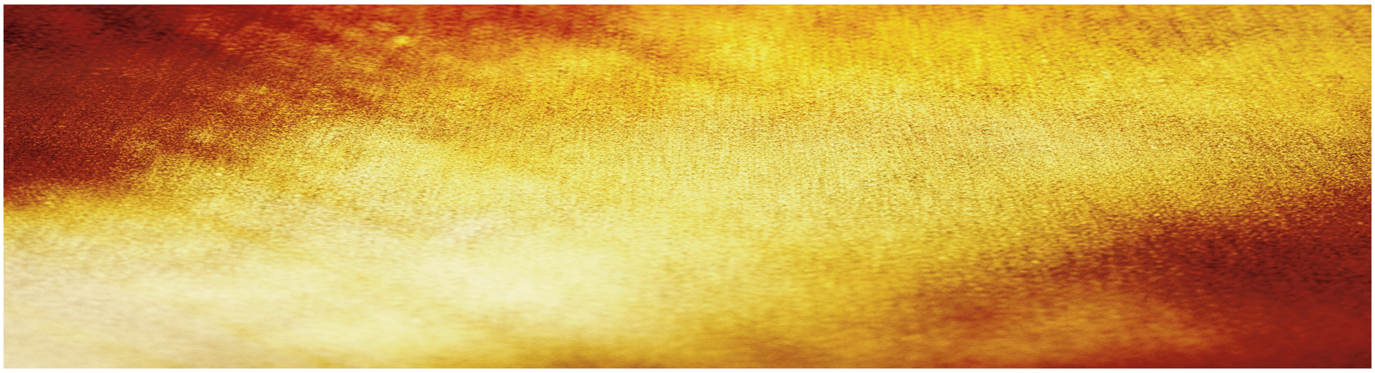

Ratio Calibration of a Digital Voltmeter for Force Measurement Using the Programmable Josephson Voltage Standard[1]

Yi-hua Tang, Thomas W. Bartel and June E. Sims

Abstract: Ratio calibration of a digital voltmeter (DVM) is critical for applications such as load cell response for force measurement. The National Institute of Standards and Technology (NIST) DVM ratio service provides ratio voltage measurements that are traceable to the Josephson Voltage Standard (JVS). Previously, the service was supported by NIST JVS systems using manual measurements. The NIST JVS uses a conventional Josephson junction array which often experiences a spontaneous step transition, caused by electromagnetic interference, during its operation. An adjustment is required to obtain a stable voltage step for the ratio calibration. The programmable JVS (PJVS), developed in the last decade, uses an array with non-hysteretic steps to provide a stable voltage. The PJVS was implemented in the DVM ratio calibration service to improve the efficiency and reliability of the service. The new protocol can be executed automatically to reduce the labor cost of the calibration service. The uncertainty of the DVM ratio calibration can be improved by taking automatic multiple measurements. This paper describes the DVM ratio calibration procedure and compares the conventional JVS and PJVS protocols. Results of an actual DVM ratio calibration are presented.

1. Introduction

Precise measurement of voltage ratio is fundamental to the use of certain strain gauge instruments such as load cells designed for force metrology. The National Institute of Standards and Technology (NIST) maintains a laboratory for the dissemination of force measurement standards through the calibration of force measuring instruments, using primary deadweight force standards to apply calibration forces as shown in Fig. 1. The force applied to a force measuring instrument causes an elastic deformation in the load-bearing sensing element within the instrument. For a load cell, this deformation results in a change in the resistive imbalance of a strain gauge bridge, where the strain gauges are attached to the sensing element as shown in Fig. 2a. Physical dimensions of strain gauges vary widely, but are typically on the order of a few millimeters.

An equivalent circuit of a load cell's strain gauge bridge is shown in Fig. 2b, where an excitation voltage, V_0, is applied to the input points A and B. Small changes in the strain gauge resistances in response to the force-induced deformation result in small variations in the bridge voltage, V, between the output

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[1] This work was performed at the Quantum Electrical Metrology Division, Electronics and Electrical Engineering Laboratory and is a contribution of the U.S. Government (U.S. Department of Commerce), and is thus not subject to copyright in the United States.

