

HOW TO EXPRESS THE RELIABILITY OF MEASUREMENT RESULTS

—The role of metrological traceability and measurement uncertainty—

*H. Imai*¹

¹ National Metrology Institute of Japan (NMIJ),

National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan

¹ Japan Electric Meters Inspection Cooperation (JEMIC) / ¹ National Institute of Technology and Evaluation (NITE)

E-mail: imaihdtk@aol.com

Abstract – Recent situation on global metrology is reviewed from the view point of requirements of science and technology. Basic infrastructure on quantities and units is built up under the international recognition and rules in science of measurement. Metrological traceability to a metrological reference such as a measurement unit, a reference procedure, and a reference material is considered to be fundamentals in calibration and measurement. In order to confirm the reliability of a measurement result, statement of metrological traceability chain together with attributed measurement uncertainty is required for calibration and testing laboratories. Concepts and definitions of terms are documented in such as SI brochure, VIM, GUM and some other standard documents of ISO, IEC, OIML and ILAC.

In Mutual Recognition Arrangement (MRA) such as CIPM and ILAC, statements of competence for both quality management system and technology based on ISO/IEC 17025 [1] are required. Detailed description on metrological traceability and measurement uncertainty for a measurement result is also required in many fields of science, industry and our social life from the safety point of view.

Keywords : metrological traceability, measurement uncertainty, GUM, VIM

1. INTRODUCTION

Under the umbrella of Metre Convention (MC), International System of units (SI) was established in 1960, and it has been utilized worldwide in many fields of science and technology. In 1999, the signing of Mutual Recognition Arrangement (CIPM-MRA) has initiated among 38 National Metrology Institutes (NMIs) of member states of MC and 2 international organizations. As of March 2011, it has been signed by the representatives of 81 institutes from 48 Member States, 30 Associates of the CGPM, and 3 international organizations, and covers a further 135 institutes designated by the signatory bodies.

The credibility of both management system and technical competence of NMIs can be reviewed by peer reviewers based on the key-comparison results which are organized by a suitable Consultative Committee under the CIPM and the requirements in ISO/IEC 17025 or ISO/Guide 34 [2]. The review system and process are

being discussed in Joint Committee between the Regional Metrology Organizations and the BIPM (JCRB).

The Joint Committee for Guides in Metrology (JCGM) was established in 1997 and its task is to maintain and promote the use of the GUM (*Guide to the Expression of Uncertainty in Measurement*) and the VIM (*International Vocabulary of Basic and General Terms in Metrology*). The JCGM has taken over the responsibility for these two documents from ISO TAG 4, who originally published them under the auspices of the BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML (now, ILAC is included).

In our daily life, there exist urgent requirements for safety and reliability in such fields as global environment, food science, and clinical chemistry. During the 19th World Congress of IMEKO held at Lisbon in 2009, related presentations and discussions on metrological traceability and measurement uncertainty were carried out in TC7 (Measurement Science), TC8 (Traceability in Metrology), TC23 (Metrology in Food and Nutrition), and so on.

In March 2010, the BIPM and World Meteorological Organization (WMO) organized a workshop concerning the real life assessments of uncertainty [3]. Considerations for metrological traceability and uncertainty in measurement and in forecast have been key elements of the assessment reports on climate change that the Intergovernmental Panel on Climate Change (IPCC) has published since 1990. They are introducing ‘Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties’. In the ILAC, they are preparing ‘ILAC Policy for Uncertainty in Calibration’ [4].

This paper introduces how to express the reliability of measurement results referring the concept of metrological traceability and associated measurement uncertainty.

2. BACKGROUND OF WORLD METROLOGY

In today’s life, we are routinely using measurement units such as metre in length, kilogram in mass, kelvin in temperature, which are defined as SI. Under the MC, both base units and derived units are reasonably defined in SI.

