design and development function, manufacture function, quality assurance function, metrology function, etc.

This Technical Specification is of special importance in relation to ISO 9000 quality assurance systems, where it is a requirement that the uncertainty of measurement is known [e.g. 4.11.1, 4.11.2 a) and 4.11.2 b) of ISO 9001:1994].

In this Technical Specification the uncertainty of the result of a process of calibration and a process of measurement is handled in the same way:

- calibration is treated as "measurement of metrological characteristics of a measuring equipment or a measurement standard";
- measurement is treated as "measurement of geometrical characteristics of a workpiece".

Therefore, in most cases no distinction is made in the text between measurement and calibration. The term "measurement" is used as a synonym for both.

Geometrical product specifications (GPS) — Inspection by measurement of workpieces and measuring equipment —

Part 2:

Guide to the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification

1 Scope

This Technical Specification gives guidance on the implementation of the concept of "*Guide to the estimation of uncertainty in measurement*" (in short GUM) to be applied in industry for the calibration of (measurement) standards and measuring equipment in the field of GPS and the measurement of workpiece GPS-characteristics. The aim is to promote full information on how to achieve uncertainty statements and provide the basis for international comparison of results of measurements and their uncertainties (relationship between purchaser and supplier).

This Technical Specification is intended to support ISO 14253-1. This Technical Specification and ISO 14253-1 are beneficial to all technical functions in a company in the interpretation of GPS specifications (i.e. tolerances of workpiece characteristics and values of maximum permissible errors (MPE) for metrological characteristics of measuring equipment).

This Technical Specification introduces the Procedure for Uncertainty Management (PUMA), which is a practical, iterative procedure based on the GUM for estimating uncertainty of measurement without changing the basic concepts of the GUM and is intended to be used generally for estimating uncertainty of measurement and giving statements of uncertainty for:

- single results of measurement;
- comparison of two or more results of measurement;
- comparison of results of measurement — from one or more workpieces or pieces of measurement equipment — with given specifications [i.e. maximum permissible errors (MPE) for a metrological characteristic of a measurement instrument or measurement standard, and tolerance limits for a workpiece characteristic, etc.], for proving conformance or non-conformance with the specification.

The iterative method is based basically on an upper bound strategy, i.e. overestimation of the uncertainty at all levels, but the iterations control the amount of overestimation. Intentional overestimation — and not underestimation — is necessary to prevent wrong decisions based on measurement results. The amount of overestimation shall be controlled by economical evaluation of the situation.

The iterative method is a tool to maximize profit and minimize cost in the metrological activities of a company. The iterative method/procedure is economically self-adjusting and is also a tool to change/reduce existing uncertainty in measurement with the aim of reducing cost in metrology (manufacture). The iterative method makes it possible to compromise between risk, effort and cost in uncertainty estimation and budgeting.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this Technical Specification. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this Technical Specification are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 1:2002, *Geometrical Product Specifications (GPS) — Standard reference temperature for geometrical product specification and verification*.

ISO 4288:1996, *Geometrical Product Specifications (GPS) — Surface texture: Profile method — Rules and procedures for the assessment of surface texture*.

ISO 9001:2000, *Quality management systems — Requirements*.

ISO 9004:2000, *Quality management systems — Guidelines for performance improvements*.

ISO 14253-1:1998, *Geometrical Product Specification (GPS) — Inspection by measurement of workpieces and measuring instruments — Part 1: Decision rules for proving conformance or non-conformance with specifications*.

ISO 14253-3:2002, *Geometrical Product Specifications (GPS) — Inspection by measurement of workpieces and measuring equipment — Part 3: Guidelines for achieving agreements on measurement uncertainty statements*.

ISO 14660-1:1999, *Geometrical Product Specification (GPS) — Geometric features — Part 1: General terms and definitions*.

Guide to the expression of uncertainty in measurement (GUM). BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 1st edition, 1995.

International Vocabulary of Basic and General Terms in Metrology (VIM). BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 2nd edition, 1993.

3 Terms and definitions

For the purposes of this Technical Specification, the terms and definitions given in ISO 14253-1, ISO 14660-1, VIM, GUM and the following apply.

3.1

black box model for uncertainty estimation

method of/model for uncertainty estimation in which the output value of a measurement is obtained in the same unit as the input (stimuli), rather than by measurement of other quantities functionally related to the measurand

NOTE 1 In the black box model — in this Technical Specification — the uncertainty components are assumed additive, the influence quantities is transformed to the unit of the measurand and the sensitivity coefficients are equal to 1.

NOTE 2 In many cases a complex method of measurement may be looked upon as one simple black box with stimulus in and result out from the black box. When a black box is opened, it may turn out to contain several "smaller" black boxes and/or several transparent boxes.

NOTE 3 The method of uncertainty estimation remains a black box method even if it is necessary to make supplementary measurements to determine the values of influence quantities in order to make corresponding corrections.