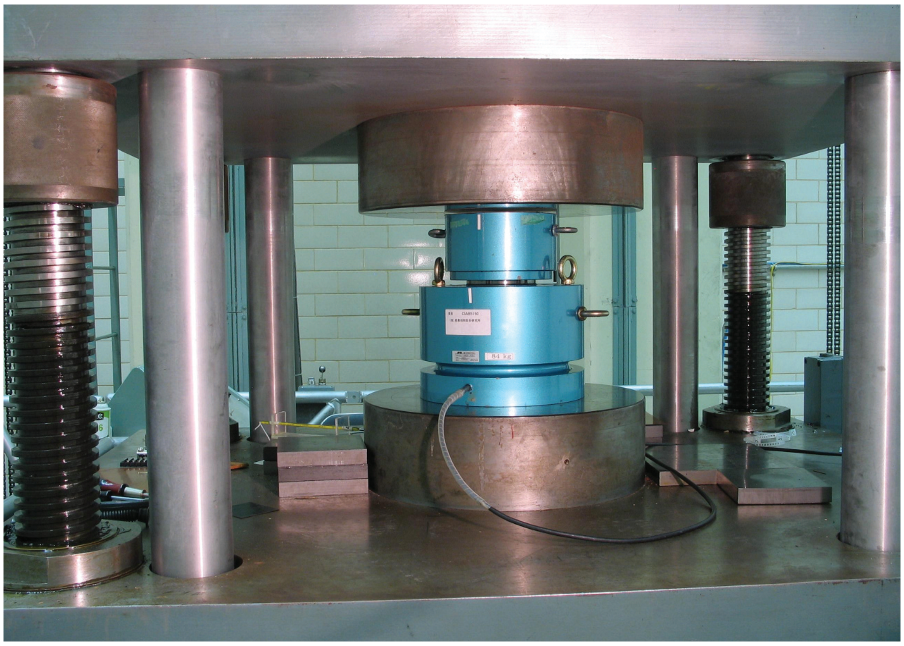

Figure 1. A load cell positioned for calibration in the NIST 4.448 MN (1 000 000. pound-force) deadweight force standard machine. The height of the load cell assembly (blue object) between the deadweight machine compression plates is 0.33 m.

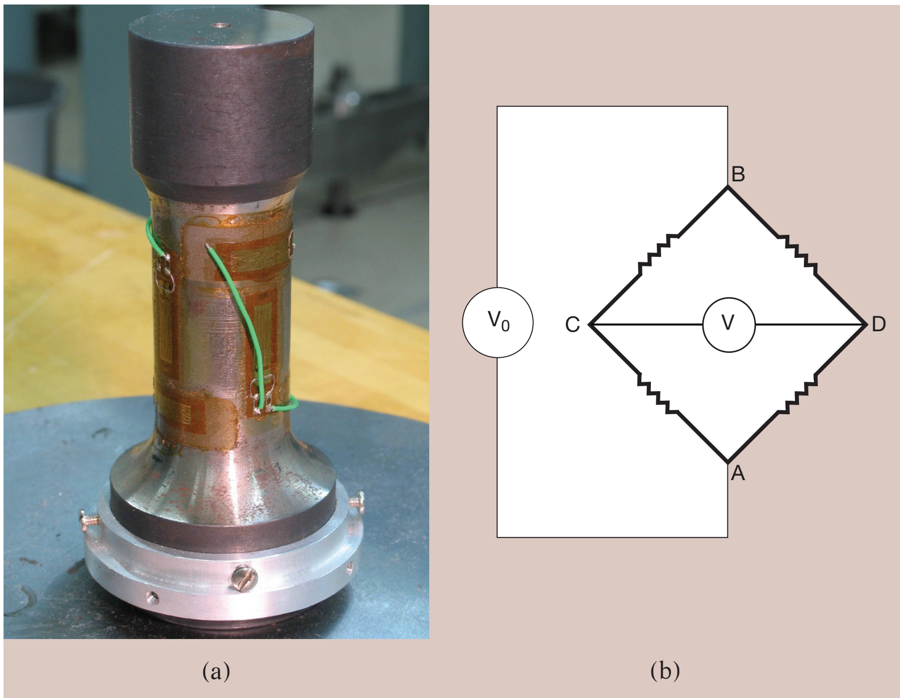

Figure 2. (a) A sensing element of a load cell with strain gauges attached. (b) Equivalent circuit of the full-bridge strain gauge network depicted in the photograph.

