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Experimental Validation of TCal for DC Voltage Calibrations Through Internet

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Abstract: In 2018, as contribution to the area of Metrology for Industry 4.0, the concept of Touchless Calibration (TCal) was introduced. In the next three years, in many papers presented on conferences, the most important aspects of the TCal were considered. All these considerations showed that the TCal could provide a benefit for the manufacturing companies in regards the calibrations of the measurement systems used in the production processes. The next step was the experimental validation of the TCal for DC voltage calibrations and, it was done for two possible cases. The results, analysis and comments on the practical experiment in both cases, were pretty much encouraging. The work presented in this paper deals with the experiment regarding the case of use of TCal through Internet for the companies in the manufacturing industry. The experiment is done for DC voltage calibrations in the range from 0 to 10V by using a VFC (Voltage to Frequency Converter) as a Sensor&Transducer and a FVC (Frequency to Voltage Converter) as a Sensor & Actuator. The experiment is designed and executed without any physical connection between the Sensor&Transducer and Sensor&Actuator. The idea was to investigate the use of TCal through Internet, without the digital communication provided by the Industry 4.0 network. The focus was set on the worst-case scenarios. In this paper, it is shown that, the TCal through Internet can be used by the manufacturing companies for the calibration of measurement systems used to measure DC voltages in the range from 0V to 10V with tolerances (USL – LSL) bigger than 1.0677V (± 0.534V).

Keywords: Industry 4.0, TCal, Touchless Calibration, Voltage Calibration

1. Introduction

The concept of Touchless Calibration (TCal) was introduced in 2018 [1] as contribution to the Metrology for Industry 4.0. The idea was to use the advanced digitalization of the production processes, which will be provided by Industry 4.0 and to decrease the costs, needed resources and the speed of calibrations for the measurement systems in the manufacturing industry. For the last few years, many aspects of TCal were analyzed with intention to determine and, possibly, to check its feasibility and its range of use in the manufacturing companies.

The considerable analysis of the Type A and Type B uncertainties [2] showed that the TCal is superior regarding the Type A uncertainties comparing to the classical calibration. Regarding the Type B uncertainties, the TCal highly depends on the method chosen for transducing the calibration data at the Transmitter side and its recreation at the Receiver side. The Cost-Benefit analysis [3] in regards the costs and the time, showed that there is considerable benefit of using the TCal by the manufacturing companies. In the scope of the requirements for the laboratories expressed by ISO 17025:2017 standard, the FMEA for TCal was produced and analyzed [4] for voltage calibrations. It showed that there are no considerable risks to implement TCal in the laboratories. Having in mind that, the most critical for decreasing the Type B uncertainties and with intentions to provide more guidance for general application of TCal, some considerations regarding the method chosen for TCal were presented in [5].

At the end of 2020, the experiment for validation of the TCal was executed in the calibration laboratory of the Institute for Measurements and Electric Materials at the Faculty of Electrotechnics and IT (FEIT) in Skopje. The experiment [6] provided the criteria in which situations, based on the product tolerances, the TCal could be used in the manufacturing industry for DC voltage calibrations in the range from 0 to 10V.

2. Previous Works in Regards Internet Calibration

Internet and its benefits are highly appreciated in the scientific community, so it is understandable, that in the past two decades, there were few attempts to provide calibrations of measurement systems through Internet. Anyway, most of these attempts were limited in their content and their applications.

A paper presented in IEEE Transactions on Instrumentation and Measurement by M. M. Albu et. al. in 2005 [7] was regarding the communication capabilities embedded in modern measurement system. The design of secure communication system for Internet-enabled calibration services was considered by M. Jurchevic et. al. [8]. An excellent paper was presented in Measurements (Elsevier) by T. Kobata et. al. in 2012 [9]. It was regarding the Internet-supported calibrations for measurement systems used for the pressure measurements.

The most theoretical and practical efforts to promote the Internet calibration were put by O. Velychko who, alone or together with co-authors, has published few papers regarding this topic. His paper [10] at X International Congress of Electrical Metrology (X SEMETRO) deals with calibration of Digital Multimeters for electrical signals, a topic similar to the one presented in this paper.

The main point of all these efforts was that they use a Transferring Standard which is calibrated in the laboratory where the Reference Calibration Standard (RCS) is. The Transferring Standard is then sent to the manufacturing (customer) laboratory and the calibration is done at the customer location. So, the Internet services are used only for the remote monitoring and control of the Transferring Standard by the calibration laboratory.