Fig.1 shows the relationship among international organizations such as the BIPM, OIML, ILAC, and others including academia. Today, we have five regional metrology organizations (RMO) including AFRIMET, APMP, COOMET, EURAMET, and SIM. They construct JCRB and it has review system of both Intra-regional (within RMO)

and Inter-regional (within JCRB) concerning submitted documents from an NMI on management system and technology. Through these reviews, management system and technical competence of an NMI can be confirmed and the result has been recorded in Key-comparison database at the BIPM as KCDB. In KCDB, each NMI declares its measurement uncertainty for specific quantities based on the result of a Key-comparison. **Table 1** shows the outline of CIPM-MRA as its Appendix. In Appendix C, Calibration and Measurement Capability (CMC) is defined as measurement uncertainty and it is usually expressed at a 95 % level of confidence

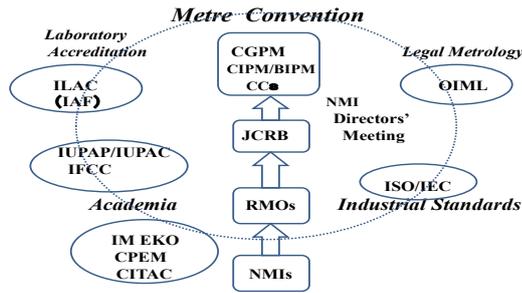


Fig. 1 Global Liaison in Metrology

Appendix	Contents
A	Signed NMIs
B	B1: Results of CIPM key comparisons B2: Results of RMO key comparisons B3: Results of supplementary comparisons.
C	Quantities for which calibration and measurement certificates are recognized by institutes participating in part two of the agreement. The quantities, ranges and calibration and measurement capabilities expressed as an uncertainty (normally at a 95% level of confidence) are listed for each participating institute. CMC: Calibration and Measurement Capability
D	List of key comparisons
E	Terms of reference of the Joint Committee of the Regional Metrology Organizations and the BIPM (JCRB).

In Fig.2, metrological traceability is seen as hierarchical chains from the bottom level to top standard and the magnitude of uncertainty pyramid is illustrated in the figure.

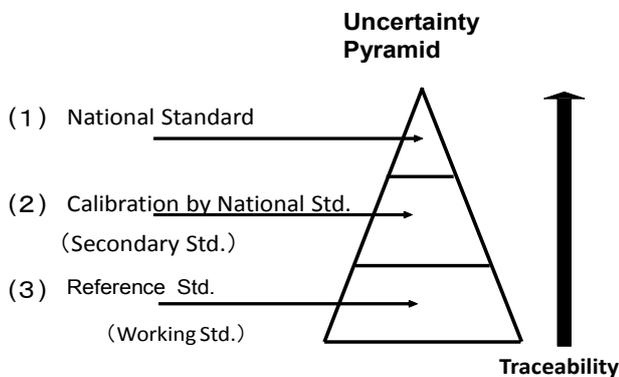


Fig. 2 Metrological Traceability and Uncertainty Pyramid

In the field of conformity assessment, as is seen in **Table 2**, similar requirements for both management system and technology are listed in their own document standards. In these documents, statements on metrological traceability and measurement uncertainty are recommended.

Table 2 Requirement for Competence in ISO Documents

ISO/IEC17025:2005 (Testing & Cal. labs)	ISO Guide 34:2009 (Reference Material)	ISO 15195:2003 (Laboratory Medicine)
5.4 Method of testing and calibration Validation		5.4 Reference Material 5.5 Reference Procedure
5.6 Traceability	5.12 Metrological traceability	5.6 Metrological traceability Measurement uncertainty
5.9 Quality assurance of testing & calibration result	5.13 Homogeneous 5.14 Stability	
5.10 Reporting of result	5.16 Measurement uncertainty	5.8 Reporting of result

3. ACTIVITIES IN JCGM

There are two Working Groups and one Ad-hoc group in JCGM. Working Group 1 (WG1) has responsibility for maintaining the GUM which is now used worldwide at all levels of the metrological traceability chain, from industry to NMIs. A corrected version of the GUM has been prepared under the name JCGM 100:2008 (GUM 1995 with minor editorial corrections) and published as ISO/IEC Guide 98-3 in 2008. In addition, the JCGM-WG1 has decided to produce a series of complementary documents to cover some topics of interest in more detail, whilst also directing them to groups of users with different levels of expertise. Working Group 2 (WG2) has responsibility for maintaining the VIM. The third edition of the *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms* was published as ISO/IEC Guide 99 in 2007 (JCGM 200). **Fig. 3** shows historical review on the activity around measurement uncertainty with international organizations.

