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Introduction:

R205 – Specific Requirements: Calibration Laboratory Accreditation Program states that for each measurement parameter and associated range(s), the laboratory shall provide with the application an uncertainty budget showing how the claimed Calibration and Measurement Capability (CMC) was derived. The assumptions made for the determination of the uncertainty budgets, if any, must be specified and documented. A2LA accredited and enrolled calibration laboratories shall calculate measurement uncertainties using the method detailed in the ISO "Guide to the Expression of Uncertainty in Measurement" (GUM)[1]

Purpose:

The purpose of this document is to provide guidance for determining the proper contributors of electrical parameters that should be taken into consideration when developing uncertainty calculations that support the Calibration and Measurement Capability (CMC) claim made on a scope of accreditation. This guidance also serves as a means for Conformance Assessment Bodies (CABs) to be in compliance with *P110 – Policy on Measurement Uncertainty in Calibration*. Finally this guidance serves to clarify how an approach that includes the simple use of the specification of the standard along with the resolution of the standard and "best" unit under test is not sufficient for meeting the GUM.

Background:

Historically an acceptable approach for generating electrical uncertainty budgets has excluded the determination of any "Type A" data and included only three "Type B" considerations: specification of the standard used, resolution of the standard and resolution of the (best) unit under test.

This approach does not appear to meet the GUM[1], M3003[2] or RP-12[3] for the following reasons:

It does not provide any evidence for:

a) Traceability
b) Type A contributors such as:

- Short term stability
- Repeatability error

[1] Guidance documents based on the GUM include Expression of the Uncertainty of Measurement in Calibration, NIST Technical Note 1297, and UKAS M3003, The Expression of Uncertainty and Confidence in Measurement, 2007.

c) Type B contributors such as:

- Operator error
- System performance including cable behavior and/or faults
- Environmental effects

a. Traceability

P102 – A2LA Policy on Measurement Traceability requires that uncertainty budgets be compliant with Traceability:

(T4) Where measurement uncertainty analysis is applicable[2]*, A2LA requires laboratories to calculate measurement uncertainty in accordance with the ISO "Guide to the Expression of Uncertainty in Measurement." These uncertainties, when reported, shall be reported as the expanded uncertainty with a defined coverage factor, k (typically k = 2) and the confidence interval (typically to approximate the 95% confidence level).*

ISO/IEC 17025:2005 states: *When estimating the uncertainty of measurement, all uncertainty components which are of importance in the given situation shall be taken into account using appropriate methods of analysis.*

b. Type A Uncertainty Contributors

- The GUM states that all statistical data is treated as Type A contributors with normal distributions. Typical examples in these areas are:

  1) Repeatability
  2) Reproducibility
  3) Stability / Drift
  4) others

  Repeatability is required by the GUM and M3003, and is recommended by NCSLI RP-12 and G103 – A2LA Guide for Estimation of Uncertainty of Dimensional Calibration and Testing Results.

- **In the GUM, Section 8.2 and 8.3 states:**

  8.2 Determine x_i, the estimated value of the input quantity X_i, either on the basis of statistical analysis of series on observations ***or by other means.***

  8.3 Evaluate the standard uncertainty $u(x_i)$ of each input estimate xi. For an input estimate obtained from the statistical analysis of series of observations, the standard uncertainty is evaluated as described in 4.2 (Type A evaluation of standard uncertainty). For an input estimate

[2] Measurement uncertainty analysis is required for all calibrations and dimensional inspections. For applicability of testing, please see the *P103 - Policy on Estimating Measurement Uncertainty for Testing Laboratories* and the relevant Annexes *P103a-P103d*.

obtained by other means, the standard uncertainty u (x_i) is evaluated as described in 4.3 (Type B evaluation of standard uncertainty).

Comment: In electrical calibrations one determines x_i, the estimated value of the input quantity X_i by measurement; hence the need for repeatability.

