Interlaboratory Comparison of Josephson Voltage Standards Between NIST and Lockheed Martin Astronautics

Yi-hua Tang and William B. Miller

Abstract—**Two Josephson voltage standard (JVS) systems operated at the National Institute of Standards and Technology (NIST) and Lockheed Martin Astronautics (LMA) were compared by using four traveling Zener standards. A Measurement Assurance Program (MAP) protocol was adopted for the comparison. The Zener data were first corrected based on their pressure coefficients to compensate for the pressure difference due to the lab elevations and local meteorological conditions. The Welch–Satterthwaite formula and effective degrees of freedom (DOF) were then used to calculate the expanded uncertainty. The mean difference between the measurements of the two laboratories was found to be 0.059 μV with an expanded uncertainty of $\pm$ 0.189 μV at the 95% confidence level.**

Index Terms—**Intercomparison, Josephson voltage standard (JVS), measurement assurance program (MAP), uncertainty, Zener pressure correction.**

I. Introduction

AN INTERCOMPARISON of Josephson voltage standards (JVS) between the National Institute of Standards and Technology (NIST) and Lockheed Martin Astronautics (LMA)[1] was carried out from May 28 to June 30, 1999. The main purpose of the intercomparison was to determine the difference (if any) between the volt realized by LMA's JVS and the US national representation of the SI volt, in support of a JVS intercomparison organized by the National Conference of Standard Laboratories (NCSL). The second purpose of the NIST-LMA intercomparison was to test the technique of applying pressure corrections for traveling Zener standards. In the past, corrections for environmental effects on Zener standards due to pressure were not based on independent determinations of these effects. Rather, an environmental effect such as pressure was treated as a fit parameter in the data analysis [1]. Since the pressure coefficient of a Zener standard is independent from the Zener drift rate with time, we proposed to measure the pressure coefficient of the traveling Zener standards. Then the data from both laboratories could be adjusted to a relative pressure to exclude the pressure effects due to geological elevation and meteorological changes. A similar protocol was used in an earlier BIPM-NIST comparison carried out from October 1998 to January 1999 [2].

A Measurement Assurance Program (MAP) is commonly used to establish the difference between the measurement units realized at NIST and at a customer laboratory. In a voltage MAP, a set of traveling Zener standards is measured at NIST and then sent to a customer for measurement, e.g., using a JVS. After a certain number of measurements have been taken, the traveling Zener standards are returned to NIST for further measurements. The data are then analyzed to find the difference between the NIST and customer measurements and a total uncertainty that includes all known uncertainty contributions. In the case of JVS systems when the offset between the NIST and customer measurements can not be explained by the uncertainty analysis, a further investigation should be conducted to find the source of the difference.

II. Experimental Description

A set of four traveling Zener standards was measured at 10 V against the JVS at NIST and LMA from May 28, 1999 to June 30, 1999. NIST received the Zener standards on May 27 and the first round of measurements at NIST was carried out from May 29 through June 7. LMA performed its measurements between June 10 and June 21. NIST started its second round of measurements on June 23 and finished the intercomparison on June 30. All the shipments were handled by overnight express delivery. For a single point measurement of a Zener output, an integration time of 100 s was used for averaging at NIST, and 20 s at LMA. An established procedure was used to minimize the thermal voltages existing in the wires and contacts between the scanner and Zener standards. Each Zener output was measured consecutively twice, once normally and once with the positive and negative outputs reversed. Four low-thermal reversing switches were attached directly to the Zener terminals for this purpose. During the first set of measurements at NIST, it was noticed that the reversing switches attached to two Zener standards exhibited excessive offset voltages. As a result, these two switches were not used during the subsequent measurements. Instead, the measured polarity of the two affected Zener standards was changed by manually reversing the measurement leads with great caution. The mean difference of the paired Zener outputs was used to derive a single measurement for the data analysis. A total of

Manuscript received May 14, 2000; revised October 30, 2000. This work was performed partly at NIST in the Electricity Division, Electronics and Electrical Engineering Laboratory, Technology Administration, U.S. Department of Commerce, and partly at LMA, Metrology Laboratory.

Y. Tang is with the National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899 USA.

W. B. Miller is with Lockhead Martin Space Systems Company—Astronautics Operations (formerly Lockheed Martin Astronautics), Denver, CO 80201 USA.