The concept of TCal is quite different [1, 2]. With TCal, there is a Sensor&Transducer which transduces the calibration data from the RCS in the calibration laboratory and these data are sent through Industry 4.0 network to the company's laboratory. There, the received data are recreated (an inverse transducing is done) by the Sensor&Actuator and recreated data are used for the calibration. To provide traceability and to increase the accuracy of the calibrations, the process of Relative Calibration is executed between the Sensor&Transducer and Sensor&Actuator in the company's laboratory. When the necessary pairing between these two devices is achieved [2], the Sensor&Transducer is sent to the calibration laboratory and connected there to the RCS.

So, if the TCal is used, there is no travel of the measurement system or any standard between the calibration and company's laboratories. Only the Sensor&Transducer travels and there is only interchange of the data between the calibration and company's laboratories.

3. Experiment for Checking the TCal Through Internet

The experiment, used to check the suitability of TCal through Internet calibrations of DC voltage digital multimeters in the range from 0 to 10V, is similar to the experiment used for the TCal validation explained in [6].

The experiment and connections between the instrumentation are presented on Figure 1.

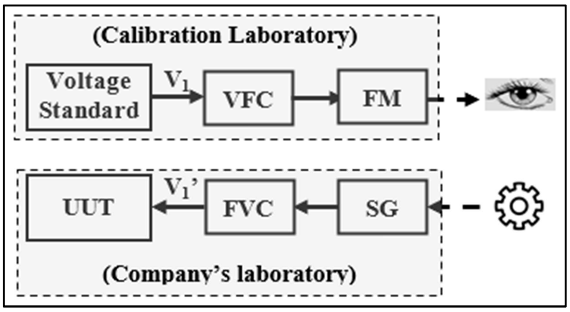

Figure 1. *Connection of the devices for TCal for DC calibration through Internet.*

As it can be seen on Figure 1, in the "calibration laboratory", there were Voltage Standard, VFC and Frequency Meter (FM). In the "company laboratory", there were Signal Generator (SG), FVC and UUT.

Of course, the "calibration laboratory" and "company's laboratory" were just simulated. The experiment was done in the same laboratory as the experiment in [6] and the same instrumentation was used (Figure 2):

1) digital multimeter Fluke 8846A used as UUT;
2) Voltage calibration standard Fluke 5500 used as Voltage Standard;
3) Voltage to Frequency Converter (VFC); and
4) Frequency-to Voltage Converter (FVC).

In addition, there was a need for Frequency Meter (Fluke 8846A was used) and Signal Generator (Fluke 5500 was used).

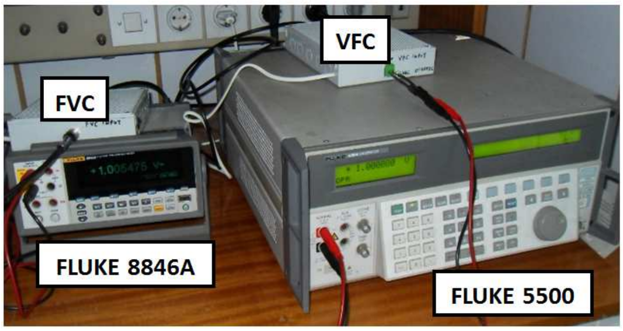

Figure 2. *Calibration system used for TCal for DC calibration through Internet.*

3.1. The Experiment

The experiment was conducted by alternate changes of the Calibration Laboratory configuration (upper part of the Figure 1) and Company Laboratory configuration (lower part of the Figure 1). The reason for that is that the Fluke 5500 was alternatively used as Voltage Standard and as SG and the Fluke 8846A was alternatively used as UUT and as Frequency Meter in the different phases of the experiment. So, the overall experiment was done in two configurations, each of them executed as separate phase. It means that there were two phases where two configurations were changed alternatively.

The first phase was:

The configuration for the "calibration laboratory" was set: The Fluke 5500 (as Voltage Standard) was connected to the input of VFC and the output of the VFC was connected to the Fluke 8846A (in the mode of operation as Frequency Meter).

The operator will adjust the voltage of 1V on the Fluke 5500 and he will read the frequency shown on the Fluke 8846A (the "eye" on Figure 1). The operator will write it, in previously prepared, measurement table. When this is done, the Fluke 5500 and Fluke 8846A would be disconnected from that configuration.

