Metrol. Meas. Syst., Vol. 26 (2019) No. 2, pp. 283–296.

METROLOGY AND MEASUREMENT SYSTEMS

Index 330930, ISSN 0860-8229

www.metrology.pg.gda.pl

EVALUATION OF A HIGH-PRECISION DIGITAL MULTIMETER BY THE LABORATORY OF CALIBRATION OF MULTIFUNCTION ELECTRICAL INSTRUMENTS OF INRIM

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Abstract

A metrological verification of a high precision digital multimeter was made by the laboratory of calibration of programmable electrical multifunction instruments of the National Institute of Metrological Research (INRIM) in order to verify its accuracy and stability. The instrument had been tested for a period of six months for five low-frequency electrical quantities (DC and AC Voltage and Current and DC Resistance). Its stability and precision were compared with the accuracy specifications of the manufacturer. As a new approach, a performance index of the DMM was introduced and evaluated for each examined measurement point. The DMM showed a satisfactory agreement with its specifications to be considered at the level of other top-class DMMs and even better in some measurements points.

Keywords: digital multimeter, calibration, measurement uncertainties, low-frequency electrical measurements, performance index, measurement specifications.

1. Introduction

Since the late eighties, high precision electrical electronic instruments, such as *digital multimeters* (DMMs) and *multifunction calibrators* (MFCs), have been used by calibration and industrial laboratories for the five basic electrical low-frequency quantities (DC and AC Voltages and Currents and DC Resistance), both as reference or working Standards. Hence, the traceability from the national standards usually maintained at the National Measurement Institutes (NMIs) has significantly changed from the past when electrical laboratories were equipped mainly with material standards as DC Voltage cells, resistors, shunts and manually-operating dividers. In addition, in modern electrical calibration laboratories a high precision DMM plays an important role not only to calibrate the customer's sources or standards but it can also fulfil a further double job: it can act as a laboratory reference standard or as transfer instrument by means of which to trace other instruments of a laboratory to the national standards [1]. To meet the need of calibration of top-level DMMs and MFCs, at the National Institute of Metrological Research (INRIM) since the early nineties the laboratory of calibration of programmable electrical multifunction instruments (INRIM-Lab) has been set up. The INRIM-Lab is equipped with a group of reference standards (Fig. 1): a 10 V Zener-diode based DC Voltage standard, a DMM calibrated in linearity used as a voltage divider and an automated fixed ratio DC Voltage divider [2], a set of standard resistors and

Article history: received on Oct. 16, 2018; accepted on Dec. 23, 2018; available online on Jun. 28, 2019; DOI: 10.24425/mms.2019.128356.

shunts, and a programmable AC/DC Voltage transfer standard. All these standards are periodically calibrated vs the national standards. Complete the INRIM-Lab equipment three MFCs, used as working instruments, and some other auxiliary instruments to extend the measurement fields.

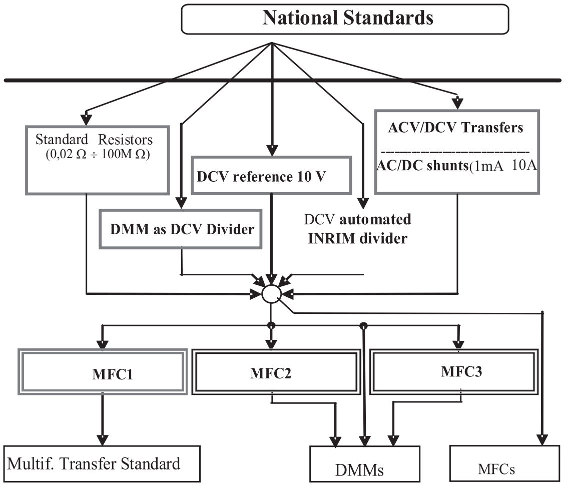

Fig. 1. The traceability chain from the national standards of the INRIM-Lab.

The INRIM-Lab is withthe new "Applied Metrology and Engineering" Unit of INRIM whose missions are, in addition to the research, the NMI role, the knowledge transfer and the support to industry. In the framework of this last task, the INRIM-Lab made a metrological evaluation of an 8.5-digit high-precision DMM, ordered by its manufacturer. At the INRIM-Lab, a complete calibration of a DMM consists of three steps: an initial verification, an adjustment as suggested by the manufacturer and a final verification [1]. With the verifications, a set of measurement values are applied to the DMM by the reference measurement system to establish for each value a relative deviation of the DMM from the applied reference value.