Publisher Item Identifier S 0018-9456(01)02604-3.

[1]Lockhead Martin Astronautics is now Lockhead Martin Space Systems Company - Astronautics Operations (LMAO).

TABLE I
PRESSURE COEFFICIENTS AND STANDARD DEVIATIONS FOR THE FOUR ZENER STANDARDS

	Z1	Z2	Z3	Z4
Coefficient (nV/hPa)	-0.714	-1.720	-1.186	-0.821
1 σ (nV/hPa)	0.039	0.036	0.041	0.041

ten pairs of measurements were taken in the first round at NIST. LMA took 12 pairs of measurements. In the final round at NIST, seven pairs of measurements were taken.

The pressure effect on Zener voltage standards was first reported in [3]. The pressure coefficients of the four Zener standards for the NIST-LMA intercomparison have been measured at NIST and Sandia National Laboratory (SNL). The results from both laboratories were consistent within the uncertainty of the measurements. The Zener outputs depend linearly on the pressure and they track the variations in the ambient pressure very closely. The mean value of the NIST and SNL measurements of these coefficients was used to correct the output voltage of each Zener to a standard atmospheric pressure of 1013.25 hPa. The four pressure coefficients and their standard uncertainties are listed in Table I.

The barometric pressure at NIST was measured with a digital barometer that has been checked against a NIST primary pressure gauge. The uncertainty in the calibration of this instrument contributes negligibly to the results of this comparison. A summary of the environmental conditions and their variability during the comparison is listed in Table II.

All measurements at NIST and LMA were made under battery power within 30 min after the Zener standards were disconnected from ac power. The ac line was reconnected to each Zener standard for recharging its battery after a pair of measurements finished.

III. RESULTS

In analyzing the data, we first computed the average value for each pair of positive and negative Zener outputs. The corrections due to the difference in barometric pressure were then made to the NIST and the LMA measurements. The corrected Zener output is calculated using

$$V\ (\text{corrected}) = V\ (\text{paired}) - C_p(p - 1013.25)/1000 \quad (1)$$

where V (corrected) and V (paired) are in microvolts, C_p is the pressure coefficient in nV/hPa, p is the pressure in hPa, and 1013.25 is the reference pressure in hPa. Second, it was assumed that during the comparison the traveling Zener standards drifted linearly with time. Fig. 1 shows the data of the traveling Zener standard Z4 measured at NIST and LMA. A least-sum-of-squares (LSS) fit was applied to the NIST data. The fit results for the four traveling Zener standards are listed in Table III. Fig. 2 is the residual lag diagram of the traveling Zener standard Z4, which plots the residual $(i-1)$ versus residual (i) for NIST and LMA measurements. The random distribution of the residuals in the lag diagrams indicates that the linear drift model is a reasonable assumption.

Third, it was assumed that the traveling Zener standards drift with the same rate at LMA as at NIST. An offset between LMA and NIST for the jth Zener standard was calculated based on

TABLE II
AVERAGE ENVIRONMENTAL CONDITIONS DURING THE INTERCOMPARISON

	Pressure (hPa)		Temperature (°C)		Humidity (%)	
	Mean	1 σ	Mean	1 σ	Mean	1 σ
NIST	1001.2	5.2	22.2	0.4	46	2
LMA	830.1	3.0	22.2	0.2	45	4

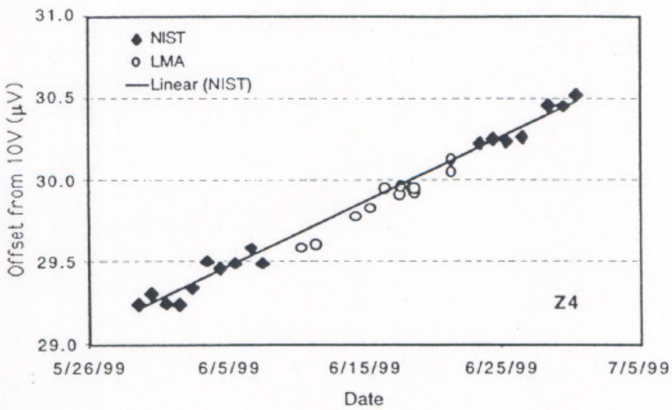

Fig. 1. Measurements of the traveling Zener standard Z4 at NIST and LMA. The data have been adjusted to the standard atmosphere pressure of 1013.25 hPa. A LSS fit line is obtained using NIST data only.

