

# MEASUREMENT UNCERTAINTY COMBINED WITH THE MODEL OF PRODUCT AND MEASUREMENT REALIZATION IN 3D METROLOGY

*C. R. Baldo, G. D. Donatelli*

Instituto de Pesquisas Tecnológicas - IPT, Microprecision Metrology, Brazil, [crbaldo@ipt.br](mailto:crbaldo@ipt.br)  
Fundação CERTI, Centre for Metrology and Instrumentation, Brazil, [gd@certi.org.br](mailto:gd@certi.org.br)

**Abstract:** Even though coordinate metrology has been proven to be priceless to industries and despite the existence of methods to estimate uncertainties, e.g. sensitivity analysis, computer simulation, experimental method; uncertainty has been barely assessed and stated by industrial metrologists. Part of that perception may be attributed to a restricted way of employing the measurement uncertainty concept, which is not compatible with the growing importance of metrology. The merging of the well-known product and measurement realization process with measurement uncertainty concept is outlined in this work. The main idea is to use in a rational sense different techniques of evaluating the uncertainty of a measurement result, where the estimated accuracy required to the uncertainty estimation defines the suitable technique. Within the proposed context, the drawing-up of classical uncertainty budgets for GPS characteristics are shown and discussed for different measurement scenarios.

**Keywords:** Uncertainty Evaluation and Traceability, GPS Characteristics, Industrial Coordinate Metrology.

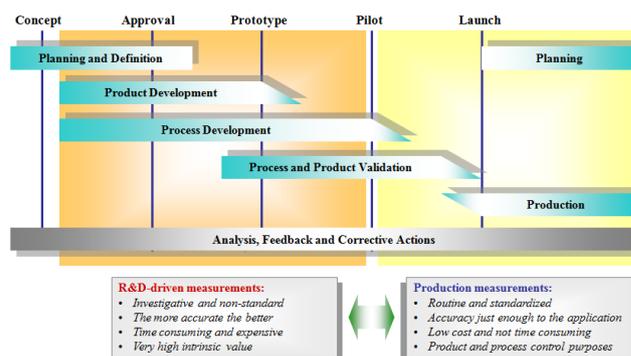
## 1. INTRODUCTION

Measurements may be applied to many distinct purposes and demand quite particular requirements. One can invoke the so-called Advanced Product Quality Planning (APQP) concept to exemplify that scenario. As shown in Fig. 1, from product concept approval to product launching, production measurements in industries may be used for research and development purposes, and not only for production purposes.

Both measurement cases intend to provide information about product properties. Production-driven measurements require sufficient accuracy only for checking product quality, without unnecessarily inflating inspection costs. They need to be quick and simple to not create production bottlenecks and to not claim for highly skilled operators. R&D-driven measurements are usually more complex and hence time-consuming, and their performance needs to be known and optimized to minimize measurement error impact on product characterization and specifications.

Since measurements may be interpreted as a sequence of interrelated processes as well, by analogy with the product development lifecycle, the expression measurement process realization could be employed to reference them. Within the measurement process realization cycle the following macro-activities may be defined: (a) measurement planning, which

embodies strategic operations that may guide measurement equipment definition, installation needs, and measuring plan preparation, and that should give rise to a potential solution capable of satisfying specific metrological and operational requirements; (b) measurement execution, which involves the measurement *per se* of prototypes, first articles, and production parts, and may induce measurement process changes in order to correct errors observed in preliminary phases of the measurement process realization.



**Fig. 1. APQP timing chart together with measurement requirements and purposes**

One can reasonably infer that technical, metrological and economical decisions may be better driven and taken as long as a statement about the measurement quality is available to the user. Despite the availability of techniques for evaluating uncertainties, e.g., sensitivity analysis, computer simulation, and experimental method; uncertainty has been barely used (i.e., evaluated and stated) by the industrial metrologist. This is particularly true for the field of coordinate metrology. In this work a concept which merges the uncertainty concept with the process of product and measurement realization is proposed, and the use of classical uncertainty budgets within that concept is outlined and discussed.