points C and D. The ratio of V/V_0 , which can be measured with a digital voltmeter, then becomes a suitable indication of the applied force. If the input and output voltages are sampled almost simultaneously, the measured voltage ratio is relatively insensitive to minor variations in the excitation voltage. When properly calibrated with the application of known forces and the appropriately precise measurement of the resulting voltage ratios, load cells can subsequently be employed to measure force with relative expanded uncertainties (k = 2) approaching 0.002 %. The different sources of uncertainty associated with the force calibration measurements conducted at NIST are discussed in Reference [1] and include those associated with the realization of force by the NIST deadweight force standards, the measurement of the transducer responses, and the characteristics of the transducers being calibrated.

The NIST force laboratory maintains its own strain gauge excitation and voltage-ratio measuring instruments for use in calibrating load cells that are not accompanied by customer supplied indicating instruments. A direct current excitation voltage V_0 of 10 V is normally employed, and both voltages V and V_0 are acquired for each applied force with a precision digital voltmeter (DVM) operating in voltage-ratio mode. It is desired to have the DVM calibrated in voltage-ratio mode to a relative standard uncertainty (k = 1) of no more than 0.0003 %.

Use of NIST instrumentation to obtain the load cell responses during force calibrations mandates that the voltage ratio measurements be traceable to national electrical standards. [1] This is accomplished by the periodic "primary" calibration of the NIST Force Laboratory's digital voltmeters by the Quantum Electrical Metrology (QEM) Division of the NIST Electronics and Electricity Engineering Laboratory (EEEL). Such a calibration is carried out in the DVM voltage-ratio mode, by providing dc voltage signals simultaneously to both input channels with the calibrated signals derived from the 1 V and 10 V Josephson Voltage Standards (JVS) maintained by the Quantum Electrical Metrology Division. Different DVMs are selected for succeeding calibrations in order to avoid bias that could be associated with the repeated calibration of the same DVM. The Mass and Force Group then maintains the calibrations of all of its DVMs at least quarterly by comparisons with the DVM most recently calibrated by the QEM Division.

During the DVM voltage-ratio calibration, the QEM Division maintains a 10 V dc signal from a solid-state voltage standard that is calibrated against the NIST 10 V Josephson Voltage Standard (JVS) at the DVM's ratio reference input while applying a sequence of reference signals

