INVESTIGATIONS OF NOISE IN MEASUREMENTS OF ELECTRONIC VOLTAGE STANDARDS

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Abstract⊗

We have studied the voltage noise of electronic voltage standards based on Zener diode references (Zeners). Ten volt Zener outputs were compared to NIST Josephson standards using a digital voltmeter (DVM) to record voltage differences. The data were analyzed using the Allan variance. We have characterized the $1/f$ noise of 22 Zeners of three types. We also present evidence for the presence of a high level of white noise in Zeners.

Introduction

The uncertainty in voltage measurements of Zener standards is limited by $1/f$ noise that is characterized quantitatively by the Allan variance. This was demonstrated at the BIPM by using an analog voltmeter to compare ten-volt Zener outputs to the output of a ten-volt array of Josephson junctions [1]. Apart from the actual data acquisition, the BIPM system is operated manually.

The NIST has an active program to characterize its Zeners, particularly those used as traveling standards in its Measurement Assurance Program [2]. Here we report on a collaborative project designed to estimate the uncertainty limits imposed by $1/f$ noise in the NIST Zeners. In contrast to the methods used in [1], for this work DVMs were used to compare Zener voltages with array voltages using the NIST Josephson voltage standard systems operating entirely under computer control. In these respects, the NIST methods are similar to those used in most laboratories operating Josephson standards and should therefore be more generally applicable.

Methods of Measurement and Analysis

When measuring a Zener, the voltage difference between the array and the Zener under test is first set to within one millivolt or less. DVM measurements of the voltage difference are repeated at time intervals, τ_0, ranging from 0.6 s to 1 s or more, depending on the setting of the programmable integration period of the DVM (specified by the number of power line cycles or NPLC) and the number of DVM readings averaged to define one point. To reject undesired common-mode voltages, the NPLC was set to 1 or 10. Measurement points (time-voltage pairs) were typically in frames of 8192 points. A typical set of measurements consisted of ten to twenty frames.

The NIST data acquisition software is designed to accommodate unintended changes in the order number of the Josephson voltage step if the new step is stable. With an operating frequency near 75 GHz, a single step voltage corresponds to about 155 μV so that if the step order changes by more than six, the DVM must measure a voltage difference >1 mV. For the DVM used in this work, the two highest-sensitivity ranges are 1 mV and 10 mV. To avoid the obvious disadvantages of range changes, many of the measurements were made on the 10 mV range. This led us to investigate the decreased precision on the 10 mV range with respect to that of the 1 mV range.

Voltmeter readings include contributions from the DVM's own noise as well as that of the instrument under test. DVM noise is usually estimated from complete series of measurements made with a short-circuited input. If it is true that, within the same range, DVM noise is independent of the value of the voltage being measured, then the short-circuit results can be used to estimate voltmeter noise when measuring inputs of several hundred microvolts or more. To check this, we examined the variation of voltage noise with input voltage by using the DVM to directly measure the output of an array operating on steps having voltages between 0.156 mV and 1.564 mV.

The 22 Zeners we investigated included four Fluke 732B instruments fitted with Motorola reference/amplifiers (Type M), ten 732B instruments fitted with Linear Technology reference/amplifiers (Type L) and eight Wavetek 7000 series instruments.§

Measurement results were analyzed using the Allan variance. For an infinite number of voltages, y_i, read at regular time intervals τ_0, the Allan variance is based on averages of y_i over successive groups of n measurements, corresponding to the sampling time $\tau = n\tau_0$. Beginning with $n = 1$, the value of n is increased in some regular series. The Allan variance is defined as

$$\sigma_y^2(\tau) = \left\langle (\bar{y}_{j+1}(\tau) - \bar{y}_j(\tau))^2 \right\rangle / 2, \qquad (1)$$

where, $\bar{y}_j(\tau)$ is the average voltage of the j-th group of n successive readings and the angular brackets indicate an infinite time average. In general the Allan variance is not constant but varies with sampling time. The Allan variance of M measurements is estimated using

$$s_y^2(\tau) = (2P)^{-1} \sum_{j=1}^{P} [\bar{y}_{j+1}(\tau) - \bar{y}_j(\tau)]^2, \qquad (2)$$

where P = Int(M/n)−1 is the number of available first differences, $\bar{y}_{j+1}(\tau) - \bar{y}_j(\tau)$, corresponding to $\tau = n\tau_0$. In low-frequency electrical measurements we observe only $1/f$ noise and white noise. The spectral density is $S_y(f) = h_{-1} f^{-1} + h_0 f^0$

⊗ This work was partially performed at NIST in the Quantum Electrical Metrology Division, Electronics and Electrical Engineering Laboratory, and Time and Frequency Division, Physics Laboratory, Technology Administration, U.S. Department of Commerce, not subject to copyright in the United States.

