NORTH AMERICAN INTERLABORATORY COMPARISON OF 10 V JOSEPHSON VOLTAGE STANDARDS

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ABSTRACT

An interlaboratory comparison of Josephson voltage standards has been made among 16 national, industrial, and military standards laboratories in North America and 1 in Europe. The comparison was made at 10 V using a set of four travelling Zener reference standards. A pivot laboratory made measurements at the beginning, at the end, and at 9 other times during the comparison. The measured differences and their uncertainties are reported and used to establish a table of equivalence between each participant and the pivot, and between each participant and the National Institute of Standards and Technology (NIST). All but two of the differences fall within 2 parts in 10^8.

I. INTRODUCTION

The use of intrinsic standards such as the Josephson Voltage Standard (JVS) requires facilities to perform periodic inter-laboratory comparisons (ILC). Results of such ILCs are then utilized for audit purposes especially accreditation approvals or re-approvals. In addition, such

ILCs provide supporting arguments for traceability to a particular internationally recognized parameters, in this case dc voltage.

In the 1999 JVS 10 V comparison (the fifth semiannual such comparison), a set of four 10 V Zener reference standards was circulated among the 17 participants listed in Table 1 using 19 independent JVS systems. A link to NIST (Gaithersburg) was provided by an independent ILC between the pivot laboratory and NIST using the same set of travelling standards. NIST data reported here are obtained from the report on that ILC (as amended)[1] and essentially constitute an eighteenth indirect participant. All of the participants used a 10 V Josephson standard to measure each of the four standards. The organization and management of the ILC follow the NCSL Guide for Interlaboratory Comparisons [2]. In this paper we discuss the philosophy and methods of the comparison, the results, and differences with past comparisons.

II. PROCEDURES

In the 1997 JVS ILC [3] each participant made 64 measurements (16 for each of the four Zeners) over 2-4 days. Analysis of that data showed that the scatter of residuals to the fit line was essentially the same if only 32 measurements were used. This is a result of the non-Gaussian noise typical of Zener standards. As a consequence, the standard data set for ILC99 was reduced to 8 measurements of each of the four Zener standards. The eight measurements were made as four +/- pairs using a new type of manual reversing switch that was mounted directly on the Zener terminals. (Unfortunately four data sets did not use the reversing switches as prescribed in the procedure.) In addition to the Zener measurements, each participant was requested to make 8 short circuit measurements using exactly the same procedure as that used in the Zener measurements. (16 of 19 were received.) These short circuit measurements allow an independent evaluation of most of the sources of uncertainty in each participant's JVS [4]. Also travelling with the Zener standards was a switch box that allowed each participant to record the Zener battery voltages and thermister resistances, as well as the atmospheric pressure. Each participant was requested to make these measurements at the conclusion of each +/- pair measurement of the four Zeners. Fourteen of the 17 facilities complied fully with this procedure. Data from the remaining three is included as appropriate. Each participant was requested to provide an uncertainty budget.

III. ANALYSIS

The output voltage of Zener standards is well known to be dependent on time, atmospheric pressure, temperature and humidity. This creates a significant complication in comparing one lab to another. The usual approach is to establish a model for the Zener output voltage and then to determine the difference of each participant with the model and the uncertainty of that difference. In ILC97, the model included time and pressure dependence. The coefficients were determined using a least squares fit to the data from all participants. This was the only practical approach considering that the pressure coefficients were not known and that there was no pivot lab to independently determine the drift rate. There are two disadvantages to this method: (1) bad data from one participant can "pull" the model and affect everyone's result and (2) any correlation between time and elevation allows the model to distort real differences between participants. In ILC99 this situation is much improved because (1) two independent measurements of the pressure coefficients were made before the comparison began, and (2) the existence of regular pivot lab data allows the drift rate to be established independently of the data of participants. Another complication arises because, when the data spans a significant portion of one year, as in ILC99, a linear time fit is clearly inadequate. This may be a result of a periodic seasonal variation owing to humidity. This can be accounted for by adding additional fitting parameters but each additional parameter adds opportunity to mask real differences and opens up the procedure to criticism. For this reason we have adopted the following algorithm for analyzing the data:

(1) All raw data is corrected to a standard pressure by applying the previously determined pressure coefficient.

(2) The 32 measurements from each pivot lab data set and each participant are reduced to a single mean value of voltage and time.

(3) The model of the Zener voltage vs. time is taken to be a point to point series of line segments that pass exactly through each pivot lab point.

(4) The best estimate of the difference between any participant and the pivot lab is the residual to the model.

