Improvements in the Inmetro Zener Calibration Uncertainty Budgets Using Conventional and Programmable Josephson Voltage Standards

R. P. Landim[1]

[1] Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro) - Lab. de Metrologia Elétrica Quântica (Lameq)
rplandim@inmetro.gov.br

***Abstract* — This paper describes the reevaluation of Inmetro Conventional (CJVS) and Programmable (PJVS) Josephson Voltage Standards uncertainty budgets for Zener calibration. An intralaboratory indirect comparison between the two systems was made in order to check the consistency of the uncertainties. The achieved uncertainties are ±40 nV (at 1.018 V) and ±250 nV (at 10 V), *k*=2.**

***Index Terms* — CJVS, drift, measurement uncertainty, PJVS, Zener calibration.**

I. INTRODUCTION

The discovery of the Josephson Effect (by Brian D. Josephson, in 1962), the development of Josephson Voltage Standards (JVS) and the recognition of such systems as representation of the SI volt (in 1988, by the General Conference on Weights and Measures – CGPM) led to numerous JVSs systems being currently in use around the world in national, industrial, and military standard laboratories [1]. That helped the improvement of the reproducibility of calibration results by up to two orders of magnitude during the last two decades [1]. However, a large number of National Metrology Institutes (NMIs), calibration laboratories and industrial laboratories, all around the world, still use Zener-diode based solid state electronic voltage standards (Zeners) as reference standards calibrated directly with Josephson arrays, as travelling standards or as primary reference standards. For these applications, uncertainties ranging from one part in 10^6 to below one part in 10^8 are claimed [2].

The Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro) implemented its Conventional JVS (CJVS) back in 1998 and its Programmable JVS (PJVS) in 2012. Both systems are used to calibrate Inmetro Zener working standards, which are used to calibrate Inmetro clients' Zeners, using the Inmetro Secondary system. The achieved uncertainties (for the Secondary system) are 0.09 μV (for either 1.018 V or 1 V) and 0.4 μV (for 10 V) [3]. The present work shows some results related to the reevaluation of Inmetro CJVS and PJVS uncertainty budgets for Zener calibration, in order to use them for a new Zener calibration service with much smaller uncertainties. An intralaboratory indirect comparison between the two systems was made, since, in the opinion of the author, this is the most straightforward way to check the consistency of the Zener calibration uncertainties using JVSs. Hence, without leaving the laboratory, Zener external variation effects are minimized.

II. JVS UNCERTAINTY BUDGET

The uncertainty budget for the Inmetro CJVS and PJVS systems follow the recommendations in [4]. The uncorrected leakage uncertainty (u_L, type B) is typically 0.2 nV (for Inmetro CJVS system [5]), while for PJVS systems, values around 0.3 nV can be reached [6]. For Zener calibration, u_L is negligible compared to the type A uncertainties. Hence, for simplicity, $u_L = 0.3$ nV will be used for both JVS systems in this work. The uncertainty due to the microwave frequency (u_F, type B) is typically 1 nV (for Inmetro CJVS system [5]). From the PJVS rf generator manufacturer specification, typical values are smaller than 0.5 nV. For simplicity, $u_F = 1$ nV will be used for both JVS systems. The zero-offset uncertainty (u_z, type A) was obtained from the properly cleaned lowest emf scanner channels (after 50 short-circuit measurements). Since the same scanner and the same DVM are used by both systems, $u_z = 11.6$ nV will be used for both JVS systems. So far, those uncertainties are valid for both Zener outputs: 1.018 V (or 1 V) and 10 V.

The outputs of Zener standards, in spite of their short-term good stability, are affected by (a) deterministic effects (drift and external variations, like pressure, humidity and, mainly, temperature) and (b) random variations (white noise and *1/f* noise). In fact, *1/f* noise in Zeners are the ultimate limit to Zener voltage measurement uncertainties, which can reach eight parts in 10^9 [7]. Considering the room pressure, humidity and temperature stability at the Inmetro/Lameq laboratory (maximum variations around ±14.70 hPa, ±14.33 % ur and ±0.2 °C, respectively), the uncertainty due to the Zener (u_{DUT}, type A) is caused mainly by *1/f* noise.

In order to get more reliable Zener standards calibration results (in the presence of *1/f* noise in its outputs), it is needed to use a set of measurements (instead of only a single measurement) [4]. The averaging process reduces the dispersion between the final averaged points but increases the dispersion of each averaged point, increasing the final uncertainty. Increasing the number of the averaged points may reduce the type A uncertainty, but this is only a statistical process and this is not faithful to the physical meaning, leading to more outliers. A box plot graph analysis of 1, 5, 10 and 20 averaged points indicated both lower type A uncertainties and lower outliers for 5 averaged points. Hence, the author has decided to average a set of five measurements in a row. Also, a moving average was used in order to keep a large number of measurements. u_{DUT} was estimated as the

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biggest value (in a very conservative way, including overnight measurements) from a row of Zener noise measurements (type A of single measurements) using both the CJVS and the PJVS for Zener calibration (sequentially) within two weeks. The CJVS/PJVS uncertainty budgets can be seen in Table 1. Inmetro CJVS and PJVS details can be seen in [5] and [8], respectively.

