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Using a Programmable JVS for evaluation of Zener voltage standards stability and secondary uncertainty under controlled temperature variation

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Abstract. A study was carried out with two 732B model Zener-diode based electronic voltage standards, in order to analyze the influence of external temperature variation in their outputs. The temperature was controlled and the external variations were monitored. Inmetro Programmable Josephson Voltage Standard (PJVS) and Secondary systems were used for this purpose. Studies have shown that, despite the internal temperature control, there is a strong correlation between the external temperature and the internal thermistor value, for both Zeners. Inmetro Zener calibration uncertainty budget was revisited and the achieved uncertainties are ±0.09 µV (at 1.018 V) and ±0.4 µV (at 10 V), k=2.

1. Introduction

Zener-diode based solid state electronic voltage standards (Zeners) are used worldwide by National Metrology Institutes (NMIs) [1]. The Instituto Nacional de Metrologia, Qualidade e Tecnologia (Inmetro) uses the Fluke 732A and 732B models, in order to disseminate the Brazil legal volt and to maintain internationally consistent and traceable voltage standards tied to the SI units. Since 1998 Inmetro has been using a Conventional Josephson Voltage Standard (CJVS) as a primary reference standard of voltage. In 2012 Inmetro started using its Programmable Josephson Voltage Standard (PJVS) for this task, too. The Zeners calibrated using a JVS are used as a reference standard (in the Secondary system) to calibrate Inmetro client's Zeners (from the Brazilian Network Calibration), which are used to provide traceability to all other laboratories and research institutes in Brazil [2].

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; hence, calibration using Zeners as reference standards are limited to one part in 10^8 [3]. The present work shows some results related to the Zener output voltage variation under the presence of controlled external temperature, targeting lower uncertainties calibration in the Secondary system.

2. Experimental Procedure

We mounted an experimental setup, composed by an air bath (temperature controlled), a thermometer, a humidity meter and a barometer to monitor those quantities inside the air bath (hence, "external" in this paper refers to the quantities inside it and surrounding the Zeners), as well as two ohmmeters to measure the Zeners' thermistors. Two Fluke 732B Zeners (named Z4 and Z7, connected to the thermistor meters) and the temperature, humidity and pressure sensors were placed inside the air bath. A LABView software was developed to automatically monitor all the measured quantities. In order to keep the Zeners always powered only on batteries (reducing the power line noise effects), each Zener was connected to its own external battery pack (outside the air bath and whose voltages were monitored daily and replaced when needed). Hence, there was no need to open the air bath during the whole measurement cycles.

An intralaboratory comparison (at controlled external temperature) was performed using two systems (at each measurement cycle) from the Quantum Electrical Metrology Laboratory (Lameq/Inmetro): (a) the PJVS, used to calibrate both Zeners (during around six hours); and (b) the Secondary calibration system, which used Z4 to calibrate Z7 (during around one hour). Both systems use the differential comparison method. We used the Measurements International 9300 air bath, which provides controlled temperature with ± 0.05 °C stability within 15 °C to 40 °C. The Zeners were connected to the lower *emf* (electromotive force) channels of a scanner, reducing the measurement uncertainties. Table 1 shows the measurement cycles and their respective temperature values. The temperature steps were made non-sequentially, in order to make it easier to analyze separately the temperature drift from the temporal drift effects. Due to the normative laboratory temperature calibration (22.5 °C ±1 °C), the 23 °C temperature was chosen to be measured at the beginning, middle and end of the cycles, in order to help the Zeners' temporal drift analysis.

Table 1. Measurement cycles (from May 14, 2015 through June 1, 2015).

Cycle	Temperature	Cycle	Temperature	Cycle	Temperature
1	23 °C	**6**	21 °C	**11**	21 °C
2	23 °C	**7**	25 °C	**12**	24 °C
3	23 °C	**8**	23 °C	**13**	22 °C
4	20 °C	**9**	22 °C	**14**	26 °C
5	24 °C	**10**	25 °C	**15**	23 °C

3. Results

First, we discarded all the transition measurements (the ones whose thermistors were still changing above 30 Ω). Then, we discarded some of the PJVS measurements, keeping the five ones which are closest (in time) to the ones used in the Secondary system analysis. The remaining measurements are considered the "useful raw data". For each system (either PJVS or Secondary), and for each temperature, the final value is an average from all "useful raw data". The analysis was made considering two approaches: (a) the influence of the external temperature on the internal Zener's thermistor; and (b) the influence of the external temperature on the Zener's output voltage.