## 2. MERGING CONCEPT

### 2.1. Background

In order to provide a useful uncertainty solution to the industrial metrologist at least the following conceptual dimensions need to be weighed: *purpose* of the uncertainty evaluation, *criticalness* of the measurement application, and *singularity* of the measurement case. The first relates to the

product, feature or characteristic intrinsic value and the measurement process relative capability; the second, to the phase of the measurement process realization cycle; and the third, to the phase of the product realization cycle.

Fig. 2 depicts the reasoning described and suggests that the accuracy of a given measuring uncertainty estimate, i.e., how close the estimated uncertainty is from the hypothetical true uncertainty value (true uncertainty is defined in ISO/TS 14253-2 [1], item 3.7), be evaluated considering the decision factors aforementioned. It is worth mentioning that similar reasoning may be observed in subclause 7.2.2 of ISO 10012 [2] under the following terms: "... the effort devoted to determining and recording uncertainties of measurements should be commensurate with the importance of the measurement results to the quality of the product ...", and in the Guide to the Expression of Uncertainty in Measurement, GUM [3], subclause 3.4.1: "... a measurement can be modelled mathematically to the degree imposed by the required accuracy of the measurement."

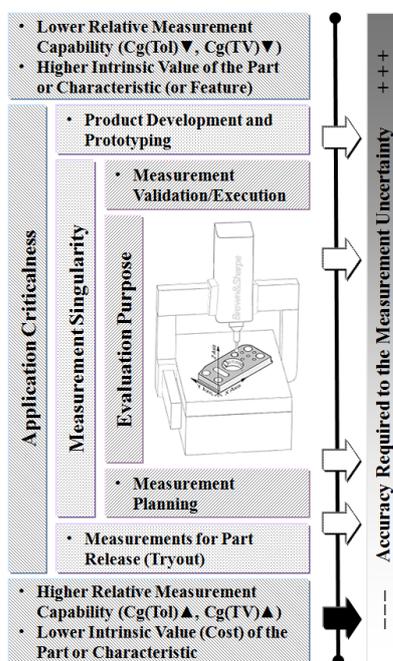


Fig. 2. Accuracy required to the uncertainty estimation as a function of the following dimensions: application criticalness, measurement singularity, and evaluation purpose

Based on Fig. 2 one can infer that the accuracy expected to the uncertainty estimate in the measurement planning phase would be lower, since only generic data would be likely available, that for a barely capable measuring process the uncertainty estimate should be more accurate, and so on. That means the most suitable approach to evaluating the measurement uncertainty for a particular measuring scenario would not be necessarily a one-size-fits-all approach. Hence it is possible to consider the use of a generic measurement mathematical modeling, or a sufficiently specific modeling, or even a specific experimental approach.

## 2.2. Uncertainty evaluation method

In order to assess the measurement uncertainty and thus provide traceability to the result of measurements performed

on coordinate measuring machines, the following methods have been identified: (a) sensitivity analysis, the classical GUM analytical method, as described in reports of Salsbury [4] and Hernla [5-6] for coordinate measurement cases; (b) experiments using calibrated workpieces, as described in ISO/TS 15530-3 [7]; (c) Monte Carlo simulation, as described in ISO/TS 15530-4 [8]; and (d) expert judgment, in line with the GUM, subclause 4.3.2.

The scorecard shown in Fig. 3 summarizes how the first three uncertainty evaluation techniques behave against the following properties: accuracy, extensibility, adaptability, autonomy, transparency, economicity, and simplicity; each property is shortly explained in the scorecard cells.

		Sensitivity Analysis (Classical GUM)	Experimental Method (ISO/TS 15530-3)	Monte Carlo Simulation (ISO/TS 15530-4)
Property	<b>Extensibility</b> <i>to support relevant GPS characteristics and influence quantities</i>	1	3	2
	<b>Adaptability</b> <i>to use data from different sources with minimum effort</i>	3	1	1
	<b>Autonomy</b> <i>to be not dependent on dedicate software or mathematical model of the part</i>	3	2	1
	<b>Transparency</b> <i>to clearly exhibit the main contributions to the uncertainty</i>	3	1	1
	<b>Economicity</b> <i>to be a low cost solution and not time-consuming</i>	2	1	2
	<b>Simplicity</b> <i>to be intuitive, simple and straightforward to the industrial metrologist</i>	1	3	2
	<b>Accuracy</b> <i>to provide accurate and useful results for a given measuring task</i>	1	3	2
<b>Total</b>	<b>14</b>	<b>14</b>	<b>11</b>	