- **In M3003, it is strongly recommended to include random effects**. A Type A evaluation will normally be used to obtain a value for the repeatability or randomness of a measurement process. For some measurements, the random component of uncertainty may not be significant in relation to other contributions to uncertainty. **It is nevertheless desirable for any measurement process that the relative importance of random effects be established**. When there is a significant spread in a sample of measurement results, the arithmetic mean or average of the results should be calculated.

  In all the examples listed in M3003, repeatability is included.

- **In NCSLI RP-12, section 2.3 states:**

  Identify Measurement Errors and Distributions Measurement process errors are the basic elements of uncertainty analysis. Once these fundamental error sources have been identified; we can begin to develop uncertainty estimates. The errors most often encountered in making measurements include, but are not limited to the following:

  - *Measurement Bias*
  - ***Random or Repeatability Error***
  - *Resolution Error*
  - *Digital Sampling Error*
  - *Computation Error*
  - *Operator Bias*
  - *Environmental Factors Error*
  - *Stress Response Errors*

  Clearly, repeatability is required.

  Example 1 shows an uncertainty budget that clearly indicates the need for repeatability.

Table 1

In this example there are two concerns with the approach taken:

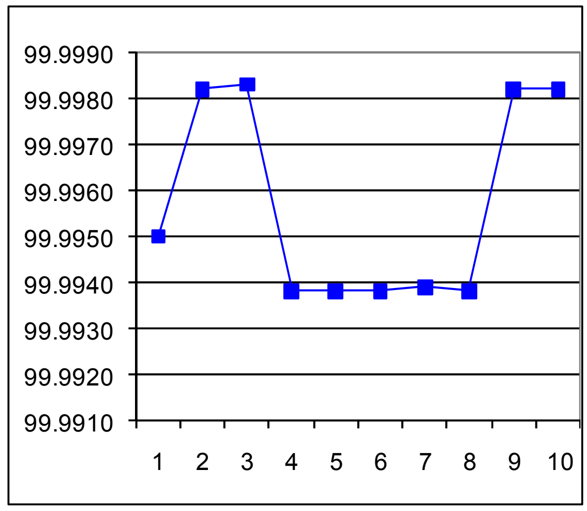
1. The repeatability is too high.
2. The actual uncertainty (from the calibration certificate) is greater than those noted on the specifications.

Data in support of Example 1:

Example1: 100 kΩ Range

	U		DIST	DIV	STD U	Squared	% of Total
Type A							
Repeatability	0.002335	kΩ	N	1	0.0023	5.45E-06	53.2
Type B							
Specifications of 5520A	0.0028	kΩ	Norm	2.58	0.0011	1.18E-06	11.5
UUT Resolution, Std.	0.000005	kΩ	Rec	1.732	0.0000029	8.33E-12	0.00008
Uncertainty of 5520A	0.0038	kΩ	Norm	2.0	0.0019	3.61E-06	35.2
Resolution of 5520A	0.00005	kΩ	Rec	1.732	0.000029	8.33E-10	0.008
					Sum	1.02E-05	100.0
					U	0.00320	
					U(k=2)	0.00640	kΩ

Repeatability		
1	99.9950	
2	99.9982	
3	99.9983	
4	99.9938	
5	99.9938	
6	99.9938	
7	99.9939	
8	99.9938	
9	99.9982	
10	99.9982	
STDEV	0.002203	
DOF=9	1.06	0.002335



Since the repeatability value dominates the overall uncertainty budget, this clearly indicates a problem with the system and further studies are needed. Without such statistics one would not have known of any problems with the measuring system.

c. Type B uncertainty contributors

- **In the GUM section 4.3 states:**

4.3 Type B evaluation of standard uncertainty
4.3.1 For an estimate x_i of an input quantity X_i that has ***not been obtained from repeated observations****, the associated estimated variance $u^2(x_i)$ or the standard uncertainty $u(x_i)$ is evaluated by scientific judgment based on all of the available information on the possible variability of X_i. The pool of information may include:*

- *previous measurement data;*
- *experience with or general knowledge of the behavior and properties of relevant materials and instruments;*
- *manufacturer's specifications;*
- *data provided in calibration and other certificate;*
- *uncertainties assigned to reference data taken from handbooks.*

- **In M3003, it is strongly recommended to include the following contributors:**

5.3 In evaluating the components of uncertainty it is necessary to consider and include ***at least the following possible sources****:*

(a) The reported calibration uncertainty assigned to reference standards and any drift or instability in their values or readings.