3.1. Influence of the external temperature on the internal Zener's thermistor

Right after a step change in the external temperature, the tested Zeners' thermistor experienced a variation towards a new value, after some time (as expected). For instance, after a step change from 20 °C to 24 °C, the thermistors started changing around 10 min later, decreasing their values. After 30 minutes, the external temperature stabilized around 24 °C, but the thermistors kept changing, stabilizing only around 50 minutes after the beginning of the temperature step. The thermistors' resistance stability remains within ± 25 Ω as long as the external temperature remains stable within ± 0.05 °C. Similar situation occurred for all the 15 cycles (table 1). Considering that the temperature at Rio de Janeiro can reach 41 °C (even more) during summer, causing Inmetro clients' Zeners experiencing external temperature variations up to 15 °C (for laboratory room temperature stabilization), we have decided to wait, at least, 8 hours before beginning a new Zener client calibration. This is enough time for the complete Zener stabilization.

Using a Least-Squares Sum (LSS) estimation method, we have got a very good linear model between the external temperature and the internal thermistors' resistance. The thermistor angular coefficients found were -60 Ω/°C (for Z4) and -53 Ω/°C (for Z7). The maximum error between those models and the "useful raw data" was 9 Ω (in 39 kΩ). Using those models and the internal Thermal Coefficient $TC_{Tint} \approx 2$ kΩ/°C [4], we have got a good Zener internal temperature estimator:

$$Tint_{Z4} = -0.03\,Text + 44.48 \tag{1}$$

$$Tint_{Z7} = -0.03\,Text + 44.49 \tag{2}$$

From equation (1), equation (2) and the thermistor angular coefficients found, it is clear that an external temperature increase is followed by a proportional Zener internal temperature decrease, as well as Zener thermistor resistance decrease. However, thanks to its internal temperature control, this variation is small: the Zener internal temperature drops around 0.03 °C for each 1 °C increase in the external temperature (only a factor of 3 % of the external temperature variation reflects in the internal temperature variation), for the tested Zeners. Such Zener temperature stability reflects in its output voltages stability, as well.

3.2. Influence of the external temperature on Zener's output voltages

In order to verify the influence of the external temperature variation on the Zener's output voltages, we first estimated the temporal drift during the measured dates (table 1), from the 22 °C and 23 °C of the "useful raw data" (since the normative temperature range for regular calibration in the laboratory is 22.5 °C ±1 °C). Then we subtracted (accordingly to the time variation) the temporal drift from the "useful raw data". From this new data, for each Zener and each voltage tap (either 1.018 V or 10 V) and using LSS estimation, we have got (table 2):

Table 2. Voltage Temperature Coefficients (*TCv*), in (μV/V)/°C.

Tap (V)	Z4	Z7	Manufacturer
1.018	0.02	-0.01	0.04
10	-0.02	-0.02	0.1

3.3. Inmetro secondary Zener calibration uncertainty

Since 2010, Inmetro CMC for Zener calibration has been ±0.2 μV (at 1.018 V) and ±1 μV (at 10 V) [5]. A new study considering the 22.5 °C ±1 °C temperature range was recently made and the achieved uncertainties were ±0.1 μV (at 1.018 V) and ±0.4 μV (at 10 V), k=2 [5]. In this paper, the maximum temperature variation (at each targeted temperature) was ± 0.05 °C. Table 3 shows the results for this paper at the 1.018 V and 10 V taps (the sensitivity coefficients are one, so they were not presented). $U = \pm 0.373$ μV was rounded to $U = \pm 0.4$ μV. At 1.018 V, $U = \pm 0.089$ μV, rounded to $U = \pm 0.09$ μV. All the numbers (for 10 V and 1.018 V) were rounded according to $1/f$ noise limits [3].

According to table 2 (before rounding) the maximum output voltage variation due to 0.05 °C change is 0.01 μV; for 2.00 °C variation, the change is 0.36 μV (within the proposed uncertainty). Also, the uncertainty improvement due to the air bath use was not significant. That means $1/f$ noise limits avoid any better improvement and the use of a more expensive apparatus is useless. Temperature regulation of ± 2.0 °C is enough for our purposes.

Table 4 shows the Secondary system errors (compared to the PJVS system), for each temperature. The errors are smaller than the proposed uncertainties and the lowest errors were achieved at 23 °C, 24 °C and 25 °C. From table 2, one can see that a change from 20 °C to 26 °C may change up to 1.2 μV the output voltage (besides the temporal drift effect). However, since both Zener temperature changes are similar, the errors remain small.