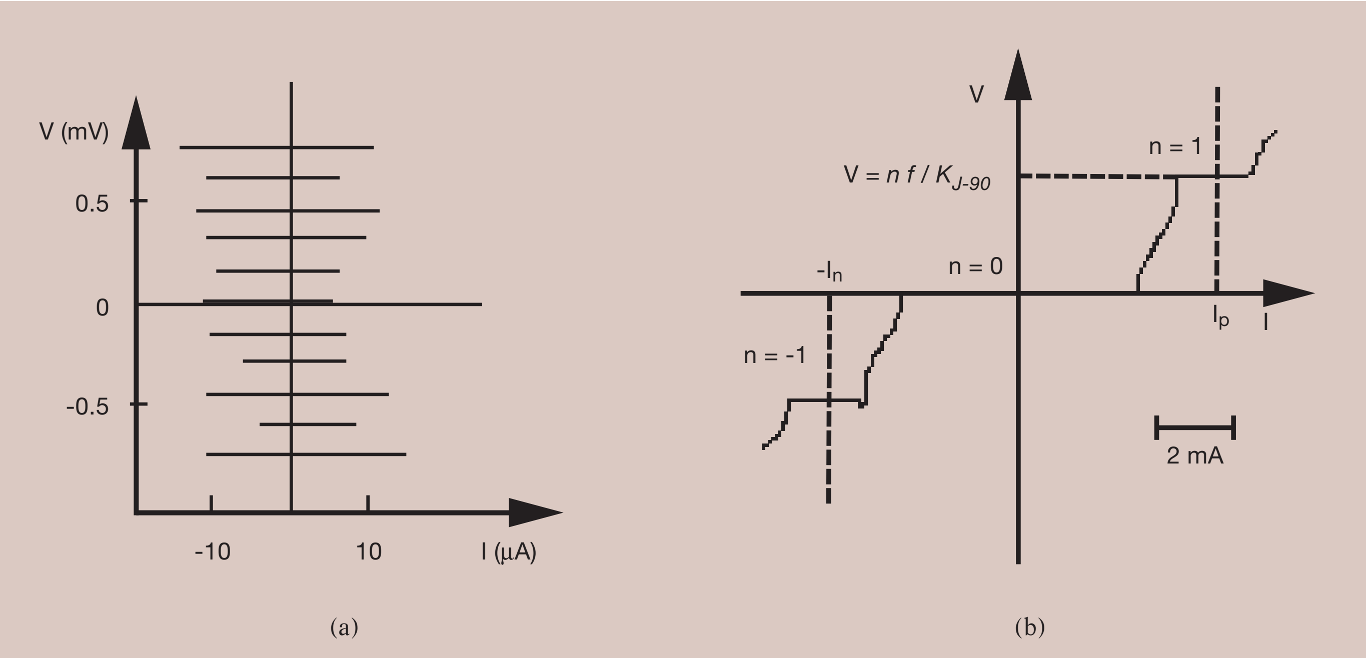

Figure 3. Voltage steps of (a) zero-current-biased Josephson junction array and (b) programmable Josephson junction array.

ranging from 5 mV to 100 mV provided by the NIST 1 V JVS to the DVM's primary input channel. The corresponding voltage-ratio range is from 0.5 mV/V to 10 mV/V. For most load cells calibrated at NIST, the output when loaded to capacity is 2 mV/V to 3 mV/V. The protocol for this ratio calibration procedure was developed by the QEM Division in conjunction with the Mass and Force Group staff to meet their requirements.

Historically, variable voltages from 5 mV to 100 mV were generated by the 1 V JVS, which uses a conventional Josephson junction array with hysteretic voltage steps. During the DVM voltage-ratio calibration, the NIST 1 V JVS must be maintained at a stable voltage step. However, the voltage steps may change spontaneously due to the electromagnetic interference from the environment. In this case, the measurement will have to be repeated for the same voltage. In order to cancel the DVM offset and thermal voltages in the measurement circuit, a voltage reversal to the DVM is required. It is necessary to keep the voltage at exactly the same voltage step during voltage reversal. When the NIST 1 V JVS was used for the DVM voltage-ratio calibration, the voltages were set manually. In the past, it took several hours to finish a series of voltages from 5 mV to 100 mV in the manual adjustment mode. In the new method, the programmable JVS uses non-hysteretic voltage steps with current margins that are 100 times that of the conventional Josephson junction array. It can be used for a DVM voltage-ratio calibration that avoids the step transition problem. Because the PJVS is capable of being programmed, it can be used for an automatic voltage-ratio measurement with improved efficiency and reliability. This paper describes the principle of how the PJVS works. Results from a protocol using the PJVS for a DVM voltage-ratio calibration will be presented.

2. Implementing the PJVS into the DVM Voltage-Ratio Calibration

The voltage steps of the conventional Josephson junction array used in NIST 1V and NIST 10 V JVS systems are all biased at zero current as shown in Fig. 3a. The step margin of the arrays is usually around 20 µA, which is generally sufficient for stable operation. However, electromagnetic interference in the typical measurement circuits can be large enough to trigger voltage step jumps during the measurement. If such a jump were to occur while a DVM voltage-ratio calibration is being performed, the voltage has to be reset to a stable step and the calibration for this voltage-ratio needs to be repeated.

