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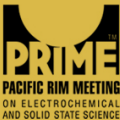
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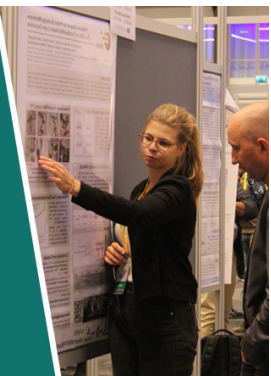
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Eleven years of monitoring an ultra-stable 10 V zener-based voltage standard

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Abstract. The long-term behaviour of a voltage standard based on 140 zeners is analyzed. This standard was developed in 2004 and was monitored up to now. Noise and drift are evaluated showing better results than commercial similar devices. This source is used as the National Voltage Standard in the Uruguayan Designated National Metrology Institute (UTE).

1. Introduction

Primary voltage standards are based on Josephson effects, but secondary standards on zener devices. There are some good commercial voltage standards using this technology [1], but their stability at long term is in the order of $1\mu\text{V/V}$ per year. Laboratories which their voltage standards are based on this type of sources must send them outside for calibration in periods around one or two years to limit the uncertainties to few $\mu\text{V/V}$. The problem to get low uncertainty is the drift these sources have. The drift has a predictable part and a random one. Although it is possible to correct for the first one, the second one can have an unpredictable behaviour. Then, the uncertainty increases with time.

All commercial sources are based on only one specially selected zener, so that any variation of this component cannot be detected. On the contrary, this project uses a large amount of zeners (140) for reducing the variation of the average voltage, and to detect variations between them [2, 3]. A prototype based on this principle has been continuously observed since 2004. Its deviations from their initial values and analysis of its noise are shown in the following sections.

2. General requirements

Figure 1 shows the schematic circuit. Each zener (REF102, 10 V) is connected to the output voltage (V_a) through a $100\ \Omega$ resistor (R_j). Then, at that output, the voltage is the average of the individual ones. All zeners are divided in four independent groups of 35 units. Each group has its own regulated 15 V power supply. In this way, intercomparisons between groups are possible for evaluating random noises. Zeners and electronic devices are placed in a small oven at $44\ ^\circ\text{C}$ with a standard deviation of $0.03\ ^\circ\text{C}$, if the external temperature is $23\ ^\circ\text{C} \pm 1\ ^\circ\text{C}$ (laboratory temperature). The oven has a thermistor to measure its internal temperature, which is continuously recorded.

The stability of the source depends on many factors. The first one is the stability of the type of zener. Its specifications states $5\ \mu\text{V/V}$ per month, but this figure is very conservative. Complementary information on stability from the manufacturer seems to be contaminated by the measuring system. Our measurements show much lower values and not correlated drift between different samples. In this way, the 140 batch reduce the drift of the average voltage at very low level, as will be shown.

Temperature variations affect the output voltage. This type of zener has a thermal coefficient, according to its specification, of $25\ \mu\text{V/K}$, but in the batch there is some compensation. The measured



temperature coefficient of a set of 35 zeners was 10 $\mu\text{V/K}$, which leads to an uncertainty due to the temperature factor of 0.03 $\mu\text{V/V}$, $k=1$.

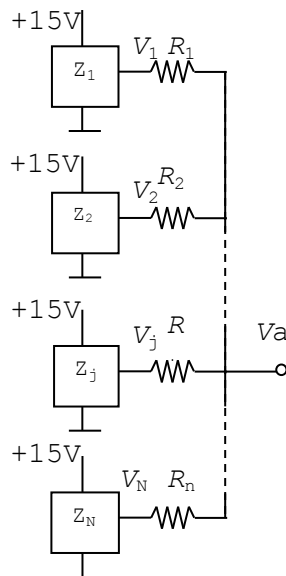


Figure 1. Schematic circuit of the developed device.

As a second uncertainty source, the variation in long time of the resistors is considered. They have 0.1% tolerance and under controlled temperature and practically zero power dissipation, the value is under that limit during years. A variation ΔR_j in the resistor R_j causes a change on the output voltage ΔV_a^j as

$$\Delta V_a^j = \frac{V_a - V_j}{N} \frac{\Delta R_j}{R_j} \quad (1)$$

The voltage differences between individual zeners are lower than 3 mV, then $|V_a - V_j| < 3 \text{ mV}$, and the value of ΔV_a^j will be lower than $2 \times 10^{-8} \text{ V}$. This voltage represents a relative variation of 2 parts in 10^9 .

