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The measurand in ISO GPS verification

R. Frizza[a], A. Balsamo (1)[b,*]

[a] *University of Bergamo and MG spa, Travagliato (Brescia), Italy*
[b] *INRIM – National Institute of Research in Metrology, Torino, Italy*

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ABSTRACT

A clear definition of the measurand is an essential precondition for measuring. When verifying conformity to ISO GPS tolerances (verification), the measurand is often unclear, particularly for geometrical tolerances. The tolerance zone is a portion of space whereas the measurand is a scalar quantity, and many such quantities may be derived from the same portion of space. We propose a unified derivation of the measurand in ISO GPS verification matching the designer's intent. Different types of tolerances are considered, from the easiest to the least obvious as to the derivation of the measurand.

1. Introduction

The VIM defines the term *measurand* as 'quantity *intended* to be measured' [1, § 2.3]. The term has a Latin root (*mensurandum*, to be measured) much in line with this definition. In its essence, the measurand indicates the measurement goal and defining the measurand is self-discipline that protects from wasting the measurement effort for lack of cognizance. When the measurand is not defined precisely, additional uncertainty is incurred, named *definitional uncertainty* in VIM [1, § 2.27] and *intrinsic uncertainty* in GUM [2, § D.3.4]. This contributor is not of experimental nature and cannot be reduced but by a better definition. A similar concept in ISO GPS (*Geometrical Product Specifications*) is named *ambiguity of specification* [3, § 3.3.2]; it is similar but not identical because it applies to *specifications* rather than to *measurands*.

In principle, any measurand should be defined with no ambiguity: when more than a quantity falls within the same definition of the measurand, then their range of values introduces definitional uncertainty. In practice, the measurand definition should introduce negligible definitional uncertainty.

The point here is that any measurement performed without a prior clear measurand definition is incognizant, with poor return of the effort and subject to avoidable uncertainty. This paper investigates the measurand in ISO GPS and proposes a derivation from tolerances.

2. Measurands vs tolerances

ISO GPS is a complex system of standards consisting of *specification* – when parts are designed – and *verification* – when they are inspected. It sets a common language to designers, production engineers and metrologists. ISO 8015 defines the *duality principle* [4, § 5.10] to keep the *specification operator* [3, § 3.2.3] and the *verification operator* [3, § 3.2.9] independent to each other, the latter mirroring the former. The specification operator allows defining a toleranced characteristic or feature by means of a sequence of sophisticated *specification operations* [3, § 3.1.1]. The verification operator is the sequence of metrological operations to verify conformity to the tolerance. The derivation of the verification operator – akin to the measurand – from the specification operator is summarised in ISO 17450-1 [5, § 5 and Fig. 10] with "*The metrologist . . . (reads) . . . the specification, . . ., in order to know the specified characteristics.*". This neat specification/verification duality hides the complexity of deriving the measurand and leaves the metrologist on his own.

ISO 1101 [6] defines the geometrical tolerances, widespread in ISO GPS. ISO 1101 is based on the concept of *tolerance zone* [6, § 3.1], which is a portion of 2D or 3D space. This is perfectly adequate for *specifying* but is not for *verifying*. Inspections are based on measurements, which require measurands, which are scalar quantities. Portions of space are geometrical entities instead. Different quantities may be derived from a same portion of space, each providing a different information. ISO 17450-1 leaves this to the metrologist in the assumption that it is unambiguous if not trivial, but it is not.

In the authors' opinion, the derivation of the measurand in verification is largely overlooked – particularly for geometrical tolerances – both in ISO GPS and in scientific literature. Srinivasan overviews the ISO GPS foundations and recognises that uncertainty arises 'by poor or intentionally different interpretation of the specifications' [7]. Scott addresses the definition of an ISO GPS measurand explicitly [8] but it is a surface texture parameter rather than derived from a geometric tolerance. Humienny and Zdrojewski title their paper 'ISO GPS and ASME GD&T standards – differences and similarities in definitions of measurands' [9] but in fact they address the interpretation of the tolerances. Uncertainty evaluation is a subject matter where a clear definition of the measurand is essential. Morse et al. cover the uncertainty from a specification perspective [10]. In coordinate metrology [11], the focus is on solving complicated uncertainty issues – sometimes resorting to dedicated methods [12] – rather than on deriving the measurand. In form measurement (e.g. straightness [13], flatness [14], roundness [15], cylindricity [16]) the

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* Corresponding author.
E-mail address: a.balsamo@inrim.it (A. Balsamo).