Fig. 3. Scorecard for measurement uncertainty evaluation classes defined in ISO 15530 series

From the scorecard one may infer the law of propagation of uncertainty and the use of calibrated parts are potentially suitable for the concept here proposed. In Fig. 4 the merging concept as a whole is illustrated. To put it into practice the industrial metrologist is initially responsible for defining the application criticalness, the measurement task singularity and the uncertainty assessment purpose. The output is to be the uncertainty evaluation technique capable of delivering the required level of accuracy.

For the classical uncertainty budgets one can define some levels of knowledge which would demand particular information and effort, such as: (a) elementary level, which may be suitable for preliminary analysis of the measurement process (equipment selection, measuring strategy definition) and require data such as the maximum permissible error for length measurements and for probe indexing stated by the manufacturer as per ISO 10360 series, besides compliance

of the temperature limits for regular operation of the CMM; (b) secondary level, which may be able to produce more accurate uncertainty estimates and demand knowing scale and squareness errors of the machine, task-specific probing repeatability and reproducibility (including the effect of part form deviation), scale and workpiece temperature.

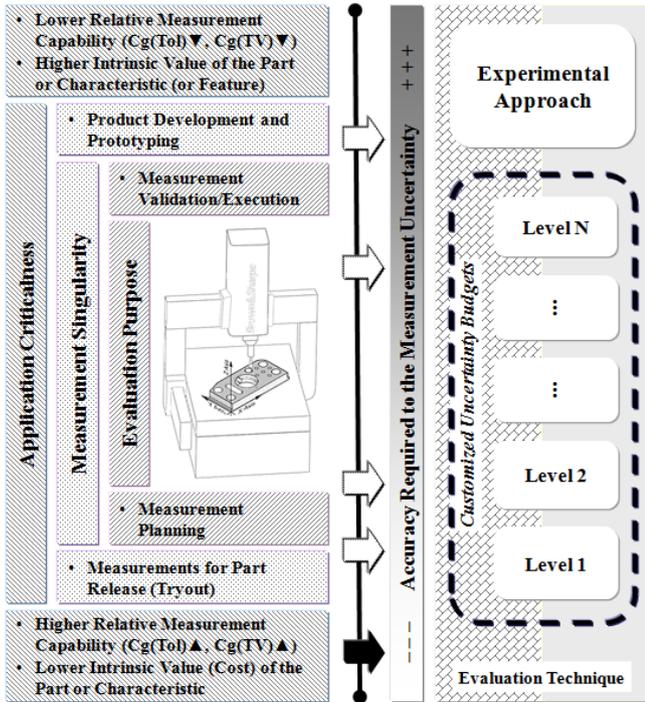


Fig. 4. Complete concept proposed from the measurement scenario (left portion) to the evaluation technique (right portion)

To be effective, however, weaknesses of both methods need to be treated. In this paper only the sensitivity analysis method is considered. Comments about the use of calibrated parts to evaluate uncertainties of coordinate measurements might be found in two former papers of the authors [9-10].

### 3. APPLICATION CASE

Whichever the method chosen to assess and express the measurement uncertainty, the definition of the measurand and the realization of the definition of the measurand have to be included. In the case of GPS characteristics the first task is in charge of the product designer, described in the product technical documentation, and the second is in charge of the industrial metrologist, described in a verification plan, as defined in ISO/TS 17450-1 [11].

#### 3.1. Scope

The uncertainty budgets described here take into account the implementation uncertainty only; the method uncertainty needs to be separately addressed if the method employed by the industrial metrologist differs from the reference method.

The uncertainty budgets directly apply to measurements of dimensional and geometrical characteristics of prismatic parts on bridge-type CMMs operating in the point-to-point probing mode without auxiliary resources like rotary table. As form, profile and run-out tolerances ideally require many

measuring points, i.e., prohibitive cost without scanning; the uncertainty budgets described here are more appropriate for location and orientation tolerances.