Each group of 35 zeners is supplied by a regulated 15 V source. The influence of the stability of these sources was evaluated according to the zener specifications and with experimental corroboration. A variation of the source in 1 V produces a variation in V_a lower than 1 $\mu\text{V/V}$. To get an uncertainty contribution of 1 part in 10^8 , the maximum variation of these power supplies must be 10 mV. Each source can be externally monitored to be within $15 \text{ V} \pm 10 \text{ mV}$, but if any of them changes, there is an external adjust to set the voltage at its nominal value with a resolution of 1 mV.

Figure 2 shows the first prototype, which has been working since 2004. Another one was constructed in 2011, shown in figure 3. The average voltages of all independent groups of 35 zeners were continuously monitored separately, and differences between them were computed by a self-developed software. Each group has an independent output (four large binding posts in figure 2 and figure 3). They can be used as separate sources, or they that can be connected in parallel to get the analog average value. In this last case, the average value of all sections is automatically got. Two scanners and two multimeter, controlled by the software, measure the voltages and temperature of each source. The first scanner has 10 channels with very low contact emfs [4]. It selects a pair of voltages from the eight groups of the two prototypes and two commercial voltage standard sources. The output voltage of the scanner is the voltage difference between the two selected sources, which is

connected to a 6½ digits multimeter [5] in the range of millivolt. Another less precision scanner with a similar multimeter measures the temperatures of the sources through the resistance of the thermistor each source has. Each measurement takes 20 s, which leads to 40 min for a complete test.

A conventional system of shielding and guarding was used.



Figure 2. First prototype of the voltage standard source .



Figure 3. Second prototype of the voltage standard.

3. Stability

To study the long term stability, two types of comparisons were done: against Josephson standards and between different groups of zeners. Up to now, four calibrations against Josephson standards of external laboratories were done on the first prototype in 2004, 2008, 2010 and 2015. It was calibrated using as traveling standard a voltage source FLUKE 732B and an 8½ DMM (Agilent 3458) as comparator. Table 1 and figure 4 show the results. The second column of the table shows the value of the average voltage of the four groups, and the third column its uncertainty. It varies because these calibrations were done in different National Laboratories. The average value of the four groups was stated as the value of the prototype. The variation between 2004 and 2008 was $-0.12 \mu\text{V/V}$, and between 2010 and 2015 was $0.05 \mu\text{V/V}$. However, between 2008 and 2010 a larger variation is observed, $0.64 \mu\text{V/V}$. It was due to a failure in the temperature control.

Table 1. Calibrations against a Josephson standard.

Date	Average value (V)	Uncertainty (k=2) (μV)	Corrected value (V)
21/08/2004	10.0006014	2.9	
29/01/2008	10.0006002	2.5	
01/08/2010	10.0006066	1.3	10.0005999
07/05/2015	10.0006071	1.3	10.0006004

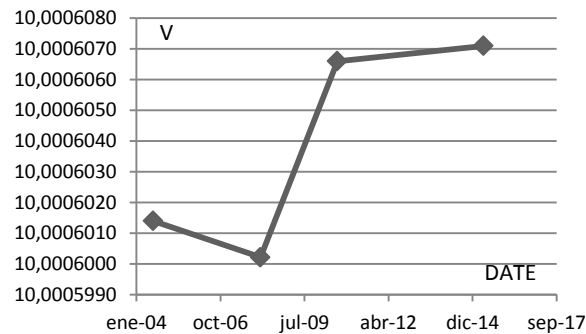


Figure 4. Calibration values against Josephson standards.

The source was out of service for nine months (10/2008 to 06/2009). Once repaired, it has been in operation until present. To correlate its voltage values previous and after the out-of-service period, the source was compared against a FLUKE 732B 10 V standard source taking into account its drift ($-2.0 \mu\text{V}/\text{year}$). The voltage variation due to repair was determined in $6.7 \mu\text{V}$. The fourth column of Table 1 and figure 5 shows the corrected values, subtracting that voltage step. In this way, all values can be analyzed as if no break had occurred. The maximum variation during 11 years was $0.16 \mu\text{V}/\text{V}$, with a drift of $-0.009 \mu\text{V}/\text{V}$ per year which is well below the calibration uncertainties ($0.13 \mu\text{V}/\text{V}$ in the best case).