By contrast, the PJVS is biased at non-zero current, leading to a non-hysteretic junction that has distinct voltage values depending on the bias current, as shown in Fig. 3b. [2] Unless the bias current changes, the voltage output of a junction is stable for an infinitely long time. In the present PJVS design, only three bias currents, $-I_n$, 0, $+I_p$, are used leading to steps of n = –1, 0, or +1, which of course implies voltage outputs of $-V$, 0, or $+V$. In the PJVS, the array junctions are grouped into segments, with all the junctions in a segment being biased by a common bias current. Hence, each segment can be individually programmed to one of the three operating states by setting its bias current. Thus, the output voltage of the full array can be digitally programmed by applying the appropriate combination of bias currents to the various segments. The value of the developed voltage, V, is simply the sum voltage of all the segments:

$$V = \sum_i \frac{n_i N_i f}{K_{J-90}} , \qquad (1)$$

where n_i is a quantum step number of the i^{th} segment either –1, 0 or +1, N_i is the number of junctions in the ith segment,

Segment	Number of Junctions	Voltage (mV)
1	8 800	327.810
2	8 800	327.810
3	8 798	327.736
4	8 800	327.810
5	8 794	327.587
6	8 800	327.810
7	8 792	327.512
8	3 888	144.833
9	1 296	48.278
10	16	0.596
11	48	1.788
12	144	5.364
13	432	16.093

Table 1. Construction of a programmable Josephson junction array and its voltage output with microwave frequency 18.014 588 GHz.

Array Segment Bias Status	Net Number of Junctions	Voltage (mV)
0 000 000 000 000	0	0.000 000 0
0 000 000 00n 0p0	128	4.768 149 9
0 000 000 00n 0np	272	10.132 318 5
0 000 000 000 npp	528	19.668 618 2
0 000 000 0pn n0n	800	29.800 936 7
0 000 000 0pn nn0	1 088	40.529 273 9
0 000 000 0p0 p00	1 344	50.065 573 6
0 000 000 0pp 0pp	1 888	70.330 210 6
0 000 000 pn0 np0	2 688	100.131 147 3

Table 2. Voltages for DVM voltage ratio calibration and corresponding programmable junction array configuration.

f is the microwave frequency, and $K_{J\text{-}90}$ = 483 597.9 GHz/V is the Josephson constant adopted in 1990 by the Consultative Committee for Electricity and Magnetism (CCEM). [3]

A state-of-the art array design can contain more than 67 000 junctions on a two-layer structure with 16 junctions in the smallest segment. [4] Table 1 shows the construction of the programmable Josephson junction array used in the NIST volt dissemination system. By programming a combination of segments and their bias currents, a stable voltage up to 2.6 V can be generated.

For a DVM voltage-ratio calibration, one of the voltage inputs to the DVM is the 10 V output from a Zener standard which is calibrated against the NIST 10V JVS system. The nominal voltages of the second voltage source to the DVM range from 5 mV to 100 mV, usually in a sequence of 5 mV, 10 mV, 20 mV, 30 mV, 40 mV, 50 mV, 70 mV, and 100 mV. These voltages can be obtained from the PJVS with a combination of different segments of the array. Table 2 shows the bias status of each segment of the total 13 segments, where each digit represents a segment. The 1st digit of the series represents the bias status of the 1st segment and the last digit represents the bias status of the 13th segment. There are three different bias states: 0, n, and p, where 0 denotes that the segment is not selected or zero current biased, n denotes that the segment is negatively biased, and p denotes that the segment is positively biased.

For example, by biasing segment 10 with negative current and biasing segment 12 with positive current, the total number of junctions would be 128, the difference between the junction numbers of segments 12 and 10. The voltage output from the array is a stable voltage 4.768 149 9 mV at the working frequency 18.014 588 GHz. In the DVM ratio-calibration, the polarity of a voltage input to the DVM must be reversed in order to cancel the offset in the circuit. This can be achieved by reversing the bias status of a selected combination of array segments. For example, by biasing segment 10 positively and segment 12 negatively, a voltage of –4.768 149 9 mV can be generated. A ratio calibration using a voltage other than the nominal values listed in the Table 2 will require the combination of different segments using the three bias options to meet the calibration requirement.