Footnote deleted

3.2**transparent box model for uncertainty estimation**

method of/model for uncertainty estimation in which the value of a measurand is obtained by measurement of other quantities functionally related to the measurand

3.3**measuring task**

quantification of a measurand according to its definition

3.4**basic measurement task (basic measurement)**

measurement task(s) which form the basis for evaluation of more complicated characteristics of a workpiece or a measuring equipment

NOTE Examples of a basic measurement are:

- a) one of several individual measurements of the deviation from straightness of a feature of a workpiece;
- b) one of the individual measurements of error of indication of a micrometer when measuring the range of error of indication.

3.5**overall measurement task**

complicated measuring task, which is evaluated on the basis of several and maybe different basic measurements

NOTE Examples of an overall measuring task are:

- a) the measurement of straightness of a feature of a workpiece;
- b) the range of error of indication of a micrometer.

3.6**expanded uncertainty (of a measurement)**

U

[3.16 of ISO 14253-1:1998 and 2.3.5 of GUM:1995]

NOTE U (capital) always indicates expanded uncertainty of measurement.

3.7**true uncertainty**

U_A

uncertainty of measurement that would be obtained by a perfect uncertainty estimation

NOTE 1 True uncertainties are by nature indeterminate.

NOTE 2 See also 8.8.

3.8**conventional true uncertainty — GUM uncertainty**

U_c

uncertainty of measurement estimated completely according to the more elaborate procedures of GUM

NOTE 1 The conventional true uncertainty of measurement may differ from an uncertainty of measurement estimated according to this Technical Specification.

NOTE 2 See also 8.8.

3.9 approximated uncertainty

U_{EN}

uncertainty of measurement estimated by the simplified, iterative method

NOTE 1 The index N indicates that U_{EN} is assessed by iteration number N . The designation U_E may be used without indication of the iteration number, when it is without importance to know the number of iterations.

NOTE 2 See also 8.8.

3.10 target uncertainty (for a measurement or calibration)

U_T

uncertainty determined as the optimum for the measuring task

NOTE 1 Target uncertainty is the result of a management decision involving e.g. design, manufacturing, quality assurance, service, marketing, sales and distribution.

AC1 NOTE 2 Target uncertainty is determined (optimized) taking into account the specification [tolerance or maximum permissible error (MPE)], the process capability, cost, criticality and the requirements of 7.6 and 8.2.4 of ISO 9001:2000, 7.6 and 8.2.3 of ISO 9004:2000 and ISO 14253-1. AC1

NOTE 3 See also 8.8.

3.11 required uncertainty of measurement

U_R

uncertainty required for a given measurement process and task

NOTE See also 6.2. The required uncertainty may be specified by, for example, a customer.

3.12 uncertainty management

process of deriving an adequate measurement procedure from the measuring task and the target uncertainty by using uncertainty budgeting techniques

3.13 uncertainty budget (for a measurement or calibration)

statement summarizing the estimation of the uncertainty components that contributes to the uncertainty of a result of a measurement

NOTE 1 The uncertainty of the result of the measurement is unambiguous only when the measurement procedure (including the measurement object, measurand, measurement method and conditions) is defined.

NOTE 2 The term "budget" is used for the assignment of numerical values to the uncertainty components, their combination and expansion, based on the measurement procedure, measurement conditions and assumptions.

3.14 uncertainty contributor

x_x

source of uncertainty of measurement for a measuring process

3.15 limit value (variation limit) for an uncertainty contributor

a_{xx}

absolute value of the extreme value(s) of the uncertainty contributor, x_x

3.16**uncertainty component** u_{xx}

standard uncertainty of the uncertainty contributor, xx

NOTE The iteration method uses the designation u_{xx} for all uncertainty components. This is not consistent with the present version of GUM which sometimes uses the designation s_{xx} for uncertainty components evaluated by A evaluation and the designation u_{xx} for uncertainty components evaluated by B evaluation.

3.17**influence quantity of a measurement instrument**

characteristic of a measuring instrument that affects the result of a measurement performed by the instrument

3.18**influence quantity of a workpiece**

characteristic of a workpiece that affects the result of a measurement performed on that workpiece

4 Symbols

For the purposes of this Technical Specification, the generic symbols given in Table 1 apply.

Table 1 — Generic symbols

Symbol	Description
a	limit value for a distribution
a_{xx}	limit value for an error or uncertainty contributor (in the unit of the result of measurement, of the measurand)
a^*_{xx}	limit value for an error or uncertainty contributor (in the unit of the influence quantity)
α	linear coefficient of thermal expansion
b	coefficient for transformation of a_{xx} to u_{xx}
C	correction (value)
d	resolution of a measurement equipment
E	Young's modulus
ER	error (value of a measurement)
G	function of several measurement values [$G(X_1, X_2, \dots, X_i, \dots)$]
h	hysteresis value
k	coverage factor
m	number of standard deviations in the half of a confidence interval
MR	measurement result (value)
n	number of ...
N	number of iterations
ν	Poisson's number
p	number of total uncorrelated uncertainty contributors
r	number of total correlated uncertainty contributors
ρ	correlation coefficient
TV	true value of a measurement
u, u_i	standard uncertainty (standard deviation)
s_x	standard deviation of a sample
$s_{\bar{x}}$	standard deviation of a mean value of a sample
u_c	combined standard uncertainty
u_{xx}	standard deviation of uncertainty contributor xx — uncertainty component
U	expanded uncertainty of measurement
U_A	true uncertainty of measurement
U_C	conventional true uncertainty of measurement
U_E	approximated uncertainty of measurement (number of iteration not stated)
U_{EN}	approximated uncertainty of measurement of iteration number N
U_R	required uncertainty
U_T	target uncertainty
U_V	uncertainty value (not estimated according to GUM or this Technical Specification)
X	measurement result (uncorrected)
X_i	measurement result (in the transparent box model of uncertainty estimation)
Y	measurement result (corrected)

