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DC Voltage Linearity Measurements and DVM Calibration with Conventional and Programmable Josephson Voltage Standards

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***Abstract* – Traditional calibration of dc voltage high accuracy digital voltmeters (DVMs) using conventional and Programmable Josephson Voltage Standards at INMETRO show improvements between 73.7 % and 98.3 % when compared with a regular calibration technique. Some calibration results as well as DVM linearity and gain drift analysis (up to 10 V range) are presented and discussed in this paper.**

I. INTRODUCTION

The Conventional Josephson Voltage Standard (CJVS) system of the Brazilian national metrology institute (INMETRO) was implemented in 1998. The current CJVS system runs with the NISTVolt [1] software and is routinely employed to calibrate Zener diode-based working standards [1]. In 2012, INMETRO implemented its Programmable Josephson Voltage Standard (PJVS) system [2], allowing more stable (but as accurately as) Zener calibrations (when compared with the CJVS), since there are no step transitions. It also allows ac calibrations, using successive dc voltage values (ac stepwise) [3-4]. A comparison between the INMETRO CJVS and PJVS systems was carried out in 2012, using the CJVS to measure the PJVS at 10 V. The average difference between the two JVSs at 10 V was 1.24 nV with a Combined Standard Uncertainty of 2.79 nV, showing that the INMETRO PJVS is working properly [5].

Traditional calibration can be performed in all DVMs, does not need adjustments in the DVM under calibration, keeps naturally the calibration history, and does not change the DVM linearity deviation (although the DVM linearity drifts in time, due to its inherent gain drift). Differently from traditional calibration, artifact calibration adjusts the instrument so that the measured value is within the manufacturer-specified absolute uncertainty limits of the nominal value [6]. It can only be performed in more advanced DVMs and it also does not seem to change the DVM linearity deviation.

DVM traditional calibration seeks the DVM errors, which are used as corrections for a regular measurement. On the other hand, DVM linearity measurement seeks the difference between the linear regression fit (usually using Least Sum of Squares - LSS- estimation) of the measured points and the ideal line, in order to check how linear is the DVM ADC. It can be determined by the “Mean DVM Gain Error from LSS Fit” and by the “LSS Fit Zero Intercept”.

One of the first applications of a CJVS to measure the linearity of an 8½ digit DVM was made by Giem [7]. Using an automated low thermal reversing switch, he found that the thermal voltages were relatively stable over the measurement times up to 15 min. Hence, the compensation for constant thermal voltages was made in the least squares curve fitting process, without causing any significant distortion of the linearity measurements. H. E. van den Brom et al. [8] used a PJVS to measure the linearity of a 7 ½ digit DVM at 10 mV dc range; in this case, the linearity deviation was within 3 µV/V of full scale.

In 2013 Georgakopoulos et al. proposed a DVM calibration technique using a dual-RF-drive PJVS, reaching dc voltages between 10 nV and 1 kV [9] and Landim et al. proposed a DVM CJVS-based calibration technique up to 10 V dc [10]. The latter technique is employed here to calibrate a DVM with either a CJVS or a PJVS system and it can automatically (or semi-automatically) be performed in any digital DVM (provided it has IEEE-488 GPIB capability), up to 10 V dc. Some 8½ digit DVM calibration results (including comparison with a classical method, as well as DVM linearity and gain drift analysis) will be presented and discussed in some detail.

In 2011 the Quantum Voltage Metrology Laboratory (LAMEQ) was created, inheriting from other labs the responsability for doing research in Josephson systems as well as in the Quantum Hall system. That change caused a strange situation: LAMEQ provides traceability to other Inmetro laboratories in dc voltages and needed to send its DVMs to be calibrated in other IMETRO laboratories (also in dc voltages). Using the proposed technique, LAMEQ can do its own DVM calibration. An interlaboratory comparison (at INMETRO) was done in order to check the consistency between the previous (potentiometric system) and the proposed technique.

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II. DVM TRADITIONAL CALIBRATION USING A JVS

A. Methodology

The intrinsic V_{JVS} voltage generated by the JVS (either CJVS or PJVS) system is given by:

$$V_{JVS} = n.\frac{f}{K_{J-90}} \quad (1)$$

where n is the number of activated steps, f stands for the microwave frequency and K_{J-90} stands for the Josephson constant.