#### 3.2. Boundary conditions

The following boundary conditions shall be observed when drawing up the uncertainty budgets:

- uniform distribution of the points over the measured feature;
- least squares method for fitting the measured points to ideal features;
- form deviations and pure random probing effects treated separately;
- straightness and rotation errors insignificant over scale and squareness errors [12-13];
- insignificant systematic probing effect when properly qualifying probe styli;
- qualification sphere vertically positioned closely to workpiece feature height;
- good metrology practices observed (e.g., proper part cleanliness, thermal equilibrium, clamping);
- measuring and evaluation software uncertainty negligible.

#### 3.3. Example

The uncertainty evaluation related to the position of a line with respect to a reference system as shown in Fig. 5 is discussed. The axis of the cylinder (i.e. the extracted median line) shall be within a cylindrical zone of diameter  $t = 2$  mm, whose axis is fixed by theoretically exact dimensions  $|ted_2| = |ted_3| = 85$  mm.

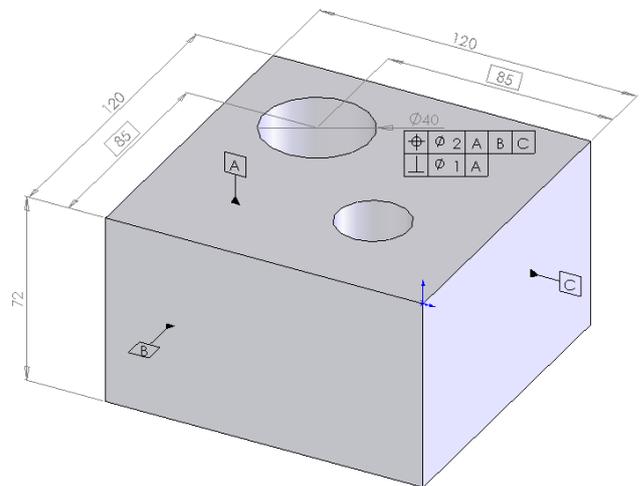


Fig. 5. Drawing of the workpiece used in the experiments with the GPS characteristics

The verification plan following ISO/TS 17450-1 rules on a CMM shall apply the following operations for the axis of the cylinder: (a) extraction of a finite number of points from the non-ideal cylindrical surface (circular cross sections), (b) association of ideal features of type circle to each circular cross section, (c) collection of all centers of the ideal circles; and for the datum surfaces: (a) extraction of a finite number of point from the non-ideal plane surface, (b) association of an ideal feature of type plane.

The axis of the specified tolerance zone is obtained by constructing an ideal feature (straight line), perpendicular to datum plane A, at a distance  $|ted_3| = 85$  mm datum plane B, and at a distance  $|ted_2| = 85$  mm from plane C. The location tolerance evaluation comprises determining the maximum of the distances between each point of the collected feature and the constructed straight line; this maximum shall be less than or equal to  $t/2$ .

Due to the operations involved in the location tolerance evaluation the following macro uncertainty components may be identified: (a) uncertainty related to the definition of the cylindrical zone position; (b) uncertainty related to each cross-section center position. The most relevant influence factors for this case are the scale and squareness machine errors, random probing effects and feature form deviations.

For drawing-up the uncertainty two levels of information are considered here: (level 1) elementary knowledge coming from machine specification figures as per ISO 10360-2 [14], reference workpiece system created using 3-2-1 alignment strategy, each cylinder cross section measured with 30 points, and local form deviation less than  $0.5 \mu\text{m}$ ; (level 2) intermediate knowledge coming from evaluations of CMM squareness and scale errors using 1D artifacts, probing repeatability by hitting 1D and 2D artifacts, and form error interaction with sampling strategy.

#### 4. RESULTS AND DISCUSSION

The drawing-up of customized uncertainty budgets for the application case described in Section 3 produced results compatible with the quality of information used, investment and effort. Table 1 shows the uncertainty values of the two macro-components and of their respective subcomponents. The reference uncertainty calculated in conformance with ISO 15530-3 is also provided.