This approach can account for nonlinear time variation of the Zener voltage and the model is completely independent of the data of the participants. In this model there are no fitting parameters and thus no opportunity for a fit in which accidental correlation distorts the results.

IV. RESULTS

Figure 1a plots the uncorrected mean values of the pivot lab (• points) and the participant labs (× points) for the entire ILC. Two participants submitted data for two different JVS systems. A large part of the scatter is a consequence of the pressure (elevation) dependence of the traveling standards. Figure 2b plots the pressure corrected data and includes the 9 line segments of the point-to-point model. The nonlinear nature of the drift is readily apparent.

Table 2 summarizes the principle results of the JVS ILC99. To preserve anonymity, the order of the list is random. Column 2 of Table 2 lists the residuals of each participant to the point-to-point model of the travelling standards. All mean values are corrected for pressure dependence using a bank mean pressure coefficient of –1.110 nV/hPa obtained from independent pressure coefficient measurements by NIST and Sandia National Laboratory. This correction produces a factor of 3 reduction in the RMS value of the residuals. The combined standard uncertainty for the participant-pivot differences is estimated in column 3. It has four components: (1) uncertainty contributed by the pivot lab system u_p, (2) uncertainty contributed by the participant lab system u_x, (3) uncertainty owing to the noise of the travelling standards u_z, and (4) uncertainty resulting from imperfect pressure corrections u_k. u_p, u_k, and u_z are the same for every difference. An upper limit on their combined value (u_{pzk} = RSS[u_p, u_z, u_k]) can be estimated as the RMS value of the 19 differences provided that u_x is always small compared to u_{pzk}. However, it is immediately clear that the differences for Lab 12 and Lab 14 are outlying points for which this requirement is not met. Their values lie almost 9 sigma from the mean and standard deviation defined by the remaining 17 points. We exclude these two points from the uncertainty estimate. The RMS value for the remaining points is u_{pzk} = 66 nV. To this we combine (RSS) a u_x value based on the short circuit measurements combined with frequency and leakage uncertainties reported by most facilities, to obtain the combined standard uncertainty values in column 3. For those facilities that did not provide short circuit measurements, the highest value of the reporting facilities (41.6 nV) was used as a default value. The effective degrees of freedom [5, first equation in Appendix B] for the uncertainties in column 3, are given in column 4 and are dominated by the 17 degrees of freedom in the u_{pzk} estimate. In ILC97 the comparable value to u_{pzk} was 83 nV. The improvement in ILC99 to 66 nV can be attributed to the use of direct pressure measurements (rather than elevation) and the ability of the ILC99 point-to-point model to adapt to nonlinear drift.

The independent ILC with NIST determined a difference of $V_{Pivot} - V_{NIST}$ = 59 nV with a standard uncertainty of 81 nV and 7.36 effective degrees of freedom. In column 6 this difference is added to show the implied differences between NIST and all participants. The combined standard uncertainties of the NIST differences and their effective degrees of freedom are listed in columns 7 and 8 and are obtained by RSS combining the Pivot/NIST uncertainty with the Pivot/participant uncertainties.

V. TRACEABILITY and EQUIVALENCE

There are several reasons for expending the considerable effort to make this comparison: (1) It provides evidence of the quality of the measurements of the participants and is therefore important for accreditation. (2) It provides a forum for participants to learn and discuss the latest measurement procedures. (3) It quantifies the level of agreement that can be achieved with Zener reference comparisons, and (4) it provides a link of traceability to national measurement laboratories. The problem with traceability is that it is generally not quantitative and does not have a universally accepted definition. Another approach is the concept of a "quantified demonstrated equivalence" (QDE) [5], in which the results of a comparison such as ILC99, together with *Guide*[6] compliant uncertainty evaluations for each participant are used to establish a quantitative confidence interval $\pm\, d_C$ for the equivalence of measurements between any two laboratories. d_C is a function of the differences, their uncertainties, and the Welch-Satterthwaite determination of effective degrees of freedom ν. Reference [5] provides a numerical approximation for d_C for the 95% confidence case and is used to compute the QDE values in columns 5 and 9 of Table 2. These values can be used to make a quantitative statement of equivalence as illustrated in the following example: On the basis of the NCSL JVS 1999 Interlaboratory Comparison, the results of similar 10 V measurements at Lab 2 and NIST can be expected to agree to within ±250 nV (2.5 parts in 10^8) with 95% confidence. Facilities with a * are for participants that did not report the specified offsets for zero measurements. In this case we assume default values as discussed above.