2. Examined DMM

Modern high-precision DMMs are developed with digital and analogue electronic components. They are very accurate (close to the best commercial standards), as they are equipped with DC Voltage references, resistance networks, ac/dc converters, and analogue-to-digital (A/D) converters. They operate in wide measurement ranges of AC and DC voltage and current and DC resistance. In addition, they are equipped with a microprocessor-based control unit for internal settings and execution of internal self-calibration procedures, storing also their correction factors. The evaluated DMM is an 8.5 5-digit meter considered to be at the same level of the best now commercially available as the Agilent/HP 3458A. Its main features are:

- Precision: 4 ppm, resolution: 8.5 digit;
- Voltages AC/DC up to 1000V;
- Currents AC/DC up to 30 A;
- DC Resistance measurements from 1 Ω to 2 TΩ;
- Electrometer function for high-value resistance measurements at low current and low noise;
- Rear-panel input terminals;
- Advanced ratio functions, as adjusted value and absolute ratio.

3. Evaluation of results

The manufacturer sent to INRIM a prototype of the DMM for technical evaluation. At this stage, some changes were suggested to the manufacturer to improve the instrument, for example concerning the input terminals. An updated DMM model was then sent to the INRIM-Lab. The introduced changes being accepted as satisfactory, the DMM was then verified in the five fundamental low-frequency electrical quantities comparing its readings with the reference values provided by an MFC J. Fluke 5700 A of the INRIM-Lab by means of an automated measurement system. This MFC is in turn calibrated vs. the reference standards of the same laboratory, also involving the system described in [3]. The DMM had been tested for a period of six months without performing an adjustment to evaluate its time stability vs. its specifications. The INRIM-Lab verified the DMM using the measurement procedures approved by INRIM as a signatory of the CIPM MRA[1] and supported by approved CMCs. In addition, in DC Voltage, the DMM was also compared with a recently built high precision High DC Voltage Standard [4].

3.1. Main results

The verification of the DMM was performed in the following measurement ranges:
- DC Voltage: 100 mV, 1 V, 10, V, 100 V and 1000 V;
- AC Voltage 100 mV at (0.04, 1, 20) kHz, 1 V at (0.04, 1, 20, 100, 300, 1000) kHz, 10 V at (0.04, 1 20, 100, 200) kHz, 100 V at (0.04, 1, 20, 50) kHz and 1000 V at (0.04, 1, 20, 30) kHz;
- DC Current: 100 µA, 1 mA, 100 mA, 1A, 10 A, 30 A;
- AC Current: 100 µA at (0.04, 0.3, 1) kHz, 1 mA, 10 mA, 100 mA, 1A, 10 A and 30 A at (0.04, 0.3, 1, 5) kHz;
- DC Resistance 4 Wires, 1 Ω, 10 Ω, 100 Ω, 1 kΩ, 10 kΩ, 100 kΩ. 2 Wires: 1 MΩ and 10 MΩ .

To facilitate the understanding of the measurement data, Figs. 2 to 21 show the results obtained as relative deviations from the applied reference values in the main measurement ranges. For some

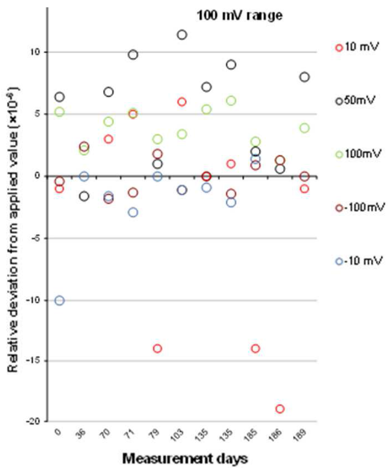

Fig. 2. Deviations for DC Voltage in the 100 mV range.

[1]The CIPM Mutual Recognition Arrangement (CIPM MRA) is the framework through which National Metrology Institutes demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the Arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes.

significant values, a comparison vs. the 180-day DMM specification was also added. The y-axis reports the relative deviations of the DMM readings vs. the standard applied values while the x-axis reports the measurement days.

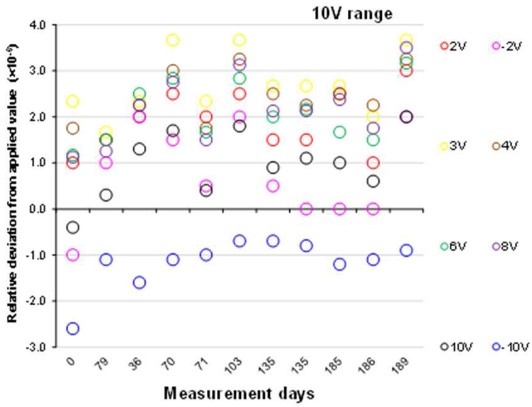

Fig. 3. Deviations for DC Voltage in the 10 V range.

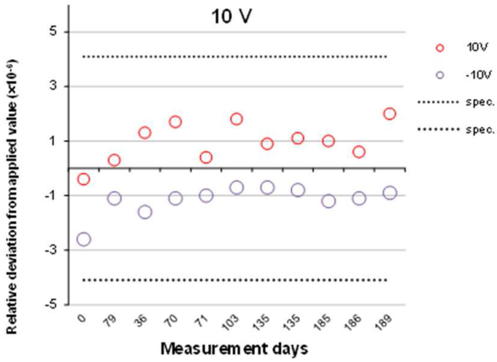

Fig. 4. Deviations for DC Voltage at 10 V vs. the 180-day specifications.