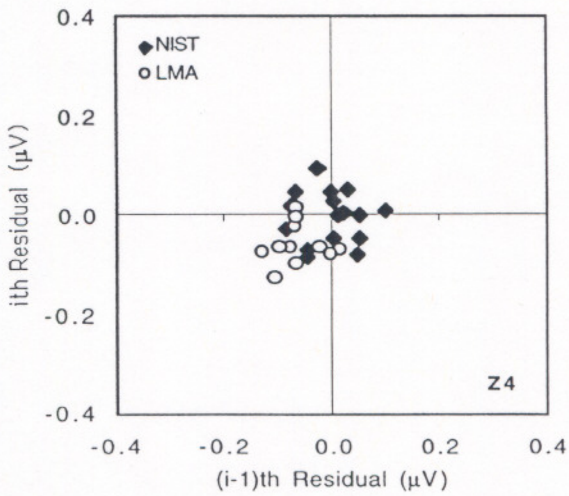

Fig. 2. Residual lag diagram of the traveling Zener standard Z4.

TABLE III
DRIFT RATES OF THE TRAVELING ZENER STANDARDS AND ASSOCIATED STANDARD DEVIATIONS

	Z1	Z2	Z3	Z4
Drift rate (nV/day)	20.32	15.40	25.42	39.86
1 σ (nV/day)	2.03	2.68	1.76	1.07

TABLE IV
THE DIFFERENCE BETWEEN LMA AND NIST AND THE UNCERTAINTY COMPONENTS IN μV

	Z1	Z2	Z3	Z4
NIST Type A	0.024	0.031	0.021	0.013
NIST Type B	0.007	0.007	0.007	0.007
LMA Type A	0.038	0.026	0.021	0.012
LMA Type B	0.034	0.034	0.034	0.034
Type B due to C_p	0.007	0.006	0.007	0.007
Δ(LMA – NIST)	0.090	-0.014	0.226	-0.064

LMAs measurements and on the drift rate from the NIST data by

$$\Delta V_j = \tfrac{1}{12}\sum_{i=1}^{12}(V_{ij}(\mathrm{LMA}) - V_{ij}(\mathrm{pred.})) \tag{2}$$

where

$V_{ij}(\mathrm{LMA})$ ith measurement for the jth Zener standard at LMA;

$V_{ij}(\mathrm{pred.})$ ith predicted value of the jth Zener standard at the time when the LMA measurement was taken using the NIST drift rate;

12 total number of paired measurements made by LMA.

The difference between the LMA and NIST measurements for each traveling Zener standard is listed in Table IV. The mean difference of the four standards was found to be 0.059 μV.

The uncertainty components of the intercomparison were evaluated and the results are listed in Table IV. The Type A uncertainty of each traveling Zener standard at NIST and LMA was calculated based on the residuals relative to the LSS fit line. The pooled standard deviation or the Type A uncertainty from the NIST measurements is obtained from

$$u^2_{A,\,\mathrm{NIST}} = \tfrac{1}{4}\sum_{j=1}^{4} u^2_{j,\,\mathrm{NIST}} \tag{3}$$

where $u_{j,\,\mathrm{NIST}}$ is the standard uncertainty of the jth Zener measurements at NIST. Similarly, the pooled standard deviation or the Type A uncertainty from the LMA measurements is obtained from

$$u^2_{A,\,\mathrm{LMA}} = \tfrac{1}{4}\sum_{j=1}^{4} u^2_{j,\,\mathrm{LMA}} \tag{4}$$

where $u_{j,\,\mathrm{LMA}}$ is the standard uncertainty of the jth Zener measurements at LMA.

