# ACCURACY COMPARISONS OF JOSEPHSON ARRAY SYSTEMS

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Abstract -- Five Josephson-array voltage standard systems were compared using several different methods. All of the tests were performed on site at a 1.018-V level, either by direct connection or through successive measurements of independent voltage sources. The resulting agreement between different systems measuring the same source were generally better than 10.0 parts in 10<sup>-9</sup>, limited by source noise and detector resolution. Direct array-to-array comparisons for independent systems achieved agreement to within random uncertainties of 0.2 parts in 10<sup>-9</sup>.

## I. INTRODUCTION

Josephson array voltage standards [1] are now used in many metrology laboratories, including several non-national standards laboratories. There are many advantages of using a Josephson array system as a voltage standard; 1) less reliance upon transfers from externally calibrated voltage sources and the possibility of more frequent "in-house" calibrations, 2) the inherent stability and repeatability of the quantum phenomena, and 3) the direct tie to the SI system by definition and the worldwide acceptance of the Josephson constant. However, the accuracy of a local array system remains an assumption that is difficult to prove satisfactorily, especially to within the uncertainty possible for these systems [2]. Assuring the accuracy of the generated volt requires more than testing the frequency and device hardware. In order to provide equivalence to a recognized voltage standard, a total system verification must include testing the system software, both its control procedure and measurement calculations, and such hardware tests as ground loops, leakage, and thermal voltages.

A comparison test is the generally accepted way to establish total system accuracy, and the most precise way is via an on-site comparison with another array system. Comparisons can be classified as either direct (array-to-array), or indirect (via an intermediary reference). Each type of test has certain benefits, either in better precision, or in more completeness. On-site tests having excellent precision have already been reported in Europe [3,4]. In a recent comparison using a standard reference shipped among eight U.S. government and industrial laboratories with array systems, testing the complete systems proved essential [5]. Two locales reported their initial determination as one Josephson voltage step off, 15 parts in 10<sup>6</sup>. Such large errors would eventually be found, but they also highlight the need for comprehensive tests. Tests involving a shipped reference, however, require long times to acquire a satisfactory number of data points and uncertainties will then be limited by long term noise inherent in the transfer standards.

This paper focuses on on-site comparisons between five array systems involving the three NIST systems, a system from the Bureau International des Poids et Mesures (BIPM), and one at the Navy Primary Standards Laboratory - East. Both the previously mentioned methods were variously employed, resulting in different levels of uncertainty and measurement durations. As expected, direct connection of the two arrays, with an analog nanovoltmeter detecting the difference between them, resulted in the most accurate comparison of the output voltages. A similar but automated test using normal system software and the system's own digital voltmeter (DVM) as the detector still resulted in very good precision. Indirect tests using an intermediary transfer standard demonstrated a wide range of resulting uncertainties but allowed for more flexible system equipment requirements.

#### II. EXPERIMENT DESCRIPTION

The three NIST systems are nearly identical [6]. One is the primary national volt standard system

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(NIST 1), one is a 10-V research system (NIST 10), and a third is referred to as a "portable" 1-V system (NIST 1P), because of the need to transport this array system to places inside and outside of NIST. The portable array system is a rack size system, so the description "portable" applies to its occasional transport rather than its smaller design. The BIPM system (BIPM 1) was independently designed but, of necessity, is schematically similar [7]. The Navy 1-V system (NAV 1) is based on an alternate NIST design and different operating software [2] but with essentially the same components. All the systems use Josephson array chips fabricated at NIST-Boulder [1].

Some of the design differences in these systems arose from early comparison experiments. Attempts to connect arrays directly proved unsuccessful because of offsets of several microvolts and increased noise. The problem was traced to multiple ground paths; through bias supplies, oscilloscopes, and voltmeters. It was solved with better array isolation from ground, either by adding a switch to disconnect the array from the bias after a step had been generated (BIPM 1), or by using commercial voltage calibrators as bias supplies (NIST 1). Eliminating ground loop offsets enabled direct coupling of the array output lines from one "source" system to a second "measurement" system. This was important in eliminating the effects of thermal emf voltages of the connection leads. The "measurement" system's voltage detector, either an analog nanovoltmeter or a DVM, can be used to measure the voltage difference. The millimeter wave frequency sources of all systems used the same external frequency reference. A simplified schematic diagram for these direct comparisons is shown in Figure 1a.