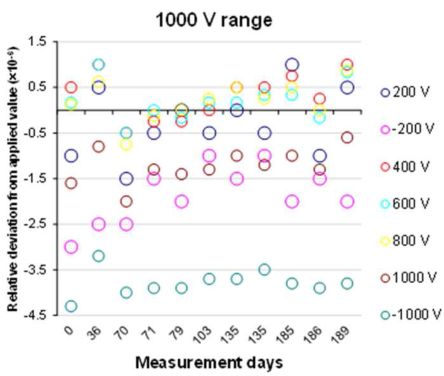

Fig. 5. Deviations in the 1000 V range for DC Voltage.

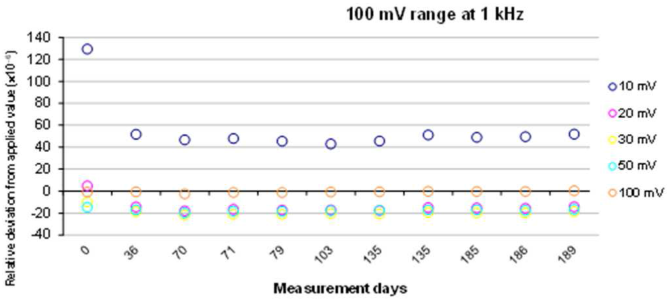

Fig. 6. Deviations in the 100 mV range at 1 kHz for AC Voltage.

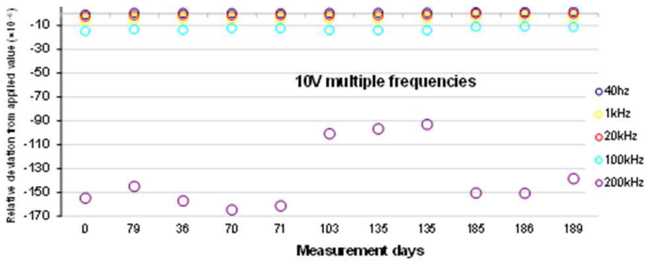

Fig. 7. Deviations at 10 V at multiple frequencies for AC Voltage.

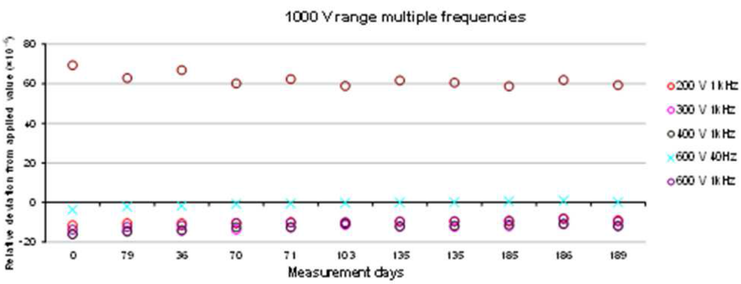

Fig. 8. Deviations in the 1000 V range at multiple frequencies for AC Voltage.

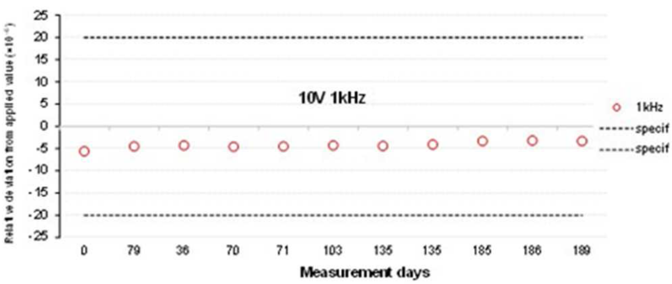

Fig. 9. Deviations for AC Voltage at 10 V 1 kHz vs. the 180-day DMM specifications.

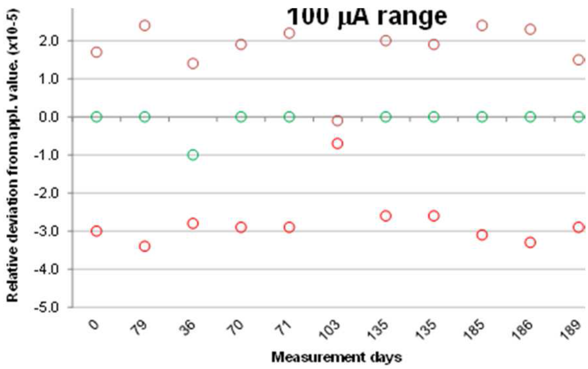

Fig. 10. Deviations in the 100 µA range for DC Current.