The second phase was:

The configuration for the "company's laboratory" was set: The Fluke 8846A (as UUT) was connected to the output of FVC and the input of the FVC will be connected to the Fluke 5500 (in the mode as Signal Generator).

The operator will adjust the frequency (corresponding to 1V from the first phase) on the Fluke 5500 and the voltage shown on the Fluke 8846A will be read by the operator. He will write the measured value in, previously prepared, measurement table.

These two phases will be changed alternatively for each voltage in the range from 1V to 10V in increments of 1V.

How this experiment simulates the TCal in the reality?

The simplified version looks like this:

The manufacturing company will purchase the VFC and FVC for the ranges of DC voltages which are subject of calibrations. The company will execute the Relative Calibration in its laboratory and they will send the VFC to the calibration laboratory. The calibration laboratory will connect the input of the VFC to their standard and the output to the Frequency Meter. The readings of the Frequency Meters will be presented to the Internet dedicated channel on the calibration laboratory website. The operators in the company's laboratory will have a User Name and Password to access this dedicated channel and they will read the output of the Frequency Meter.

In the company's laboratory, the input of the FVC will be connected to the Signal Generator and the output to the UUT. The read value from the Internet channel will be adjusted on the Signal Generator. The output of the FVC will generate the voltage which will be used to calibrate the UUT. Different voltages will be represented through different frequencies and the changes of the calibration voltages will be periodically provided in reasonable time intervals.

Of course, there will be some signed agreement in advance, between the calibration laboratory and the company, so all details about timings and transfer of data will be coordinated. In addition, all legal matters will be clarified.

3.2. Practical Realization of VFC and FVC Devices

The VFC and FVC are the same devices as for experiment explained in [6].

The VFC is based on the VFC 320 integrated circuit (produced by Burr&Brown Corporation) and the FVC device is based on the LM2907N integrated circuit (produced by National Semiconductor). To provide better accuracy and stability of the devices, particular emphasize is given to both power supplies.

For the VFC power supply, the 78L15 and on the 79L15 integrated circuits were used, because there is need for +15V and -15V. In addition, two lowpass filters in π-configuration were used to provide better stability of the voltages.

The FVC power supply is made to provide +13V and it is based on a switch technology by using a TNY254P device (Tinny-Switch II produced by Power Integration Inc.). This component is separated from the output with a CNY17-2 optocoupler (produced by Vishay). The voltage of 13V is chosen with intention to provide 30% more voltage than the highest voltage of 10V used for calibration.

Procedure for TCal through Internet

The following calibration procedure was used to check can the TCal be used for DC voltage calibrations through Internet:

1) All devices (Fluke 5500, VFC, FVC and Fluke 8846A) were switched on and a 15-minute warming time was given in order to stabilize the input and output signals;
2) The Relative Calibration [2] for pairing between the VFC and FVC was executed. The Fluke 8846A and Fluke 5500 were used to provide the pairing. The 10 measurements in 5 series, each with additional adjustments, were used for the pairing;
3) For the calibration itself, the 10 series in total with 10 measurements in each series, in both phases and configurations, were executed. Each series started from 1V and continued, in increments of 1V, until reaching 10V;
4) Before starting each of the series, the VFC and FVC were not switched off because there was no need to do that due to alternate connections and disconnections for the two configurations necessary for the two phases;
5) After finishing all 10 series, the Voltage Standard (Fluke 5500) was connected directly to the UUT (Fluke 8846A) and the classical calibration was executed with 10 measurements (each in increments of 1V) in the same range from 0 to 10V; and
6) All measurements were analyzed and compared with the classical calibration results and the manufacturing industry's requirements for the manufacturing tolerances and for the Measurement System Analysis (MSA) [6].

4. The Analysis of the Results

The same criteria, as explained in details in [6], were used also to analyze the results from this experiment. The used criteria are for the manufacturing companies (tolerances and MSA) and these two criteria have more importance than those for scientific purposes (based on the uncertainties presented by the standard deviations).