In the most precise experiment, a direct comparison between NIST 1 and BIPM 1, each system was run manually to select repeatedly the same voltage steps. The analog nanovoltmeter of the BIPM system was used, making this a test of the complete BIPM system. The frequency on NIST 1 was varied to compensate for thermal offsets in order to maintain a difference within the range of the detector of less than  $0.3 \,\mu$ V. The amplified voltage difference was recorded in 30-60 second traces on a strip chart recorder for each polarity of the detector. A single point consisted of traces combining two array voltage changes: one reversal and one return. The total time, including detector calibration and the measurement, was about 1 h for 6 points, and somewhat less for 4 points the next day.

A direct comparison was also devised to test a complete NIST system. This specifically tested the software and made the timing of such things as switch closures and voltage settling as similar to normal procedures as possible by using the programmed routine



Figure 1. Simplified schematics for array system comparisons: (a) direct, (b) indirect via mercury battery (substitution method), and (c) indirect via a Zener reference. Switches are not represented in full detail.

and switching. The DVM of the "measurement" system (NIST 1P) measured the output of NIST 1 as the "source" system. Similar to the NIST/BIPM procedure, selection of the NIST 1 voltage step was performed manually and electrically reversed, the only change from the usual procedure of physically switching a Zener reference. Both systems were so well isolated from ground that step jumps on the NIST 1P system (from automated step selection) did not affect the other array. A single measurement point was the average of four array reversals (the usual procedure), taking about 20 min per point.

Two variations of indirect comparison schemes are shown in Figure 1b and 1c. In both, a voltage reference standard was measured repeatedly and alternately by each of the array systems being compared. The most sensitive indirect test used a specially built voltage reference based on a mercury battery [4] as a very low-noise intermediary reference, as shown in Figure 1b. Switches built into the thermal enclosure of the battery reversed the analog nanovoltmeter, the mercury battery, and selected either array in a substitution method to obtain the voltage difference measurement between each array. Once again, minimum voltage difference was accomplished with manual step selection. The measurement time was about 1.5 h for 4 points. Because the same detector is part of both measurement loops, thermal emf offsets in the wires are minimized. The voltage drift in the battery was linear at about 1 nV/min. Though this tests only the complete BIPM system, it is a very precise method for comparing output voltages, especially between systems with incompatible equipment or grounding problems.

TEST	DATE OF	SYSTEMS	<b>REFERENCE/ TEST-</b>	DETECTOR(S)	TIME/	DIFFERENCE ±
#	TEST		ING "SOURCE"		POINTS	UNCERTAINTY
						10-9
1	7/26/91	NIST 10 -NIST 1	Direct/Output	DVM	1h/4	$1.1 \pm 7.5$
2	10/10/91	NIST 1P –NIST 1	Direct/System	DVM	2.5 h/11	4.2 ± 1.9
3	10/15/91	NIST 1 –BIPM 1	Direct/Output	Analog Nano- voltmeter	1.1 h / 6	0.16 ± 0.26
4	10/16/91	NIST 1 –BIPM 1	Direct/Output	Analog Nano- voltmeter	1h/4	$0.06 \pm 0.15$
5	10/16/91	NIST 1 –BIPM 1	Mercury Battery/ Output	Analog Nano- voltmeter	1.5 h / 6	0.01 ± 0.26
6	10/17/91	NIST 1 –BIPM 1	2 Zener References/ System	DVM/Analog Nanovoltmeter	2.5 h / 6	-1.4 ± 6.6
7	10/30-31/91	NAV-1 –NIST 1P	1 Zener Reference/ System	DVM/DVM	2d/9	-17 ± 11

TABLE 1. Summary of array system comparisons. Results and random uncertainties are expressed in parts in 10<sup>9</sup>, one standard deviation estimate.

The indirect method shown in Figure 1c simply employed the 1.018 V output of a commercial Zener reference standard as a short term intermediary. Each array system, with its own normal operating procedure, repeatedly measured one or more references. Two strategies were tried with no clear advantage to one; either complete determinations by one system alternated with those taken by the other, or alternate points from each system were independently averaged over several days. Since each system has its own detector, additional measurements of the thermal emf offset for each input circuit wire are required, a time consuming and error laden procedure. A data point comprised the averaged number of array reversals characteristic of each system (usually 2 or 4), and averaged again over the number of references measured.

## III. RESULTS

Table 1 summarizes the comparisons. All the results were within 3 times the one standard deviation estimate Type A random measurement uncertainty listed in the table. These random uncertainties are mainly owing to the noise of the detector and irreproducible thermal emfs in the switch contacts. Josephson junction noise from the broadband of the driving frequency spectrum could not be noticed. Reference noise is a contribution to the uncertainty in the indirect measurements, with Zener references adding rather large uncertainties from source noise and thermal emf measurements.