**Table 1. Final measurement uncertainty budget for the positional tolerance illustrated in Fig. 5**

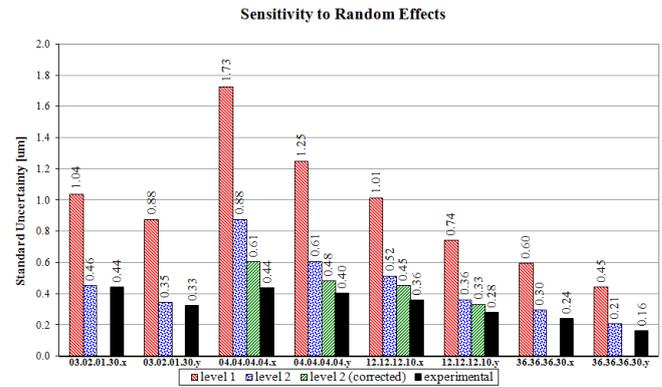
Uncertainty Component	Standard Uncertainty			
	Level 1		Level 2	
	x	y	x	Y
<i>Position of the Nominal Axis</i>	1.54	1.44	0.45	0.33
systematic geometry errors	---	---	0.10	0.04
residual geometry errors	1.16	1.16	0.12	0.06
probing errors	1.01	0.85	0.44	0.32
primary datum slope	0.61	0.61	0.08	0.08
datum system origin	1.11	0.58	0.59	0.31
secondary datum slope	0.82	0.82	0.44	0.44
centroid alignment	0.75	0.53	0.40	0.28
<i>Position of the Circle Centers</i>	0.24	0.24	0.13	0.13
form deviations	0.14	0.14	---	---
sampling plan	0.19	0.19	---	---
<b>Systematic Uncertainty</b>	<b>1.16</b>	<b>1.16</b>	<b>0.12</b>	<b>0.06</b>
<b>Random Uncertainty</b>	<b>1.04</b>	<b>0.88</b>	<b>0.46</b>	<b>0.35</b>
<b>Non-Corrected Error</b>	---	---	<b>0.10</b>	<b>0.04</b>
<b>Standard Uncertainty</b>	<b>1.56</b>	<b>1.46</b>	<b>0.47</b>	<b>0.35</b>
<b>Expanded Uncertainty (k = 2)</b>	<b>3.12</b>	<b>2.91</b>	<b>1.04</b>	<b>0.74</b>
<b>Reference Uncertainty (as per ISO/TS 15530-3)</b>				
systematic deviation	b		0.08	0.47
standard calibration uncertainty	$u_{cal}$		1.02	0.88
standard procedure uncertainty	$u_p$		0.44	0.33

In table 1, the term systematic uncertainty is a short for uncertainty due to systematic effects (e.g., machine-related geometry errors), and the term random uncertainty is a short for uncertainty due to random effects (e.g., probing errors).

The parametric equations employed in this case study are not presented or discussed here, but only their final results. Please refer to Baldo [15] for a comprehensive description of the parametric equations. One can observe an increasing agreement with reference values as the quality of data improves. That may be clearly checked for random effects, but not for systematic effects, as the workpiece calibration uncertainty is the dominant factor.

#### 4.1. Sensitivity to random effects

The graph shown in Fig. 6 illustrates how the uncertainty budget answers to probe random effects. The notation is as follows: AA.BB.CC.EE.i, where AA is the number of points taken in the primary datum, BB in the secondary datum, CC in the tertiary datum, EE in the tolerated element, and i is the coordinate in the workpiece coordinate system (x or y).



**Fig. 6. Uncertainty budget sensitivity to random effects coming from sampling strategy**

Independent of the probing strategy chosen one can observe an overestimation in the elementary level due to the conservative nature of machine specifications. One can also observe that the agreement with the reference experimental values increases as the accuracy of the uncertainty estimates improves.

#### 4.2. Sensitivity to systematic effects

In order to investigate the effectiveness of the proposed method for systematic effects stemming from machine geometry errors, not directly feasible due to workpiece calibration uncertainty, one has decided to perform measurements of the workpiece in different orientations relative to the machine coordinate system. Doing so, machine errors could be distinctly excited and thus providing information on the method accuracy.