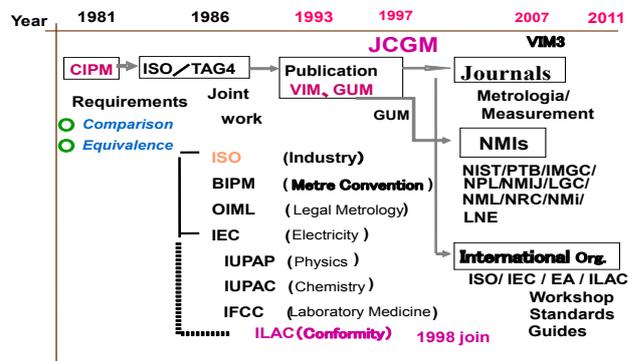


Fig. 3 Historical review for Measurement Uncertainty

In response to recent requirements from many fields of science and technology, JCGM-WG1(GUM) and JCGM-WG2(VIM) are concentrating their efforts on editing and disseminating JCGM documents to fit their requests

concerning reliability, healthy, and safety of our life. Discussions and presentations were also carried out in their recent meetings held in November 2010 at the BIPM. Table 3 shows the present activities in JCGM.

Table 3 Target and Activities of JCGM

Committee & WGs	Main Activity	Note
JCGM	<ul style="list-style-type: none"> *Establishment and revision of Charter *Promotion of WGs *Publication and copyright of documents 	Meet once a year by eight organisations since 2003.
	<ul style="list-style-type: none"> *Edition and publication of documents on valuation of measurement data *Revision of the present GUM in near future *Provision of concepts of measurement uncertainty 	Published GUM:1995 as ISO/IEC Guide 98-3 in 2008, and two other documents related to GUM in 2009. Preparing other five documents.
JCGM-WG2	<ul style="list-style-type: none"> *Publication of VIM3(revision of VIM2) *Provision of VIM3 concepts 	Published VIM3 as ISO/IEC Guide 99 in 2007.
Ad-hoc Group	*Drafting on Measurement Software	Established in 2008.

The reason why the ‘measurement uncertainty’ has been introduced in the field of measurement science is that there was a confusion of concept and terminology in error approach. Table 4 summarizes the difference between Error Approach (EA) and Uncertainty Approach (UA) from several points of view. In JCGM, they are concentrating on the shift from EA to UA by having keen liaison between WG1 and WG2 with each other.

Table 4 Comparison of EA and UA (Revolution from EA to UA)

Item	Error Approach(EA)	Uncertainty Approach(UA)
True value	Normative	Informative
Index of dispersion	Standard deviation	Standard uncertainty (Standard deviation, h-width)
Estimation of dispersion	Error (Random, Systematic)	Type A (statistics) Type B
Combination of dispersion	Least squares, Arithmetic	Least squares
Level of confidence	$k\sigma$ (σ : standard deviation)	Coverage factor k $U(ku)$ Coverage interval
Final expression	Not fixed	Expanded uncertainty $k \times$ (Combined standard uncertainty)

Table 5 Important document standards on metrology

Year	Document (related matter)	Note
1960	Establishment of SI	
1984	Publication of VIM1	BIPM, ISO, IEC, OIML
1993	Publication of VIM2 and GUM (GUM: Corrected version, 1995)	+IFCC,IUPA C, IUPAP
1997	Set up of JCGM(←ISO/TAG4)	JCGM①
1999	CIPM-MRA signed	
2004	Drafting of VIM3	
2005	Comments for Draft of VIM3	JCGM③
2006	Publication of SI 8 th edition	by BIPM
2007	Publication of VIM3 as ISO/IEC Guide 99:2007	JCGM⑤
2008	Publication of GUM:1995 as ISO/IEC Guide 98-3:2008	JCGM⑥
2010	Publication of Corrected version of VIM3. Publication of ISO/IEC 80000s	JCGM⑦

In Table 5, some important documents in metrology are summarized. Table 6 shows some important terms in VIM3.