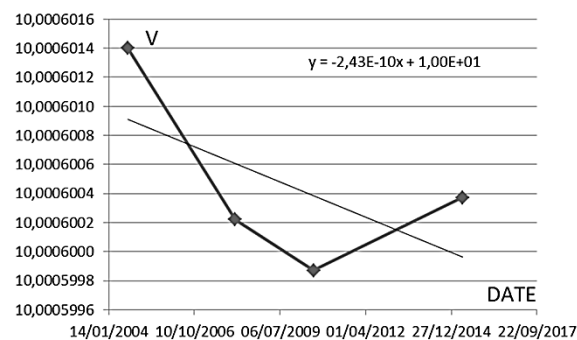


Figure 5. Corrected voltages, subtracting the variation due to repairs.

4. Noise

Other measurements were done to estimate the noise of the source. The voltage of one half of the source (70 diodes) was compared against the other half during 6 years. Allan deviation was computed and results are shown in figure 6 and figure 7. The general behavior at long term (figure 6) shows a non-white noise, similar to other zener based sources. In this case, the noise has the shape of $1/f^{1.5}$, approximately, lightly higher than flicker noise. The maximum value of Allan deviation, at one year, is $0.6 \mu\text{V}$ (6 parts in 10^8). In short term (figure 7), the noise is quite $1/f$. The value of Allan deviation at 4 h, is $0.1 \mu\text{V}$ which is equivalent to 1 part in 10^8 .

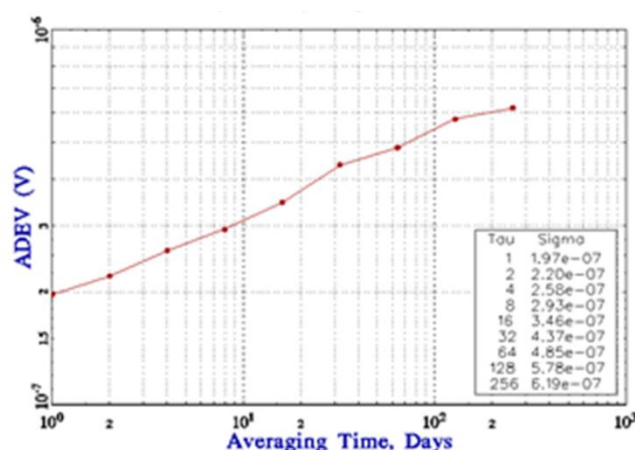


Figure 6. Allan deviation of the voltage difference between the two halves of the source, observed during six years.

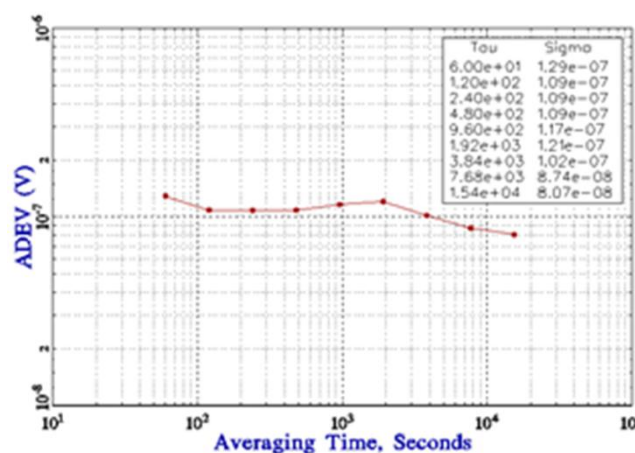


Figure 7. Allan deviation of the voltage difference between the two halves of the source, observed during sixteen hours.

Assuming that both halves have independent similar noise, the Allan deviation for the total source (140 diodes) is reduced by a factor of 2, leading to 3×10^{-8} V/V at long term and 5×10^{-9} V/V at short term. These values are smaller than most commercial zener voltage standards [1].

5. Conclusions

A proposed multi-zener based voltage-standard-source was analyzed during 11 years of operation. Its internal noise was evaluated in $0.03 \mu\text{V/V}$ at one year averaging time, and $0.005 \mu\text{V/V}$ at 4 h averaging time. The maximum variation during 11 years was $0.16 \mu\text{V/V}$, with a drift of $-0.009 \mu\text{V/V}$ per year which is well below the calibration uncertainty.

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