5 Concept of the iterative GUM-method for estimation of uncertainty of measurement

Applying the GUM method completely one will find a conventional true uncertainty of measurement, U_C .

The simplified, iterative method/procedure of this Technical Specification is to achieve estimated uncertainties of measurements, U_E by overestimating the influencing uncertainty components/contributors ($U_E \geq U_C$). The process of overestimating provides "worst-case-contributions" at the upper bound from each known or predictable uncertainty contributor, thus ensuring results of estimations "on the safe side", i.e. not underestimating the uncertainty of measurement. The simplified, iterative method of this Technical Specification is based on the following:

- all uncertainty contributors are identified;
- it is decided which of the possible corrections shall be made (see 8.4.6);
- the influence on the uncertainty of the result of measurement from each contributor is evaluated as a standard uncertainty u_{xx} , called the uncertainty component;

NOTE As a convention in the iterative method the influence of each contributor must be converted into the unit of the measurand — using relevant physical equations/formulae and sensibility coefficients.

- an iteration process, PUMA (see clause 6);
- the evaluation of each of the uncertainty components (standard uncertainties) u_{xx} can take place either by type A-evaluation or by type B-evaluation;
- type B-evaluation is preferred — if possible — in the first iteration in order to get a rough uncertainty estimate to establish an overview and to save cost;
- the total effect of all contributors (called the combined standard uncertainty) is calculated by the formula:

$$u_c = \sqrt{u_{x1}^2 + u_{x2}^2 + u_{x3}^2 + \dots + u_{xn}^2} \quad (1)$$

- the formula (1) is only valid for a black box model of the uncertainty estimation and when the components u_{xx} are all uncorrelated (for more details and other formulas see 8.6 and 8.7);
- for simplification the only correlation coefficients between contributors considered are

$$\rho = 1, -1, 0 \quad (2)$$

if the uncertainty components are not known to be uncorrelated, full correlation is assumed, either $\rho = 1$ or -1 . Correlated components are added arithmetically before put into the formula above (see 8.5 and 8.6);

- the expanded uncertainty U is calculated by the formula:

$$U = k \times u_c \quad (3)$$

where $k = 2$; k is the coverage factor (see also 8.8);

The simplified, iterative method normally will consist of at least two iterations of estimating the components of uncertainty.

- a) The first very rough, quick and cheap iteration has the purpose of identifying the largest components of uncertainty (see Figure 1);
- b) The following iterations — if any — only deal with making more accurate "upper bound" estimates of the largest components to lower the estimate of the uncertainty (u_c and U) to a possible acceptable magnitude.

The simplified and iterative method may be used for two purposes:

- a) Management of the uncertainty of measurement for a result of a given measurement process (can be used for the results from a known measuring process or for comparison of two or more of such results) — see 6.2.
- b) Uncertainty management for a measuring process. Development of an adequate measuring process i.e. $U_E \leq U_T$ — see 6.3.

6 Procedure for Uncertainty Management — PUMA

6.1 General

The prerequisite for uncertainty budgeting and management is a clearly identified and defined measuring task; i.e. the measurand to be quantified (a GPS characteristic of a workpiece or a metrological characteristic of a GPS measuring equipment). The uncertainty of measurement is a measure of the quality of the measured value according to the definitions of a GPS characteristic of the workpiece or a metrological characteristic of the GPS measuring equipment given in GPS standards.

GPS standards define the "conventional true values" (see 1.20 of VIM:1993) of the characteristics to be measured by chains of standards and global standards (see ISO/TR 14638). GPS standards in many cases also define the ideal — or conventional true — principle of measurement (see 2.3 of VIM:1993), method of measurement (see 2.4 of VIM:1993), measurement procedure (see 2.5 of VIM:1003) and Standard "reference conditions" (see 5.7 of VIM:1993).

Deviations from the standardized conventional true values of the characteristics, etc. (the ideal operator) are contributing to the uncertainty of measurement.

6.2 Uncertainty management for a given measurement process

Management of the uncertainty of measurement for a given measuring task (box 1 of Figure 1) and for an existing measurement process is illustrated in Figure 1. The principle of measurement (box 3), measurement method (box 4), measurement procedure (box 5) and measurement conditions (box 6) are fixed and given or decided in this case, and cannot be changed. The only task is to evaluate the consequence on the uncertainty of measurement. A required U_R may be given or decided.