V_{JVS} is applied to the DVM (under calibration) input terminals. The mathematical model of the measurement can be stated as follows:

$$\begin{aligned} V_{JVSest} = \; & V_{DVMmea} + V_{off} + \delta_{res} + \delta_Z \\ & = V_{DVMmeaCORR} + \delta_{res} + \delta_Z \end{aligned} \quad (2)$$

where V_{JVSest} stands for the estimated JVS voltage, V_{DVMmea} is the averaged voltage indicated by the DVM, V_{off} represents the thermal offset and DVM offset voltages in the measurement circuit, δ_{res} and δ_Z are the corrections of the indicated voltage due to the DVM's finite resolution and the JVS zero-offset voltages, respectively. $V_{DVMmeaCORR}$ is the voltage indicated by the DVM corrected from the offset errors.

The voltage provided by the JVS is measured by the DVM in error mainly due to its gain deviations, bias current, offset, input impedance loading, non-linearity and noise [11], as well as thermal voltages in the measurement path. V_{off} is the only effect that can be estimated and compensated for (the remaining effects compose the uncertainty budget). Hence, the estimated JVS voltage according to eq. (2) is compared to the known V_{JVS} (eq. (1)), which is the same as comparing $V_{DVMmeaCORR}$ to V_{JVS}, yielding the calibration error.

In the case of a CJVS, the calibration is made semi-automatically, since the operator needs to start each DVM linearity test and to run the CJVScalDVM software (which reads the report files, process the measurements data [applying the needed corrections], calculates de uncertainties and gets the final calibration report) [10]. In the case of the PJVS, the DVM gain & linearity function of the software used to control the system (PJVS-core_2012_v0207, developed by the NIST [3]) can be used to automatically make all the measurements. The thermal offsets and their first order drift are removed using a fitting method. Since each DVM linearity measurement takes 6 minutes or less (in a room temperature of 22.5 °C ± 1 °C), the thermal voltages are stable enough that they do not cause any significant distortion of the linearity measurements [7]. That suggests the thermal voltages can be estimated using the LSS fitting process. The PJVS final measurement report brings the offset voltages (which have opposite sign of those described in eq. 2). It also brings the voltages generated by the PJVS, the $V_{DVMmeaCORR}$ and the standard deviation, which are used to calculate the uncertainty budget and to generate the final calibration report, using a spreadsheet.

B. Uncertainty Budget

Tables 1, 2 and 3 show the DVM calibration uncertainty budgets for the 100 mV, 1 V and 10 V ranges, respectively, using a CJVS system. V_{DVMmea} is the average of around 10 voltage measurements. V_{off} is estimated by the indication of the DVM at 0 V (for CJVS measurements [10]). δ_{res} and δ_Z corrections are considered to be nominally zero, but their effects are taken into account in their respective uncertainty components. V_{JVSest} is obtained from eq. (2). The standard uncertainties regarding V_{DVMmea}, V_{off}, δ_{res} and δ_Z (u_{DVM}, u_{off}, u_{res} and u_z, respectively) are obtained according to [10] and [11]. The V_{DVMmea}, V_{off}, and δ_Z degrees of freedom, the coverage factor (k), the combined standard uncertainty (u_c), its respective effective degree of freedom (ν_{eff}) and the expanded uncertainty (U, for a confidence level of 95.45 %) are computed according to [11]. The estimated expanded uncertainties for 100 mV, 1 V and 10 V ranges are, respectively, 0.04 µV, 0.06 µV and 0.4 µV (k≈2).

In the case of the PJVS system, V_{off} is estimated during the PJVS measurements (see section II.A above). Preliminary investigation shows that PJVS type A uncertainties related to V_{DVMmea} can be either higher or lower than the CJVS ones. It was observed an impact of 0.01 µV in the expanded uncertainties at the 100 mV and 1 V ranges. Hence, the CJVS original uncertainties were increased 0.01 µV in those ranges. Since the PJVS system is more stable than the CJVS one, it was expected the PJVS uncertainties to be lower than CJVS ones. This investigation is still ongoing.

Table 1. JVS 100 mV range DVM calibration uncertainty budget.

Quantity Xi	Estimate xi (V)	Type	Standard Uncert. (nV)	Degrees of freedom ν_i
$V_{DVMmeas}$	0.09999994	A	15	9
V_{off}	0.00000006	A	7	9
δ_{res}	0.00000000	B	3	∞
δ_{Z}	0.00000000	A	15	9
V_{JVSest} (V)	0.10000000	k=2.12	uc=22	ν_{eff}= 22
U (µV)	0.05			

Table 2. JVS 1 V range DVM calibration uncertainty budget.