For more details how the criteria for manufacturing tolerances were established, you may consult [11-15]. The basis for this criterion is the Precision Index (C_p) which is defined as:

$$C_P = \frac{USL-LSL}{6\sigma} = \frac{USL-LSL}{V_T} \quad (1)$$

where $USL - LSL$ is the range of tolerances and V_T is total variability of the used measurement system calculated by the use of Average and Range (A&R) method (known also as Gauge R&R or GRR) for the MSA. By this method, the V_T is calculated as:

$$V_T = \sqrt{R_p^2 + R_d^2} \tag{2}$$

The values for the R_r (Repeatability) and R_d (Reproducibility) are calculated by:

$$R_p = \frac{6 \cdot AR}{d_2} \tag{3}$$

$$R_d = \sqrt{\left(\frac{6 \cdot AD}{d_2}\right)^2 - \frac{R_p^2}{n \cdot r}} \tag{4}$$

where AR is the Average of Ranges (see Table 5 in the Appendix); the d_2 is a coefficient which depends on the number of operators (3) and the number of series (10 measurements each series) by each operator. In this case, for 3 operators and 2 series by each operator, the value of d_2 is equal to 1.91; AD is the Average of Differences (see Table 6 in Appendix) and $n \cdot r$, in this case, is 20 (2 operators x 10 measurements in each series).

Having in mind that for the MSA there is need for 3 operators and 2 series for each of them, there is need for 6 groups of data. These data were calculated by scaling the values [6] from the measurements of 1V (Session 1.1), 3V (Session 1.2), 5V (Session 2.1), 7V (session 2.2), 9V (Session 3.1) and 10V (session 3.2).

For more details how the criterion for the MSA was established, you may consult [16-18]. For more details how the comparison of TCal and classical calibration is done, you my consult [6], 19-22].

The criteria for the manufacturing processes and the MSA are actually combined into one criterion expressed by:

$$USL - LSL > C_p \cdot V_T \cdot 6\sqrt{82} \; or$$

$$USL - LSL > 17.93 \cdot V_T \tag{5}$$

4.1. Comments Regarding the Results of TCal for DC Voltages by Comparing Uncertainties

Considering the results of presented in Table 2 in the Appendix, it can be noticed that for all measurements, the TCal through Internet, can achieve an accuracy of up to 10mV. In all range from 0 to 10V, the difference between different measurements is on the 2nd and the bigger decimal places.

For the comparison of the values of Type B uncertainties (σ_{ds}) for TCal [6] to the values of Type B uncertainties for classical calibration (Tables 2 and 3 from the Appendix), there is need to know the DC voltage uncertainty for the classical calibration in the range of interest (between 0V and 10V). Calculating the average value of the error [21, 22] from the Table 3 of the calibration uncertainty for classical calibration is 0.0000524.

Using the data in the Table 2, for the calculation of the average standard deviation for the TCal (σ_{ds}), gives the result of 0.0060161. Comparing these two values, for TCal and for classical calibration, it can be noticed that the Type B uncertainties for TCal are bigger 149 times.

It may look inappropriate, but please have in mind that this experiment was executed by having in mind the worst-case scenarios. In addition, please have in mind that theoretical calculations, done before the experiment predicted that this uncertainty will be approximately 330 times bigger for the TCal than for the classical calibration. So, the practical realization of TCal through Internet showed, approximately, two times better results than theoretical prediction.

Looking at the results and the analysis for each voltage in the range from 0 to 10V, it can be concluded that the manufacturing company can use TCal for calibration of their multimeters, only if the required range of accuracy is not bigger than 10^{-1}. This is the same criteria which applies for scientific purposes.

4.2. Comments Regarding the Results of TCal for Manufacturing Companies in Regards the Tolerances and MSA

The point in this analysis is given to finding the tolerances established (or accepted) by the manufacturing companies if they would like to use TCal through Internet for calibration of their multimeters for DC voltages from 0 to 10V.

For this purpose, the (5) is used. By including, calculated from the experiment, the value for the V_T in (5), the result will be $USL - LSL$ = 1.0677V. It means that the manufacturing companies may use the TCal through Internet if their tolerances for the DC voltage measurements are $USL - LSL$ = ±0.534V.

5. Conclusion

It can be noticed that, by using the criterion with uncertainties for the TCal through Internet, the TCal can be used when the manufacturing company is satisfied with the accuracy of 10^{-1}.

However, this is not applicable criterion for the manufacturing companies, so the TCal through Internet can be used there for the calibration of any measurement system used to measure DC voltage in the range from 0 to 10V with tolerances bigger than USL – LSL = ±0.534V.

