Introduction:

All calibration laboratories accredited by A2LA are required to submit uncertainty calculations for the Calibration and Measurement Capability uncertainty claims included on the scope of accreditation. 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) uncertainty claim made on a scope of accreditation. This guidance also serves as a means for Conformity Assessment Bodies (CABs) to be in compliance with section 6.8 of A2LA R205 - Specific Requirements: Calibration Laboratory Accreditation Program. 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[1] or RP-12[2] for the following reasons:

It does not provide any evidence for:

a) Traceability
b) Type A contributors such as:
   - Short term stability
   - Repeatability error

c) Type B contributors such as:
   - Operator error
   - System performance including cable behavior and/or faults
   - Environmental effects

a. Traceability

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

(T4) Where measurement uncertainty analysis is applicable[3], A2LA requires laboratories to calculate

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[1] Guidance documents based on the GUM include Expression of the Uncertainty of Measurement in Calibration, NIST Technical Note 1297, and UKAS M3003 Ed 3, The Expression of Uncertainty and Confidence in Measurement, 2012.
[2] NCSL International Recommended Practice RP-12: Measurement Uncertainty Analysis 2013
[3] 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-P103e.

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 17025:2017 states: When estimating the uncertainty of measurement, all contributions that are of significance, including those arising from sampling, 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 for Dimensional Calibration and Testing Results.

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

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

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

  Comment: In electrical calibrations one determines xi, the estimated value of the input quantity Xi 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							
	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

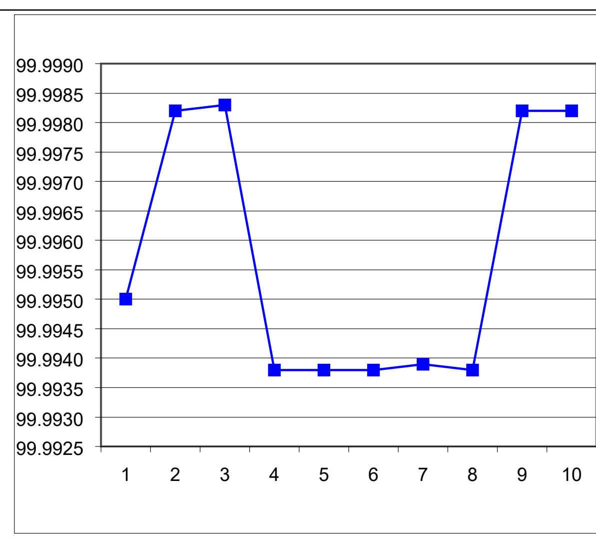
In this example there are two concerns with the approach taken:

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

Data in support of Example 1:

Table 2

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 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 xi of an input quantity Xi that has **not been obtained from repeated**

observations, the associated estimated variance u^2 (xi) or the standard uncertainty u (xi) is evaluated by scientific judgment based on all of the available information on the possible variability of Xi. 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 another 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. 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:

Table 3

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**					

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*)

Table 4

	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**

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

Table 5

	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**

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:

Table 6

	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

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.
- Reference standards with relative specifications must include their own calibration uncertainty in their subsequent uncertainty analyses to account for reference standard uncertainty;
- Reference standards with absolute specifications must include their own calibration uncertainty in subsequent uncertainty analyses to account for reference standard uncertainty unless the laboratory documents that the standard's calibration has test uncertainty ratios of at least 4:1 or their false accept risk is adequately controlled through the use of appropriate guard-banding methods.

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			
	Reference value from Traceable Certificate	Must consider*	Without this value you have no proof of traceability.
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), JCGM 100:2008

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

3) NCSLI—RP12, Determining and Reporting Measurement Uncertainties. 2013.

4) International vocabulary of metrology – Basic and general concepts and associated terms (VIM), JCGM 200:2012 3rd edition

See Appendix 1

Contributions by: Dr. Klaus Jaeger

Appendix 1

2.21 Measurement Repeatability (VIM)

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

2.20 Repeatability Condition of Measurement (VIM)

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 (VIM)

reproducibility **measurement precision** under **reproducibility conditions of measurement**
NOTE1 Relevant statistical terms are given in ISO5725-1:1994 and ISO 5725-2:1994.

2.24 Reproducibility Condition of Measurement (VIM)

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.

Conformity Assessment Body (CAB) (VIM): body that performs conformity assessment services.

DOCUMENT REVISION HISTORY

Date	Description
01/05/19	➢ Integrated into Qualtrax
09/24/19	➢ Changed references to ISO/IEC 17025 from 2005 to 2017 version ➢ Updated Header/Footer to current version ➢ Updated format and font for consistency