The Seventh Intercomparison of Josephson Voltage Standards in North America

Yi-hua Tang, Clark A. Hamilton, *Fellow, IEEE*, David Deaver, Harold Parks, and Barry M. Wood, *Member, IEEE*

***Abstract*—The seventh interlaboratory comparison of Josephson voltage standards (JVS) at 10 V, sponsored by the National Conference of Standard Laboratories International, took place from April to October 2005 with 15 participating laboratories. A traveling JVS system of the National Institute of Standards and Technology was used to make five comparisons with the subpivot laboratories. This paper describes the protocol used for the JVS intercomparison and the improvements achieved by the use of the transportable JVS.**

***Index Terms*—Compact Josephson voltage standard (CJVS), interlaboratory comparison (ILC), JVS, uncertainty, Zener standard.**

I. Introduction

THE SEVENTH National Conference of Standard Laboratories International (NCSLI) Josephson voltage standards (JVS) intercomparison at 10 V was carried out from April to October 2005. The same four traveling Zener voltage standards, as used previously in the 1995, 1997, 1999, and 2002 interlaboratory comparisons (ILCs), were used as the transfer standards in the 2005 ILC. The 2005 JVS ILC is intended to provide participating laboratories with a means of comparing dc-voltage measurements in order to meet accreditation or contractual requirements and to establish reliability, confidence, and improved system operation.

A compact JVS (CJVS) was used in the sixth NCSLI JVS intercomparison in 2002 [1] to make a single comparison between the National Institute of Standards and Technology (NIST) and the pivot laboratory, the Sandia National Laboratories. In 2005, NIST was the main pivot laboratory and made *in situ* comparisons with five subpivot laboratories using the NIST CJVS. Each subpivot laboratory was responsible for making comparison measurements with two or three participants using the same protocol that was implemented in the NCSLI JVS ILC 2002 [2]. Nonlinear drift of the Zener standards and instability associated with the environmental and transportability effects were the dominant uncertainty components in previous ILCs. Use of the CJVS in the comparisons with the subpivot laboratories significantly reduced these uncertainties in the ILC 2005. This enabled the detection of system errors well below the 2×10^{-8} level that is typically achievable with only Zener standards.

II. Experiment Description

Table I lists the 15 North American laboratories that participated in the NCSLI JVS ILC 2005. NIST was the principal pivot laboratory. Four participants representing the different geographical regions and industry sectors and another national metrology institute (National Research Council, Canada) were chosen to be the five subpivot laboratories. Fig. 1 illustrates the daisy pattern of comparisons as the CJVS and the Zener standards traveled between NIST, the subpivot laboratories, and the participant laboratories.

At the start of the 2005 ILC, NIST shipped the CJVS to a subpivot laboratory, where an *in situ* comparison was made with the subpivot JVS. In this comparison, multiple measurements of the four Fluke 732B Zener standards[1] by the two JVS systems were interleaved to significantly reduce the short-term Zener noise and drift effects. The subpivot laboratory and the NIST CJVS each took four normal/reverse-paired measurements for each Zener transfer standard according to the sequence listed in Table II. For example, in the first measurement set, the NIST CJVS took a Zener measurement with normal polarity (NIST $+$) followed by the subpivot laboratory Zener measurements with normal and reversal polarities (subpivot $+$ and subpivot $-$) and the Zener reversal measurement by the NIST CJVS (NIST $-$). These four individual measurements by the two JVS systems generated a paired difference. The difference in the measurement mean time for the two JVS systems was usually less than 2 min. Four normal/reverse pairs of measurements for each Zener standard were taken in about 2 h. The CJVS integration time for an individual Zener measurement was 40 s. The subpivot laboratory used its routine calibration procedure to make the Zener measurements so that the results of the comparison reflected the normal performance of the subpivot laboratory JVS. At least four measurements of a short