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where the intensity coefficients h_{-1} and h_0 are constants. When using a DVM having a sharp cut-off filter, the Allan variance for the mixed process is

$$\sigma_y^2(\tau) = 2h_{-1}\ln 2 + h_0/2\tau \qquad (3)$$

To lower the uncertainty of the Allan variance we use mean values of the estimated Allan variances taken over a number (10-100) of frames.

Results

Fig. 1 shows the Allan deviation (square root of the Allan variance) as a function of sampling time for two Zeners and a short circuit.

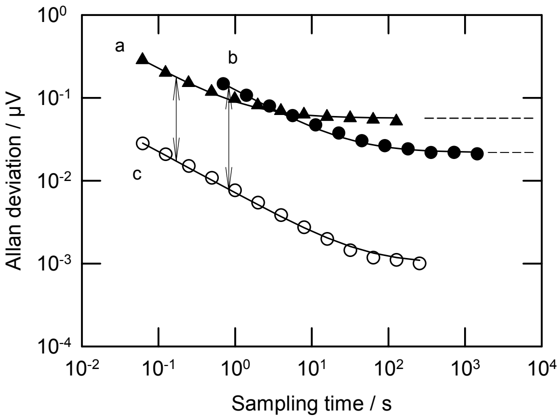

Fig. 1. Allan deviations versus sampling time for (a) 732B (L) Zener; (b) 732B (M) Zener and (c) DVM with a shorted input. Horizontal dashed lines indicate the noise floors for the two Zeners. Vertical two-headed arrows indicate considerably higher white noise levels in the Zeners.

For short sampling times, (a) and (b) asymptotically approach lines of slope −1/2, indicating the predominance of white noise in those regions. For long sampling times, (a) and (b) take on nearly constant values, termed the 1/*f*-noise floors, indicated by the dashed lines. These are characteristics of the individual Zeners. They are important because they set the lower limit of the random uncertainty achievable with each Zener. Comparing (a) and (b), we see that the 1/*f* noise of the Type M Zener is 2.6 times smaller than that of the Type L Zener. This is particularly interesting since this Type M Zener is one of the four traveling standards used in the North American comparisons of Josephson standards [3]. Plot (c) shows that the Allan deviation attributable to the DVM itself is 9.8 times smaller than the white noise in (a) and 18 times smaller than the white noise of (b). The additional white noise could originate from the Zener or from the DVM. To check the possibility that the increased white noise originates in the DVM, we examined the noise in measurements of voltages of different values within a given range, and in voltages measured on different ranges (1 mV and 10 mV).

Fig. 2 summarizes the results of the Allan deviations for DVM voltage measurements of four voltages on the 1 mV range (open symbols) and five voltages on the 10 mV range (solid symbols). Dashed lines join values corresponding to short-circuit measurements on the 1 mV range and heavy solid lines join values corresponding to short-circuit measurements on the 10 mV range. The vertical dashed line indicates the difference between the Allan deviations for short-circuit measurements on the two ranges; it corresponds to a factor of 1.8. Within the white noise regimes, the main conclusions are the following: (1) for the same sampling time, the Allan deviations for the 10 mV range are about 1.8 times greater (not 10 times greater) than those obtained on the 1 mV range; (2) for a given sampling time, there is no significant variation of the Allan deviations with applied voltage within the 1 mV range; (3) for input voltages ranging from 0 to 1.6 mV, measured on the 10 mV range, the Allan deviation is constant to within about 10 %.

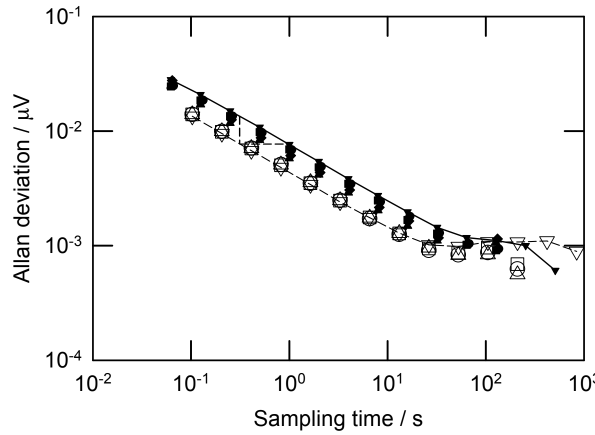

Fig. 2. Allan deviations versus sampling times for DVM measurements of four voltages between 0 and 0.782 mV on the 1 mV range (open symbols) and for five voltages between 0 and 1.564 mV on the 10 mV range (solid symbols). See text for details.

In view of the relatively small variations of the white noise level within a fixed voltage range, we conclude that the greatly increased white noise in Zener measurements, as indicated in Fig. 1, is not due to the DVM but probably due to the Zeners themselves.

The values of the 1/*f* noise floors of the 10 V outputs of the ten 732B (L) Zeners range from 50 nV to 80 nV and agree well with the results found for similar Zeners measured at the BIPM [1]. The corresponding results for the four 732B (M) Zeners range between 22 nV and 29 nV. Further details will be given at CPEM'04.

Acknowledgement

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References

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