Traceability establishment in electrical calibration laboratory using reference digital multimeter

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Abstract – **This paper presents a strategy for traceability establishment in a electrical calibration laboratory using a precison 8 ½ digit digital multimeter as reference standard. The digital multimeter is calibrated by the National Metrology Laboratory or by an accredited laboratory, and some strategies to define the calibration plan considering the characteristics of the instrument, the scope of the calibration laboratory and the cost of the calibration are presented and discussed. The goal of the calibration plan is to allow the reference multimeter to be used in every measurement function and every range related to the calibration laboratory scope with guaranteed traceability and confidence, so correction factors for every point can be estimated from the calibration points presented in the calibration report. Finally, a calibration report data from a reference digital multimeter is analysed and processed in order to estimate calibration curves and some examples are presented and discussed.**

I. INTRODUCTION

Precision digital multimeters (DMMs), like 8 ½ digit ones, are very common instruments in electrical calibration laboratories, and they are often used as reference standards in voltage, current and resistance measurements due to their key characteristics and ultimate performance.

As reference standards, these multimeters are calibrated at many discrete points, on their different measurement quantities and ranges, at different frequencies for AC quantities. It is very common that the user or laboratory may use the instrument at points different from those calibrated. So, their calibration plan should be defined in such a way to allow estimation of calibration error and uncertainty for every measurement point in all the ranges and functions of the instrument. For calibration plan definition, at least three important questions should be considered: calibration scope of the laboratory, functional structure of the multimeter and cost of the calibration.

This paper presents some strategies for traceability establishment in an electrical calibration laboratory using a precision digital multimeter as its reference standard. Some calibration plans are presented and discussed. Results of error and uncertainty estimation for measurement points not listed on the digital multimeter calibration report are analysed and validated.

II. REFERENCE DIGITAL MULTIMETER

Digital multimeters are one of the most common measurement tools, ranging from simple handhelds to the more sophisticated precision metrology grade instruments. These precision DMMs offer a range of specifications, features, and capabilities intended to allow users to make the best measurements for their particular application [1]

Modern precision digital multimeters are sophisticated measuring instruments offering more than just the ability to measure voltage, current and resistance. The accuracy and stability of metrology grade instruments approach the levels available from the standards used to calibrate them. Such high performance allows these multimeters to be used in place of many traditional laboratory instruments such as voltage dividers and resistance bridges. A modern DMM can achieve stabilities of better than 2 ppm per year, linearity of 1 part in 20 million, noise levels of less than 50nV, input bias current of <10pA and an input resistance of $>10^{10}\,\Omega$ (for an input up to ±20V) [2]. Some models of modern precision digital multimeters are Fluke 8508A, Keysight 3458A and Transmille 8104A. Figure 1 shows a Fluke 8508A and a Keysight 3458A multimeters. A DMM manufacturer has two important goals when specifying a DMM. They must ensure that the performance and functionality are clearly presented to the prospective purchaser such that the purchasing decision can be made, and he will also ensure that the instrument's metrological performance is expressed to the best possible advantage in a competitive situation. The specification is actually describing the performance of the instrument's internal circuits that are necessary to achieve the desired functionality [3].
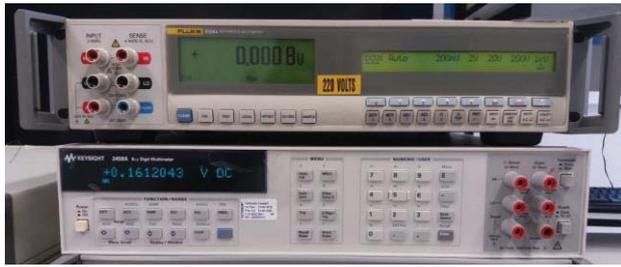
Fig. 1. Fluke 8508A and a Keysight 3458A digital multimeters

Fig. 2. DMM functionality tree example [3]

III. CALIBRATION PLAN

As the precision digital multimeter is the electrical calibration reference standard, it needs to be calibrated in a regular basis, usually in a 365-day interval. Considering its ultimate metrological characteristics, it is very common the need of performing its calibration in the National Metrology Laboratory (NML), or in a high level accredited laboratory, which can make the calibration costly. So, the definition of calibration points needs to establish a compromise between traceability needs and cost.