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

C. A. Hamilton is with the VMetrix LLC, Boulder, CO 80303 USA.

D. Deaver is with the Fluke Corporation, Everett, WA 98206 USA.

H. Parks is with the Sandia National Laboratories, Albuquerque, NM 87185 USA.

B. M. Wood is with the National Research Council, Ottawa, ON K1A OR6 Canada.

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[1]Commercial equipment and materials are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

TABLE I
PARTICIPANTS IN NCSLI JVS ILC 2005 WHERE THE PIVOT LABORATORY AND FIVE SUBPIVOT LABORATORIES ARE SHOWN IN BOLD

Agilent Technologies, Loveland, CO
Boeing Company, Seattle, WA
Fluke Corporation, Everett, WA
Hypres, Inc. Elmsford, NY
Idaho National Laboratory, Idaho Falls, ID
Lockheed Martin Astronautics, Denver, CO
Lockheed Martin Technical Operations, Stennis Space Center, MS
NASA Kennedy Space Center (Wyle Laboratories), KSC, FL
National Institute of Standards and Technology, Gaithersburg, MD (Pivot)
National Research Council (NRC), Ottawa, Canada
Sandia National Laboratories, Albuquerque, NM
US Navy Mid-Atlantic Regional Calibration Center, Norfolk, VA
US Navy Primary Standards Laboratory, San Diego, CA
US Air Force Primary Standards Laboratory (Bionetics Corporation), Heath, OH
US Army Primary Standards Laboratory, Redstone Arsenal, AL

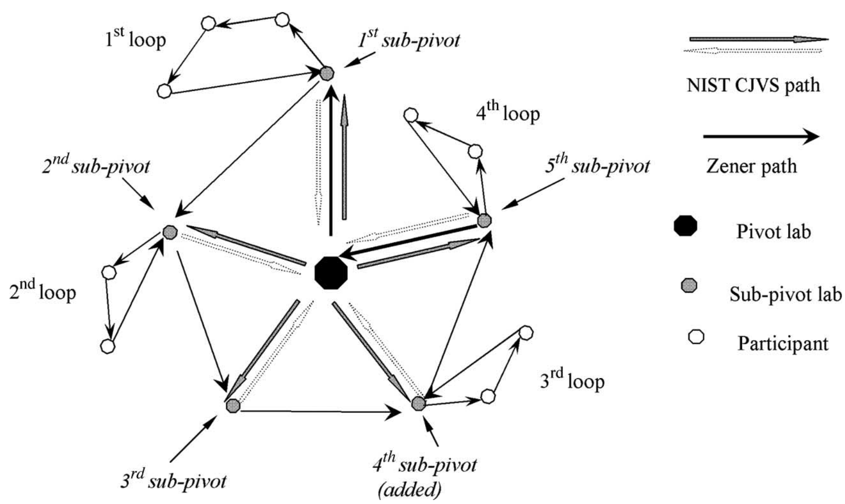

Fig. 1. Path diagram of transfer Zeners and the NIST CJVS during the NCSLI JVS ILC 2005.

TABLE II
MEASUREMENT PROTOCOL USED FOR EACH OF THE FOUR TRANSFER STANDARDS IN THE NIST CJVS VERSUS SUBPIVOT-LABORATORY COMPARISON. EACH LINE REPRESENTS THE SEQUENCE OF NORMAL/REVERSE MEASUREMENTS THAT YIELDS ONE PAIR DIFFERENCE. FOUR PAIR DIFFERENCES ARE MADE FOR EACH OF THE FOUR TRANSFER STANDARDS FOR A TOTAL OF 16 PAIRED DIFFERENCES

1st pair difference	NIST +	Sub-pivot +	Sub-pivot –	NIST –
2nd pair difference	Sub-pivot +	NIST +	NIST –	Sub-pivot –
3rd pair difference	NIST +	Sub-pivot +	Sub-pivot –	NIST –
4th pair difference	Sub-pivot +	NIST +	NIST –	Sub-pivot –

circuit were made by each JVS system before and after the Zener measurements to detect zero offset errors.