6. Discussion for Improvement

This is the criterion which is coming from the connection of the C_p and MSA. Anyway, for proper execution of the MSA for the manufacturing companies, there are plenty other parameters (linearity, sensitivity, etc.) which need to be considered [17]. In this work and in the [6], the emphasize is given only to the V_T, because this is the biggest factor that contributes to the applicability of the TCal [1, 2]. All other parameters for the MSA, are same as for the classical calibration, so they were not included in the analysis.

Furthermore, the experiment and the analysis were done for the worst-case scenarios which can be produced. For example, the value for C_p = 1.33 was used, but in reality, C_p = 1.67 (even

C_p = 2) can be used as well. Using the C_p = 1.67, gives a C_p = 1.33 for the product variability [17] and the rest (1.67 – 1.33 = 0.34) can be associated to the V_T. If the C_p = 1.67 instead C_p = 1.33 is used, the assumed value for V_T of 10% will increase to 20% [6] which will provide better results about the applicability of the TCal through Internet.

Next area for worst-case scenario is the expression of the calibration results. In the calibration procedure of the Institute for Measurements and Electric Materials of the Faculty of Electrotechnics and IT (FEIT) in Skopje, the results are expressed as $\mu \pm 2\sigma$. This result is associated with the probability of less than 95% that the true value of measurement is in that interval. In this paper, the interval $\mu \pm 3\sigma$ was used, which is associated with probability of 99.73% that the true value of the measurement is in that interval. Using $\mu \pm 2\sigma$ will provide more improvement the results in Table 2 from Appendix.

Another area for the worst -case scenario is calculation of R_p and R_d. In (3) and (4), the multiplication with 6 is used which is again, very strong requirement, because it represents 99.73% of the Repeatability (R_p) and Reproducibility (R_d) ranges. In the automotive industry, where the MSA is requirement for the ISO/TS 16949 standard certification, the multiplication with 5.15 is used in (3) and (4). With this value the R_p and R_d ranges will be 95%. Using this value in (3) and (4) will additionally improve the results for $USL – LSL$.

Also, having in mind that as Frequency Meter and as Signal Generator were used Fluke 8846A and Fluke 5500 respectively, using the high-end Frequency Meter and Signal Generator will also improve the results.

Finally, this experiment was done by the VFC and the FVC devices produced in-house. The author did not have the resources available to established companies who deal with the design and the production of high-end measurement equipment. Having high-end VFC and FVC devices, will also improve the picture about applicability of the TCal through Internet.

The presented results in this paper will hopefully provide interest for further development of the VFCs and FVCs. Improving them and using more realistic assumptions regarding worst-case scenarios used for this experiment, will also improve the results presented here.

Appendix

Table 1. *Units for results of experiment regarding TCal for dc voltage calibration with frequencies.*

Series No. 1				Series No. 2			
Standard	FM (Hz)	SG (Hz)	UUT (V)	Standard	FM (Hz)	SG (Hz)	UUT (V)
1	988.9	989	1.0160	1	989.6	990	1.0190
2	1978.4	1978	2.0241	2	1979.5	1980	2.0244
3	2967.7	2968	3.0263	3	2969.4	2969	3.0268
4	3957.0	3957	4.0234	4	3959.0	3959	4.0243
5	4946.4	4946	5.0123	5	4949.0	4949	5.0142
6	5935.7	5936	6.0010	6	5938.7	5939	6.0049
7	6925.4	6925	6.9858	7	6929.0	6929	6.9918
8	7915.3	7915	7.9787	8	7918.6	7919	7.9820
9	8905.7	8906	8.9642	9	8909.3	8909	8.9665
10	9896.4	9896	9.9490	10	9900.0	9900	9.9483
Series No. 3				Series No. 4			
Standard	FM (Hz)	SG (Hz)	UUT (V)	Standard	FM (Hz)	SG (Hz)	UUT (V)
1	990.6	991	1.0190	1	989.1	989	1.0165
2	1981.7	1982	2.0268	2	1978.6	1979	2.0234
3	2972.6	2973	3.0295	3	2968.1	2968	3.0237
4	3963.4	3963	4.0260	4	3957.7	3958	4.0186
5	4954.1	4954	5.0150	5	4947.0	4947	5.0079
6	5944.7	5945	6.0050	6	5936.7	5937	5.9948
7	6934.8	6935	6.9920	7	6926.6	6927	6.9794
8	7925.7	7926	7.9915	8	7916.7	7917	7.9670
9	8916.8	8917	8.9659	9	8907.1	8907	8.9494
10	9908.7	9909	9.9466	10	9898.1	9898	9.9290
Series No. 5				Series No. 6			
Standard	FM (Hz)	SG (Hz)	UUT (V)	Standard	FM (Hz)	SG (Hz)	UUT (V)
1	989.4	989	1.0147	1	989.1	989	1.0150
2	1979.2	1979	2.0208	2	1978.8	1979	2.0210
3	2968.9	2969	3.0205	3	2968.6	2969	3.0205
4	3958.6	3959	4.0163	4	3958.6	3959	4.0167
5	4948.3	4948	5.0018	5	4948.7	4949	5.0039
6	5938.2	5938	5.9909	6	5939.2	5939	5.9916
7	6928.1	6928	6.9770	7	6930.0	6930	6.9787
8	7918.2	7918	7.9641	8	7921.5	7922	7.9683
9	8908.9	8909	8.9480	9	8913.5	8913	8.9560
10	9899.1	9899	9.9265	10	9906.7	9907	9.9380

