GNSS CORS Calibration and Testing

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SUMMARY

Global Navigation Satellite System (GNSS) has established itself as a predominant technique in modern surveying. However, today no generally accepted standard exists to establish traceability in GNSS measurements. This poses a number of statutory problems. These problems relate GNSS measurements made in Real Time Kinematic (RTK) mode and Continuously Operating Reference Station (CORS) to legal obligations in survey. This paper reviews aspects of traceability in measurement and discusses points that should be considered when attempting to establish traceability in GNSS field measurements.

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1 INTRODUCTION

Surveyors are now regularly using Global Navigation Satellite Systems (GNSS) for many of their day-to-day surveys. GNSS measurements are also increasingly used in Real Time Kinematic (RTK) mode and linked with Continuous Operating References Stations (CORS). However, even though the importance of these measurements is recognized in industry and society as a whole, at present there is no unified approach to issues such as calibration and traceability in their measurements.

Legal traceability or simply traceability with GNSS is closely related to legal metrology. Legal metrology itself falls under the auspices of the International Organization of Legal Metrology (OIML). The acronym is for Organisation Internationale de Métrologie Légale. This body, 'develops model regulations, International Recommendations, which provide Members with an internationally agreed-upon basis for the establishment of national legislation on various categories of measuring instruments'.

More generally 'Legal Metrology is the entirety of the legislative, administrative and technical procedures established by, or by reference to public authorities, and implemented on their behalf in order to specify and to ensure, in a regulatory or contractual manner, the appropriate quality and credibility of measurements related to official controls, trade, health, safety and the environment'.

The OIML worked originally with the Technical Advisory Group on Metrology (TAG4) and continues today to work through the Joint Committee for Guides in Metrology (JCGM) to produce the Guide to the Expression of Uncertainty in Measurement (GUM) and its supplements. [1, 2] The JCGM consists also of the International Organization for Standardization (ISO), the Bureau International des Poids et Mesures (BIPM), the International Electrotechnical Commission (IEC), the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), and the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP) and the International Organization of Legal Metrology (OIML).

The key to traceability in GNSS measurement lies in the establishment of traceable measurements to an international standard. One of, if not the main aims of the GUM is to create an agreed upon set of rules to establish traceability in measurement. There is a strong impetus to use the GUM to establish this traceability.

This paper will discuss instrument calibration in the context of traceability and the GUM. Based on this information consideration in establishing traceability in GNSS a field measurement is discussed.

2 INSTRUMENT CALIBRATION

2.1 International System of Units/ Le Système International d'Unités (SI)

Formally, calibration links the measurements made by an instrument directly to quantities and units defined by the International System of Units/ Le Système International d'Unités (SI).

There are seven official base units defined by the SI; the unit of length (metre), the unit of mass (kilogram), the unit of time (second), the unit of electric current (ampere), the unit of thermodynamic temperature (kelvin), the unit of amount of substance (mole), and the unit of luminous intensity (candela).[3]

In addition to the seven base units, there are a number of SI derived units which are defined uniquely only in terms of SI base units. For example, the coherent SI derived unit of resistance, the ohm, symbol Ω, is uniquely defined by the relation $\Omega = m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$, which follows from the definition of the quantity electrical resistance. Another example is the unit of plane angle (radian). One radian is the angle subtended at the centre of a circle by an arc of circumference that is equal in length to the radius of the circle. There is 2π rad in a full circle. The radian is expressed in terms of the SI base unit the metre and is defined as $m \cdot m^{-1}$ (i.e. it is a dimensionless unit). (p. 118 [3])

It is important to distinguish between the definition of a unit and its realization. The definition of each base unit of the SI is carefully drawn up so that it is unique and provides a sound theoretical basis upon which the most accurate and reproducible measurements can be made. The realization of the definition of a unit is the procedure by which the definition may be used to establish the value and associated uncertainty of a quantity of the same kind as the unit.