It is a very common strategy to define a calibration plan for a precision digital multimeter considering five points in each measurement range, ranging from 10% to 100% of the final measurement range value, as stated in [4]. This can make easier and more confident to evaluate errors from the beggining to the full scale. However, the number of calibration points can be very high. Considering the Fluke model 8508A precision digital multimeter, there are 46 voltage, current and resistance measurement ranges [5]. If each range is calibrated in five points, and each AC voltage range or AC current range is calibrated in at least three frequencies, there will be at least 340 calibration points.

As a way to reduce the number of calibration points and maintain traceability confidence, a strategy for calibration points definition based on the most important functional and calibration parameters of the precision digital multimeters, as seen in [3] and [6], can be evaluated. In this strategy, the DMM's functionality tree is very important. The DMM's functionality and range dependence is quite logical and is generally designed to get the maximum use out of a minimum of components through the use of common circuits wherever possible. As an example the ADC will be used for all functions, the current sensing resistors will be used for both ac I and dc I, the AC rms converter will be used for both ac V and ac I. An example of DMM's functionality tree can be seen in Figure 2. Each digital multimeter has its funcionality tree, so it is important do know it before calibration plan definition.
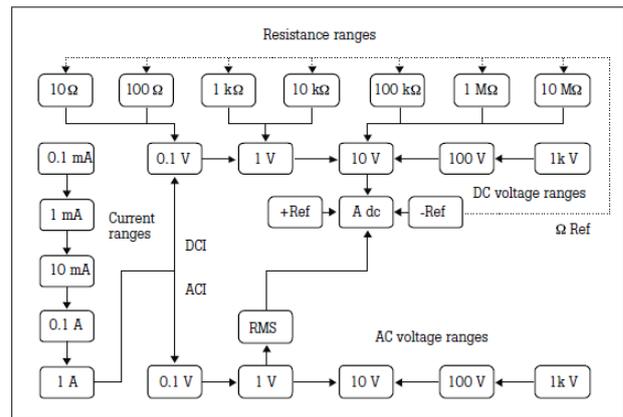
Considering the Figure 2, the ADC is common to all ranges of all functions, therefore its characteristic errors will affect all functions. Fortunately, this means that the basic DC linearity need only be verified on the basic (usually 10 V) range. This range needs to be calibrated in a reasonable number of points (at least five points). Other DC voltage ranges can be calibrated in fewer poins, in order to evaluate the errors of amplifiers and attenuators.

The AC functions have the added dimension of frequency. This complicates calibration by introducing additional test points for each amplitude range. In a typical DMM, the AC measurement is made by an AC converter. The linearity of this converter should also be evaluated, so the prime AC voltage range should be carefully analyzed. The gain of a DMM's ac function will vary with frequency. This is known as its Frequency Response and requires that measurements are made at key points throughout each amplitude range.

A DMM measures current by sensing the DC or AC voltage developed across a current sensing resistor or shunt. The same shunts will be used for both dc and ac current. A separate pair of terminals will be provided to simplify internal signal switching and minimize the impedance of the internal connections to the shunts. It is very desirable to keep the burden voltage as low as possible, typically this will be in the region of 100 mV.

The resistance function of a DMM consists primarily of a constant current source providing a range of currents typically from 10 nA to 10 mA. Selecting a resistance range selects an appropriate constant current to pass through the unknown or standard resistance. The voltage developed across the resistance is then measured by the DMM's DC voltage function with an appropriate range set.

So, considering the interdependances between the ranges discussed above, a calibration plan can be developed in order to meet traceability requirements and cost effectiveness. This paper presents calibration plans and their results for two measurement functions of a reference multimeter: DC voltage and AC voltage (at central frequency). Calibration points are defined as a percent of

the final range value (full scale). Table 1 shows calibration points for DC voltage considering the traditional strategy and two new strategies. In the first new strategy, intermediate points should be evaluated using linear interpolation, while in the second, linearity error is evaluated through the prime range calibration results, combined with the gain error of each range in order to obtain the intermediate points results (in the prime range intermediate points results are obtained using linear interpolation).