(b) The calibration of measuring equipment, including ancillaries such as connecting leads etc., and any drift or instability in their values or readings.
(c) The equipment or item being measured, for example its resolution and any instability during the measurement. It should be noted that the anticipated long-term performance of the item being calibrated is not normally included in the uncertainty evaluation for that calibration.
(d) The operational procedure.
(e) Variability between different staff carrying out the same type of measurement.
(f) The effects of environmental conditions on any or all of the above.

- ***In NCSLI RP-12, section 2.2 states:***

  2.3 Identify Measurement Errors and Distributions Measurement process errors are the basic elements of uncertainty analysis. Once these fundamental error sources have been identified, we can begin to develop uncertainty estimates. The errors most often encountered in making measurements include, but are not limited to the following:

  - *Measurement Bias*
  - *Random or Repeatability Error*
  - *Resolution Error*
  - *Digital Sampling Error*
  - *Computation Error*
  - *Operator Bias*
  - *Environmental Factors Error*
  - *Stress Response Errors*

  Most of these can be covered by statistics, specifications, traceable values, etc.

Example 2: AC Current

Accredited A2LA certificate issued includes the following information:

AC Current	Frequency	Range	Value		Uncertainty
	1 kHz	100 µA	99.9926*	µA	0.0200 µA
	1 kHz	1 mA	1.000029*	mA	0.000110 mA
	1 kHz	10 mA	10.00023	mA	0.001000 mA

	1 kHz	100 mA	100.0057	mA	0.01000 mA
	1 kHz	1A	1.000018	A	0.000100 A
* Ranges are not accredited					

Table 2

While there is nothing wrong with this report format, the **CAB** used all the data to claim traceability and uncertainties on the scope for all ranges.

Example 3: 1 mA Range (*Measure)*

	U		DIST	DIV	STD U	Squared	% of Total
Type A							
Repeatability	6.28E-07	mA	N	1	6.28E-07	3.95E-13	0.012
Type B							
Specification of 3458A	2.50E-05	mA	Rec	1.732	1.44E-05	2.08E-10	6.4
Resolution of HP 3458A	5.00E-08	mA	Rec	1.732	2.89E-08	8.33E-16	0.000026
5520A Resolution	5.00E-06	mA	Rec	1.732	2.89E-06	8.33E-12	0.26
Cert value	1.10E-04	mA	N	2	5.50E-05	3.03E-09	93.3
					Sum	3.24E-09	100.0
					U	0.00006	
					U(k=2)	0.00011	mA

Table 3

In this example the uncertainty from the calibration certificate is too high. The traceable uncertainty should never be larger than the specification. See also example 1.

Example 4: 300 mV Range

U		DIST	DIV	STD U	Squared	% of Total

Type A							
Repeatability	**5.43E-05**	**mV**	**Norm**	**1**	**0.000054**	**2.95E-09**	**0.29**
Type B							
Specifications	**0.0020**	**mV**	**Norm**	**2.0**	**0.0010**	**1.00E-06**	**99.6**
UUT Resolution	**0.00005**	**mV**	**Rec**	**1.732**	**0.0000289**	**8.33E-10**	**0.08**
Standard Resolution	**0.000005**	**mV**	**Norm**	**2**	**0.0000**	**6.25E-12**	**0.00062**
Uncertainty of 5520A	**0**	**mV**	**Rec**	**1.732**	**0.000000**	**0.00E+00**	**0.000**
					Sum	**1.00E-06**	**100.0**
					U	**0.0010**	
					U(k=2)	**0.0020**	**mV**

Table 4

In this example, the uncertainty from the calibration certificate is higher than the specification and was ignored in favor of the specification. In this case the laboratory did have a traceable certificate with a value stated. However since the value stated was higher than the specification, it was ignored.