The realization of the value of a quantity of a SI unit or derived unit is typically made by national metrology laboratories (NMLs). Examples of NMLs are; the National Physical Laboratory (NPL) in the UK, the Physikalisch-Technische Bundesanstalt (PTB) in Germany, and the National Institute of Standards and Technology (NIST) in the USA.

One of the pillars of instrument calibration is the notion of traceability. Indeed traceability is at the root of all legal metrology and measurement. Traceability is a method of ensuring that a measurement with its uncertainties is an accurate representation of what it is trying to measure. With traceability, it is possible to demonstrate an unbroken chain of comparisons that ends at a NMI and its realization of the definition of a unit.

2.2 Agreements underpinning the SI

The basis of the SI system of units is the Convention of the Metre (Convention du Mètre). The Convention of the Metre is a treaty that created the International Bureau of Weights and Measures (BIPM), an intergovernmental organization under the authority of the General Conference on Weights and Measures (CGPM) and the supervision of the International Committee for Weights and Measures (CIPM). The BIPM acts in matters of world metrology, particularly concerning the demand for measurement standards of ever increasing accuracy, range and diversity; and the need to demonstrate equivalence between national measurement standards.

The Convention was signed in Paris in 1875 by representatives of seventeen nations. As well as founding the BIPM and laying down the way in which the activities of the BIPM should be financed and managed, the Metre Convention established a permanent organizational structure for member governments to act in common accord on all matters relating to units of measurement. The Convention, modified slightly in 1921, remains the basis of international agreement on units of measurement. The BIPM now has fifty-one Member States, including all the major industrialized countries.

At a meeting held in Paris on 14 October 1999, the directors of the National Metrology Institutes (NMIs) of thirty-eight Member States of the BIPM and representatives of two international organizations signed a Mutual Recognition Arrangement (CIPM MRA) for national measurement standards and for calibration and measurement certificates issued by NMIs. The CIPM MRA has now been signed by the representatives of 74 institutes – from 45 Member States, 27 Associates of the CGPM, and 2 international organizations – and covers a further 123 institutes designated by the signatory bodies.

On the occasion of the 22nd CGPM national delegations unanimously endorsed a resolution dealing with the importance of mutual recognition of measurement standards, calibrations and tests. Resolution 6 asked the CIPM to draw up a declaration on the importance and application of its MRA for trade, commerce, and regulatory affairs. The Resolution also invited Member States of the Metre Convention to promote the CIPM MRA as a framework for the acceptance of calibration and measurement certificates from NMIs as well as from accredited laboratories which could demonstrate traceability of their measurements to the SI.

In preparing the declaration, the CIPM recognized that its MRA was complemented by similar arrangements drawn up by the Organization of Legal Metrology (OIML) and the International Laboratory Accreditation Cooperation (ILAC). Indeed all three are interlinked and all support the equivalence and acceptability of SI-traceable measurements world-wide. The aim of this international measurement system is to provide users with measurement results which can be accepted everywhere without the need for further measurements. An important feature of this system is that its use can help reduce the effects of technical barriers to trade and can provide a secure base for scientific and other measurements throughout society. [4]

Through the MRA and a common statement between BIPM, OIML and ILAC, measurements made by different NMIs and accredited laboratories are recognized between signatories. A calibration certificate issued by a COmité FRançais pour l'Accréditation (COFRAC) accredited laboratory is recognized in the UK and a calibration certificate issued by a United Kingdom Accreditation Service (UKAS) accredited laboratory is recognized in France. Similarly, referring forward to an example that will be discussed, a COFRAC calibration certificate is recognized by the Department of Standards Malaysia (DSM) and JUPEM, the Malaysian Department of Survey and Mapping.

Figure 1 provides a diagram showing schematically the interaction between the different bodies in the accreditation chain.