Using the iterative GUM method the first iteration is only for orientation, and to look for the dominant uncertainty contributors. The only thing to do — in the management process in this case — is to refine the estimation of the dominant contributors to come closer to a true estimate of the uncertainty components thus avoiding a too big overestimate — if necessary.

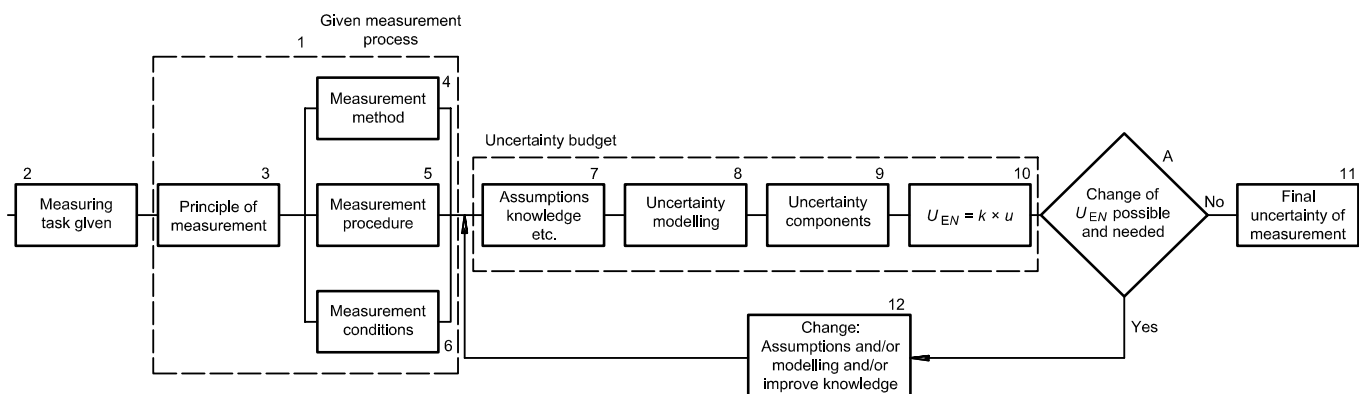


Figure 1 — Uncertainty management for a result of measurement from a given measurement process

The procedure is as follows:

- a) make a first iteration based preferably on a black box model of the uncertainty estimation process and set up a preliminary uncertainty budget (boxes 7 to 9) leading to the first rough estimate of the expanded uncertainty, U_{E1} (box 10). For details about uncertainty estimation see 9. All estimates of uncertainties U_{EN} are performed as upper bound estimates;
- b) compare the first estimated uncertainty, U_{E1} , with the required uncertainty U_R (box A) for the actual measuring task
 - 1) If U_{E1} is acceptable (i.e. if $U_{E1} \leq U_R$), then the uncertainty budget of the first iteration has proven that the given measurement procedure is adequate for the measuring task (box 11);
 - 2) If U_{E1} is not acceptable (i.e. if $U_{E1} > U_R$) or if there is no required uncertainty, but a lower and more true value is desired, the iteration process continues;
- c) before the new iteration, analyze the relative magnitude of the uncertainty contributors. In many cases a few uncertainty components dominate the combined standard uncertainty and expanded uncertainty;
- d) change the assumptions or improve the knowledge about the uncertainty components to make a more accurate (see 3.5 of VIM:1993) upper bound estimation of the largest (dominant) uncertainty components (box 12).

Change to a more detailed model of the uncertainty estimation process or a higher resolution of the measuring process (box 12);

- e) make the second iteration of the uncertainty budget (boxes 7 to 9) leading to the second, lower and more accurate (see 3.5 of VIM:1993) upper bound estimate of the uncertainty of measurement, U_{E2} (box 10);
- f) compare the second estimated uncertainty U_{E2} (box A) with uncertainty required U_R for the actual measuring task
 - 1) if U_{E2} is acceptable (i.e. if $U_{E2} \leq U_R$), then the uncertainty budget of the second iteration has proven that the given measurement procedure is adequate to the measuring task (box 11);
 - 2) if U_{E2} is not acceptable (i.e. if $U_{E2} > U_R$), or if there is no required uncertainty, but a lower and more true value is desired, then a third (and possibly more) iteration(s) is (are) needed. Repeat the analysis of the uncertainty contributors [additional changes of assumptions, improve in knowledge, changes in modelling, etc. (box 12)] and concentrate on the currently largest uncertainty contributors;
- g) when all possibilities have been used for making more accurate (lower) upper bound estimates of the measuring uncertainties without coming to an acceptable measuring uncertainty $U_{EN} \leq U_R$, then it is proven, that it is not possible to fulfil the given requirement U_R .

6.3 Uncertainty management for design and development of a measurement process/procedure

Uncertainty management in this case is performed to develop an adequate measurement procedure [measurement of the geometrical characteristics of a workpiece or the metrological characteristics of a measuring equipment (calibration)]. Uncertainty management is performed on the basis of a defined measuring task (box 1 in Figure 2) and a given target uncertainty, U_T (box 2 in Figure 2). Definition of the measuring task and target uncertainty are company policy decisions to be made at a sufficiently high management level. An adequate measurement procedure is a procedure which results in an estimated uncertainty of measurement less than or equal to the target uncertainty. If the estimated uncertainty of measurement is much less than the target uncertainty, the measurement procedure may not be (economically) optimal for performing the measuring task (i.e. the measurement process is too costly).