A low-thermal rotary-switch box was used to connect one of the four Zeners to the desired JVS system (either the NIST CJVS or a subpivot laboratory JVS) and to select Zener polarity. The short-circuit measurements of all channels and polarities were less than 10 nV.

After completion of the comparison between the NIST CJVS and a subpivot laboratory JVS, the Zener standards were shipped around the loop for measurements at the group of laboratories and then returned to the subpivot laboratory for a second set of measurements. The Zeners usually arrived to the participant's laboratory on a Thursday and remained in the laboratory for stabilization over the weekend. The measurements started on Monday and finished on Tuesday. This daisy pattern was repeated for the four loops as shown in Fig. 1. The standard measurement procedure was the same as the one implemented in ILC 2002 and consisted of 4 $\pm$ pair measurements of each of the four Zener standards (total of 32 measurements), typically performed in two days. A barometer traveling with the Zener standards recorded the atmospheric pressure during all of the measurements. The collected pressure data was used to correct the Zener standards to a standard pressure of 1013.25 hPa based on previously determined pressure coefficients. A temperature and humidity logger also traveled with the Zener standards and recorded the environmental conditions during the shipment and at the participant laboratories. The participant laboratory temperatures were between 22.0 °C and 23.8 °C and the relative humidity was in the range of 30% to 50%. No temperature and humidity corrections were made for the transfer Zener standards.

The CJVS was shipped back to NIST after each subpivot-laboratory comparison. Before it was shipped to the next subpivot laboratory, a direct array-to-array comparison between the

TABLE III
RESULTS OF THE *in situ* COMPARISONS BETWEEN THE CJVS AND THE SUBPIVOT LABORATORIES AND THE IMPROVEMENT IN UNCERTAINTY COMPARED TO THE 2002 JVS INTERCOMPARISON

Lab	Date	Lab – CJVS (nV)	U_c (95%) (nV)	Lab – NIST (nV) in 2002	U_c (95%) (nV) in 2002	U_c factor 2002 / 2005
Sub-1	4/5/2005	4.7	26.8	30.0	206.0	7.7
Sub-2	5/10/2005	7.0	19.0	–41.0	206.0	10.8
Sub-3	6/7/2005	–3.5	26.8	–6.0	205.0	7.6
Sub-4	7/12/2005	–2.4	25.0	–59.0	215.0	8.6
Sub-5	8/16/2005	–15.0	24.5	0.0	205.0	8.4

CJVS and a programmable JVS was carried out to confirm the performance of the CJVS.

III. Results of the CJVS Comparisons

The difference D between a subpivot laboratory and the NIST CJVS is computed as the mean of the 16 differences of the paired measurements:

$$D = \frac{1}{16}\sum_{i=1}^{16}\left(V_{\text{ith paired}}^{\text{subpivot}} - V_{\text{ith paired}}^{\text{NIST-CJVS}}\right) \qquad (1)$$

where $V_{\text{ith paired}}^{\text{subpivot}}$ is the average of a normal and reverse measurement of one of the four Zener standards by the subpivot laboratory. Since there are four paired measurements of each of the four standards, there are 16 differences to average. The expanded uncertainty of the comparison at 95% confidence can be calculated as

$$U_c = t_{95}(\nu) \times \sqrt{\frac{1}{(16-1)}\sum_{i=1}^{16}\left\{\left(V_{\text{ith paired}}^{\text{subpivot}} - V_{\text{ith paired}}^{\text{NIST-CJVS}}\right) - D\right\}^2} \qquad (2)$$

where $t_{95}(\nu)$ is the t distribution factor for degrees of freedom ν at 95% confidence [3]. For all of the NCSLI JVS ILC 2005 comparisons between the subpivot laboratories and the NIST CJVS, ν is equal to 15. The uncertainty U_c [from (2)] in the subpivot–NIST difference [from (1)] includes Zener noise and the type-B contributions from both JVS systems [1].