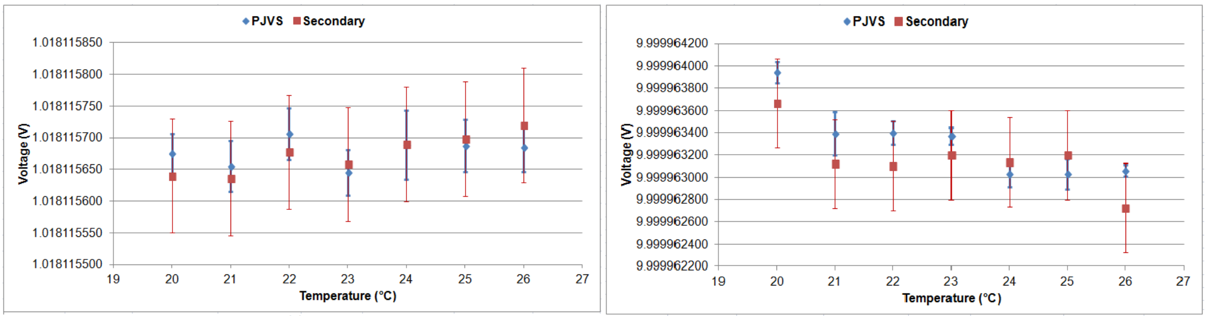
Table 3. 1.018 V and 10 V uncertainty budgets.

Number of measurements (n)	10					
	1.018 V			10 V		
Uncertainty Budget	*U(xi)*	**Prob Distr**	**Std. Unc.(µV)**	*U(xi)*	**Prob Distr**	**Std. Unc. (µV)**
Reference Certificate, *u(x1)* - µV	0.040	norm	0.020	0.250	norm	0.121
Reference drift, *u(x2)* - µV	0.034	rect.	0.019	0.087	rect.	0.050
Reference Thermal Coef., *u(x3)* - µV	0.008	rect.	0.004	0.087	rect.	0.050
DVM Gain/Linearity error, *u(x4)* - µV	0.001	rect.	0.001	0.001	rect.	0.001
DUT Thermal Coef., *u(x5)* - µV	0.005	rect.	0.003	0.069	rect.	0.040
Thermal *emf*, *u(x6)* - µV	0.056	rect.	0.032	0.056	rect.	0.032
Measurement dispersion, *u(x7)* - µV	0.044	norm	0.014	0.337	norm	0.106
Combined Uncertainty, u_C (µV)			0.045			0.183
Effective degrees of freedom (ν_{eff})			∞			79
Coverage factor *k*			2.003			2.032
Expanded Uncertainty, *U* (µV)			**0.089**			**0.373**

Table 4. The Secondary system errors.

Text (°C)	20	21	22	23	24	25	26
$E_{S(1.018)}$ (µV)	-0.04	-0.02	-0.03	0.01	0.01	0.01	0.03
$E_{S(10)}$ (µV)	-0.3	-0.3	-0.3	-0.2	0.1	0.2	-0.3

Figure 1 shows the consistency between the proposed uncertainty and the measured values, at 1.018 V (a) and at 10 V (b).



(a) (b)

Figure 1. Measurements with the Secondary system and its uncertainty proposal as well as the PJVS with its estimated uncertainty (k=2).

The reference Zener (Z4) value used to calibrate Z7 in the Secondary system was kept unchanged (for each temperature) since day one, according to our current calibration procedure. Updating Z4 value everyday would allow even lower errors, since the reference Zener temporal drift affects the object Zener values. However, it is not worthwhile, since it would be needed to calibrate the reference Zener against a JVS system every day.

Starting from the temporal drift estimation, it was possible to estimate the maximum time needed to update the reference Zener value, in order to keep the proposed uncertainty unchanged. For the 1.018 V tap, it is needed, at least, around 200 days until its uncertainty gets higher than $U = \pm 0.09$ µV. On the other hand, for the 10 V tap, 40 days are enough to get $U = \pm 0.5$ µV; 60 days are enough to get $U = \pm 0.6$ µV; and so on. Of course, those values depend on the Zeners involved (since drift and noise are particular to each Zener/tap).

4. Conclusion

We used Inmetro PJVS and Secondary systems to investigate two 732B Zeners' behavior under controlled external temperature variation. We have found that only a factor of 3 % of the external temperature variation reflects in the internal temperature variation. Due to the $1/f$ noise limits, there is no significant advantage in using an air bath for Zener calibration in a Secondary system. At 10 V (figure 1), the PJVS could detect a higher Z7 temperature drift (above 0.5 µV) at the lowest temperature (20 °C); at 21 °C, 22 °C and 23 °C, no such drift was seen; however, between 23 °C and 24 °C we can notice a 0.4 µV shift; no significant temperature drift was detected with the Secondary system, between 21 °C and 25 °C. At 1.018 V, there was no significant temperature drift (either PJVS or Secondary). Also, the lowest Secondary system errors occurred at 23 °C, 24 °C and 25 °C (table 3). All things considered, we have decided to adopt (23.0 °C ±2.0 °C) as the new temperature range Zener calibration in the laboratory. In this case, the achieved uncertainties (Secondary system) are $U = \pm 0.4$ µV (at 10 V) and $U = \pm 0.09$ µV (at 1.018 V), k=2.

Pressure and humidity (not controlled) maximum variations observed were 14.70 hPa and 14.33 % ur, respectively. Pressure and humidity variations are not significant to the Zeners' output voltages stability, at constant external temperature.

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