Quantity Xi	Estimate xi (V)	Type	Standard Uncert. (nV)	Degrees of freedom ν_i
$V_{DVMmeas}$	1.00000609	A	26	9
V_{off}	-0.00000023	A	10	9
δ_{res}	0.00000000	B	3	∞
δ_{Z}	0.00000000	A	15	9
V_{JVSest} (V)	1.00000586	k=2.16	uc=32	ν_{eff}= 17
U (µV)	0.07			

Table 3. JVS 10 V range DVM calibration uncertainty budget.

Quantity Xi	Estimate xi (V)	Type	Standard Uncert. (nV)	Degrees of freedom ν_i
$V_{DVMmeas}$	10.0000595	A	148	9
V_{off}	-0.0000003	A	40	9
δ_{res}	0.0000000	B	29	∞
δ_{Z}	0.0000000	A	15	9
V_{JVSest} (V)	10.0000592	k=2.25	uc=157	ν_{eff}= 11
U (µV)	0.4			

III. CALIBRATION RESULTS AND DISCUSSION

INMETRO's CJVS is used to provide traceability to the S.I. to its potentiometric system (which is used to calibrate the dc voltage sources and meters of Brazilian main laboratories) through Zener calibrations. In order to evaluate the proposed technique, an unofficial internal interlaboratory comparison was performed between the 12th and 22nd of March 2013. An 8½ digit DVM (Agilent 3458A)[1] was used as a "travelling standard", which was calibrated first against the potentiometric system and later on against the CJVS [10].

[1] Certain commercial equipment, instruments, or materials are identified in this report to facilitate understanding. Such identification does not imply recommendation or endorsement by INMETRO, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

Fig 1 shows the 8½ digit DVM calibration errors at 1 V range using the potentiometric system and the CJVS system. For better visualization, only the first quadrant of both axes is shown. The results are consistent with each other, but calibrations with CJVS display a much more linear behavior, as expected from an 8½ digit DVM. The DVM error at 1.018 V (resulted from a Zener calibration) is also presented. In this latter case, the uncertainty budget is composed of DVM noise and zero-offset uncertainties (both type A; type B uncertainty components were neglected). The lines follow the DVM linear trend, indicating the good consistency of the method used and its expected uncertainties.

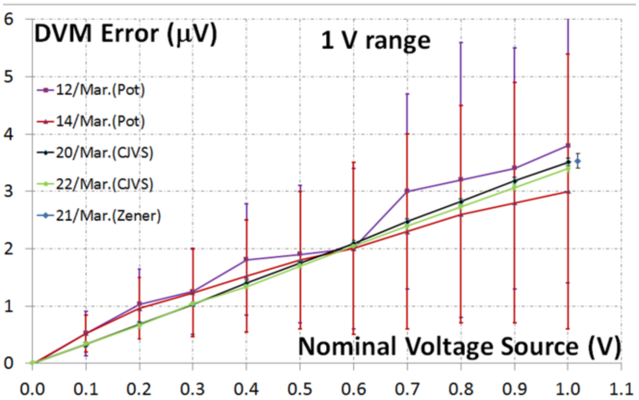

Fig. 1. 8 ½ Digit DVM Calibration Errors at 1 V Range (Potentiometric and CJVS Systems), 2013. The uncertainty bars correspond to k ≈ 2.

Fig. 2 shows the linear characteristics and gain error drift of the DVM at 100 mV range, calibrated against the CJVS system during several months in 2013. For better visualization, only the first quadrant of both axes is shown. Between 20th of Mar and 28th of Aug, the gain error increased from 3.43 µV/V to 5.40 µV/V (Table 4). In order to check the behavior of the DVM, an artifact calibration was done between 28th of Aug and 2nd of Sep (using a Zener dc voltage reference standard, immediately after its calibration against the CJVS). The DVM gain error calibration was reduced to a negative value close to zero. Between 2nd of Sep and 12th of Sep, the gain error increased from -0.13 µV/V to 0.01 µV/V (Table 4). *m* is the gain error variation rate.

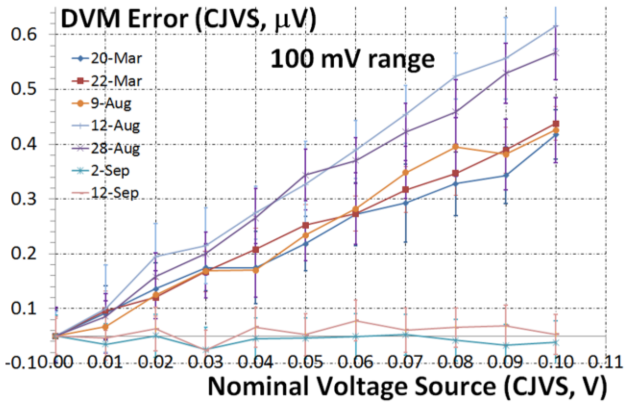

Fig. 2. 8 ½ Digit DVM Calibration Errors at 100 mV Range (CJVS), 2013. The uncertainty bars correspond to k ≈ 2.