The PUMA, based on a given measuring task (box 1) and a given target uncertainty U_T (box 2), includes the following (see Figure 2):

- a) choose the principle of measurement (box 3) on the basis of experience and possible measurement instruments present in the company;
- b) set up and document a preliminary method of measurement (box 4), measurement procedure (box 5) and measurement conditions (box 6) on the basis of experience and known possibilities in the company;
- c) make a first iteration based preferably on a black box model of the uncertainty estimation process and set up a preliminary uncertainty budget (boxes 7 to 9) leading to the first rough estimate of the expanded uncertainty, U_{E1} (box 10). For details about uncertainty estimation see clause 9. All estimates of uncertainties U_{EN} are performed as upper bound estimates;
- d) compare the first estimated uncertainty, U_{E1} , with the given target uncertainty, U_T (box A);
 - 1) if U_{E1} is acceptable (i.e. if $U_{E1} \leq U_T$), then the uncertainty budget of the first iteration has proven that the measurement procedure is adequate for the measuring task (box 11);
 - 2) if $U_{E1} << U_T$, then the measurement procedure is technically acceptable, but a possibility may exist to change the method and/or the procedure (box 13) in order to make the measuring process more cost effective while increasing the uncertainty. A new iteration is then needed to estimate the resulting measurement uncertainty, U_{E2} (box 10);
 - 3) if U_{E1} is not acceptable (i.e. if $U_{E1} > U_T$), the iteration process continues, or it is concluded that no adequate measurement procedure is possible;
- e) before the new iteration, analyze the relative magnitude of the uncertainty contributors. In many cases a few uncertainty components pre-dominate the combined standard uncertainty and expanded uncertainty;
- f) if $U_{E1} > U_T$, then change the assumptions, the modelling or increase the knowledge about the uncertainty components (box 12) to make a more accurate (see 3.5 of VIM:1993) upper bound estimation of the largest (dominant) uncertainty components;
- g) make the second iteration of the uncertainty budget (boxes 7 to 9) leading to the second, lower and more accurate (see 3.5 of VIM:1993) upper bound estimate of the uncertainty of measurement, U_{E2} (box 10);
- h) compare the second estimated uncertainty U_{E2} with the given target uncertainty, U_T (box A);
 - 1) if U_{E2} is acceptable (i.e. if $U_{E2} \leq U_T$), then the uncertainty budget of the second iteration has proven that the measurement procedure is adequate for the measuring task (box 11);
 - 2) if U_{E2} is not acceptable (i.e. if $U_{E2} > U_T$) then a third (and possibly more) iteration(s) is (are) needed. Repeat the analysis of the uncertainty contributors (additional changes of assumptions, modelling and increase in knowledge (box 12)) and concentrate on the currently largest uncertainty contributors;
- i) when all possibilities has been used for making more accurate (lower) upper bound estimates of the measuring uncertainties without coming to an acceptable measuring uncertainty $U_{EN} \leq U_T$, then a change of the measurement method or the measurement procedure or the conditions of measurement (box 13) is needed to (possibly) bring down the magnitude of the estimated uncertainty, U_{EN} . The iteration procedure starts again with a first iteration;
- j) if changes in the measurement method or the measurement procedure or conditions (box 13) do not lead to an acceptable uncertainty of measurement, the final possibility is to change the principle of measurement (box 14) and start the above mentioned procedure again;

- k) if change of the measuring principle and the related iterations described above do not lead to an acceptable uncertainty of measurement the ultimate possibility is to change the measuring task and/or target uncertainty (box 15) and start the above mentioned procedure again;
- l) if change of measuring task or target uncertainty is not possible, it is demonstrated, that no adequate measurement procedure exists (box 16).