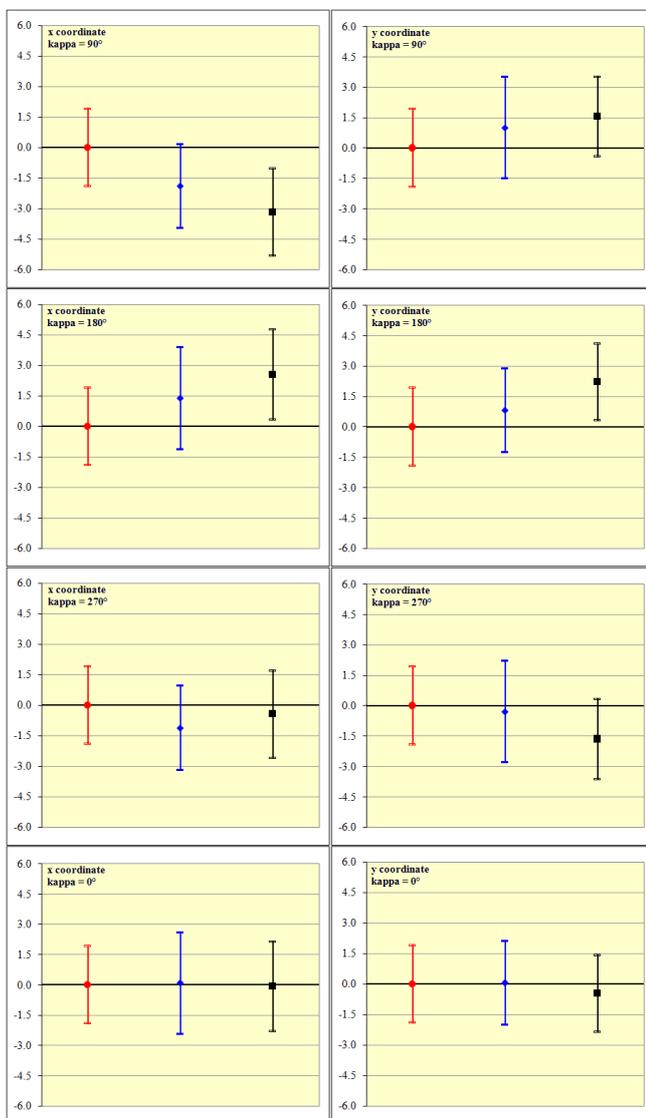
The best estimate and the respective uncertainty for each part orientation (kappa angle) and level of knowledge are depicted in Fig. 7. The experimental bias is identified by a black square; the uncertainty estimate for the elementary level is identified by a red circle; the uncertainty estimate for the intermediate level is identified by a blue diamond.

For the location tolerance, as defined in ISO/TS 17450-1, the circular cross-section centre location in each coordinate

(workpiece reference system) is determined. One can notice a good agreement between the results of both measurement scenarios and the reference values.

## 5. CONCLUDING REMARKS AND OUTLOOK

The merging model briefly outlined in this paper aims at promoting the evaluation and application of measurement uncertainty under different measurement circumstances. The merging concept itself is based on tenets cited in the GUM, ISO/TS 14253-2 and ISO 10012. On the other hand, the choice for uncertainty evaluation tools proposed in the classical GUM has taken into account the fulfilment of requirements relevant to a solution driven to industrial metrologist. The drawbacks of the uncertainty budgets and experimental methods have required strategies to minimize or eliminate them.



**Fig. 7. Uncertainty budget sensitivity to systematic effects resulting from machine geometry errors**

The strategies themselves have not been fully described here. However their use to simple measuring tasks (Fig. 5) and even to complex measuring tasks, which usually involve

many stylus orientations in the same measuring run, datum features other than plane; has shown good correlation against reference values obtained by experiment for random and systematic effects. For details see Baldo [15].

The transparency of the classical GUM technique is worth of noticing. Not being a black-box approach one can use the uncertainty budget table, for instance, to identify the major contributions to the measurement uncertainty and to qualify industrial metrologists and users in training programs for coordinate metrology.

Even though the domain of application of the uncertainty budgets has been conveniently adjusted to the purpose of the current discussion, it is quite possible with little additional effort to extend the concept to profile tolerances used for checking location and circular run-out in the axial direction. Future developments within the merging concept here described could be focused on increasing uncertainty budget capability in order to account for effects of contact scanning on measurements and for effects of performing a measuring task using multisensory capability (multisensory coordinate metrology).

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