Table 4. 8 ½ Digit DVM Gain Error Drift at 100 mV range (CJVS).

Date	Gain Error (µV/V)	m	m (%/Day)
3/20/2013	3.43	0.011	1.08
3/22/2013	3.62		
8/9/2013	4.12		
8/12/2013	5.79		
8/28/2013	5.40		
	artifact calibration		
9/2/2013	-0.13	0.014	1.40
9/12/2013	0.01		

Fig. 3 shows the linear characteristics and gain error drift of the DVM at 1 V range, calibrated against the CJVS system. Between 20th of Mar and 28th of Aug, the gain error increased from 3.52 µV/V to 5.81 µV/V (Table 5). For better visualization, only the first quadrant of both axes is shown. Right after the artifact calibration, the DVM gain error calibration was also reduced to a negative value close to zero. Between 2nd of Sep and 12th of Sep, the gain error increased from -0.23 µV/V to -0.12 µV/V (Table 5).

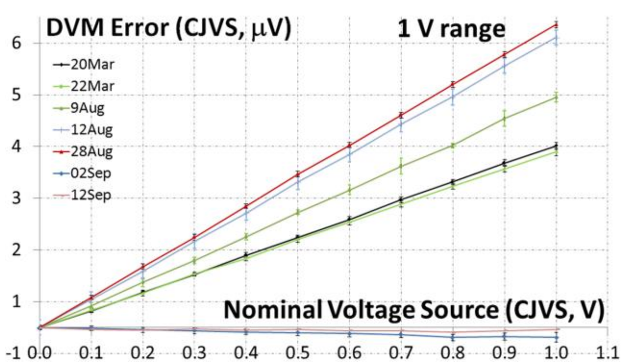

Fig. 3. 8 ½ Digit DVM Calibration Errors at 1 V Range (CJVS), 2013. The uncertainty bars correspond to k ≈ 2.

Table 5. 8 ½ Digit DVM Gain Error Drift at 1 V range (CJVS).

Date	Gain Error (µV/V)	m	m (%/Day)
3/20/2013	3.52	*0.013*	*1.25*
3/22/2013	3.37		
8/9/2013	4.43		
8/12/2013	5.58		
8/28/2013	5.81		
	artifact calibration		
9/2/2013	-0.23	*0.011*	*1.09*
9/12/2013	-0.12		

Fig. 4 shows the linear characteristics and gain error drift of the DVM at 10 V range, using both the CJVS (identified with an uppercase “C”) and the PJVS (identified with an uppercase “P”). The first DVM linearity measurement was done on 20th of March, 2013, black line with a round mark, coincident with the second one, done on 22nd of March. The next measurement was done in 9th of August (green line), showing the increase of the gain error. The next two DVM linear measurements were done on 12th and 28th of August (purple and red lines, respectively). Right after that, an artifact calibration was done. Consequently, the next DVM linearity measurement presented an almost horizontal line (2nd of September, blue line with diamond shape). The DVM linearity line obtained on 19th of February, 2014, shows the gain error is increasing again. Right after that, another artifact calibration was done and the next DVM linearity measurement was (again) almost horizontal (27th of February, 2014, purple line, diamond marker). This DVM linearity measurement was done using the PJVS system and the results were coincident with the one obtained with the CJVS system (2nd of

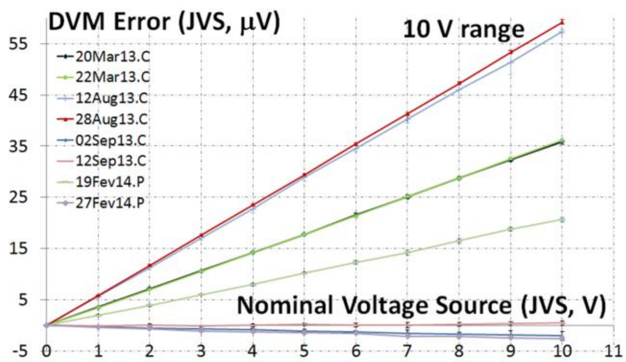

Fig. 4. 8 ½ Digit DVM Calibration Errors at 10 V Range (JVS), 2013 and 2014. The uncertainty bars correspond to k ≈ 2.