Table 6 Important terms in VIM3

Term	Definition
measurement	process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity
metrology	science of measurement and its application
measurement uncertainty	non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used
standard uncertainty	measurement uncertainty expressed as a standard deviation
combined standard uncertainty	standard measurement uncertainty that is obtained using the individual standard measurement uncertainties associated with the input quantities in a measurement model
uncertainty budget	uncertainty budget statement of a measurement uncertainty, of the components of that measurement uncertainty, and of their calculation and combination
expanded uncertainty	product of a combined standard measurement uncertainty and a factor larger than the number one
coverage factor (k)	number larger than one by which a combined standard measurement uncertainty is multiplied to obtain an expanded measurement uncertainty
coverage interval	interval containing the set of true quantity values of a measurand with a stated probability, based on the information available

In designing a measurement, so-called 4WIH conditions can be considered and it will be illustrated as is shown in Fig.4. This is same as a fish bone diagram known in production process.

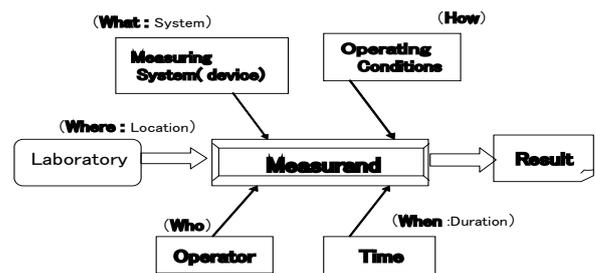


Fig. 4 Fish bone diagram : Components to be considered

In order to have a credible and reliable measurement result, it is necessary to consider several measuring conditions such as procedure, operator, system, location, and time. In Table 7, combinations of these conditions are compared and clarified as repeatability and reproducibility based on the definition in VIM3.

Table 7 Comparison of Precision Conditions (Same concepts as ISO/TC69)

Measuring conditions	Repeatability	Intermediate precision	Reproducibility
Procedure	○	○	(×)
Operator	○	(×)	×
Measuring system	○	(×)	×
Operating conditions	○	(×)	
Location	○	○	×
Duration of time	Short interval	Long interval	

Note: ○ : Same × :Different (×):Not identify

4. METROLOGICAL TRACEABILITY AND MEASUREMENT UNCERTAINTY

In the VIM, metrological traceability is defined as follows:
Metrological Traceability [VIM 2.41]

<Definition>

property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty

<Notes> [not all]

- 1) (metrological) Reference can be a definition of a unit through its practical realization or a procedure including the unit for a non-ordinal quantity, or a standard.
- 2) Calibration hierarchy is required.
- 5) A comparison between two measurement standards may be viewed as a calibration if the comparison is used to check.
- 7) The ILAC considers the six elements for confirming metrological traceability to be an unbroken metrological traceability chain to an international measurement standard or a national measurement standard.
- 8) Distinction is necessary for metrological traceability and other traceability such as history of a product, a sample or document, and a material.

Based on the definition of metrological traceability mentioned above and measurement standards of several levels of hierarchy in VIM, Fig. 5 can be obtained.

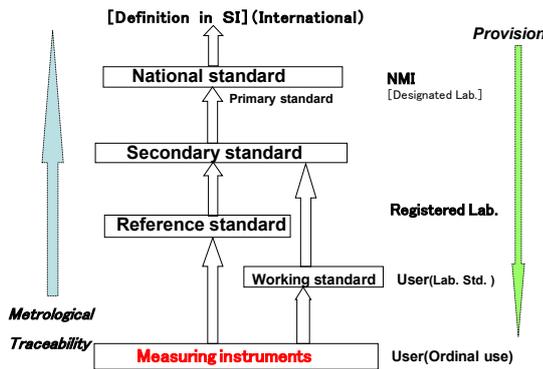


Fig. 5 Metrological traceability chain based on VIM

As for measurement uncertainty, it is defined as follows:
Measurement Uncertainty [VIM 2.26]

<Definition>

non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

<Notes> [not all]

- 1) Includes systematic effects.
- 2) The parameter may be a standard deviation, or the half width of an interval, having a stated coverage provability.
- 3) Uncertainty comprises, in general, many components.
- 4) Measurement uncertainty is associated with a stated quantity value attributed to the measurand.

In JCGM-WG1, two additional documents related to original GUM have been published and there are two kinds of approaches for the estimation of measurement uncertainty

as illustrated in Fig. 6. One is a method based on original GUM approach and the other is a numerical calculation such as Monte Carlo method. The former uses principle of propagation and the latter uses probability distribution function.

