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

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Abstract: The long-term behavior of a voltage standards 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 National Metrology Institute (UTE).

Keywords: Standard; zener; drift; noise; Josephson; voltage.

1. INTRODUCTION

Primary voltage standards are based on Josephson effects, but secondary standards on zener devices. There are some good commercial voltage standard using this technology [1], but their stability at long term is in the order of 1µV/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 µV/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 behavior. 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 for detecting variations between them [2, 3]. A prototypes based on this principle has been continuously observed since 2004. Its deviations from their initial values and analysis of its noise will be shown in the following sections.

2. DESCRIPTION

Fig. 1 shows the schematic circuit. Each zener (REF102, 10 V) is connected to the output voltage (*V*a) through a 100 Ω 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 evaluate random noises.

Zeners and electronic devices are placed in a small oven at 44 °C with a standard deviation of 0.03 °C, if the external temperature is 23 °C ±1 °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 used. Its specifications states 5 µV/V per month, but this figures is very conservative. Other 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. The zener used has a thermal coefficient, according to its specification, of 25 µV/K, but in the batch there is some compensation.

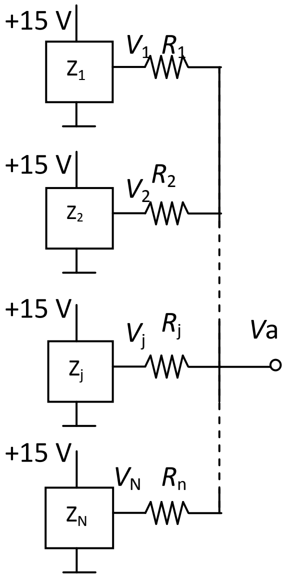

Fig. 1. Schematic circuit of the developed device.

The measured temperature coefficient of a set of 35 zeners was 10 µV/K, which leads to an uncertainty due to the temperature factor of 0.03 µV/V, k=1.

As a second uncertainty source, the variation 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

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

The voltage differences between individual zeners are lower than 3 mV, then $|Va\text{-}Vj|<3$ mV, and the value of ΔV_a^j will be lower than 2×10^{-8} 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 µV/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 inside 15 V ±10 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.

Fig. 2 shows the first prototype, which has been working since 2004. Another one was constructed in 2011, shown in Fig. 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 Fig. 2 and Fig. 3). They can be used as separate sources, or they that can be connected in parallel if needed. In this last case, the average value of the parallel 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 8 groups of the two prototypes and 2 commercial voltage standard sources. The output voltage of the scanner is the difference between the two selected sources, which is connected to a 6 ½ 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.

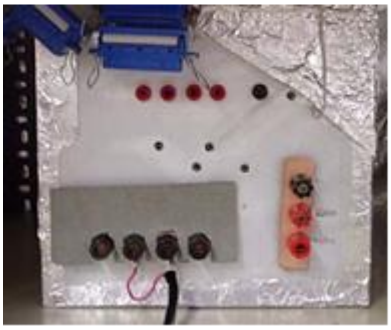

Fig. 2. First prototype of the voltage standard source.

Fig. 3. Second prototype of the voltage standard.

3. STABILITY

To study the long term stability, two types of comparison were done, comparisons against Josephson standards and comparisons between different groups. Up to now, four comparisons against Josephson standard were done on the first prototype in 2004, 2008, 2010 and 2015. It was compared against traveling standards using an 8 ½ DMM as comparator (Agilent 3458). Fig. 4 and Table I show the results. Second column shows the certificate value of the source and third column, the uncertainty. The average value of the four groups was stated as the value of the prototype. The variation between 2004 and 2008 was -0.12 µV/V, and the variation between 2010 and 2015 was 0.05 µV/V. However, between 2008 and 2010 a larger variation is observed. It was due to a failure in the temperature control.

Table I. Calibrations against a Josephson standard.

Date	Certificate value (V)	Uncertainty (k=2) (µV)	Corrected value (V)
21/08/2004	10,0006014	2,9	10,0006014
29/01/2008	10,0006002	2,5	10,0006002
01/08/2010	10,0006066	1,3	10,0005999
07/05/2015	10,0006071	1,3	10,0006004

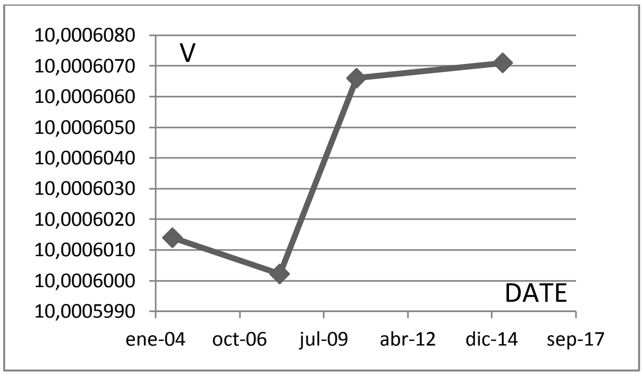

Fig. 4. Graphics of calibrations against Josephson standards.