Table III lists the results of the comparisons between the CJVS and the five subpivot laboratories in the ILC 2005 and the corresponding results of ILC 2002 [2]. The differences between the CJVS and the subpivot laboratories varied from 3.5 to 15 nV with a 95% confidence uncertainty of 19 to 27 nV at 10 V. The uncertainty improvement factor relative to ILC 2002 varies from 7.6 to 10.8.

The initial comparison between the subpivot lab 1 and the NIST CJVS showed a difference of -49 nV with a 95% uncertainty of 27 nV. This apparent discrepancy was resolved when it was discovered that a leakage correction factor that was previously entered into the software of subpivot lab 1 had a misplaced decimal point. This resulted in a computation error of -54 nV. After correcting the leakage adjustment, the difference between subpivot lab 1 and the NIST CJVS was 5 nV with an unchanged uncertainty of 27 nV. This small error of relative value, five parts in 10^9, would not have been detected without the improved uncertainty of the CJVS comparison.

IV. Loop 1 and 2 Results

The participant-laboratory results are analyzed as in ILC 2002. All measurements for a given laboratory are corrected for pressure dependence and reduced to a single mean voltage and mean time. Each point in Fig. 2 is the mean voltage and mean time for one laboratory. The best estimate of the time-dependent Zener bank mean value is taken to be a straight line drawn between the NIST CJVS values at either end of the loop. This point-to-point model is shown in Fig. 2. The estimated difference between each laboratory and the CJVS is the corresponding residual of the linear fit. We assume that the uncertainty of this difference is completely dominated by the Zener contribution. The uncertainty of this difference can then be estimated by using results from ILC 2002 and by observing the behavior of the Zener bank in the seven months before the ILC. The history is used to simulate the ILC by selecting bank means at one-week intervals. A straight line is drawn through points that are four weeks apart, and the residuals of the intervening points are calculated. This was done for seven consecutive loops. The RMS value of the residuals is an estimate of the standard uncertainty of the straight-line prediction over a four-week interval. For the data tested, this number was 96 nV which compared favorably with the 99 nV calculated independently from the ILC 2002 data [2]. The fact that the ILC 2002 result includes travel effects, whereas the seven-month data-history calculation does not, implies that travel effects and imperfect pressure corrections are a minor contribution to the total uncertainty.

Table IV shows the Lab–NIST results for loops 1–4. Column four represents the standard deviation of the mean σ_m for the 16 $\pm$ pair measurements made at each laboratory. The uncertainty (95% confidence) is determined from the least square sum of the ILC 2002 uncertainty result (99 nV), and the result in column four multiplied by a Student t factor. Results for labs 2 and 5 are well outside the expected range for both offset and scatter. In the case of lab 5, the cause turned out to be an inadequate frequency reference for the Gunn oscillator. The cause of the discrepancy at lab 2 has not been determined.

V. Loop 3 and 4 Results

At the start of loop 3, the batteries of all four traveling Zener standards were exhausted due to a shipment delay. The comparison was halted for five weeks to allow the Zeners to stabilize. An extra subpivot laboratory was added and the schedule was modified accordingly. Even with the five-week recovery time, it is apparent from Fig. 2 that the battery failure resulted in an offset and increased noise of the transfer standards for the remainder of the ILC. The uncertainty determination used for loops 1 and 2, therefore, does not apply to measurements performed after the battery failure. Since there are no obvious outliers, the residuals of the point-to-point model were used to make an estimate of the uncertainty of the point-to-point model