TABLE I

Inmetro CJVS/PJVS Uncertainty Budget

CJVS/PJVS Uncertainty Components	Type	1.018 V	10 V	Deg. of Freedom
Zener noise (u_{DUT}, nV)	A	13.6	119.4	37
Zero Offset (u_Z, nV)	A	11.6	11.6	50
Microwave frequency (u_F, nV)	B	1.0	1.0	∞
Uncorrected leakage (u_L, nV)	B	0.3	0.3	∞
Combined Standard Uncertainty (u_C, nV)	AB	17.9	120.0	
Effective degrees of freedom (ν_{eff})		79.7	37.7	
Coverage factor (k)		2.0	2.1	
Overall Uncertainty (U, nV)		40	250	

III. RESULTS

A preliminary indirect comparison (at 1.018 V and at 10 V) between Inmetro's CJVS and PJVS systems was made at Lameq. Fig. 1 shows the result for 16 single Zener measurements at 10 V. The vertical bars represent the expanded uncertainty (104 nV maximum, k=2). One can see the compatibility of the measurements, as well as the LSS fit of the Zener 10 V output, indicating it decreases around 1 μV/day (short-term drift). Another short-term drift measurement will show a different result (even the signal can be different). The same occurs between each JVS single Zener measurement: the instant drift is completely different from each other. That happens mainly because *1/f* noise, what justifies the importance of averaging several measurements.

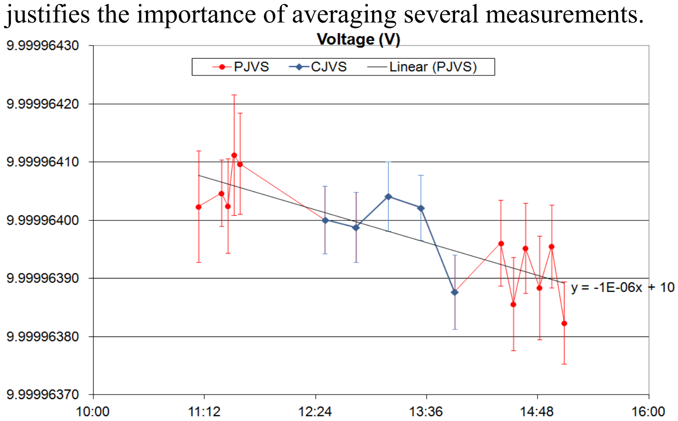

Fig. 1. PJVS and CJVS single Zener measurements at 10 V

Fig. 2 shows the difference from the moving averaged (5 single Zener measurements) points to the LSS fit (x-axis), in order to eliminate the drift effect in this analysis. ±*Umax* refers to the declared expanded uncertainty limits and the vertical bars represent the estimated expanded uncertainties (k=2). It is clear that the chosen uncertainty (Table I) is a very safe limit. According to the 7 year history of this Zener, its long-term drift is -4 nV/day (at 10 V). The drift obtained from the averaged two-week data was -9 nV/day (at 10 V), much

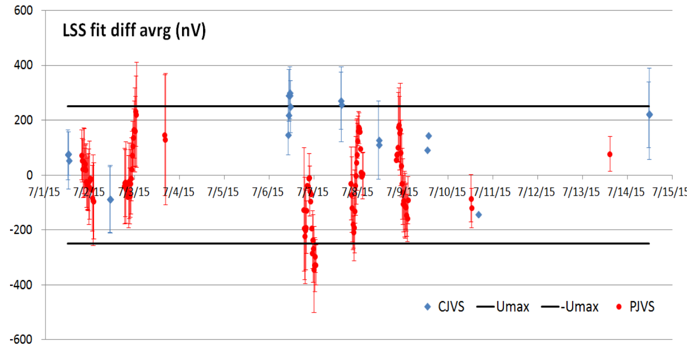

Fig. 2. PJVS and CJVS averaged Zener measurement differences from the LSS fit at 10 V

more close to the long-term drift. The results for 1.018 V are even better, since the noise affect less this voltage level.

VI. CONCLUSION

Inmetro is ready to offer ±40 nV (at 1.018 V) and ±250 nV (at 10 V) Zener calibration uncertainties (k=2). The author believes a more careful evaluation of u_{DUT} will allow ±30 nV (at 1.018 V) and ±160 nV (at 10 V) uncertainties.

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