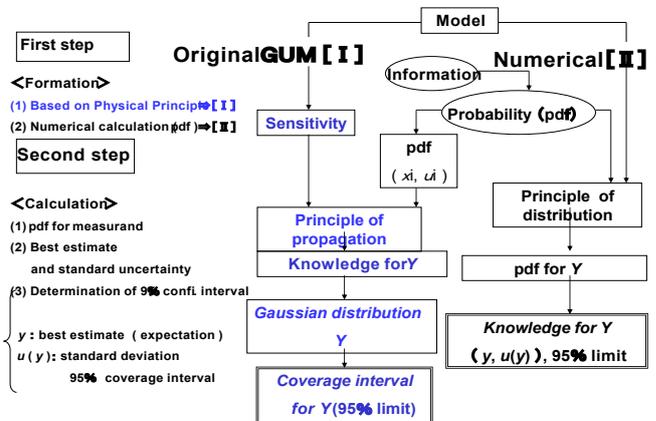


Fig. 6 Estimation of measurement uncertainty [I , II]

In JCGM, both WGs have been liaison with each other and introduces same concepts for metrological traceability and measurement uncertainty. Fig. 7 shows the outline to evaluate measurement uncertainty based on GUF (GUM framework). Fig. 8 illustrates the flowchart of measurement process from modelling to the expression of measurement result.

- (1) Modelling of a measurement principle
- (2) Selection of uncertainty components
→Application of Fish bone diagram
- (3) Analysis of uncertainty components
→Evaluation matrix
- (4) Confirmation of Flowchart of measurement
- (5) Construction of uncertainty budget(Table)
 - ① measurand
 - ② procedure
 - ③ measurement
 - ④ Evaluation of a measurement result
 - ⑤ Final expression
→Total uncertainty:
→Coverage interval (Factor, Probability)

Fig. 7 Evaluation of measurement results based on uncertainty approach

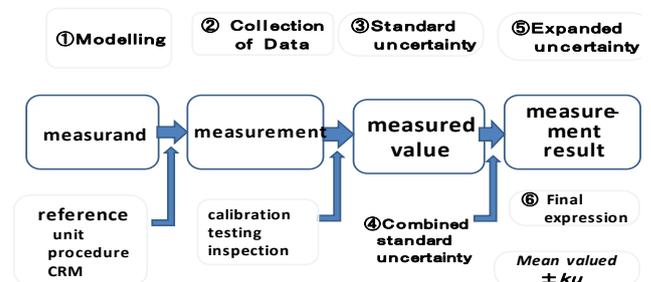


Fig. 8 Flow of measurement Expression of uncertainty

Through this process, estimation of each uncertainty factor and the combination of effective factors can be done, and final expression is usually an expanded uncertainty.

In **Table 8** and **Table 9**, some examples of CMCs listed in KCDB of the BIPM are shown. As is already mentioned in Appendix C of Table 1, quantities, ranges and CMCs of quantities expressed as an expanded uncertainty (normally at a 95% level of confidence) are shown together with standard instruments.

Table 8 Examples of CMC: Length [NMIJ]

Quantity	Range	Instrument (Device)	Expanded Uncertainty ¹ L in nm
Length	0.5 mm~250 mm	Gauge Block	17.2+0.228L ² (k=2, 95 % Confidence interval)
Length	150 mm~1000 mm	Gauge Block	20.0+0.164L ^{1.5} (k=2, 95 % Confidence interval)
Length	50 mm~500 mm	Line Scale	200 nm (k=2, 95 % Confidence interval)
Length	500 mm~1000 mm	Line Scale	300 nm

Table 9 Examples of CMC: Electricity [BIPM]

Note : From the Homepage of the BIPM

Quantity	Range	Instrument (Device)	Expanded Uncertainty (k=2, 95 % Confidence interval)
Direct current	1.018 V	Zener diode voltage standard	28 nV/V
Direct current	10 V	Zener diode voltage standard	28 nV/V
Resistance	1 Ω	Standard Resistor (23 °C)	34 nΩ/Ω
Resistance	100 Ω	Standard Resistor (23 °C)	36 nΩ/Ω

Table 8 shows CMCs of length at National Metrology Institute of Japan (NMIJ), and Table 9 shows CMCs of electricity at the BIPM. Metrological traceability of these instruments and devices can be maintained by following up the hierarchy to reach suitable SI units as shown in Figure 5.