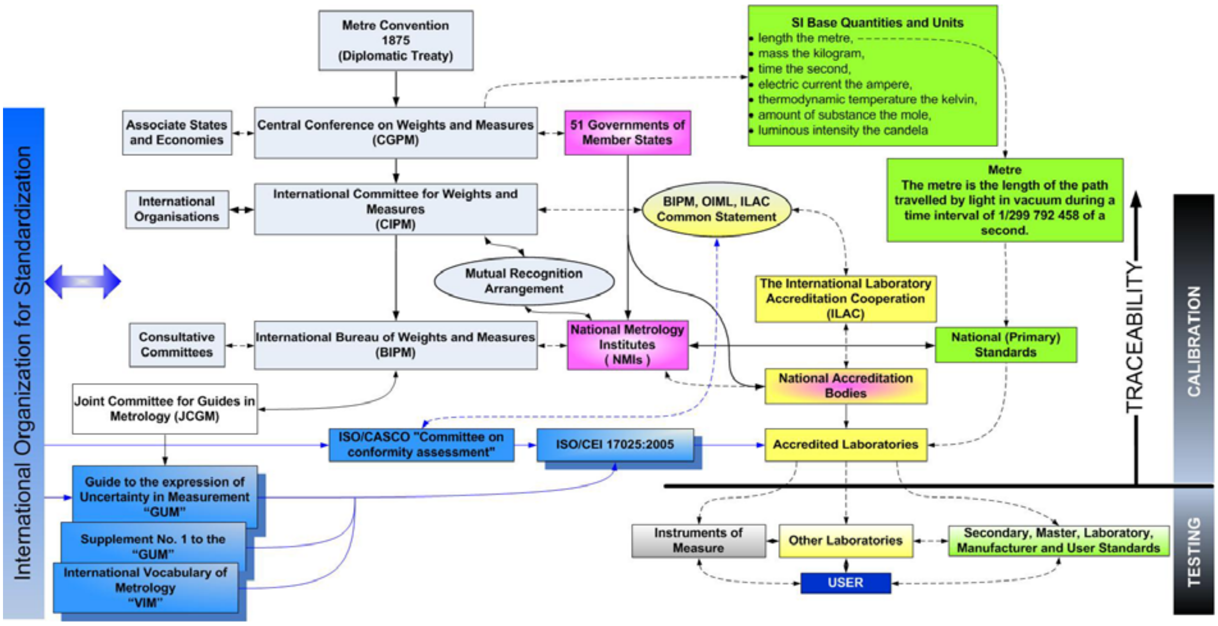

Figure 1 Schematic diagram showing the interaction between the different bodies in the accreditation chain. The main players at the national level are the national accreditation bodies (e.g. UKAS and COFRAC) and the national metrology institutes (e.g. NPL and LNE). Through the MRA and a common statement between BIPM, OIML and ILAC, measurements made by different NMIs and accredited laboratories are recognized between different signatories.

2.3 Calibration laboratories and ISO/CEI 17025

Calibration laboratories are accredited under the International Standard ISO/CEI 17025 ‘General Requirements for the Competence of Testing and Calibration Laboratories’. [5] ISO/CEI 17025 comprises two main parts. The first specifies the requirements for sound management, while the second the requirements for technical competence for the type of tests and/or calibrations the laboratory undertakes.

Calibration laboratories that comply with this international standard also operate in accordance with ISO 9001. The technical requirements of ISO/CEI 17025 concentrate on the reliability aspects of the laboratory and in particular the way in which calibrations and measurements made by the laboratory are traceable to the SI. In particular, ISO/CEI 17025 stipulates a calibration laboratory must establish traceability of its own measurement standards and measuring instruments to the SI by means of an unbroken chain of calibrations or comparisons linking them to relevant primary standards of the SI units of measurement.