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Table 1
ISO GPS tolerances classified according to the derivation of measurands in verification.

	Specification by dimension	Specification by zone	
Tolerance definition	Range of permissible values of an intrinsic or situation characteristic (the dimension)	Portion of space encompassing the toleranced feature	
Tolerance nature	Scalar quantity	Geometrical entity	
Derivation of the measurand	The measurand is the deviation of the toleranced characteristic from its nominal value	**Tolerances of form but line and surface profiles** Guidance given in specific standards	**Other geometrical tolerances** No guidance given in ISO GPS

measurand is detailed by dedicated ISO GPS standard and not an issue. Maltauro and Morse address the duality principle to highlight the importance of “Geometric Verification Specifications” [17]. ASME GD&T is more advanced than ISO GPS on this subject and defines the “*actual value*” for many tolerances [18 § 1.5.1], akin to the measurand definition.

This paper proposes a unified derivation of the measurand in ISO GPS verification.

3. Derivation of measurands from ISO GPS tolerances

ISO GPS tolerances are diverse and so is the complexity of deriving measurands in verification (Table 1). A common feature is that the magnitude of the tolerance – the tolerance value – is a quantity value either of length or of angle (when two values are indicated, e.g. ±0.05, they jointly define the tolerance). This is deemed as revealing the designer’s intent and the quantity of the tolerance value is taken as the measurand. The measurand is null when the actual and nominal characteristic or feature coincide, and takes the tolerance value when the actual characteristic or feature is the most permissibly deviated from the nominal. The measurand is then the *geometrical and/or dimensional deviation from the nominal*. This definition enables verifying conformity to specifications: the measured value is to be compared with the tolerance limit(s) [19], which requires that they are all values of the same quantity. Normalising the measurand by the tolerance results in the same information expressed as a percentage. Conformity is verified when the measurand is not >100 % of the tolerance (minus the percentage due to the measurement uncertainty). A perfect part would result in a measurand of 0 % of the tolerance. Intermediate values indicate how good the part is relative to the tolerance. Note that conformity or nonconformity can be verified by hard-gauging too: the added value of measuring is the disclosure of the actual deviation in addition to the mere go/no-go.

The following sections deal with classes of tolerances, from the most direct and simplest in deriving the measurands to the most complex and least obvious.

4. Specification by dimension

Specifications fall in two categories according to ISO 14750-1*: by dimension* and *by zone*. The former “*… limits the permissible value of an intrinsic characteristic or of a situation characteristic between ideal features*” [5, § 3.6.1].

4.1. Tolerances of size

Specifications (tolerances) of size are the most conventional in technical drawings. Their use with features not of size possibly leads to ambiguities and is deprecated. Indications such as (Ø 10 ± 0.05) regulate the size (10) of a feature of size (a diameter Ø). The tolerance is defined as an interval (±0.05) within which the size shall lie. The measurand in size verification is simply the deviation of the toleranced size from its nominal value. Sophisticated definitions of toleranced sizes are given in [20]; the deviation of that size from the nominal value is the measurand, whichever the defined size.

4.2. Tolerances in micro-geometry

A class of specifications by dimension not included in [20] is about micro-geometry, either profile method [21] or areal [22]. Similarly to size, the measurand in verification is the toleranced parameter, in spite of the sophistication allowed in its definition.

A difference between size and micro-geometry tolerances is that the toleranced characteristics are nominally null for the latter and greater than zero for the former. The ultimate intent of the verification is to measure the *deviation from the nominal*. With that, size and micro-geometrical tolerances are no different in the derivation of the measurand.

5. Specification by zone

Specification by zone “*… limits the permissible variation of an non-ideal feature inside a space limited by an ideal feature or by ideal features*” [5, § 3.6.2]. It is the case of geometrical tolerancing, regulated in ISO 1101 [6].

5.1. Tolerances of form

Most tolerances of form are elaborated on in specific standards for cylindricity [23], roundness [24], straightness [25] and flatness [26]. These series of standards follow a consistent approach and specifically define the *local deviation* (Part 1, § 3.2.3) as the signed minimum distance of any point of the toleranced feature to the reference feature. A range of options are offered for the definition of the reference feature (least-squares, minimum circumscribed, etc.) and for the global statistics of the local deviations (peak-to-valley, root-mean-square, etc.); standardised codes are provided (e.g. LSCI for least-square reference circle, RONt for peak-to-valley roundness deviation). ISO 1101 implicitly assumes the minimum-zone and peak-to-valley options with no reference to the relevant detailing standards. They seem intended more for measuring – as in calibration – than for tolerancing. They make the derivation of the measurand in verification straightforward: the measurand is the given statistic of the local deviations from the given reference feature (e.g., RONt given LSCI).