September, blue line with diamond shape, also right after an artifact calibration). In general, although the measurements were done using both JVSs systems, the results were similar, showing the consistency of the method. However a comparison between both systems was not performed yet, because they usually are not working at the same time, due to the liquid helium high price. Between 20th of Mar and 28th of Aug, 2013, the gain error increased from 3.56 µV/V to 5.89 µV/V (Table 6). Right after the artifact calibration, the DVM gain error calibration was also reduced to almost zero. Between 2nd of Sep and 12th of Sep, 2013, the gain error increased from -0.23 µV/V to 0.00 µV/V (Table 6).

Table 6. 8 ½ Digit DVM Gain Error Drift at 10 V range (CJVS).

Date	Gain Error (µV/V)	m	m (%/Day)
3/20/2013	3.56	0.014	1.36
3/22/2013	3.55		
7/11/2013	4.73		
8/12/2013	5.70		
8/28/2013	5.89		
	artifact calibration		
9/2/2013	-0.23	0.022	2.25
9/12/2013	0.00		

The gain error variation rate (m) can be bigger a few days right after the artifact calibration. In all measured ranges, right after the artifact calibration, the gain error was reduced to a negative value close to zero and then started to increase again. The residual offset voltages (obtained from linear fit of $V_{DVMmeaCORR}$ versus V_{CJVS}, when V_{CJVS} is equal to zero) did not present any significative change. Considering each DVM range has its own set of electronic components (whose behavior can be slightly different from each other), the gain error variation rate must be characterized for each DVM range, as well as for each DVM.

Fig. 5 shows the 8 ½ Digit DVM Linearity Deviation at 10 V Range (Potentiometric and CJVS systems). A similar shape was obtained for the 100 mV and the 1 V ranges. Hence, the DVM linearity deviation seems not to change significantly in time. According to Giem [7], this kind of DVM is specified to have a deviation from linearity smaller than 0.1 µV/V for the 10 V range. Our measurements indicate 0.05 µV/V maximum (Fig. 5).

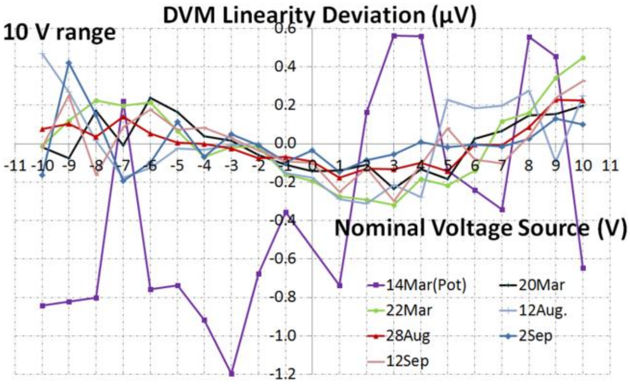

Fig. 5. 8 ½ Digit DVM Linearity Deviation at 10 V Range (Potentiometric and CJVS systems), 2013.

IV. CONCLUSION

An 8½ digit DVM was calibrated using CJVS and PJVS systems. The results indicate excellent agreement with those obtained with the potentiometric system. When compared with the potentiometric system, the JVS system calibration uncertainties were reduced between 73.7 % and 98.3 %. This indicates a sensible measurement improvement. Also, the estimated DVM errors at 1.018 V (resulted from a Zener calibration using a JVS with online offset voltage compensation) are very close to the estimated values using the JVS to directly calibrate the DVM. It was also possible to characterize the gain error drift for 100 mV, 1 V and 10 V ranges of the tested DVM. However, this characterization must be done for each unit, due to differences between the electronic components used in each DVM. No significant offset drift was observed. This method can be used for DVM calibration at higher voltages, using a resistive voltage divider [9].

The δ_Z standard uncertainty (u_Z) is well known as Josephson Voltage Standards Zero-offset uncertainty of Zener calibration. u_Z is estimated by making a set of N measurements of the Josephson voltage across a short circuit (a zero-voltage reference) that is placed in the same position as the Zener in a standard measurement [11]. This circuit is the same used for V_{off} estimation (at zero voltage). By one hand, u_Z is measured only at the lowest DVM range, while V_{off} is measured at all calibrated DVM ranges. By the other hand, u_Z measurement eliminates the stable offset voltages in the measurement circuit (through its polarity reversals), while V_{off} is measured without any polarity reversal. It seems u_Z and u_{off} have more similarities than we thought and u_Z can be eliminated from our uncertainty budgets (since u_{off} would bring u_Z contribution). If that is true, the 100 mV uncertainty budget can be reduced even more (to a half of the presented values). This investigation is ongoing.

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