The mechanics by which this traceability is actually achieved is through the statement of uncertainty. Chapter 5.4.6 of ISO/CEI 17025 stipulates: “A calibration laboratory, or a testing laboratory performing its own calibrations, shall have and shall apply a procedure to estimate the uncertainty of measurement for all calibrations and types of calibrations.” It specifically cites the GUM as a reference for the general rules used in evaluating and expressing uncertainty in measurement. [5] (pp 14-15)

2.4 Guide to the expression of uncertainty in measurement (GUM)

What is the GUM? The answer to this question is summed up in [6] which is itself largely inspired from the GUM Forward [1] : "The GUM provides general rules for evaluating and expressing uncertainty in measurement that are intended to be applicable to a wide range of measurements and for use within standardization, calibration, laboratory accreditation and measurement services. The basis of the GUM is Recommendation INC–1 (1980), 'Expression of experimental uncertainties' of the Working Group on the Statement of Uncertainties, convened in 1980 by the Bureau International des Poids et Mesures (BIPM) in response to a request by the Comité International des Poids et Mesures (CIPM). The CIPM approved the Recommendation in 1981, and reaffirmed it in 1986. The responsibility for developing a detailed guide based on the Working Group Recommendation was given to the Technical Advisory Group on Metrology (TAG4) of the International Organization for Standardization (ISO), in which six other international organizations were represented, namely, the BIPM, the International Electrotechnical Commission (IEC), the International Federation of Clinical Chemistry and Laboratory Medicine (IFCC), the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP) and the International Organization of Legal Metrology (OIML). The resulting document was published in 1993 and reprinted with minor corrections in 1995.

In 1997 a Joint Committee for Guides in Metrology (JCGM), chaired by the Director of the BIPM, was created by the seven international organizations that had originally prepared the GUM and the 'International Vocabulary of Basic and General Terms in Metrology' (VIM) [5]. The JCGM assumed responsibility for these two documents from ISO TAG4. In 1998 a further organization joined these seven international organizations, namely, the International Laboratory Accreditation Cooperation (ILAC).

The JCGM has two Working Groups. Working Group 1, 'Expression of uncertainty in measurement', has the task of promoting the use of the GUM and preparing supplements for its broad application. Working Group 2, 'Working Group on International Vocabulary of Basic and General Terms in Metrology (VIM)', has the task of revising and promoting the use of the VIM."

The GUM is the currently accepted international consensus on the expression of uncertainty and comprises the techniques and methodology prescribed for use by the CIPM. The GUM [1], its Supplement Number 1 [2] and the VIM [7] constitute the main references used to establish the uncertainty of measurement in the rest of this chapter. Nevertheless, there are other very good comprehensive sources of information that can be used to this end. [8-11]

2.5 Guide to the expression of uncertainty in measurement (GUM)

"The uncertainty of the result of a measurement reflects the lack of exact knowledge of the value of the measurand[1]. The result of a measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and imperfect correction of the result for systematic effects." ([1] p. 7) Uncertainty of measurement defined in the GUM is a parameter associated

[1] Measurand: quantity intended to be measured (VIM).

with the result of a measurement that characterises the dispersion of values that could reasonably be attributed to the measurand. There are many possible sources of uncertainty in a measurement.

The GUM was originally published in 1993 and reprinted with minor corrections in 1995. It has been successful in providing a probabilistic based framework for uncertainty evaluation. The GUM adopts a pragmatic approach which is not overly-prescriptive. Notably the concept of Type B (refer to section 2.6) evaluations of uncertainty provides certain flexibility. When justifiable, it subscribes to alternative methods to its recommended approach.

The GUM, and its underlying philosophy have been extensively adopted across metrology. The NMIs and industry have invested heavily in developing procedures that comply with it. For this reason, the body overseeing the development of the GUM, the JCGM is keen that the GUM remains unchanged in the foreseeable future and that any clarification and extensions are published as supplements. [12]

Nevertheless, the GUM has recognized weaknesses. Its standard approach is considered weak for nonlinear models or in situations in which the distribution for the value of the output quantity is asymmetrical or otherwise differs appreciably from normality. Some view the use of degrees of freedom as an unnecessary complication. The scope of the GUM is generally restricted to models with a single output quantity. [12]

With this in mind, it has been judged timely to supplement it with a number of documents. The publications planned by JCGM/WG1 comprise: an introductory document; a document concerned with concepts and basic principles, three supplements to the GUM, and two documents concerned with the use of measurement uncertainty in the context of first conformance to specified requirements, and second the application of the method of least squares. The titles of these supplementary documents are: [2]

- An introduction to the 'Guide to the Expression of Uncertainty in Measurement' and related documents,
- Concepts and basic principles,
- Supplement 1 to the GUM: Propagation of distributions using a Monte Carlo method (published 2008),
- Supplement 2 to the GUM: Models with any number of output quantities.
- Supplement 3 to the GUM: Modelling.
- The role of measurement uncertainty in deciding conformance to specified requirements.
- Applications of the least-squares method.