Series No. 7				Series No. 8			
Standard	FM (Hz)	SG (Hz)	UUT7 (V)	Standard	FM (Hz)	SG (Hz)	UUT (V)
1	990.4	990	1.0159	1	989.3	989	1.0138
2	1981.4	1981	2.0227	2	1979.3	1979	2.0194
3	2972.3	2972	3.0232	3	2969.4	2969	3.0186
4	3963.1	3963	4.0198	4	3959.8	3960	4.0163
5	4953.6	4954	5.0058	5	4950.4	4950	5.0046
6	5944.3	5944	5.9939	6	5941.3	5941	5.9958
7	6935.1	6935	6.9818	7	6932.6	6933	6.9860
8	7926.2	7926	7.9680	8	7924.6	7925	7.9790
9	8917.1	8917	8.9530	9	8917.0	8917	8.9670
10	9909.2	9909	9.9270	10	9911.6	9912	9.9590
Series No. 9				Series No. 10			
Standard	FM (Hz)	SG (Hz)	UUT (V)	Standard	FM (Hz)	SG (Hz)	UUT (V)
1	990.4	990	1.0166	1	989.1	989	1.0136
2	1981.3	1981	2.0247	2	1978.7	1979	2.0193
3	2972.3	2972	3.0254	3	2968.4	2968	3.0169
4	3963.0	3963	4.0212	4	3958.3	3958	4.0118
5	4953.7	4954	5.0078	5	4948.6	4948	5.0001
6	5944.4	5844	5.9936	6	5938.8	5939	5.9876
7	6934.7	6935	6.9824	7	6930.4	6930	6.9750
8	7925.2	7925	7.9668	8	7920.4	7920	7.9615
9	8916.5	8917	8.9511	9	8912.2	8912	8.9470
10	9908.1	9908	9.9238	10	9905.6	9906	9.9239

Table 2. *Units for Results of Experiment regarding TCal For DC Voltage Calibration.*

Series	**1 V**	**2 V**	**3 V**	**4 V**	**5 V**	**6 V**	**7 V**	**8 V**	**9 V**	**10 V**
1	1.0160	2.0241	3.0263	4.0234	5.0123	6.0010	6.9858	7.9787	8.9642	9.9490
2	1.0190	2.0244	3.0268	4.0243	5.0142	6.0049	6.9918	7.9820	8.9665	9.9483
3	1.0190	2.0268	3.0295	4.0260	5.0150	6.0050	6.9920	7.9915	8.9659	9.9466
4	1.0165	2.0234	3.0237	4.0186	5.0079	5.9948	6.9794	7.9670	8.9494	9.9290
5	1.0147	2.0208	3.0205	4.0163	5.0018	5.9909	6.9770	7.9641	8.9480	9.9265
6	1.0150	2.0210	3.0205	4.0167	5.0039	5.9916	6.9787	7.9683	8.9560	9.9380
7	1.0159	2.0227	3.0232	4.0198	5.0058	5.9939	6.9818	7.9680	8.9530	9.9270
8	1.0138	2.0194	3.0186	4.0163	5.0046	5.9958	6.9860	7.9790	8.9670	9.9590
9	1.0166	2.0247	3.0254	4.0212	5.0078	5.9936	6.9824	7.9668	8.9511	9.9238
10	1.0136	2.0193	3.0169	4.0118	5.0001	5.9876	6.9750	7.9615	8.9470	9.9239
μ	1.0160	2.0227	3.0231	4.0194	5.0073	5.9959	6.9830	7.9727	8.9568	9.9371
σ_{ds}^2	0.000003545	0.000006120	0.000015860	0.000019096	0.000026187	0.000034745	0.000034281	0.000091530	0.000067945	0.000163203
σ_{ds}	0.001882935	0.002473953	0.003982517	0.004369897	0.005117334	0.005894527	0.005854998	0.009567125	0.008242903	0.012775102
Rounded $3\sigma_{ds}$	0.0056	0.0074	0.0119	0.0131	0.0154	0.0177	0.0176	0.0287	0.0247	0.0383
Final results	1.0160 ± 0.0056	2.0227 ± 0.0074	3.0241 ± 0.0119	4.0201 ± 0.0131	5.0073 ± 0.0154	5.9959 ± 0.0177	6.9830 ± 0.0176	7.9727 ± 0.0287	8.9616 ± 0.0247	9.9371 ± 0.0383