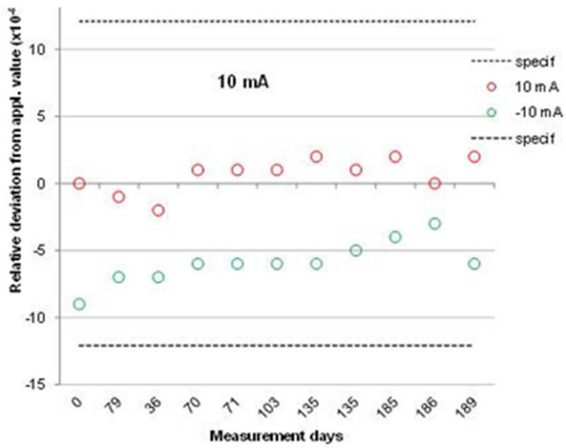

Fig. 11. Deviations for DC Current at 10 mA vs. the 180-day DMM specifications.

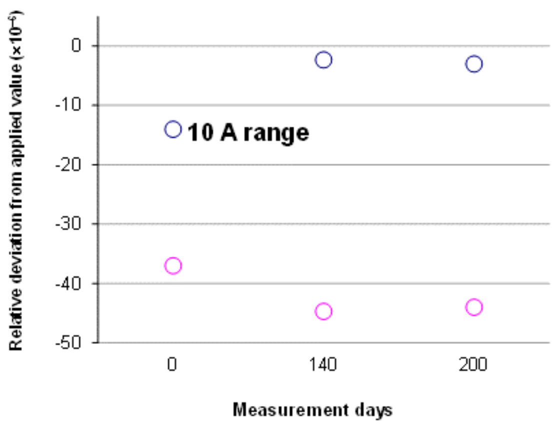

Fig. 12. Deviations in the 10 A range for DC Current.

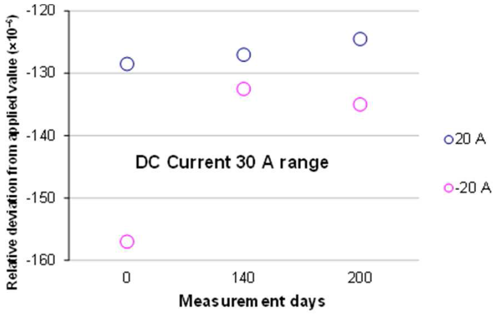

Fig. 13. Deviations in the 30 A range for DC Current.

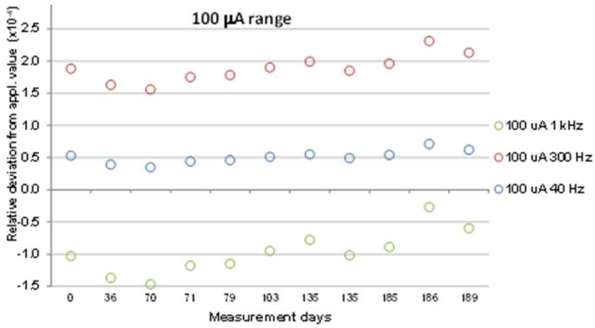

Fig. 14. Deviations in the 100 µA range at multiple frequencies for AC Current.

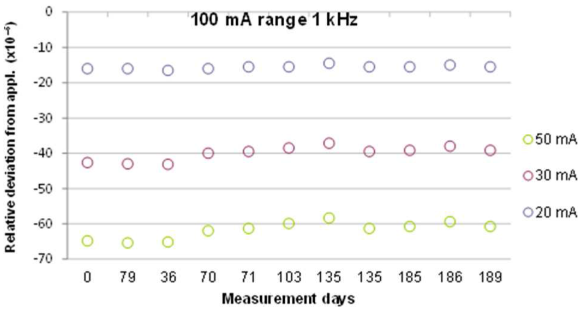

Fig. 15. Deviations in the 100 mA range at 1 kHz.

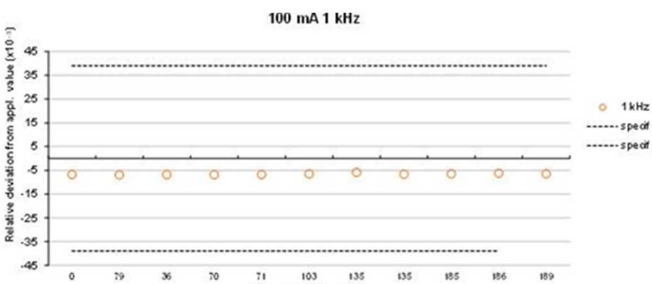

Fig. 16. Deviations at for AC Current at 100 mA, 1 kHz vs. the 180-day specifications.