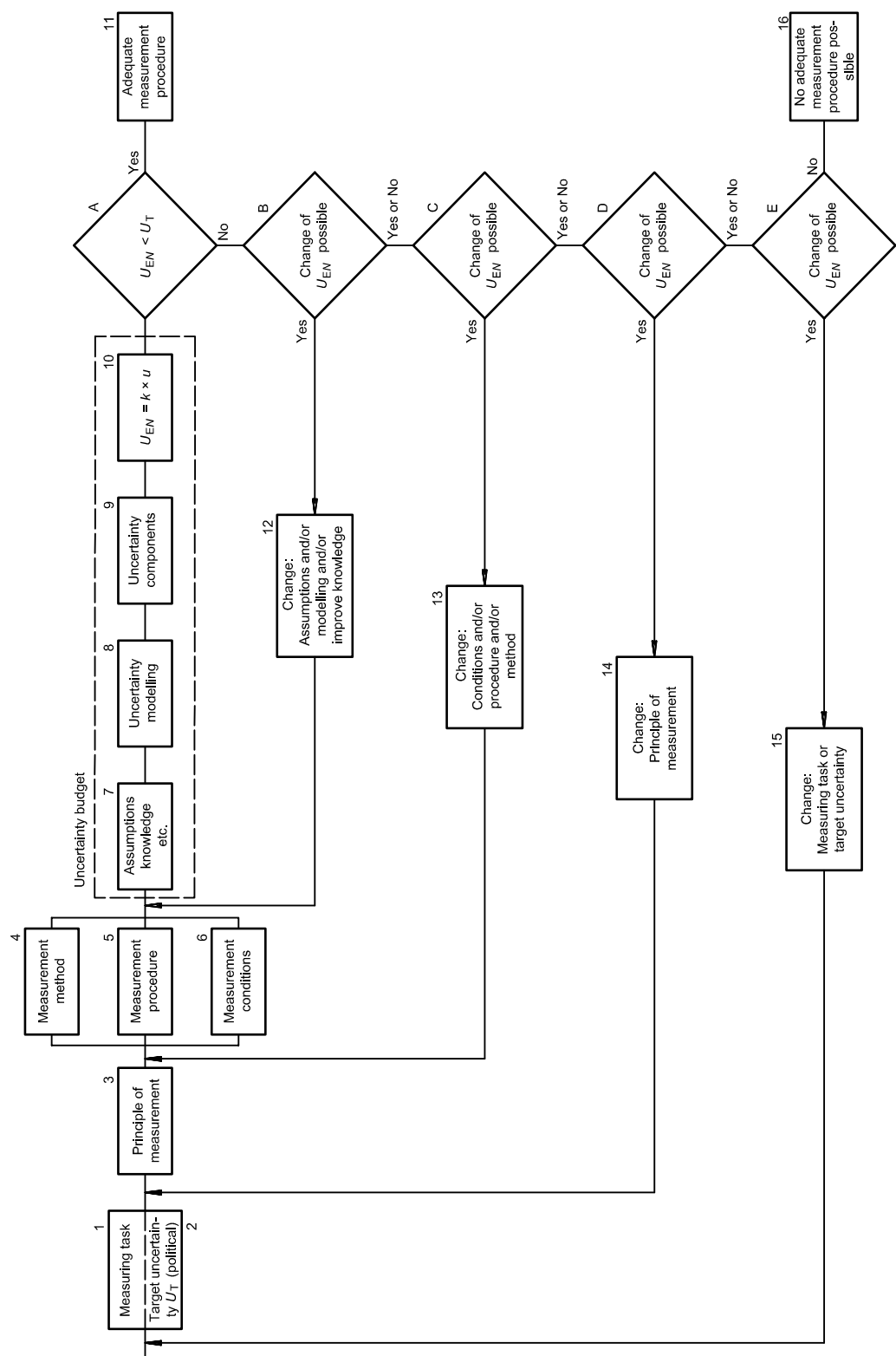


Figure 2 — Procedure for Uncertainty of Measurement Management (PUMA) for a measurement process/procedure

7 Sources of errors and uncertainty of measurement

7.1 Types of errors

Different types of errors regularly shows up in measurement results.

- systematic errors;
- random errors;
- drift;
- outliers.

All errors are by nature systematic. When we see errors as non-systematic it is because the reason for the error is not looked for or because the level of resolution is not sufficient. Systematic errors may be characterised by size and sign (+ or -).

$$ER = MR - TV$$

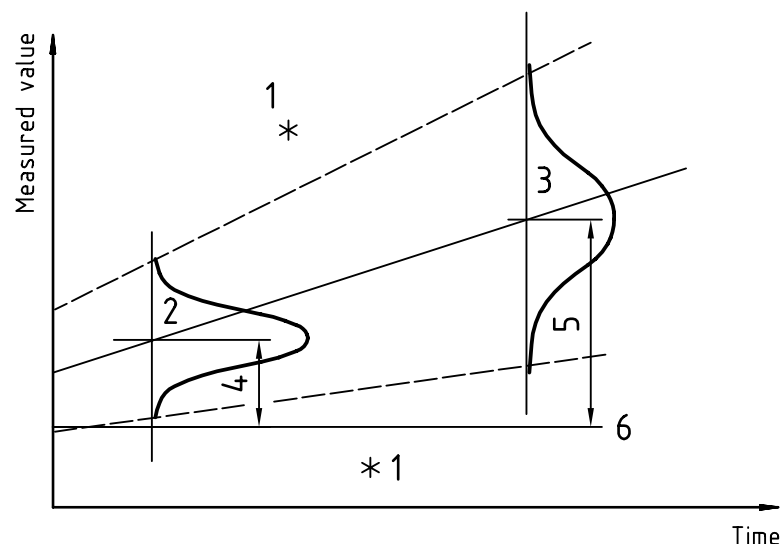
where

ER is the error,

MR is the measurement result;

TV is the true value.

Random errors are systematic errors caused by non-controlled random influence quantities. Random errors may be characterized by the standard deviation and the type of distribution. The mean value of the random errors is often considered as a basis for the evaluation of the systematic error (see Figure 3).