In the field of chemical metrology and so on, it is not always easy to follow SI units. Therefore, primary reference procedures and certified reference materials are introduced as a metrological reference in some fields.

5. FUTURE TARGET OF JCGM

In JCGM-WG1, after the publication of present GUM (year of 1995 version) as ISO/IEC Guide 98-3, they are preparing some further documents to extend the fields of application of philosophy of uncertainty approach (UA). Two of them have been published. JCGM-WG2 published 3rd edition of VIM as ISO/IEC Guide 99, and its corrected version was published in 2010. Already published and under edition documents in JCGM are listed in **Table 10**.

Table 10 Present Status of documents under JCGM

Title of document	JCGM Number	ISO/IEC Guide	Note
International Vocabulary of Metrology – Basic and general concepts and Associated Terms (VIM)	JCGM 200	99	Published(2007) (Corrected 2011)
Guide to the expression of uncertainty in measurement, GUM 1995, with minor modifications	JCGM 100	98-3	Published (2008)
Supplement 1 to the “Guide to the expression of uncertainty in measurement” —Propagation of distributions using a Monte Carlo method	JCGM 101	98-3/ Supplement1	Published (2008)
Supplement 2 to the “Guide to the expression of uncertainty in measurement” — Extension to any number of output quantities	JCGM 102	98-3/ Supplement2	Final voting
Supplement 3 to the “Guide to the expression of uncertainty in measurement”— Modelling	JCGM 103	98-3/ Supplement3	In preparation
An introduction to the “Guide to the expression of uncertainty in measurement” and related documents	JCGM 104	98-1	Published (2009)
Concepts, principles and methods for the assessment of measurement uncertainty	JCGM 105	98-2	In preparation
The role of measurement uncertainty in conformity assessment	JCGM 106	98-4	First voting
Applications of the least-squares method	JCGM 107	98-5	In preparation

In WG1 and WG2 of JCGM, they have one or two meetings a year at the BIPM and are discussing how to

introduce and disseminate JCGM documents into metrology world, academia and industry through participating eight international organizations.

At present, in the fields of physics, mechanics and electricity, it is understood to consider measurement uncertainty in the expression of a measurement result. In addition, this kind of concept is being extended to such fields as chemical metrology, biology, environmental assessment, clinical medicine, food science, climate change assessment, and even in forensic science. The results of international comparisons are listed as KCDB for Key-comparisons organized by CIPM or RMOs. Comparison results organized by JCTLM (Joint Committee for Traceability in Laboratory Medicine) are also listed in the homepage of the BIPM.

An Ad-hoc group on measurement software was set up in JCGM in 2008 to submit a draft guide as is shown in Table 3. There is an urgent need especially in legal metrology and conformity assessment.

5.1. Future GUM

Two supplemental documents of GUM for numerical calculations to any number of output quantities and modelling are now in drafting. Theoretical document is also considered in succession. Application documents of GUM for conformity assessment and the method of least squares are now in preparation. In 2009, it was decided to revise the present GUM at the JCGM principal meeting and JCGM-WG1 was asked to start the discussion for drafting a skeleton of new GUM. In the new GUM, main concept of the present GUM may be maintained and theoretical background will be added together with suitable examples.

As is mentioned in Fig. 6, both principle of propagation and principle of distribution can be introduced in the new GUM. In the present GUM, so-called bottom-up approach is introduced to summarize uncertainty components. For the new GUM, top-down approach which applies statistical experimental design as is shown in some document standards published by ISO/TC69 (Application of statistical methods) may be introduced together with present bottom-up approach. Another new concept is how to deal with dynamic phenomena in time-and frequency domain.

Fig. 9 shows presently planned and published documents in JCGM-WG1 and classified by their category..