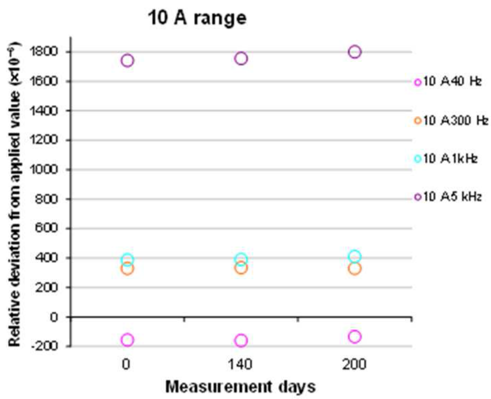

Fig. 17. Deviations in the 10 A range at multiple frequencies for AC Current.

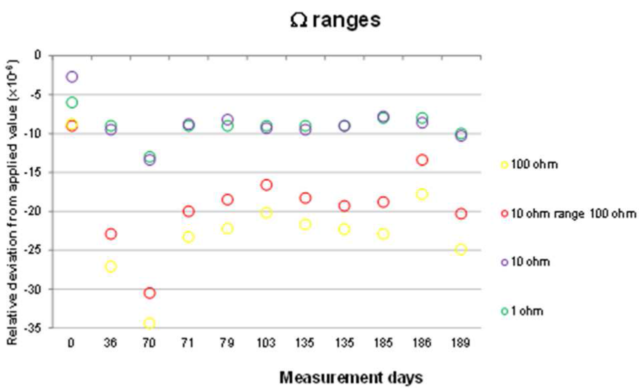

Fig. 18. Deviations in the 1 Ω, 10 Ω and 100 Ω ranges for DC Resistance.

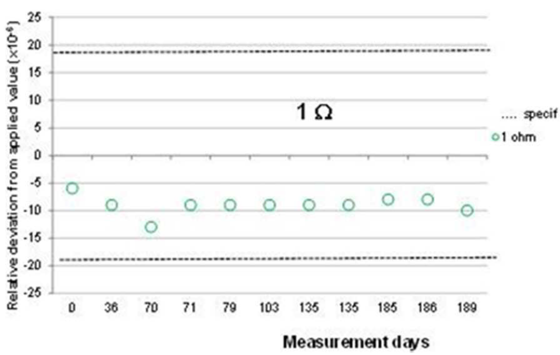

Fig. 19. Deviations for DC Resistance at 1 Ω vs. the 180-day specifications.

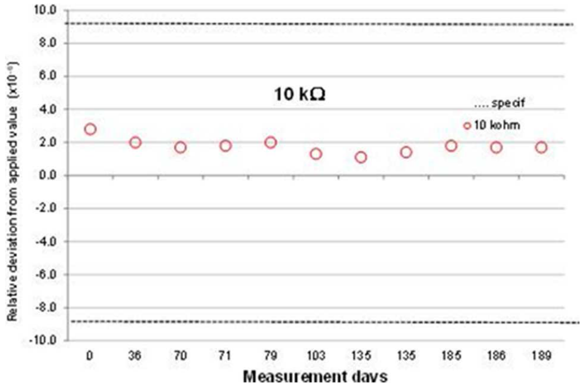

Fig. 20. Deviations at 10 kΩ vs. the 180-day specifications for DC Resistance.

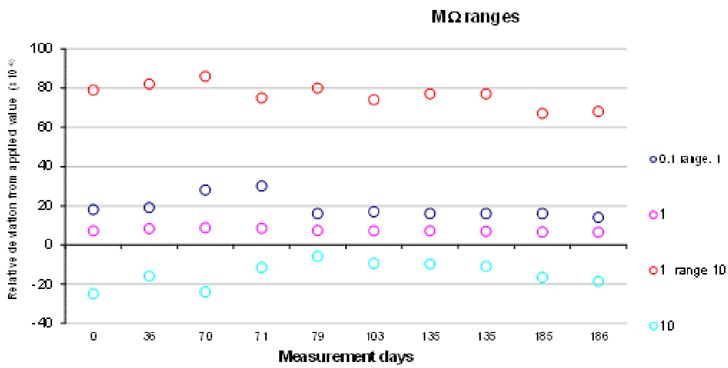

Fig. 21. Deviations in the 1 MΩ and 10 MΩ ranges for DC Resistance.

4. Data analysis

In Tables from 1 to 5, the obtained values, expressed as relative deviations vs. the applied standard values, are compared with the 180-days manufacturer specifications. In columns 1 to 8 are reported respectively: the range, the measurement value, the frequency, the 180-day specification, the difference between the first and the last verification values ($\Delta_{\text{fin-first}}$), the maximum difference between the applied standard value and the absolute value ($\Delta_{\max\text{-}abs}$), the relative uncertainty of the applied reference value and an introduced performance index of the DMM evaluated as follows:

$$pi = \frac{\Delta_{\max\text{-}abs}}{\sqrt{U_{DMM}^2 + U_{INRIM}^2}}, \tag{1}$$

where U_{DMM} is the 180-day accuracy specification of the DMM while U_{INRIM} is the expanded on used uncertainty [5] of the INRIM-Lab measurements [5]. The performance can be considered satisfactory if $|pi| \leq 1$. The introduction and evaluation of this performance index can be considered a new approach in the evaluation of top-level electrical instruments, such as DMMs and MFCs.