Line and surface profile tolerances can also be tolerances of form [6, Table 2] but enjoy no specific definition of local deviation in ISO GPS. They are addressed later on in this paper.

5.2. Other tolerances by zone

This is the case of the tolerances of orientation, location and run out, and of line and surface profile. It is the case when the derivation of the measurand in verification is least intuitive and furthest from any given definition. We show that the proposed approach stands in this case too.

ISO 1101 gives the details of how to form the tolerance zones [6, § 7]. They may or may not be subject to orientation and/or location constraints to a datum system. The quantity subject to the tolerance value is the width of the tolerance zone, which we take as the measurand in verification. Note that the value of such width for a nominal feature is null, so the quantity itself coincides with its deviation from the nominal. Let us define *gauging zone* a portion of space identical to the tolerance zone but for its width, subject to the same constraints to a datum system, if any. Then the measurand is the minimum width of the gauging zone that encompasses the toleranced feature.

The derivation of the measurand in verification can be visualised as an inflation. At beginning, the gauging zone has null width and coincides with the nominal feature. Then it inflates and progressively incorporates the toleranced feature. When the gauging zone encompasses it all, the inflation stops and the gauging zone width is taken as the measurand (Fig. 1).

This definition of the measurand in verification enjoys a special interpretation for profile and surface tolerances. ISO 1101 [6] defines the tolerance zone in this case as the portion of space between two lines or surfaces enveloping (all) circles or spheres, respectively, whose diameter is the tolerance value and whose centres lay on the reference feature (usually but not necessarily coincident with the TEF, *Theoretical Exact Feature* [6, § 3.8]). The tolerance may be of form, orientation or location depending on possible constrains to a datum system. ISO 1660 [27] elaborates on profile and surface tolerances. Whatever the constraints to datum systems and the definitional subtleties of the tolerance zone introduced in ISO 1660, the proposed definition of the measurand is nicely equivalent to the diameter of the smallest *gauging sphere*. This is the sphere whose centre is constrained to lay on the reference feature and that generates the gauging zone by sliding along the reference feature (Fig. 2).

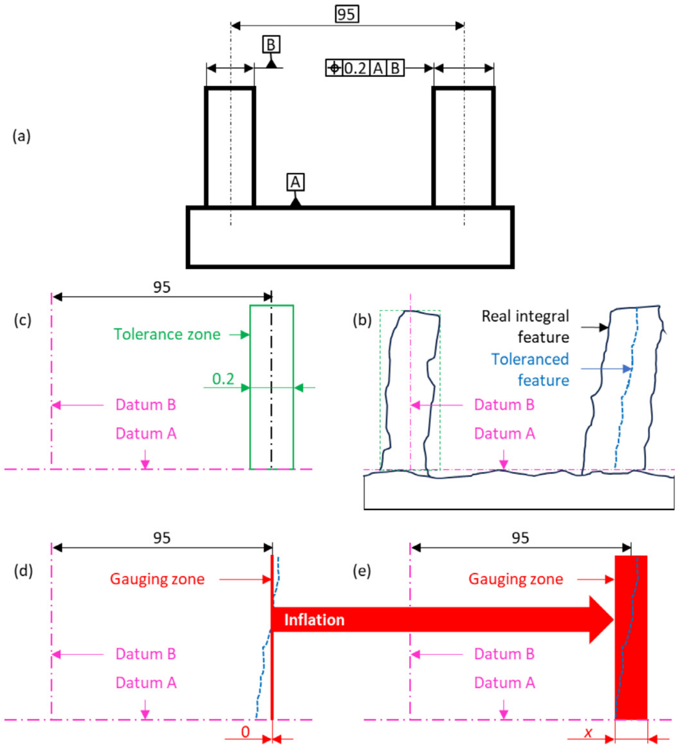

Fig. 1. Example of derivation of the measurand in verification. (a) drawing; (b) features essential for interpretation; (c) tolerance zone; (d) starting gauging zone with null width; (e) final gauging zone, whose width is the measurand *x*.