If it had been included, the budget would have been:

	U		DIST	DIV	STD U	Squared	% of Total
Type A							
Repeatability	5.43E-05	mV	Norm	1	0.000054	2.95E-09	0.03
Type B							
Specifications	0.0020	mV	Norm	2.0	0.0010	1.00E-06	10.7
UUT Resolution	0.00005	mV	Rec	1.732	0.0000289	8.33E-10	0.01
Standard Resolution	0.000005	mV	Norm	2	0.0000	6.25E-12	0.00007
Uncertainty from Certificate	0.005	mV	Rec	1.732	0.002887	8.33E-06	89.250
					Sum	9.34E-06	100.0
					U	0.00306	
					U(k=2)	0.00611	mV

Table 5

There is a large difference between this overall uncertainty and the one without the certificate value included. In this case the CAB chose to use the budget without the certificate value. This means that there is no claimed traceability.

The CAB should have complied with ISO/IEC 17025, section 4.6.3 and reviewed the traceable certificate. This discrepancy should have been discussed with the facility that provided the "traceable" certificate and corrective actions should have been taken. The CAB could also have chosen to accept the value as reported and used it in the uncertainty budget. In that case it would have been com pliant with traceability requirements.

Recommendations

A. Based on all the above mentioned requirements and recommendations, we are recommending that at least the following contributors are identified in all electrical uncertainty budgets:

Item 1: Repeatability
Per M3003 this is highly recommended and listed in all their examples. Therefore the CAB shall consider with documentation of the consideration made.

Item 2: Reproducibility
This is required or strongly recommended by the GUM, M3003, and RP-12. If available, the CAB shall consider it with documentation of the consideration made.

Item 3: Stability
This is extremely useful if a CAB requires tighter uncertainties. If this is not available, a CAB shall include Item 6, specifications in order to cover the instrument specifications between calibrations. An exception would be if the customer only requires the uncertainty at the date of calibration. In that case, it is the customer's responsibility to add long term behavior.

Item 4: Others
In many cases, statistical data is available for items usually listed under Type B. In that case include them under Type A and treat the distributions as normal.

Item 5: Traceable Certificate Value
This is required by the GUM, M3003 and RP-12.

- By listing the value, it is demonstrated that the traceability is current and that the certificate from an NMI or ISO accredited calibration source was reviewed and approved (see ISO/IEC 17025, 5.4.7 Control of data; 5.5.9 Equipment; 4.6.3 Purchasing services and supplies).

- In addition, a CAB can compare with Item 1 and see if the repeatability makes sense; i.e., calibration system is operating correctly. (As long as Item 1 is << Item 5.)

- Furthermore a CAB can check if this value is < Item 6. Sometimes the traceable calibration value as received is larger than the specifications. Should this occur, a CAB would need to investigate in order to find a reason for this discrepancy. Usually it is a typographical error that increases your overall uncertainty significantly or the accredited facility / NMI could not perform the traceability to the required specification.

Item 6: Absolute Specifications
This is required or strongly recommended by the GUM, M3003 and RP-12.

- By listing the specifications, the CAB indicates that they are using (or not) the latest manuals. In comparing with Item 5, these values should always be larger. If not, a CAB should investigate and find out why.

- Also, Item 1, repeatability should never be larger than Item 6 and in fact they should be much smaller. If not, there are problems with the system, operator, incorrect cables, etc.

- Also, as mentioned before, if tighter uncertainties are really required, set the divisor/multiplier in the spreadsheet to 0, but ensure that Item 3, stability data, is available.

Item 7: Resolution of UUT
This is required or strongly recommended by the GUM, M3003 and RP-12. This is really a sanity check to ensure that all the listed contributors make sense. For instance, it does not make sense to list a contributor to four decimal places when the resolution has only two. It is also useful to compare with the resolution of the (best) unit under test (UUT), Item 8. If the latter is worse than the reference, the CAB is limited by the UUT.