Table 1. DMM performance in DC Voltage.

Range	**Value (mV)**	**freq.**	**180 days spec.** ($\times 10^{-6}$)	$\Delta_{\text{fin-first}}$ ($\times 10^{-6}$)	$\Delta_{max\text{-}abs}$ ($\times 10^{-6}$)	U_{INRIM} ($\times 10^{-5}$)	***pi***
100 mV	1		174	−150	280	35	0.7[2]
	10		21	0.0	26	3.9	0.6[1]
	−10		21	−1.6	40	3.9	0.9[1]
	50		7.7	1.6	11.4	1.0	0.9[1]
	100		6.0	−1.3	6.1	0.5	0.8
	−100		6.0	0.4	2.4	0.5	0.3
	(V)					($\times 10^{-6}$)	
1 V	0.2		6.5	−0.5	3.0	4.0	0.4
	−0.2		6.5	1.0	3.5	4.0	0.5
	0.5		4.7	−2.0	5	3.5	0.9
	1		4.1	−0.3	2.7	3.0	0.5
	−1		4.1	2.3	2.6	3.0	0.5
10 V	2		6.9	2.0	3.0	2.0	0.4
	−2		6.9	3.0	2.0	2.0	0.3
	3		5.5	1.3	3.7	1.8	0.6
	4		5.0	1.5	3.3	1.8	0.6
	6		4.5	2.0	3.2	1.7	0.7
	8		4.3	2.4	3.5	1.7	0.8
	10		4.1	2.4	2.0	1.7	0.5
	−10		4.1	1.7	2.6	1.7	0.6
100 V	20		9.2	0.5	2.0	2.8	0.2
	−20		9.2	−0.5	1.0	2.8	0.1
	50		7.4	−0.2	0.8	2.8	0.1
	100		6.6	0.4	2.2	2.8	0.3
	−100		6.6	0.5	4.1	2.8	0.6
1000 V	200		11.2	1.5	1.5	3.5	0.1
	−200		11.2	1.0	3.0	3.5	0.3
	400		8.2	0.5	1.0	3.5	0.1
	600		7.2	0.7	1.0	3.5	0.1
	800		6.7	0.8	0.9	3.5	0.1
	1000		6.4	1.0	2.0	3.5	0.3
	−1000		6.4	0.5	4.3	3.5	0.6

[2]For these values the *pi* cannot be considered completely significant as the DMM declared 180-days specification is smaller than the INRIM capability, that comprehends the uncertainties of National standards, those of the traceability transfer to the MFC J. Fluke 5700 A of the INRIM-Lab and its one year use uncertainty.

Table 2. DMM performance in AC Voltage.

Range	Value (mV)	freq. (kHz)	180 days spec. ($\times 10^{-5}$)	$\Delta_{fin-first}$ ($\times 10^{-5}$)	$\Delta_{max\text{-}abs}$ ($\times 10^{-5}$)	U_{INRIM} ($\times 10^{-5}$)	*pi*
100 mV	10	1	95	−77.6	129.4	20	0.6
	20	1	55	−19.0	18.2	10	0.2
	30	1	42	−8.6	21.5	10	0.2
	50	1	31	−1.9	19.6	10	0.2
	100	0.04	28	0.7	2.1	7	0.0
	100	1	23	1.1	2.6	7	0.0
	100	20	33	−0.3	6.8	7	0.1
1 V	0.2	1	44	5.5	11.5	6	0.2
	0.5	1	26	1.4	18.2	5	0.3
	1	0.04	23	1.4	5.3	4	0.1
	1	1	20	1.2	4.7	4	0.1
	1	20	33	1.3	15.2	5	0.3
	1	100	104	1.9	12.3	8	0.1
	1	300	3400	13.5	267.5	38	0.1
	1	1000	3400	89.2	419.3	100	0.1
10 V	2	1	44	1.5	9.5	4	0.2
	4	1	29	1.8	17.8	4	0.4
	6	1	24	2.0	15.3	4	0.3
	8	1	22	2.1	10.6	4	0.2
	10	0.04	23	2.5	1.6	4	0.1
	10	1	20	2.3	5.6	4	0.1
	10	20	33	2.4	2.6	6	0.1
	10	100	104	3.4	14.8	9	0.1
	10	200	3400	16.4	164.7	40	0.0
100 V	20	1	51	1.5	18.0	4	0.3
	40	1	34	2.0	20.0	4	0.4
	60	1	28	2.0	15.2	4	0.3
	100	0.04	27	2.3	1.5	5	0.0
	100	1	23	2.1	3.2	5	0.1
	100	20	37	−9.3	10.4	5	0.2
	100	50	122	−57.9	64.2	10	0.4
1000 V	200	1	51	2.5	11.5	5	0.2
	300	1	39	4.3	16.0	5	0.3
	400	1	34	4.0	16.0	5	0.3
	600	0.04	33	3.8	3.7	6	0.1
	600	1	28	4.2	13.7	6	0.2
	600	20	44	−10.0	69.3	12	0.5
	600	100	80	0.0	0.0	55	0.0
	1000	0.04	27	5.5	5.1	6	0.1
	1000	1	23	4.7	10.7	6	0.2
	1000	20	37	−12.8	92.4	13	0.7
	1000	30	77	−25.2	190.4	26	0.7

Table 3. DMM performance in DC Current.