For some comparisons, additional Type B uncertainties can be up to 5 nV for the irreproducibility of thermal emfs of various switch contacts. The uncertainty of the millimeter wave frequencies cannot be easily stated. The external frequency reference used for both systems is stable to better than  $0.01 \times 10^{-9}$  over 100 s integration times, but the counter uncertainty and short term variation of the frequency references between the successive measurements in the indirect methods could be  $0.3 \times 10^{-9}$  or more. Contributions from leakage resistance to ground or across the wires within each array cryostat were measured to be less than  $0.1 \times 10^{-9}$  (~ $10^{13} \Omega$  through 22  $\Omega$  for NIST 1). However, this type of systematic error would not be clearly revealed in these tests, since in some cases errors due to leakage resistance would tend to cancel.

The NIST systems have been compared to each other several times over the years in an effort to establish self consistency. Some general comments can be made about the variations in testing. Two of the NIST systems, NIST 10 and NIST 1P, were each compared to the primary 1-V array system (NIST 1) just prior to the BIPM comparisons. Test # 1 demonstrated the feasibility of simply connecting two NIST systems directly to make a comparison, for a difference of  $1.1 \pm 7.5 \times 10^{-9}$  over 4 points. Test # 2 employed NIST 1P's own software/hardware system to measure its difference from a volt generated by the primary NIST 1 system. Because of the ease and speed of this procedure, 11 points were recorded to enhance the precision, yielding a difference of  $4.2 \pm 1.9 \times 10^{-9}$ .

Since system comparisons are the only way to establish equivalence, the authors from BIPM brought one of their Josephson array systems to the NIST laboratory for comparison, both to demonstrate their methods for this procedure and to provide a basis of experimental data for establishing levels of equivalence between the various national standards laboratories. BIPM has performed several of these comparisons with other national laboratories [8]. The two most sensitive direct array comparisons, tests # 3 and # 4, showed differences of  $\pm 0.16 \pm 0.26 \times 10^{-9}$  for 6 points and  $\pm 0.06 \pm 0.13 \times 10^{-9}$  for 4 points. Weighting the data of the NIST-BIPM comparisons using the reciprocal of the type-A variance of the results leads to a difference of  $0.1 \pm 0.3 \times 10^{-9}$ , the uncertainty including both type-A and Type-B components.

Two indirect comparisons were performed with NIST 1 and BIPM 1. Nearly as good as the direct comparisons, test # 5 used the stable and quiet mercury battery reference specially built by BIPM, for a result of  $\pm 0.01 \pm 0.26 \times 10^{-9}$  for 6 points. Note that detector reversals are part of the normal operating procedure for these systems, because of unpredictable effects. This is mentioned because an unusual problem arose during test # 5, when the detector high-input terminal was aligned relative to the voltage low and was subsequently perturbed by electromagnetic interference, resulting in a 1 nV offset for this polarity. This would not have been noticed without detector reversals.

As mentioned earlier, the series of indirect comparisons involving Zener references suffered from higher uncertainties. The resulting difference from tests # 6 between NIST 1 and BIPM 1 was  $-1.4 \pm 6.6 \times 10^{-9}$  for 6 points. Test # 7 occurred at the Navy Primary Standard Laboratory-East. The large result and associated error of  $-17 \pm 11 \times 10^{-9}$  arose from a discrepancy in measuring the thermal emfs of the Zener connecting wires. There was a significant difference, 30 nV, between shorting the wires to a free standing binding post or to one of the reference terminals, with the latter more reliable because of the elevated temperature of the reference's terminals. This difficulty in determining the thermal emfs underscores one of the problems of using the indirect Zener reference tests. The other problem, that of Zener reference noise, can be especially severe in tests using Zener references at the 1.018-V level over several days. A direct arrayto-array comparison was also attempted on this system, which has a grounded bias supply. Only a single point was recorded in well over an hour at a reduced test value of only 0.7 V. A difference of 9 x 10<sup>-9</sup> was obtained, the result of only one array reversal.

## IV. CONCLUSIONS

Our basic conclusion is that Josephson-array voltage standard systems can be readily transported and tested to assure on-site equivalence. Also, these tests can be done quickly and with high precision, lim1877

ited by the detector noise if directly compared, or by the transfer reference noise if done indirectly. Representative limits are shown in Table 1. System equivalence has been documented to well below the  $0.4 \times 10^{-6}$ uncertainty in the Josephson constant established by the Consultative Committee on Electricity. Assuring equivalence at various levels of uncertainty has been shown, with significant flexibility in both equipment and time needed for data acquisition. Although laboratories have demonstrated equivalence to better than 1 part in  $10^7$  via shipping Zener references, major parts in  $10^6$  differences have been seen [4]. At present, only system-to-system comparisons can provide the inter laboratory equivalence at the parts in  $10^9$  or better uncertainties seen in these on-site comparisons.

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