Table 1. DC voltage calibration points

	Traditional strategy (TR)	New strategy 1 (NS1)	New strategy 2 (NS2)
Prime range	10%, 30%, 50%, 70%, 97.5%		
Other ranges	Same than prime range	10%, 50%, 97.5%	97.5%

Table 2 shows calibration points for AC voltage at central frequency (usually 1 kHz). In the new strategy, intermediate points are obtained from linearity analysis of the prime range combined with the gain result of the range (in the prime range intermediate points are obtained by linear interpolation).

Table 2. AC voltage calibration points at central frequency

	Traditional strategy (TR)	New strategy (NS)
Prime range	10%, 30%, 50%, 70%, 97.5%	10%, 50%, 97.5%
Other ranges	Same than prime range	97.5%

IV.   CALIBRATION RESULTS ANALYSIS

For calibration plans evaluation, a calibration report from a Fluke model 8508A 8 ½ digit digital multimeter was used and analyzed. The multimeter was calibrated in every measurement range, five points in each range, and calibration points were equal to 10%, 30%, 50%, 70% and 97.5% of the final range value. So, it was possible to compare the estimated results of different strategies with the calibration results. According to its manufacturer, 8508A digital multimeter has no interdependance between measurement functions, so the strategies defined and discussed in this paper consider only the dependance between ranges in each measurement function.

Table 3 show calibration results for 2 V DC, 20 V DC and 200 V DC ranges. 20 V is the prime range. Using new strategy 1, errors at 0.5 V and 1.5 in 2 V range were estimated using linear interpolation between adjacent calibration points, and their uncertainties were the highest of each pair of adjacent points (in µV/V). Using new

strategy 2, the linearity error of the prime range for each point was added to the gain error of the 2 V range, which was assumed to be the 1.95 V calibration point error. Uncertainty was estimated using root sum square (RSS) of uncertainty of the linearity and the uncertainty of the 2 V range gain. Table 4 and Fig. 3 show a comparison of 0.5 V and 1.5 V errors and uncertainties estimation using the three strategies.

This same procedure was done to 200 V DC range, for estimation of 50 V and 150 V error and uncertainty. Table 5 and Fig. 4 show the comparison of their errors and uncertainties estimation using the three strategies. A small difference appeared in 50 V error at NS2, but its uncertainty was high compared to the others and so the results were compatible.

Table 3. DC voltage calibration results

Range (V)	Point (V)	Error ($\mu V/V$) e	Uncertainty ($\mu V/V$) U
2	0.2	-0.2	1.4
	0.5	-0.5	1.3
	1	-0.7	1.0
	1.5	-0.8	0.9
	1.95	-0.9	0.9
20	2	2.4	1.3
	5	1.6	1.3
	10	1.4	1.0
	15	1.3	0.9
	19.5	1.2	0.8
200	20	2.2	1.3
	50	1.3	1.5
	100	0.9	1.1
	150	0.1	1.7
	195	0.3	1.5

Table 4. 2 V range DC voltage estimation

Strategy	Points			
	0.5 V		1.5 V	
	e ($\mu V/V$)	U ($\mu V/V$)	e ($\mu V/V$)	U ($\mu V/V$)
TR	-0.5	1.3	-0.8	0.9
NS1	-0.4	1.4	-0.8	1.0
NS2	-0.6	1.6	-0.9	1.2
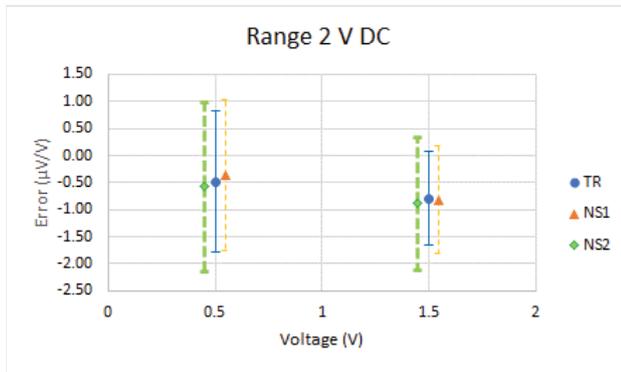
Fig. 3. Range 2 V DC estimation results