VI. DISCUSSION

Since the dependence of Zener voltage on oven temperature (as indicated by thermister readings) was not determined before the ILC began, no temperature correction is made in this ILC. However, it is relevant to look for a correlation with temperature to decide if temperature should be included in the next ILC. This was done by searching for a temperature correction coefficient that would further reduce the RMS deviations to the fit. No improvement could be found, indicating that temperature is not a significant parameter for the bank mean of this set of Zener standards. Similarly, we can probe the veracity of the pressure correction by adjusting k_p to look for a further improvement in the RMS deviations to the fit. Again, no significant improvement could be found indicating that the optimum value as determined from a fit is the same (within their respective uncertainties) as the independently measured value.

The submitted data for the two outlying points has been examined for any evidence of a failure of the procedure, reference standards, or reversing switches. Both outlying points are bracketed by normal points, the offset is consistent for all four of the travelling references, and no unusual difference was detected between normal and reverse measurements. We conclude that these two labs have a previously undetected offset of unknown origin. The magnitude of the offset, 0.06 parts in 10^6, would not be considered very significant in most voltage comparisons but the high resolution of this ILC makes it quite apparent. The reasons for the offset are under investigation.

At one point in the ILC, a significant offset was detected in 2 of the 4 reversing switches and for this reason these switches were not used for a number of measurements after day 150. In place of the switches, the reversals were made by physically reversing the wires on the Zener reference terminals. The effect of the reported offset would be an approximate 50 nV shift in the mean value of a 32 measurement data set. Post ILC measurements of the switches could not reproduce the offset.

VI. ACKNOWLEDGEMENTS

All participants in the ILC gratefully acknowledge the loan of the four travelling standards from the Fluke Corporation and the loan of the reversing switches and pressure monitor from NIST.

REFERENCES

[1] Report of Special Test, "Intercomparison of Josephson Voltage Standards between NIST and Lockheed Martin Astronautics", NIST Report # 811/262290-99, 1999 as amended March 14, 2000.

[2] Guide for Interlaboratory Comparisons Recommended Practice RP-*15* Available from National Conference of Standards Laboratories (NCSL), Boulder, CO, March 1999.

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

[4] C. A. Hamilton, and Y. H. Tang, "Evaluating the uncertainty of Josephson voltage standards", in Metrologia, Vol. 36, pp. 53-58, 1999.

[5] B. M. Wood, and R. J. Douglas, "Confidence-interval interpretation of a measurement pair for quantifying a comparison", in Metrologia, Vol. 35, pp.187- 196, 1998.

[6] Guide to the Expression of Uncertainty in Measurement, Geneva, International Organization for Standardization, 1995.

Table 1. Participants in the 1999 NCSL JVS ILC.

Agilent Technologies, Loveland, CO
Air Force Primary Standards Lab., Heath, OH
Army Primary Standards Lab. Redstone Arsenal, AL
Boeing Company, Seattle, WA
CENAM, MEXICO
Electromagnetic Technology Div., Boulder, CO
Fluke Corporation, Everett, WA
Fluke, Germany
Hypres, Inc. Elmsford, NY (2 sets)
Keithley Instruments, Cleveland, OH
Lockheed Martin Astronautics, Denver, CO – PIVOT
Lockheed Martin Technical Operations, Sunnyvale, CA
NASA Kennedy Space Center, Kennedy Space Center, FL
Naval Aviation Depot, San Diego, CA
Navy Mid Atlantic Cal. Center, Norfolk, VA
NRC, Ottawa, CANADA
Sandia National Laboratories, Albuquerque, NM (2 sets)

NIST, Gaithersburg, MD (indirect participant)

Table 2. Differences and uncertainties between the pivot lab and each participant, and between NIST and each participant, in nV or parts in 10^{10}.

Facility ID	Lab– Pivot in nV	u_C in nV	DoF	QDE in nV	Lab- NIST in nV	u_C in nV	DoF	QDE in nV
Pivot	0				59			
Lab 1	-33	67	18	157	26	107	17	235
Lab 2	-9	67	18	145	50	107	18	250
Lab 3	-48	72	21	177	11	110	19	239
Lab 4	-83	67	18	202	-24	107	17	235
Lab 5	2	77	21	165	61	113	22	274
Lab 6	-93	73	21	222	-34	111	20	249
Lab 7a	37	68	19	162	96	108	18	291
Lab 7b	23	69	20	154	82	108	19	280
Lab 8 a	3	72	21	155	62	110	19	267
Lab 8 b	36	78	20	181	95	115	23	305
Lab 9	21	69	20	153	80	108	18	278
Lab 10	-35	68	18	160	24	107	17	235
Lab 11	121	68	19	240	180	108	18	371
Lab 12	-668	68	19	785	-609	107	18	786
Lab 13	-105	74	22	234	-46	111	20	257
Lab 14*	-690	79	21	826	-631	115	23	833
Lab 15*	-59	78	20	200	0	115	23	253
Lab 16*	147	79	21	284	206	115	23	411
Lab 17	8	67	18	145	67	107	17	264

* Facilities did not provide zero offsets. Default uncertainty values were used.