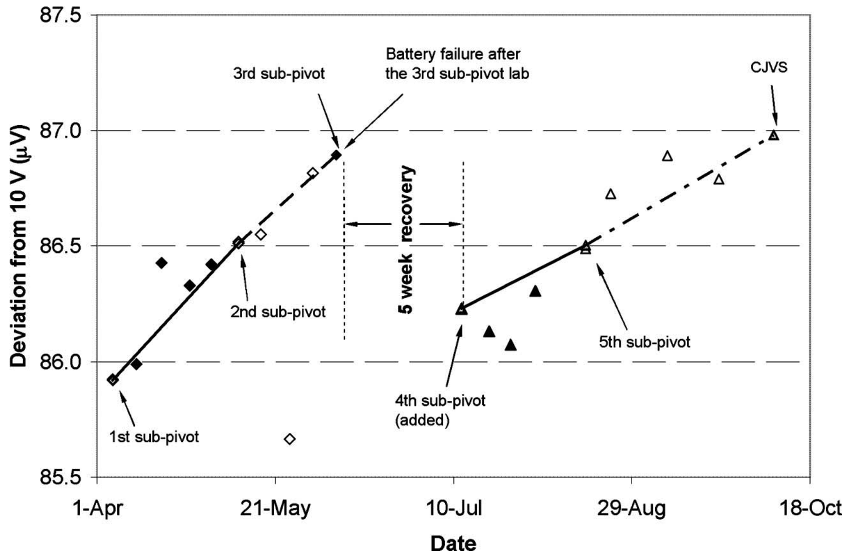

Fig. 2. Plot of the mean voltage versus mean time for all of the CJVS, subpivot, and participant measurements of the bank of four transfer Zener standards. The independent straight-line estimates of the Zener bank mean are shown for each of the four loops. The data points from the CJVS are shown in gray.

TABLE IV
COMPARISON RESULTS FOR THE FOUR MEASUREMENT LOOPS, NOT INCLUDING THE *in situ* DATA. THE SUBPIVOT RESULTS ARE FOR CLOSING THE LOOP MEASUREMENT RELATIVE TO THE POINT-TO-POINT LINE

Lab #	Date	Lab – CJVS (nV)	Lab σ_m (nV)	U_c (95%) (nV)
Loop 1				
1	4/11/2005	–42	17	199
2	4/18/2005	277	175	412
3	4/26/2005	52	12	198
Sub-1	5/2/2005	36	28	204
Loop 2				
4	5/16/2005	–49	20	200
5	5/24/2005	–1046	86	261
Sub-2	5/31/2005	14	12	198
Loop 3				
6	7/19/2005	–160	12	329
7	7/25/2005	–265	23	332
Sub-4	8/1/2005	–86	18	330
Loop 4				
8	8/22/2005	160	23	332
9	9/7/2005	181	15	330
Sub-5	9/22/2005	–52	32	335

for loops 3 and 4. The estimate is likely to be conservative, because a large error from any one laboratory causes an increase in the uncertainty of all of the laboratories. The resulting standard uncertainty of the model for loops 3 and 4 was 166 nV, which was 67% higher than that obtained before the battery failure.

VI. CONCLUSION AND DISCUSSION

The use of the CJVS in ILC 2005 improved the relative uncertainty of the subpivot comparisons by about an order of magnitude to a few parts in 10^9 and also provided a more direct link between NIST and the other nine participants in the ILC. Because the subpivot comparisons are made *in situ*, uncertainty from nonlinear drift, transportation, and environmental effects to the Zener transfer standards is largely eliminated. Small system errors of a few parts in 10^9 can be detected and corrected with a CJVS comparison. The discovery of system problems at three of the 15 laboratories in the ILC 2005 demonstrates the value of intercomparisons for Josephson systems.

Using the CJVS in the NCSLI JVS ILC 2005 also helped to reduce the impact of the Zener voltage offset and increased noise that occurred during the recovery from the battery failure. Adding a fifth subpivot CJVS measurement after the battery failure localized the effect of the failure to loops 3 and 4.