Table 5. 200 V range DC voltage estimation

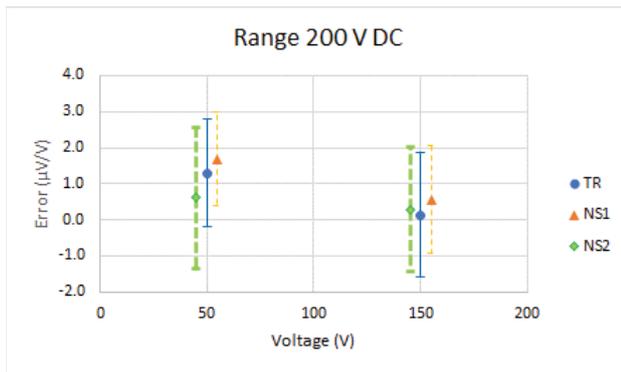| Strategy	Points			
	50 V		150 V	
	e (µV/V)	U (µV/V)	e (µV/V)	U (µV/V)
TR	1.3	1.5	0.1	1.7
NS1	1.7	1.3	0.6	1.5
NS2	0.6	2.0	0.3	1.7

Fig. 4. Range 20 V AC (1 kHz) estimation results

Table 5 shows calibration results for 2 V and 20 V AC @1 kHz. 2 V is considered the prime range. Using the new strategy (NS), errors at 2 V and 10 V were estimated adding the linearity error of the prime range to the gain error of the 20 V range, which was assumed to be the 19.5 V calibration point error. Uncertainty was estimated using root sum square (RSS) of the uncertainty of the linearity and the uncertainty of the 20 V range gain. Table 6 shows a comparison of 2 V and 10 V errors and uncertainties estimation using both strategies.

As it can been seen in the tables and graphs above, all the estimated points were compatible with measurement results. Considering the number of calibration points, for DC voltage function, using new strategy 1 reduces the number of calibration points from 25 to 17, a 32% reduction, while the use of new strategy 2 represents a reduction from 25 to 9 calibration points, or a 64% reduction. These reductions probably influence the cost of the precision digital multimeter calibration.

Table 5. AC voltage (1 kHz) calibration results

Range (V)	Point (V)	Error (%) e	Uncertainty (%) U
2	0.2	0.007 5	0.004 5
	0.5	0.005 2	0.003 2
	1	0.001 3	0.003 0
	1.5	0.001 3	0.002 9
	1.95	0.001 3	0.002 9
20	2	0.009 5	0.003 0
	5	0.003 8	0.002 8
	10	0.003 2	0.002 9
	15	0.003 0	0.003 3
	19.5	0.002 8	0.003 2

Table 6. 20 V range AC voltage (1 kHz) estimation

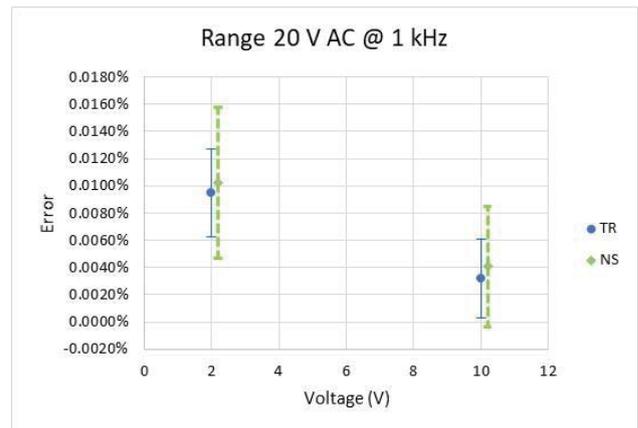| Strategy	Points			
	2 V		10 V	
	e (%)	U (%)	e (%)	U (%)
TR	0.009 5	0.003 0	0.003 2	0.002 9
NS	0.010 3	0.005 5	0.004 1	0.004 4

Fig. 5. Range 20 V AC (1 kHz) estimation results

V. CONCLUSIONS

This paper presented strategies for definition of a calibration plan for a precision digital multimeter used as reference standard in an electrical calibration laboratory. The aim of the calibration plan was to provide confidence and traceability to all the measurements performed by the digital multimeter related to the calibration laboratory scope, while keeping the number of calibration points and consequentely the cost of calibration as low as possible. The results of estimations for the measurement points not listed in the multimeter calibration report were analysed and validated with measurement results.

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