At the time of writing, only the Supplement 1 to the GUM: Propagation of distributions using a Monte Carlo method (GUM1 [2]), of the above mentioned documents has been published.

The GUM and Supplement 1 to the GUM: Propagation of distributions using a Monte Carlo method (GUM1) provides two different approaches to the problem of uncertainty evaluation. The principal difference is that although the GUM is rooted in probability theory, GUM1 uses the richer information available in the probability density functions (PDFs) [13] for the values of the input quantities to a measurement model. In contrast, the GUM uses just the expectations and standard deviations of these PDFs to determine the PDF for the value of the output quantity. In other words, no approximations to the measurement model or about the PDF for the output value are made. The GUM1 approach can be used to validate the use of the GUM uncertainty framework in any particular instance. [14]

"The GUM provides a framework for assessing uncertainty based on the law of propagation of uncertainty and the characterization of the output quantity by a Gaussian distribution or a scaled and shifted *t*-distribution. Within that framework, the law of propagation of uncertainty provides a means for propagating uncertainties through the model. Specifically, it evaluates the standard uncertainty associated with an estimate of the output quantity, given;

- the best estimates of the input quantities;
- the standard uncertainties associated with these estimates, and, where appropriate,
- degrees of freedom associated with these standard uncertainties, and
- any non-zero covariances associated with pairs of these estimates.

Also within the framework, the PDF taken to characterize the output quantity is used to provide a coverage interval, for a stipulated coverage probability, for that quantity." (p. vii GUM1 [2])

A measurement comprises four elements; a value, a unity (when appropriate), a statement of uncertainty, and a coverage interval or expanded uncertainty. Both the GUM and GUM1 can provide an estimate of the output quantity (of a measurement/s), the standard uncertainty associated with this estimate and a coverage interval for that quantity corresponding to a specified coverage probability. The coverage interval is determined by multiplying the standard uncertainty by a coverage factor. Typically the coverage factor is 2; which when the Gaussian distribution applies, corresponds to a coverage interval having a level of confidence of approximately 95%.

Both the GUM and GUM1 are composed of two stages; the formulation and calculation. The formulation stage used in both approaches is unique to each application and requires the development of a model of measurement as a basis for the evaluation of uncertainty. This model can have any number of input quantities. Under the GUM and GUM1 uncertainty frameworks, this model produces a single output quantity referred to as the measurand.

Generally speaking, a measurand Y is not measured directly, but is determined from N other quantities through a functional relationship f; $Y = f\left(X_1, \cdots, X_N\right)$. An estimate of the measurand Y denoted by y is obtained from this equation using estimates $x_1, \cdots, x_N$ of the N quantities $X_1, \cdots, X_N$. The output estimate y, which is the result of the measurement is given by $y = f\left(x_1, \cdots, x_N\right)$. The approaches of the GUM and GUM1 diverge at the calculation stage.

In fact there are (at least) three methods calculation. The analytical approach is the method of choice when it can be applied. It does not introduce any approximation. However, it is applicable in relatively simple cases only. It is not used in this work. The second approach is that outlined by the GUM uncertainty framework. This approach can be regarded as an approximate analytical method. The third approach, the Monte Carlo simulation method, is the one taken by GUM1. [14]

2.6 The GUM uncertainty evaluation approach

The GUM uncertainty framework is founded on probability theory where information regarding measured quantities is characterized by probability distributions. At the time of its writing, the evaluation of uncertainty for general (linear or non-linear) models was considered too complex to form its basis. For this reason, the GUM provided a simplified approach, the so-called GUM uncertainty framework. This framework linearizes the measurement model about the best available estimates of the input quantities. Rather than working with the distributions themselves, the approach uses summarizing parameters of the distributions, namely, expectations (means), and standard deviations. The expectations and standard deviations are propagated through the linearized model. A Gaussian distribution (or a scaled and shifted *t*-distribution) is then used to characterize the output quantity Y in order to obtain a coverage interval corresponding to a stipulated coverage probability. [6] The justification for the use of the Gaussian distribution is the invocation of the well know central limit theorem.