Fig. 1a: Measured mean voltage of the pivot and participant labs for the comparison, without pressure corrections.

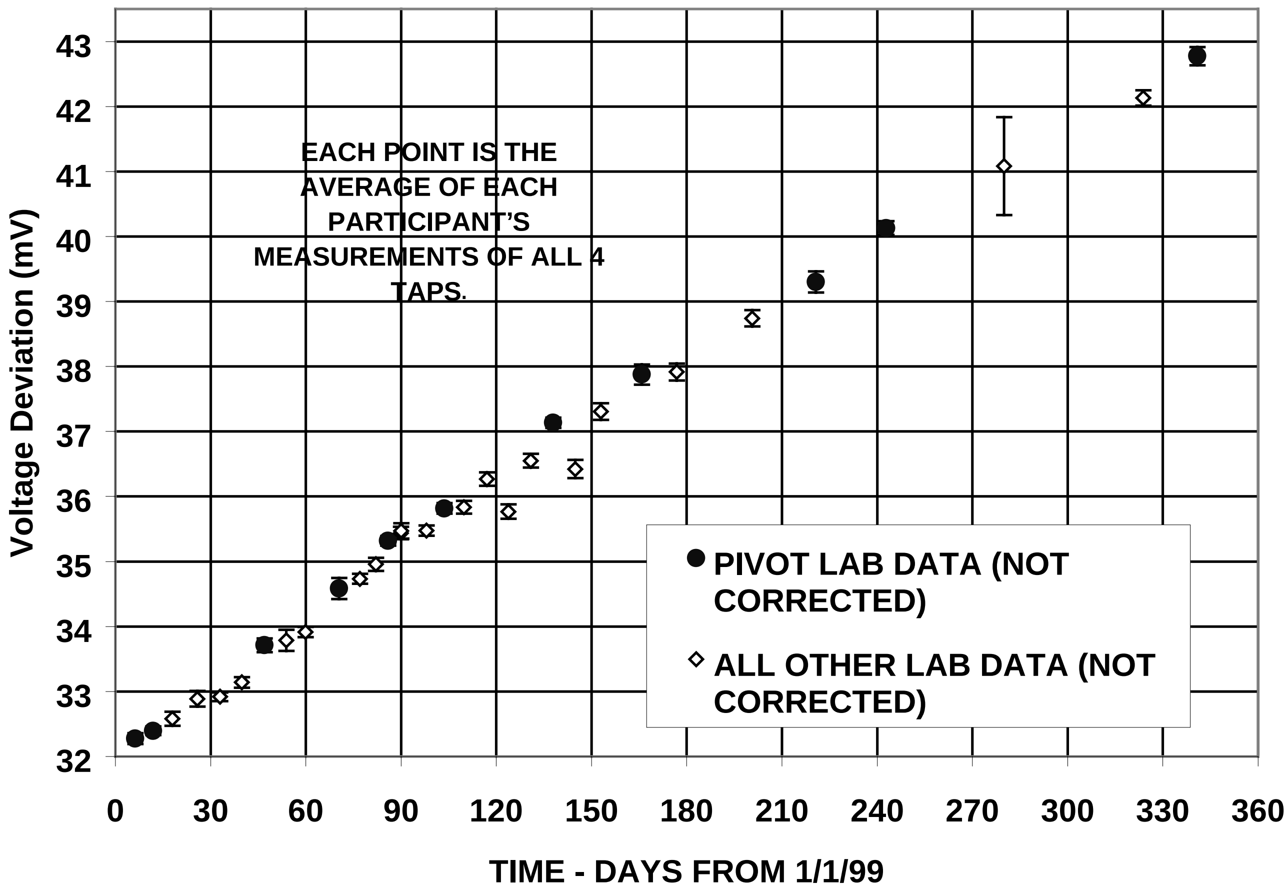

Fig. 1b: Measured mean voltages of the pivot and participant labs for the comparison with pressure corrections and the 9 line segments of the point-to-point fit model.