Range	**Value** (μA)	**freq. (kHz)**	**180 days spec.** ($\times 10^{-5}$)	$\Delta_{fin-first}$ ($\times 10^{-5}$)	$\Delta_{max\text{-}abs}$ ($\times 10^{-5}$)	U_{INRIM} ($\times 10^{-5}$)	***pi***
100 μA	10		46	0.0	18.0	9.8	0.4
	100		10	−0.2	2.4	2.3	0.2
	−100		10	0.1	3.4	2.3	0.3
	(mA)		($\times 10^{-6}$)	($\times 10^{-6}$)	($\times 10^{-6}$)	($\times 10^{-6}$)	
1 mA	0.1		46	0.0	20.00	23	0.4
	1		10	8.0	40.00	15	0.4[3]
	−1		10	5.0	23.00	15	0.3[2]
10 mA	1		48	0.0	10.0	15	0.2
	10		12.1	2.0	2.0	13	0.1
	−10		12.1	3.0	9.0	13	0.5
100 mA	10		84	10.0	40.0	15	0.5
	20		54	5.0	35.0	15	0.6
	50		36	4.0	36.0	15	0.9
	100		30	9.0	39.0	15	0.3[4]
	−100		30	8.0	38.0	15	0.3[3]
1 A	0.1		265	10.0	30.0	20	0.1
	0.2		200	5.0	25.0	20	0.1
	0.5		161	24.0	28.0	20	0.2
	1.0		148	21.0	24.0	20	0.2
	−1.0		148	19.0	19.0	20	0.1
10 A	10		355	−11.0	14.0	100	0.0
	−10		355	7.0	44.7	100	0.1
Range	**Value** (A)	**freq. (kHz)**	**180 days spec.** ($\times 10^{-6}$)	$\Delta_{fin-first}$ ($\times 10^{-6}$)	$\Delta_{max\text{-}abs}$ ($\times 10^{-6}$)	U_{INRIM} ($\times 10^{-6}$)	***pi***
30 A	20		658	−4.0	128.5	100	0.2
	−20		658	−22.0	157.0	100	0.2

Table 4. DMM performance in AC Current.

Range	**Value** (μA)	**freq. (kHz)**	**180 days spec.** ($\times 10^{-4}$)	$\Delta_{fin-first}$ ($\times 10^{-4}$)	$\Delta_{max\text{-}abs}$ ($\times 10^{-4}$)	U_{INRIM} ($\times 10^{-4}$)	***pi***
100 μA	100	0.04	3.9	0.2	0.7	1.5	0.2
	100	0.3	3.9	0.3	1.6	1.5	0.4
	100	1	3.9	0.3	3.0	1.5	0.7
	mA		($\times 10^{-5}$)	($\times 10^{-5}$)	($\times 10^{-5}$)	($\times 10^{-5}$)	
1 mA	1	0.04	39	−4.8	9.1	12	0.2
	1	0.3	39	−0.4	4.6	12	0.1
	1	1	39	9.9	9.2	12	0.2
	1	5	93	23.0	22.7	20	0.2

[3] These performance values were evaluated taking into account $\Delta_{fin-first}$ instead of $\Delta_{max\text{-}abs}$ as the declared accuracy in these points is presumably too small.

[4] These performance values were evaluated taking into account $\Delta_{fin-first}$ instead of $\Delta_{max\text{-}abs}$ as presumably a systematic error in the DMM adjustment process happened.

Table 4. [c.d.]

Range	Value (μA)	freq. (kHz)	180 days spec. (×10^{-5})	$\Delta_{fin-first}$ (×10^{-5})	$\Delta_{max\text{-}abs}$ (×10^{-5})	U_{INRIM} (×10^{-5})	*pi*
10 mA	10	0.04	28	5.9	5.6	8	0.2
	10	0.3	28	1.0	0.9	8	0.0
	10	1	28	5.5	5.4	8	0.2
	10	5	30	27.6	27.0	15	0.8
100 mA	20	1	87	16.5	16.5	8	0.2
	30	1	67	28.6	27.0	8	0.4
	50	1	51	22.8	22.4	8	0.4
	100	0.04	39	5.8	5.6	8	0.1
	100	0.3	39	3.4	3.1	8	0.1
	100	1	39	7.3	7.0	8	0.2
	100	5	93	31.5	31.3	15	0.3
	(A)						
1 A	0.3	1	86	30.9	30.0	10	0.3
	1	0.04	51	−1.3	5.5	10	0.1
	1	0.3	51	−15.3	19.0	10	0.4
	1	1	51	5.1	5.2	10	0.1
	1	5	113	−26.4	29.1	20	0.3
	(A)		(×10^{-6})	(×10^{-6})	(×10^{-6})	(×10^{-6})	
10 A	10	0.04	1120	−22	160	300	0.1
	10	0.3	930	0	335	300	0.3
	10	1	930	−23	410	300	0.4
	10	5	930	−58	1800	500	1.7[5]
30 A	20	0.04	1320	−55	75	300	0.1
	20	0.3	780	−25	400	300	0.5
	20	1	780	−35	590	300	0.7
	20	5	780	−40	1995	500	2.2[4]