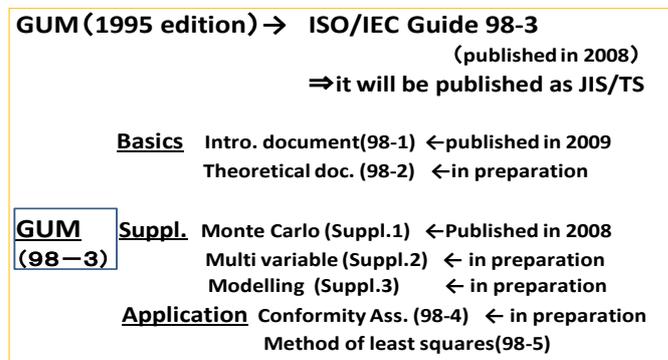


Fig. 9 Future plan of GUM and related documents

5.2. Future VIM

After the publication of VIM3 in JCGM-WG2, they are preparing rationale papers for the sake of dissemination of VIM concepts. In the VIM3, there includes continuous quantities traceable to the SI units, ordinal quantities, and nominal properties. In the future revision of present VIM3 (Edition of VIM4), it was decided to consider the inclusion of such frameworks as standards, metrological traceability, measurement uncertainty, and so on for nominal properties by the proposal from IFCC and IUPAC (An explanatory paper has been prepared by IFCC as “An outline for a vocabulary of nominal properties and examinations – basic and general concepts and associated terms”[5]).

The addition of concepts and terms concerned with CIPM-MRA, conformity assessment, and dynamic phenomena can also be considered for VIM4 in ten year time framework.

6. CONCLUSIONS

Eleven years have passed since the first signing of CIPM-MRA in 1999 and we have now about 24 000 KCDB in nine different areas. Not only in metrology but also in other fields such as biology, environmental science, food science, clinical laboratory medicine, and climate change assessment, concepts and expression of metrological traceability and measurement uncertainty are introduced. Furthermore, in some international documents they require description of competence for both quality management system and technology in their specific fields.

In response to this kind of urgent circumstances in science and technology, GUM and VIM have been recognized as international guidance documents and they have been published as ISO/IEC Guide by the proposal from JCGM. In the near future, ISO/IEC 17025, GUM and VIM will be mentioned in ISO/IEC Directive: Part 2. It is fundamentally encouraged to introduce and disseminate the concepts and terms of GUM and VIM in such fields as academia, science and industry worldwide.

[The author is a liaison member of JCGM (WG1 and WG2) from ILAC.]

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<Lit of abbreviations>

- **SI** : International System of units
- **JCGM** : Joint Committee for Guides in Metrology
- **GUM** : Guide to the expression of Uncertainty in Measurement JCGM 100 (ISO/IEC Guide 98-3, 2008)
- **VIM**: International Vocabulary in Metrology –Basic and general concepts and associated terms (VIM) JCGM 200(ISO/IEC Guide 99, 2007: Corrected version, 2010)
- **MRA** : Mutual Recognition Arrangement
- **NMI** : National Metrology Institute
- **CMC** : Calibration and Measurement Capability
- **JCRB**: Joint Committee of the Regional Metrology Organizations (RMO) and the BIPM
- **JCTLM**: Joint Committee for Traceability in Laboratory Medicine
- **BIPM**: Bureau International des Poids et Mesures(F), International Bureau of Weights and Measures (E)
- **IEC** : International Electrotechnical Commission
- **IFCC** : International Federation of Clinical Chemistry and Laboratory Medicine
- **ISO** : International Organization for Standardization
- **IUPAC** : International Union of Pure and Applied Chemistry
- **IUPAP** : International Union of Pure and Applied Physics
- **OIML** : International Organization of Legal Metrology
- **ILAC** : International Laboratory Accreditation Cooperation
- **CGPM** : General Conference on Weights and Measures
- **CIPM** : International Committee for Weights and Measures
- **WMO**: World Meteorological Organization
- **KCDB** : Key-comparison Database (at the BIPM))

<From the homepage of the BIPM>

- **SI**:
⇒http://www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf
- **GUM** ⇒<http://www.bipm.org/en/publications/guides/gum.html>
- **VIM** ⇒ <http://www.bipm.org/en/publications/guides/vim.html>
- **CIPM-MRA** ⇒<http://www.bipm.org/en/cipm-mra/>
- **Signatories of the CIPM MRA**
<http://www.bipm.org/en/cipm-mra/participation/signatories.html>
- **Appendix C of CIPM-MR** ⇒ <http://kcdb.bipm.org/appendixC/>
- **Database of KCDB & JCTLM** ⇒<http://www.bipm.org/en/db/>

Title:

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Name: Hidetaka IMAI

Affiliation: National Metrology Institute of Japan/AIST

Mail address: 1-1-1, Umezono, Tsukuba, Ibaraki 305-8563 Japan

E-mail: imaihdtk@aol.com