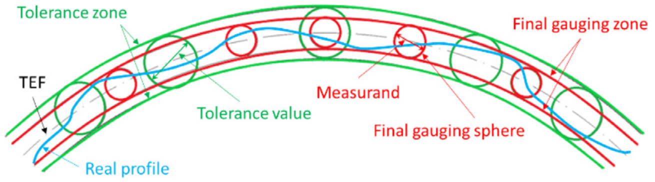

Fig. 2. Interpretation of a profile tolerance and derivation of the measurand in verification.

5.3. Special cases of geometrical tolerances

Three cases are met in ISO GPS that require special attention in the derivation of the measurand in verification: the multiple and the pattern specification and the tolerance zones with variable width.

Multiple tolerancing occurs when a same feature is subject to multiple tolerances, resulting in stacked tolerance indicators. For the independency principle [4, § 5.5], they must be taken separately. This leads to as many measurands as tolerances, and the proposed derivation apply to each independently.

The tolerancing of patterns of features is regulated in ISO 5458 [28]. Tolerance zone patterns are subject to *internal constraints* [28, § 3.9] and *external constraints* [28, § 3.10]. The former hold between the individual tolerance zones of the pattern, the latter between a tolerance zone or a tolerance zone pattern and a datum system. The external constraints embed a priority: the datum system is established first and the tolerance zone(s) follows. The internal constraints are simultaneous: all the features in the pattern contribute to the definition of the tolerance zone pattern 'without priority between them' [28, § 3.3]. The internal constraints impose no orientation or location constraint on the tolerance zone pattern [28, § 3.5], which is free to float. External constraints, if any, limit the floating in one or more degrees of freedom. The part complies with specifications if a location and orientation exists of the tolerance zone pattern that encompasses the toleranced feature pattern. The proposed derivation of the measurand is tolerant to this floating. The gauging zone evolves to the gauging zone pattern.

By definition, the gauging zone pattern follows the tolerance zone pattern. The gauging zone pattern is initially null and coincides with the TEF pattern. Then it inflates, free to float in the allowed degrees of freedom. At the end, all features in the toleranced pattern are encompassed. The final location and/or orientation of the gauging zone pattern are the result of the optimisation effectively occurred over the unconstrained degrees of freedom. Note that the location and/or orientation of the found solution is not relevant for conformity assessment, as the part is accepted if a solution exists no matter which (taking account of the uncertainty). This can be achieved by hard gauging with the gauge floating along the unconstrained degrees of freedom. On the contrary, the measurement of the proposed measurand yields an identified and optimised solution of minimum value to compare with the tolerance value. We have no proof that this minimum solution is unique, but the inflation process suggests that either it is or a limited set of equally valued solutions exists, resulting in a single measured value of the measurand and just as many locations and/or orientations of the gauging zone pattern.

The case of pattern specification highlights the issue of optimisation, which occurs elsewhere too. Whenever a tolerance zone is not fully constrained to the datum system – or is not constrained at all as in form tolerances – then the tolerance zone is free to float and so is the gauging zone. Optimisation for measuring form errors is very customary and dealt with in dedicated standards (cylindricity [23], roundness [24], straightness [25], flatness [26]).

Tolerance zones with variable width are addressed in ISO 1101 [6, clauses 7.2 and 8.2.2.1.1] and in ISO 1660 [27, § 5.3.5]. ISO 1101 covers only the case of variations linear to the curvilinear distance over the profile, but does not excludes other cases '*indicated by other means*'. The gauging zone follows the tolerance zone and inherits its variability (Fig. 3). The gauging zone width follows the same (usually linear) variation function of the tolerance zone width, multiplied by an *inflation factor*. This is initially null and generates a null gauging zone coincident with the nominal feature. The inflation occurs by increasing the factor, until the gauging zone encompasses the toleranced feature. The final inflation factor is the fraction of the tolerance zone taken by the toleranced feature and compliance is verified if it is less than one (minus the contribution of the uncertainty). In spite of being the natural result of the measurement, it is dimensionless whereas the result of the measurement is expected with the