The source was out of service for nine months (10/2008 to 06/2009). Once repaired, it was put in operation until present. To correlate its voltage values previous and after this period, the source was compare with a FLUKE 732B 10 V standard source taking into account its drift (-2.0 µV/year). A step voltage variation due to reparations was determined in 6.7 µV. The fourth column of Table I and Fig. 5 shows corrected values, subtracting that voltage step. The first two values, corresponding to 2004 and 2008, have no correction because they were determined previous to the failure. The two last values are the result of subtracting 6.7 µV from the corresponding value of the second column. In this way, all values can be compared as no break had occurred. The maximum variation during 11 years was 0.16 µV/V, with a drift of -0.009 µV/V per year which is well below the calibration uncertainties (0.13 µV/V in the best case).

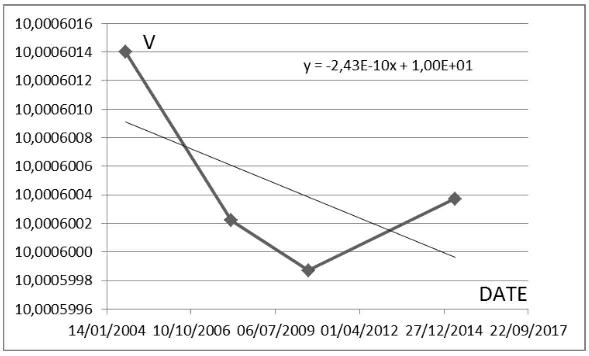

Fig. 5. Corrected voltages, subtracting the variation of the source due to repairs.

4. NOISE

Other measurements were done to estimate the noise of the source. One half of the source (70 diodes) was compared against the other one during 6 years. Allan deviation was computed for both data, and results are shown in Fig. 6 and Fig. 7. The general behavior at long term (Fig. 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 µV (6 parts in 10^8). In short term (Fig. 7), the noise is quite 1/f. The value of Allan deviation up to 4 h, is 0.1 µV which is equivalent to 1 part in 10^8.

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. The internal noise was evaluated in 3×10^{-8} V/V at one year averaging time, and 1×10^{-8} V/V at 4 h averaging time. The maximum variation during 11 years was 0.16 µV/V, with a drift of -0.009 µV/V per year which is well below the calibration uncertainty.

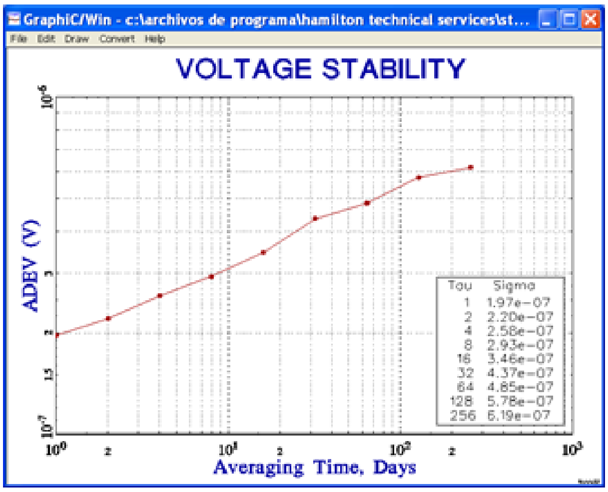

Fig. 6. Allan deviation of the voltage difference between both halves of the source, observed during six years.

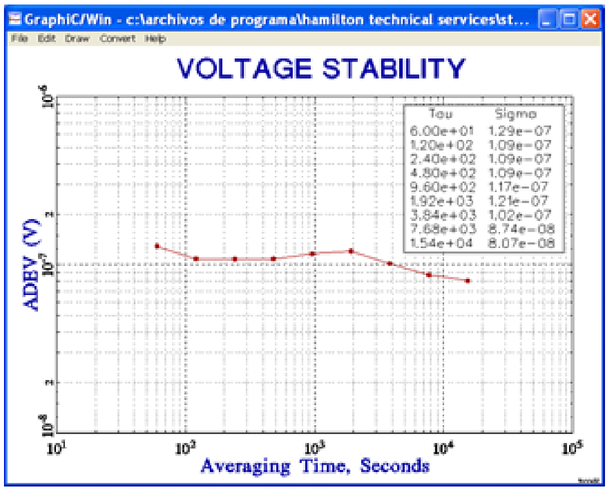

Fig. 7. Allan deviation of the voltage difference between both halves of the source, observed during one day.

6. REFERENCES

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