Item 8: Resolution of standards used
This is required or strongly recommended by the GUM, M3003, and RP-12. This is essentially the same arguments as for Item 7. It serves as a sanity check.

Item 9: Environmental Effects
This is required or strongly recommended by: GUM, M3003, and RP-12. There could be multiple entries for this. Sometimes additional specifications for temperature and relative humidity at certain specific ranges require additional entries in addition to Item 6. (Keep in mind also that if Stability is used in Item 3 and Specifications are calculated as 0 value contributors, then these need to be considered.) It is even possible that pressure coefficients and vibrational effects need to be considered.

Item 10: Others
Required or strongly recommended by the GUM and M3003. It is recommended to list here any other possible uncertainty contributors. It really helps to have as much as possible listed to indicate that you have reviewed these possibilities.

Table 6: Summary of Recommendations:

Type A			
Item #	Name		Comment
1	Repeatability	Must consider*	Try getting at least 10 measurements so you have at least 9 DoF.
2	Reproducibility	If possible	
3	Stability	If available	See item 6 below.
4	Others	If identified	
Type B			
5	Reference value from Traceable Certificate	Must consider*	Without this value you have no proof of traceability.

Type B (cont)			
6	Absolute Specification for calibration interval	Must have to check if item 5 is less than item 6	Also, if you have long term stability for this parameter for this range, you can set the multiplier/divisor to 0.
7	Resolution of standards used	Must consider*	This is usually small with respect to the rest, but there are exceptions.
8	Resolution of UUT	Must consider*	This is usually small with respect to the rest, but there are exceptions.
9	Environmental effects	There can be multiple lines for it.	This is usually small with respect to the rest, but there are exceptions.
10	Any other entries that might be helpful		

*Must consider with documentation of the consideration made.

Having these basic frameworks for uncertainties, both the assessors and CABs can be reasonably assured of consistency from assessment to assessment. It avoids the confusion of the A2LA customers and covers not only uncertainty requirements but also document control as well as incoming inspections, etc.

References

1) Guide to the Expression of Uncertainty in Measurement (GUM), ISBN 92-67-10188-9, 1993

2) The Expression of Uncertainty and Confidence in Measurement UKAS - M3003, January 2007

3) NCSLI—RP12, Determining and Reporting Measurement Uncertainties. 2009 edition scheduled for release in 2009.

4) International vocabulary of metrology – Basic and general concepts and associated terms (VIM), GCGM 2090-2008, 2.21
See Appendix 1

5) International vocabulary of metrology – Basic and general concepts and associated terms (VIM), GCGM 2090-2008, 2.25
See Appendix 1

Appendix 1

2.21 measurement repeatability

repeatability **measurement precision** under a set of **repeatability conditions** of measurement

2.20 repeatability condition of measurement

repeatability condition -- condition of measurement, out of a set of conditions that includes the same **measurement procedure, same operators**, **same measuring system**, **same operating conditions** and **same location**, and **replicate measurements** on the **same or similar objects** over a short period of time NOTE 1 A condition of measurement is a repeatability condition only with respect to a specified set of repeatability conditions. NOTE 2 In chemistry, the term "intra-serial precision condition of measurement" is sometimes used to designate this concept.

2.25 measurement reproducibility

reproducibility **measurement precision** under **reproducibility conditions of measurement**
NOTE Relevant statistical terms are given in ISO5725-1:1994 and ISO 5725-2:1994.

2.24 reproducibility condition of measurement

reproducibility condition -- condition of **measurement,** out of a set of conditions that **includes different locations**, **operators**, **measuring systems,** and **replicate measurements** on the same or similar objects NOTE 1 The different measuring systems may use different measurement procedures. NOTE 2 A specification should give the conditions changed and unchanged, to the extent practical.

Document Revision History

Date	Description
01/01/2012	Initial Issue of Document