In the NCSLI JVS ILC 2005, Zener standards were used as transfer standards. For the regular participants, the uncertainty of the comparison was determined by the characteristics of the transfer Zener standards, including their long-term stability, nonlinear drift, environmental effects due to the temperature and humidity changes (pressure effect was corrected in the NCSL JVS ILC 2005), and shipping impacts. For the comparisons between the subpivot laboratories and NIST CJVS, the ultimate limiting factor of the comparison uncertainty is the $1/f$ noise floor of the transfer standards [4].

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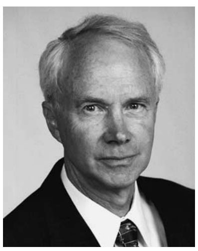
Yi-hua Tang received the Ph.D. in low-temperature physics from the University of Florida, Gainesville, in 1987.

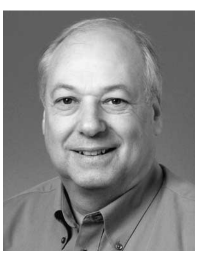
He worked in the private sector from 1991 to 1996 in the field of Josephson arrays and voltage standards. In January 1997, he joined with the Quantum Electrical Metrology Division, National Institute of Standards and Technology, Gaithersburg, MD, where he is currently working on the Josephson voltage standard and its applications in metrology. He is responsible for maintaining the U.S. legal volt and providing for the dissemination of an internationally consistent and traceable voltage standard tied to the SI units. His research interest is to develop applications of Josephson technology for dc and ac voltage metrology.

Dr. Tang is a member of the American Physical Society.



Clark A. Hamilton (S'64–M'71–SM'94–F'95) was born in Rochester, NY, on April 22, 1944. He received the B.S. degree from Union College, Schenectady, NY, in 1966, and the M.S. and Ph.D. degrees from the University of Rochester in 1968 and 1971, respectively, all in electrical engineering.

In 1971, he joined with the National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards), Boulder, CO, and became a NIST Fellow in 1987. Most of his career at NIST has focused on Josephson devices and voltage standards. In 1999, he retired from NIST to start his own company, VMetrix LLC, Boulder, which specializes in system design, consulting, and training related to Josephson voltage standards. He has authored 80 publications and is the holder of three patents.



David Deaver received the B.S.E.E. degree from Washington State University, Pullman, in 1969, and the M.S.E.E. degree from the Colorado State University, Fort Collins, in 1974.

He has spent his career designing and calibrating electronic instrumentation. For the past 20 years, he has worked on calibration of products with Fluke Corporation, Everett, WA, most recently, as Head of the Primary Standards Laboratory. He is the holder of two patents and has authored a number of technical papers dealing with the instruments he helped develop as well as some of the statistical aspects of metrology.

Harold Parks received the Ph.D. degree in physics from the University of Colorado, Boulder, in 1998.

He then received a National Research Council Postdoctoral Fellowship to work at National Institute of Standards and Technology and Joint Institute for Laboratory Astrophysics (JILA), Boulder, and, following this, held a Postdoctoral Fellowship at the Bureau International des Poids et Measures. He is currently a member of the technical staff with the Sandia National Laboratories, Albuquerque, NM.

Barry M. Wood (M'87) was born in Oshawa, ON, Canada, on September 27, 1951. He received the B.Sc. degree in physics and mathematics from the University of New Brunswick, Fredericton, NB, Canada, in 1973, the M.Sc. degree from the University of Western Ontario, London, ON, Canada, in 1974, and the Ph.D. degree in physics from the University of Toronto, Toronto, ON, Canada, in 1982.

Since 1981, he has been with the Physics Division of the National Research Council, Ottawa, ON, Canada. In 1986, he became the Section Head of the Thermometry and Electrical Standards Section of the Laboratory for Basic Standards. His research concerns the Josephson volt, the quantum Hall effect, the calculable capacitor, ac bridges, and cryogenic standards.

Dr. Wood is a member of the CODATA Task Group on Fundamental Constants and the Chairman of the Consultative Committee for Electricity and Magnetism's working group on the SI.