Table 3. *Results For Classical DC Voltage Calibration.*

	1 V	**2 V**	**3 V**	**4 V**	**5 V**	**6 V**	**7 V**	**8 V**	**9 V**	**10 V**
Measured	0.999986	1.99997	2.99998	3.99995	4.99994	5.99993	6.99992	7.99991	8.99990	9.99999
Error	0.000014	0.00003	0.00002	0.00005	0.00006	0.00007	0.00008	0.00009	0.00010	0.00001

Table 4. *Measurement Results for MSA Calculations Using A&R Method.*

Series	**Session 1.1**	**Session 1.2**	**Range 1**	**Session 2.1**	**Session 2.2**	**Range 2**	**Session 3.1**	**Session 3.2**	**Range 3**
1	1.0160	1.0088	0.0072	1.0025	0.9980	0.0045	0.9960	0.9949	0.0011
2	1.0190	1.0089	0.0101	1.0028	0.9988	0.004	0.9963	0.9948	0.0015
3	1.0190	1.0098	0.0092	1.0030	0.9989	0.0041	0.9962	0.9947	0.0015
4	1.0165	1.0079	0.0086	1.0016	0.9971	0.0045	0.9944	0.9929	0.0015
5	1.0147	1.0068	0.0079	1.0004	0.9967	0.0037	0.9942	0.9927	0.0015
6	1.0150	1.0068	0.0082	1.0008	0.9970	0.0038	0.9951	0.9938	0.0013
7	1.0159	1.0077	0.0082	1.0012	0.9974	0.0038	0.9948	0.9927	0.0021
8	1.0138	1.0062	0.0076	1.0009	0.9980	0.0029	0.9963	0.9959	0.0004
9	1.0166	1.0085	0.0081	1.0016	0.9975	0.0041	0.9946	0.9924	0.0022
10	1.0136	1.0056	0.0080	1.0000	0.9964	0.0036	0.9941	0.9924	0.0017
	1.01601	1.0077	0.00831	1.00148	0.99758	0.0039	0.9952	0.99372	0.00148

Table 5. *Results For Repeatability Calculations Using A&R Method.*

Average for Operator 1	Average for Operator 2	Average for Operator 3	Total Average	Average of Ranges (AR)	Repeatability
1.011855	0.99953	0.99446	1.001948	0.004563333	0.02427305

Table 6. *Data For Reproducibility Calculations Using A&R Method.*

Series	Smallest	Highest	Difference
1	0.9960	1.0160	0.0200
2	0.9963	1.0190	0.0227
3	0.9962	1.0190	0.0228
4	0.9944	1.0165	0.0221
5	0.9942	1.0147	0.0205
6	0.9951	1.0150	0.0199
7	0.9948	1.0159	0.0211
8	0.9963	1.0138	0.0175
9	0.9946	1.0166	0.0220
10	0.9941	1.0136	0.0195
1	0.9949	1.0088	0.0139
2	0.9948	1.0089	0.0141
3	0.9947	1.0098	0.0151
4	0.9929	1.0079	0.0150
5	0.9927	1.0068	0.0141
6	0.9938	1.0068	0.0130
7	0.9927	1.0077	0.0150
8	0.9959	1.0062	0.0103
9	0.9924	1.0085	0.0161
10	0.9924	1.0056	0.0132
Average of Differences (AD)			0.017395

Table 7. *Values For V_T Calculated Using A&R Method.*

Repeatability	Reproducibility	V_T
0.02427305	0.054373757	0.05954567

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