Key

- 1 Outlier
- 2 Dispersion 1
- 3 Dispersion 2
- 4 Systematic error 1
- 5 Systematic error 2
- 6 True value

Figure 3 — Types of errors in results of measurements

Drift is caused by a systematic influence of non-controlled influence quantities. Drift is often a time effect or a wear effect. Drift may be characterized by change per unit time or per amount of use.

Outliers are caused by not repeatable incidents in the measurement. Noise — electrical or mechanical — may result in outliers. A frequent reason for outliers is human mistakes as reading and writing errors or wrong handling of measuring equipment. Outliers are impossible to characterize in advance.

Errors or uncertainties in a measuring process will be a mix of known and unknown errors from a number of sources or error contributors.

The sources or contributors are not the same in each case, and the sum of the components are not the same.

It is still possible to make a systematic approach. There are always several sources or a combined effect of the ten different ones indicated in Figure 4.

In the following, examples and further details about each of the ten contributors are given.

What is often difficult is that each of the contributors may act individually on the result of measurement. But in many cases they even interfere with each other and cause additional errors and uncertainty.

Figure 4 and the following non-exhaustive lists (see 7.2 to 7.11) shall be used for getting ideas in a systematic way when making uncertainty budgets. In each case the evaluation of the actual error/uncertainty component needs knowledge about physics and/or experience in metrology.

In uncertainty budgets the uncertainty contributors and the uncertainty components may be grouped for convenience.

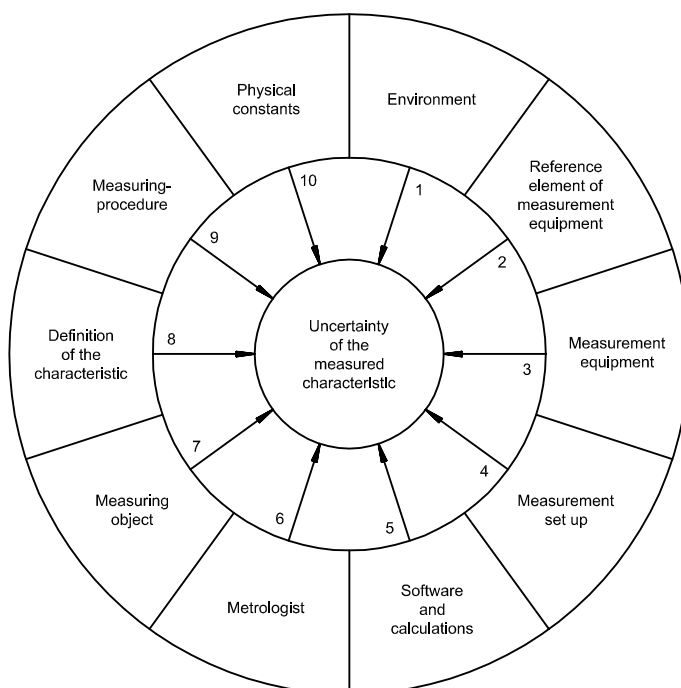


Figure 4 — Uncertainty contributors in measurement

7.2 Environment for the measurement

In most cases — especially in GPS measurements — the temperature is the main uncertainty contributor of the environment. Other uncertainty contributors may be:

- Temperature: absolute temperature, time variance, spatial gradient
- Vibration/noise
- Humidity
- Contamination
- Illumination
- Ambient pressure
- Air composition
- Air flow
- Gravity
- Electromagnetic interference
- Transients in the power supply
- Pressured air (e.g. air bearings)
- Heat radiation
- Workpiece
- Scale
- Instrument thermal equilibrium

7.3 Reference element of measurement equipment

The measuring equipment is divided into "reference element" and the "rest of the equipment", and it often pays to look at the equipment that way.

- Stability
- Scale mark quality
- Temperature expansion coefficient
- Physical principle: line scale, optical digital scale, magnetic digital scale, spindle, rack & pinion, interferometer
- CCD-techniques
- Uncertainty of the calibration
- Resolution of the main scale (analogue or digital)
- Time since last calibration
- Wavelength error

7.4 Measurement equipment

- Interpretation system
- Magnification, electrical or mechanical
- Error wavelength
- Zero-point stability
- Force stability/absolute force
- Hysteresis
- Guides/slideways
- Probe system
- Geometrical imperfections
- Stiffness/rigidity
- Reading system
- Linear coefficient for thermal expansion
- Temperature stability/sensitivity
- Parallaxes
- Time since last calibration
- Response characteristic
- Interpolation system, error wavelength
- Interpolation resolution
- Digitization

7.5 Measurement setup (excluding the placement and clamping of the workpiece)

In many cases there is no setup; the measurement equipment can measure "alone".

- Cosine errors and sine errors
- Abbe principle
- Temperature sensitivity
- Stiffness/rigidity
- Tip radius
- Form deviation of tip
- Stiffness of the probe system
- Optical aperture
- Interaction between workpiece and setup
- Warming up

7.6 Software and calculations

Observe that even the number of digits or decimals can have an influence!