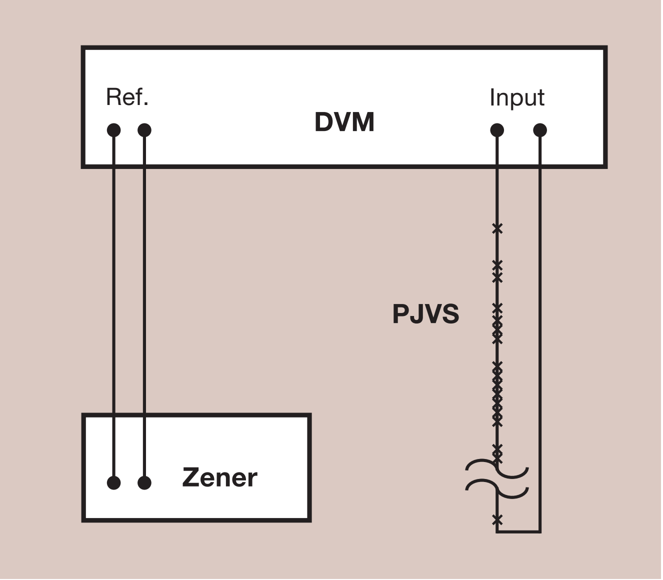

Figure 4. Setup for DVM ratio calibration.

3. DVM Voltage-Ratio Calibration

A setup for DVM ratio calibration using the PJVS is shown in Fig. 4. The reference voltage of 10 V is provided by a Zener voltage standard which is calibrated against a conventional JVS system. The calibration is usually carried out before and after the DVM calibration, which spans a period of 3 to 4 h. During

Nominal PJVS Voltage (mV)	Relative Uncertainty (µV/V)
5	0.78
10	0.39
20	0.20
30	0.13
40	0.10
50	0.08
70	0.06
100	0.04

Table 3. PJVS uncertainty at its nominal voltage output for DVM ratio calibration.

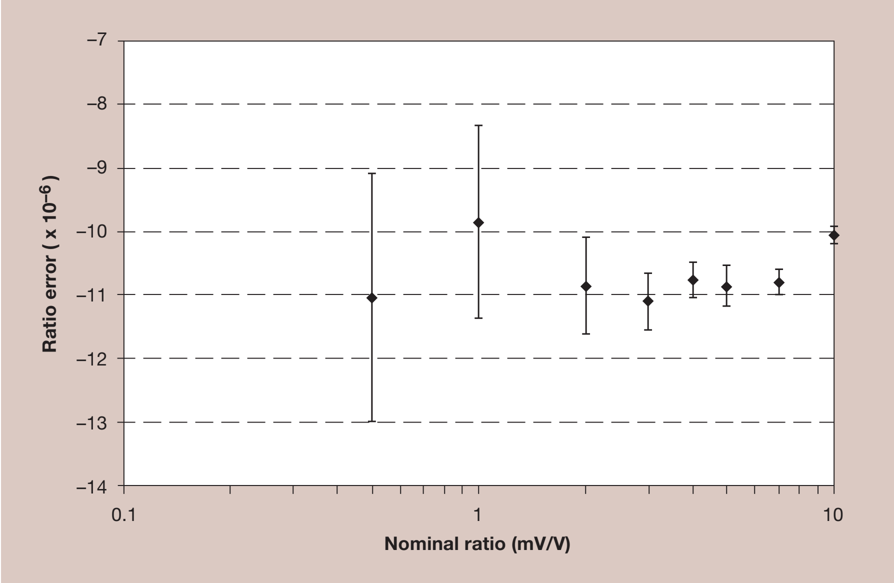

Figure 5. An example of a DVM ratio calibration at several nominal voltages. The error bars represent one standard deviation of six repeated measurements. The ordinates represent the uncorrected ratio error for this particular instrument.