The variability resulting from the transportation effect is evaluated by the Type B standard uncertainty of the mean difference between NIST and LMA for all four traveling Zener standards by

$$u^2_{B,\,\mathrm{transfer}} = \frac{1}{4(4-1)}\sum_{j=1}^{4}\left(\Delta V_j - \frac{1}{4}\sum_{j=1}^{4}\Delta V_j\right)^2. \tag{5}$$

TABLE V
UNCERTAINTY COMPONENTS AND THE ASSOCIATED DEGREES OF FREEDOM

Source	Uncertainty(μV)	DOF
Pooled Type A of NIST, $u_{A,NIST}$	0.023	15
Pooled Type A of LMA, $u_{A,LMA}$	0.026	11
Standard deviation of mean of four Zener differences $u_{B,transfer}$	0.064	3
Type B uncertainty from NIST, LMA JVS systems and pressure, $u_{B,NIST,LMA,pressure}$	0.035	∞

There was a Type B uncertainty contribution from the pressure coefficient measurements. The uncertainty u_p, due to the pressure difference between NIST and LMA is given by

$$u_p = u_{Cp}(p_{\mathrm{NIST}} - p_{\mathrm{LMA}}) \tag{6}$$

where u_{Cp} is the standard uncertainty of the pressure coefficient measurements whose results are listed in Table I, and p_{NIST} and p_{LMA} are the mean pressures at NIST and LMA respectively, during the time when the respective measurements were taken. This Type B uncertainty contribution is listed in Table IV for each Zener standard. The Type B uncertainty contribution of the measurement systems of the two laboratories and pressure coefficient measurements can be obtained using

$$u^2_B = u^2_{B,\,\mathrm{NIST}} + u^2_{B,\,\mathrm{LMA}} + \tfrac{1}{4}\sum_{j=1}^{4} u^2_{j,\,cp}. \tag{7}$$

The combined standard uncertainty u_c of the NIST and LMA intercomparison at 10 V, obtained from

$$u^2_c = u^2_{A,\,\mathrm{NIST}} + u^2_{A,\,\mathrm{LMA}} + u^2_{B,\,\mathrm{transfer}} + u^2_B \tag{8}$$

is 0.081 μV.

The transfer effect and measurements at NIST and LMA may not be correlated. A prudent estimation of the combined variance is made by summing up the variances of all sources. This is due to the lack of detailed information of the correlation between the random noise of each Zener standard and variability among the Zener standards.

Table V lists the uncertainty components and their associated degrees of freedom (DOF). In order to estimate an expanded uncertainty at a certain confidence level, the effective DOF, ν_{eff}, can be evaluated by the Welch–Satterthwaite formula according to the Guide to the Expression of Uncertainty in Measurement (GUM) [4], that is

$$\nu_{\mathrm{eff}} = \frac{u_c^4}{\frac{u^4_{A,\,\mathrm{NIST}}}{15} + \frac{u^4_{A,\,\mathrm{LMA}}}{11} + \frac{u^4_{B,\,\mathrm{transfer}}}{3}} = 7.36. \tag{9}$$

The Student t factor corresponding to the 95% confidence level for the effective DOF, 7.36, is found to be 2.33 from [3]. Consequently, the expanded uncertainty tu_c of the MAP at the 95% confidence level is 0.189 μV at 10 V or 1.9 parts in 10^8.

IV. CONCLUSION

In a JVS intercomparison, the final uncertainty of the experiment is often limited by the characteristics of transport voltage standards. Most of Zener voltage standards being used as transport standards in a JVS intercomparison are affected by atmospheric pressure due to geological elevation and meteorological changes. The ability to make pressure corrections for the transport of Zener standards reduces the uncertainty of JVS intercomparisons.

ACKNOWLEDGMENT

The authors would like to thank C. Croarkin of NIST for her valuable suggestions to analyze the data. They would also like to thank S. L. Kupferman of the SNL for providing the measurement results of the pressure coefficients of the traveling Zener standards, D. Deaver of Fluke Corporation for providing the traveling Zener standards, and C. Hamilton of NIST for providing the reversal switches.

REFERENCES

[1] C. M. Wang and C. A. Hamilton, "The fourth interlaboratory comparison of 10 V Josephson voltage standards in North America," *Metrologia*, vol. 35, pp. 33–40, 1998.

[2] T. J. Witt, D. Reymann, Y. H. Tang, and C. A. Hamilton, "Bilateral comparison of 10 V standards between the NIST, Gaithersburg, the NIST, Boulder and the BIPM,", BIPM Rappaport BIPM-99/07, Oct. 1998–Jan. 1999.

[3] T. J. Witt, "Pressure coefficients of some Zener diode-based electronic voltage standards," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 329–332, Apr. 1999.

[4] G. Annex, "Guide to the expression of uncertainty in measurement," International Organization for Standardization, 1993.