Table 5. DMM performance in DC Resistance.

Range (Ω)	Value (Ω)	freq.	180 days spec. (×10^{-6})	$\Delta_{fin-first}$ (×10^{-6})	$\Delta_{max\text{-}abs}$ (×10^{-6})	U_{INRIM} (×10^{-6})	*pi*
1	1		19	−4.0	13.0	10	0.6
10	10		12	−3.6	3.3	5	0.3
100	10		18	−3.7	17.1	5	0.9
	100		9	−4.8	4.6	5	0.4
(kΩ)	(kΩ)						
1	0.1		15	−4.0	3.0	5	0.2
	1		7.8	−4.4	2.9	5	0.3
10	1		16.5	1.0	5.0	5	0.3
	10		9.3	−1.1	2.8	5	0.3

[5] These measurement points were evaluated although outside the 8081 DMM specifications and considering the same specification value at 1 kHz.

Table 5. [c.d.]

Range (kΩ)	**Value (kΩ)**	**freq.**	**180 days spec. (×10^{-6})**	**$\Delta_{fin-first}$ (×10^{-6})**	**$\Delta_{max\text{-}abs}$ (×10^{-6})**	**U_{INRIM} (×10^{-6})**	***pi***
100	10		17	1.0	7.0	5	0.4
	100		9.8	−0.7	4.1	5	0.4
(MΩ)	(MΩ)						
1	0.1		30	−14.6	30	5	1.0
	1		12	−2.8	8.7	8	0.6
10	1		94	−73.6	86	8	0.9
	10		22	31.3	24.9	16	0.9

5. Conclusions

This paper presents an example of the support activity to the manufacturing sector by the new “Applied Metrology and Engineering” Unit of INRIM). A high-precision DMM had been evaluated by the INRIM-Lab for calibration of multifunction programmable electrical instruments in for a period of six months. The DMM showed a satisfactory stability and a good agreement with its accuracy specifications. They are close to and somewhere even better than those of other top-class 8.5-digit DMMs. An introduced performance index for the evaluation of the DMM appeared to be satisfactory in each of the tested points. Nevertheless, the 10 mA and 100 mA ranges of DC current have to be further verified. In the 10 A and 30 A ranges of AC Current, the DMM was evaluated also at 5 kHz (values that currently are not reported in the DMM specifications), showing a satisfactory stability. Hence, the evaluation of the specification values for these points could be made by the manufacturer to successively add them to the current specifications. This instrument is then also suitable for accurate measurement comparisons (ILCs) between NMIs and high level secondary accredited electrical calibration laboratories. An example of this kind of ILC is described in [6] in which a top-class MFC was involved as the instrument to be calibrated. Similar instruments could be evaluated with the same approach by NMIs or by calibration laboratories equipped with suitable capabilities.

References

[1] Cassiago, C., La Paglia, G., Pogliano, U. (2000). Stability Evaluation of High–Precision Multifunction Instruments for Traceability Transfer. *IEEE Trans. Meas*., 49(6) 1206–1210.

[2] Galliana, F., Capra, P.P., Cerri, R., Lanzillotti, M. (2018). Automated precision DC voltage fixed ratios divider. *Measurement*, 122, 291–296.

[3] Galliana, F., Capra, P.P., Cerri, R., Lanzillotti, M. (2018). Automated setup to accurately calibrate electrical dc voltage generators. *Measurement*, 123, 1291–134.

[4] Galliana, F., Cerri, R., Roncaglione Tet, L. (2017). High perfomance selectable value transportable high dc Voltage standard. *Measurement*, 102, 131–137.

[5] Bich, W., Pennecchi, F. (2004). On the in-use uncertainty of an instrument. P. Ciarlini, M.G., Cox, E., Filipe, F., Pavese, D., Richter (eds). *Advanced Mathematical & Computational Tools in Metrology, World Scientific, Singapore*, 59–169.

[6] Galliana, F., Lanzillotti, M. (2017). Accurate comparison between INRIM and a secondary calibration laboratory using a top-class multifunction electrical calibrator. *Measurement*, 103, 353–360.