The uncertainty of measurement generally consists of several components which the GUM approach groups into two categories according to the method used to estimate their numerical values:

- Type A: method of evaluation of uncertainty by the statistical analysis of series of observations,
- Type B: method of evaluation of uncertainty by means other than the analysis of series of observations. [1]

Broadly speaking, a Type A determination of uncertainty will be made with a series of measurements of the measurand. Typically, Type B determinations of uncertainty will incorporate uncertainties determined by manufacturer's specifications, calibration certificates, recognized handbooks or simply experience with, or general knowledge of the behaviour of materials or instruments.

Individual uncertainties whether they are Type A or Type B are combined together by applying the usual method for the combination of variances, the law of propagation of uncertainty; this is to say by the summing the variances[2]. This combined uncertainty is then expressed in terms of an expanded uncertainty which is obtained by multiplying it by a coverage factor.

The steps for the uncertainty estimation following the GUM framework are (p.12 [2]) :

- Obtain from the PDFs for the input quantities $\mathbf{X} = \left(X_1, \cdots, X_N\right)^T$ the expectations $\boldsymbol{x} = \left(x_1, \cdots, x_N\right)^T$ and the standard deviations (standard uncertainties)

[2] The standard deviation is the square root of the summed variance (squared standard deviation) contributions.

$\boldsymbol{u}(\boldsymbol{x}) = \left[u(x_1),\cdots,u(x_N)\right]^T$. Use instead the joint PDF for $\mathbf{X}$ if pairs of the X_i are not independent (in which case they have non-zero covariance);

- Set the degrees of freedom (infinite or finite) associated with each $u(x_i)$;
- For each pair i, j for which X_i and X_j are not independent, obtain from the joint PDF for X_i and X_j the covariance (mutual uncertainty) $u(x_i, x_j)$ associated with x_i and x_j;
- Form the partial derivatives of first order of $f(\mathbf{X})$ with respect to $\mathbf{X}$;
- Calculate y, the model evaluated at $\mathbf{X}$ equal to $\boldsymbol{x}$;
- Calculate the model sensitivity coefficients as the above partial derivatives evaluated at $\boldsymbol{x}$ (i.e. $\delta f / \delta x_i$);
- Calculate the standard uncertainty $u_c(y)$ by combining $\boldsymbol{u}(\boldsymbol{x})$ (i.e. $u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\delta f}{\delta x_i}\right)^2 u^2(x_i)$), the $u(x_i, x_j)$ (i.e. $u_c^2(y) = \sum_{i=1}^{N}\sum_{i=1}^{N} \frac{\delta f}{\delta x_i}\frac{\delta f}{\delta x_j} u(x_i, x_j)$) and the model sensitivity coefficients;
- Calculate ν_{eff}, the effective degrees of freedom associated with $u_c(y)$, using the Welch-Satterthwaite formula [GUM formula (G.2b)];
- Calculate the expanded uncertainty U_p, and hence a coverage interval (for a stipulated coverage probability p) for Y, regarded as a random variable, by forming the appropriate multiple of $u(y)$ through taking the probability distribution of $(Y - y)/u(y)$ as a standard Gaussian distribution ($\nu_{eff} = \infty$) or *t*-distribution ($\nu_{eff} < \infty$).

There are no conditions for the valid application of the GUM uncertainty framework for linear models. However, there are conditions, outlined in the GUM1, to its validity when applied to non-linear models. (p. 13 [2]) This is considered one of its primary weaknesses that GUM1 aims to overcome with the more comprehensive Monte Carlo simulation approach.