Nominal Ratio Input (mV/V)	Type A ($\times 10^{-6}$)	Type B of 10 V ($\times 10^{-6}$)	Type B of PJVS ($\times 10^{-6}$)	Combined Std. Unc., u_c ($\times 10^{-6}$)
0.5	1.95	0.01	0.78	2.10
1	1.51	0.01	0.39	1.56
2	0.77	0.01	0.20	0.79
3	0.44	0.01	0.13	0.46
4	0.27	0.01	0.10	0.29
5	0.32	0.01	0.08	0.33
7	0.20	0.01	0.06	0.21
10	0.14	0.01	0.04	0.14

Table 4. An example of DVM ratio calibration uncertainty budget, where u_c is the combined standard uncertainty (k = 1).

this time Zener drifting is negligible. The mean value of all Zener measurements is used for the reference voltage in ratio calculation. The uncertainty of the Zener reference voltage is usually within 1 part in 10^8 ($k = 1$). The variable voltage input is provided by a PJVS. We have measured the combined uncertainty contributed by the thermal voltage in the leads, RF induced offset, and the noise in the measurement circuit. Over approximately 15 min, the standard deviation of zero voltage measurements at the operating frequency and power level for the PJVS was found to be 3.9 nV with k = 1. [4] This is considered as a Type B contribution to the final ratio calibration uncertainty budget. Table 3 lists the relative uncertainty of the PJVS at nominal voltages for the DVM ratio calibration.

The voltage measured by the DVM consists of the voltage generated by the array, DVM zero offset, and thermal voltage in the measurement loop. The leads of the PJVS running from liquid helium temperature of 4.2 K to room temperature of 296 K can generate a thermal voltage of a few tenths of a microvolt up to 1 microvolt. This offset can be cancelled by reversing the polarity of the PJVS input voltage. The ratio error, Error, for the DVM is given by:

$$Error = \frac{R_{in}^{(+)} - R_{in}^{(-)}}{2\dfrac{V_{PJVS}}{V_{Ref}}} - 1\,, \qquad (2)$$

where $R_{in}^{(+)}$ is the DVM reading for the positive polarity voltage input, $R_{in}^{(-)}$ is the DVM reading for the negative polarity voltage input, V_{Ref}, is the reference voltage provided by a Zener standard, and V_{PJVS} is the calculated voltage from the PJVS. At each nominal input voltage, the measurements are repeated several times to establish a confidence level for the measurements. The Type A uncertainty of the ratio error at each input can be expressed by the standard deviation of the multiple measurements. A protocol has been developed to perform the measurements automatically.

Figure 5 shows an example of a DVM ratio calibration from 0.5 mV/V to 10 mV/V. The error bar is the standard deviation of six repeated measurements. This is considered as the Type A contribution to the final ratio calibration uncertainty budget. In the earlier ratio measurements, manual adjustments were required. This limited the number of repeated measurements. By implementing the PJVS in the ratio calibrations, the voltages can be maintained as long as needed. The measurements can also be taken automatically, and the number of repeated measurements can be easily increased to reduce the uncertainty.

The combined standard uncertainty (k = 1) can be calculated as root sum square of Type A uncertainty of the multiple measurements, Type B uncertainty of the 10 V reference voltage, and Type B uncertainty of the PJVS at the nominal voltage output. The Type B contributions are much smaller compared to the Type A contribution which primarily represents the variation in the repeated ratio readings returned by the DVM. As an example Table 4 lists the three uncertainty components and the combined standard uncertainty for the measurements taken in Fig. 5.

4. Summary

Using the conventional JVS for the DVM ratio calibration often requires a manual adjustment to obtain a fixed stable voltage when a spontaneous step jump occurs. The PJVS provides biased voltage steps with current margins 100 times higher when compared to the conventional Josephson array. The voltage generated by the PJVS is highly stable and immune to electromagnetic interference. Using a PJVS for the DVM ratio calibration improves the efficiency and reliability of the measurement process with reduced uncertainty. The PJVS has been successfully implemented into the NIST DVM ratio calibration service which the NIST force laboratory depends upon.

5. References

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