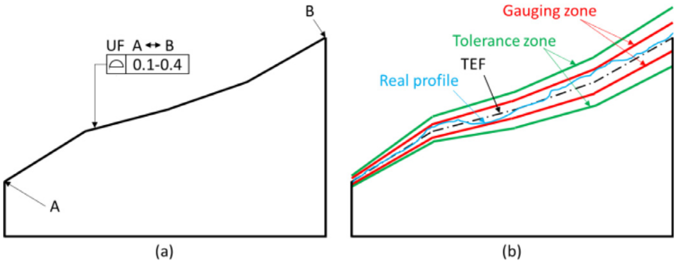

Fig. 3. Example of variable-width tolerance zone: (a) drawing; (b) interpretation. By default, the variation function is linear in the range (0.1-0.4) mm.

dimension of a length. This situation stems from a non-unique tolerance value, a function in fact. How can a single measurement result compare? A possible solution is a conventional statistics of the variation function, such as the maximum or mean value, to serve as the tolerance value to compare with. The measured inflating factor is then multiplied by the same statistics and compared. ISO GPS provisions should be added to standardise this conventional statistic.

6. Conclusions

ISO GPS charges the derivation of the measurand in verification from the specifications (tolerances) to the metrologist and gives it for granted. It covers the case when the metrologist adopts an *actual verification operator* [3, § 3.2.12] that differs from the *perfect verification operator* [3, § 3.2.10], resulting in *method uncertainty* [3, § 3.3.4]. There is very little provision instead in ISO GPS and in scientific literature for deriving the measurand for the *perfect* verification operator, in spite that a clear definition of the measurand is an essential precondition for any measurement. This is particularly severe in case of *specifications by zone* [5, § 3.6.2]. The tolerance zones are portions of space whereas measurands are scalar quantities and the derivation is but obvious. It is much easier for *specifications by dimension* [5, § 3.6.1] as a characteristic rather than a feature is toleranced, which is a scalar quantity. Most form tolerances are elaborated on in dedicated series of standards. They help metrologists by defining the local deviation and a standardised statistic of all local deviations of a feature. This statistic is a scalar quantity, obviously the measurand in verification. There is very little provision for all other geometrical tolerances. ISO 17450-1 [5, § 9.4] devotes two lines to the *deviation* in specifications by zone, without a formal definition. The authors think that this concept of deviation is extremely powerful for the derivation of the measurand in verification and the proposed approach is fully in line. Unfortunately, the description given in ISO 17450-1 is far too little elaborated on to be an operative tool for metrologists.

The concepts of ‘actual value’ [§ 1.5.1] and ‘actual zone’ [§ 8.3.1] in ASME Y14.5.1 [18] are very similar to those we propose of measurand and gauging zone. However, there is no explicit measurement intent in [18], the actual value is a quantity value whereas the measurand is a quantity and the actual zone applies to profile tolerances only. Among the several tolerance cases considered, some have no actual value defined [18 § 7.4.1, 7.5.1, 7.6] or have two at the same time [18 § 7.4.2]. When some degrees of freedom are not constrained by the datum system, different actual values can be derived [18 § 7.4.2] leading to ambiguity in the measurand. Only for profile tolerances an optimization concept is introduced to reduce the ambiguity to a single value.

It is proposed that the measurand in verification is the *maximum geometrical and/or dimensional deviation from the nominal*. This is applied to the different tolerance types as follows:

- for specifications by dimension (size tolerances and surface texture parameters), the measurand in verification is the deviation of the toleranced characteristic from its nominal;
- for form errors but profile and surface tolerances, it is the agreed statistics of the local deviations defined in [23–26];
- for the other specifications by zone (geometric tolerances), it is the minimum width of the *gauging zone*, defined as a portion of space identical to the tolerance zone but for its width, subject to the same (external) constraints to the datum system and to the same internal constraints in tolerance patterns, if any.

The concept of gauging zone is complemented with the conceptual image of inflation: the gauging zone is initially of null width and progressively inflates to encompass the whole toleranced feature. It was shown in the paper that this derivation of the measurand can be interpreted as the diameter of the smallest *gauging sphere* for profile and surface tolerances.

For tolerances with variable width, the *inflation factor* is introduced: the inflation occurs by multiplying the (usually linear) variation function along the tolerance by an increasing inflation factor. To convert the inflation factor resulting from the measurement to a length quantity – as expected for the measurand – it is multiplied by a conventional statistic of the variation function (e.g. the maximum or the mean), which should be standardised in ISO GPS. Note that the inflation factor approach is rather a generalisation of than an exception to the general concept of inflation: for fixed-width tolerance zones, the variation function is simply constant and all possible (unbiased) statistics result in the constant, releasing from agreeing on a conventional one.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

R. Frizza: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **A. Balsamo:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing.

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