2.7 The GUM supplement number 1 approach

"The Monte Carlo simulation method provides a general approach to obtain an approximate numerical representation $\mathbf{G}$, say, of the distribution function $G_Y(\eta)$ for Y. The heart of the approach is repeated sampling from the PDFs for the X_i and the evaluation of the model in each case. Since $G_Y(\eta)$ encodes all the information known about Y, any property of Y such as expectation, variance and coverage intervals can be approximated using $\mathbf{G}$. The quality of these calculated results improves as the number of times the PDFs are sampled increases.

Expectations and variances (and higher moments) can be determined directly from the set of model values obtained. The determination of coverage intervals requires these model values to be ordered. If y_r, for $r = 1 \mathrm{L}\ M$, represent M model values sampled independently from a probability distribution for Y, then the expectation $E(Y)$ and variance $V(Y)$ can be approximated using the y_r. In general, the moments of Y (including $E(Y)$ and $V(Y)$) are approximated by those of the sampled model values. Let M_{y_0} denote the number of y_r that are no greater than y_0, any prescribed number. The probability $\Pr(Y \le y_0)$ is approximated by M_{y_0}/M. In this way, the y_r provide a step function (histogram-like) approximation to the distribution function $G_Y(\eta)$. Each y_r is obtained by sampling at random from each of the PDFs for the X_i and evaluating the model at the sampled values so obtained. $\mathbf{G}$, the primary output from MCM, constitutes the y_r arranged in strictly increasing order." (GUM1 p14 [2])

The steps in the Monte Carlo simulation method are outlined as (p. 14 [2]) :

- select the number M of Monte Carlo trials to be made;
- generate M vectors, by sampling from the assigned PDFs, as realizations of the (set of N) input quantities X_i;
- for each such vector, form the corresponding model value of Y, yielding M model values;
- sort these M model values into strictly increasing order, using the sorted model values to provide $\mathbf{G}$;
- use $\mathbf{G}$ to form an estimate y of Y and the standard uncertainty $u_c(y)$ associated with y;
- use $\mathbf{G}$ to form an appropriate coverage interval for Y, for a stipulated coverage probability

3 DISCUSSION

The key establishing traceability with GNSS measurements lies in somehow linking them to one of the SI base units. However, what is the measurand? This of course is of fundamental importance. If the measurand is not fully defined then its uncertainty and hence traceability cannot be established.

The GUM states that "The uncertainty of the result of a measurement reflects the lack of exact knowledge of the value of the measurand.... The result of a measurement after correction for recognized systematic effects is still only an estimate of the value of the measurand because of the uncertainty arising from random effects and from imperfect correction of the result for systematic effects.

NOTE The result of a measurement (after correction) can unknowably be very close to the value of the measurand (and hence have a negligible error) even though it may have a large uncertainty. Thus the uncertainty of the result of a measurement should not be confused with the remaining unknown error.

In practice, there are many possible sources of uncertainty in a measurement, including:

a) incomplete definition of the measurand;
b) imperfect realization of the definition of the measurand;
c) non-representative sampling — the sample measured may not represent the defined measurand;
d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect
e) measurement of environmental conditions;

f) personal bias in reading analogue instruments;
g) finite instrument resolution or discrimination threshold;
h) inexact values of measurement standards and reference materials;
i) inexact values of constants and other parameters obtained from external sources and used in the
j) data-reduction algorithm;
k) approximations and assumptions incorporated in the measurement method and procedure;
l) variations in repeated observations of the measurand under apparently identical conditions.

These sources are not necessarily independent, and some of sources a) to i) may contribute to source j). Of course, an unrecognized systematic effect cannot be taken into account in the evaluation of the uncertainty of the result of a measurement but contributes to its error." [1]

GNSS measurements are inherently complex. If one considers the full measurement chain comprising the control, the space and the user segments and all of their associated error sources, the definition of the measurand becomes difficult or even impossible. Although it may feasible to establish traceability by including all of these elements, the actual realisation would be exceedingly complicated. Developing a consensus on the definition of this measurand would be difficult. On the other, if one considers the measurand is the baseline length, the problem becomes more tractable. Length is one of the base units of the SI.