- Rounding/Quantification
- Algorithms
- Implementation of algorithms
- Number of significant digits in the computation
- Sampling
- Filtering
- Correction of algorithm/Certification of algorithm
- Interpolation/extrapolation
- Outlier handling

7.7 Metrologist

The human being is not stable; there is a difference from day to day and often a rather large change during the day.

- Education
- Experience
- Training
- Physical disadvantages/ability
- Knowledge (precision, appreciation)
- Honesty
- Dedication

7.8 Measurement object, workpiece or measuring instrument characteristic

- Surface roughness
- Form deviations
- E-modulus (Young's modulus)
- Stiffness beyond E-modulus
- Temperature expansion coefficient
- Conductivity
- Weight
- Size
- Shape
- Magnetism
- Hygroscopic characteristic of the material
- Ageing
- Cleanliness
- Temperature
- Internal stress
- Creep characteristics
- Workpiece distortion due to clamping
- Orientation

7.9 Definition of the GPS characteristic, workpiece or measuring instrument characteristic

- Datum
- Reference system
- Degrees of freedom
- Toleranced feature
- ISO 4288
- Chain link 3 and 4 deviations (ISO/TR 14638)
- Distance
- Angle

7.10 Measuring procedure

- Conditioning
- Number of measurements
- Order of measurements
- Duration of measurements
- Choice of principle of measurement
- Alignment
- Choice of reference — reference item (standard) and value — relative to the measured value
- Choice of apparatus
- Choice of metrologist
- Number of operators
- Strategy
- Clamping
- Fixturing
- Number of points
- Probing principle and strategy
- Alignment of probing system
- Drift check
- Reversal measurements
- Multiple redundancy, error separation

7.11 Physical constants and conversion factors

- Knowledge of the correct physical values of, for example, material properties (workpiece, measuring instrument, ambient air, etc.)

8 Tools for the estimation of uncertainty components, standard uncertainty and expanded uncertainty

8.1 Estimation of uncertainty components

Estimation of uncertainty components can be done in two different ways. Type A evaluation and type B evaluation.

Type A-evaluation is evaluation of uncertainty components, u_{xx} , using statistical means. Type B evaluation is evaluation of uncertainty components, u_{xx} , by any other means than statistical.

Type A-evaluation will in most cases result in more accurate estimates of uncertainty components than type B-evaluation. In many cases Type B evaluation will result in sufficiently accurate estimations of uncertainty components.

Therefore, Type B evaluation shall be chosen in the iterative method, when it is not absolutely necessary to evaluate uncertainty by using type A evaluation. In a number of cases, no other possibilities exist than to use type A evaluation. See "standard cases" for evaluation of uncertainty components in 8.4.

NOTE The designation in this Technical Specification for both type A and B evaluated uncertainty components are u_{xx} . This is a deviation from the present version of GUM where type A evaluated uncertainty components is designated s_{xx} and type B-evaluated u_{xx} .

8.2 Type A evaluation for uncertainty components

8.2.1 General

Type A evaluation of the uncertainty component, u_{xx} , needs data from repeated measurements. The standard deviation of the distribution or the standard deviation of the mean value may be calculated using the formulas in 8.2.2.

8.2.2 Statistical tools

Regardless of the type of statistical distribution, the following statistical parameters are defined by the equations:

$$\bar{x} = \frac{1}{n} \times \sum_{i=1}^n X_i$$

The mean value of a number, n , of measurement results X_i . $\bar{x}$ is an estimate of the true value of the mean μ of the distribution.

$$s_x = \sqrt{\frac{\sum_{i=1}^n (\bar{x} - X_i)^2}{(n-1)}}$$

The standard deviation of the distribution of the sample based on n measurement values. s_x is an estimate of the standard deviation of the distribution σ .

$$s_{\bar{x}} = \sqrt{\frac{\sum_{i=1}^n (\bar{x} - X_i)^2}{n \times (n-1)}} = \frac{s_x}{\sqrt{n}}$$

The standard deviation of the mean value $s_{\bar{x}}$ of the sample is equal to the standard deviation of the sample divided by the square root of the number of measurements n .

When the mean value or the standard deviation is based on very few repeated measurements the estimated standard deviation values may be wrong, and possibly too small. For this reason, a "safety" factor h is used.

[AC1] The safety factor h (calculated based on the Student t -factor)¹⁾ can be read from Table 2. **[AC1]**

The standard deviation of the sample s_x (multiplied by the safety factor h as appropriate) is used in the uncertainty budget as the value for u_{xx} , when the measurement result is obtained using single readings of the component concerned.

$$u_{xx} = s_{x,n} \times h \quad (5)$$

The standard deviation of the mean value **[AC1]** $s_{\bar{x}}$ **[AC1]** is the value used for the standard uncertainty u_{xx} in the uncertainty budget when the measurement result is obtained using the mean of several readings of the component concerned.

$$\text{[AC1]} \quad u_{xx} = s_{\bar{x}} \times h \quad \left(s_{\bar{x},n} = \frac{s_{x,n}}{\sqrt{n}} \right) \text{[AC1]} \quad (6)$$

[AC1] 1) **[AC1]** See also bibliographic reference [2].