There are many valid arguments against using this level of simplicity. Before continuing, however, it must be noted that this definition of the measurand does not mean that common errors are not considered at all. Corrections to known errors must be made if they are available and it is possible to make them. Models exist to correct for ionospheric and tropospheric errors. Similarly, satellite and antenna phase centre variations (PCV) can be modelled. [15, 16] When appropriate these corrections must be incorporated into the baseline length determination.

However, these corrections are made upstream of, and not specifically as part of the actual baseline length measurement. They are not explicitly considered as part of the measurand. This approach is in fact in accordance with the GUM, which stipulates that all recognized systematic effects must be a-priori corrected for. Similarly, the coordinates used in and the results of the network calculations issued from the measurements are not considered as part of the measurand; nor are the personnel that make the measurements.

If the measurand is defined as the baseline distance, then an uncertainty calculation can be made and traceability to the metre, a base unit of measurement established. Several different ways of establishing traceability can be envisaged. However, there is an existing ISO standard, ISO 17123 part 8,[17] that could be used for this purpose. The advantage of using the standard to provide basic guidlines upon which to build traceability in GNSS measurement is that it exists and as such has achieved consensus by a large number of concerned parties.

The implementation of ISO 17123 is discussed in [18]. Specifically the standard stipulates "The test field consists of a base point and two rover points. The location of the rover points shall be close to the area of the task concerned. The separation of two rover points shall be a minimum of 2 m and shall not exceed 20 m. The positions of two rover points may be selected at convenience in the field .... The horizontal distance and height difference between two rover points shall be determined by methods with precision better than 3 mm other than RTK. …"

A GNSS calibration facility could be established using the principles outlined in this standard and using calibrated instruments (e.g. total stations and/or levels) with established traceability to determine the distances and height differences between the base point and the two (or possibly more) *permanent* rover points. These instrument uncertainties as well as other contributions from refraction and possibly uncertainty in latitude, longitude and ellipsoidal height of a fixed pillar could be combined into a Type B uncertainty. The repeatability of the coordinate determinations the rover points should be made several times and incorporated into the Type B uncertainty as well. The Type A uncertainty must be established by repeated independent measures of the rover points using GNSS antennas. Different Type A uncertainties could be established using different instrument types.

The final uncertainty U of the calibration is determined by combining the Type A and Type B uncertainties and multiplying by a coverage factor (typically 2).

$$U = 2 \times \sqrt{(\text{Type A})^2 + (\text{Type B})^2}$$

These last paragraphs give a very broad outline to the possible establishment of traceability in GNSS measurements at a hypothetical calibration facility. Several GNSS test facilities exist. One well documented example is discussed in [19]. Establishing traceability as discussed in section 2 of this paper at such a facility is certainly technically feasible. It is worth noting that a variant in this type of approach is used by JUPEM, the Malaysian Survey and Mapping Directorate to establish traceability in the Malaysian cadastral system. [20] Distance meters used by JUPEM to this end are calibrated at the ESRF accredited calibration bench.

SUMMARY

GNSS measurements are by their nature complex. To establish traceability and provide accredited calibration services, a well defined measurand must be established. Once the measurand has been defined, well techniques outlined in GUM and GUM1 can be used to create an uncertainty calculation and traceability can be established.

"Whereas the exact values of the contributions to the error of a result of a measurement are unknown and unknowable, the uncertainties associated with the random and systematic effects that give rise to the error can be evaluated. *But, even if the evaluated uncertainties are small, there is still no guarantee that the error in the measurement result is small*; for in the determination of a correction or in the assessment of incomplete knowledge, a systematic effect may have been overlooked because it is unrecognized. Thus the uncertainty of a result of a measurement is not necessarily an indication of the likelihood that the measurement result is near the value of the measurand; it is simply an estimate of the likelihood of nearness to the best value that is consistent with presently available knowledge." [1]

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