MAP VOLTAGE TRANSFER BETWEEN 10-V JOSEPHSON ARRAY SYSTEMS

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ABSTRACT

A Measurement Assurance Program (MAP) for voltage transfer at the 10-V level was performed among six U. S. laboratories currently operating 10-V Josephson array systems. A commercial voltage standard based on four Zener references was used as the transfer device. This experiment provided data on the precision and traceable accuracy of the various array systems relative to the national SI Volt representation at the National Institute of Standards and Technology (NIST) as well as on calibrations involving a new multi-Zener reference standard. Preliminary measurements from five other laboratories show that all agree with NIST to within 0.045 ppm with a maximum random uncertainty of 0.015 ppm (1σ).

INTRODUCTION

Since the advent of the Josephson array voltage standard, there has been both excitement about its potential for lowering the uncertainty in high-precision voltage measurements and debate about how far this potential may actually extend. To quantify the realizable benefits of their respective array standard systems, six different laboratories across the country participated in a Measurement Assurance Program (MAP). This MAP attempted to verify whether or not the accuracy of these expensive array systems indeed equals the national representation of the SI Volt at NIST at Gaithersburg using a procedure involving the transfer of a 10-V reference standard. The results indicated that the array's reputation for high accuracy is valid, but with a few bright caution flags. There is also corollary evidence from this MAP that the calibration specifications of new solid-state references can exceed the capabilities of ordinary transfers involving chemical reference cells.

JOSEPHSON ARRAY STANDARD

The details of Josephson array operation can be found in several papers [1-5], but a brief review is helpful. An array of nearly 20 000 Josephson junctions, driven with a precisely known millimeter wave frequency, can provide equally accurate voltages from less than a millivolt to over 10 V. But in order to use this accurate voltage to measure standard references, a complex measurement system is needed, and such a system is unlikely to be perfect. An array system includes wiring that extends from room temperature to near absolute zero, several electronic instruments, and a detailed procedure. Any of these parts can contribute to systematic errors. So, for owners of an array system a familiar question arises, i.e., how does the accuracy of measurements made against the in-house SI Volt representation, the array, compare to that of the national standard at NIST?

There would seem to be three possible methods that would assure the accuracy of an array standard system: perform a series of detailed checks to quantify or eliminate all systematic errors, compare the system in question directly to another system which has a reliably known accuracy, or conduct a MAP such as a round-robin with a suitable transfer standard. The first option requires expertise not readily found outside of large research laboratories and the second demands the expense and inconvenience of transporting a large system. The difficulty here is increased by the high accuracy specification and operating idiosyncrasies of an array system. The evidence of this experiment shows that the 10-V MAP option can verify 10-V array systems relatively easily and also results in a smaller uncertainty than conventional voltage MAPs based on chemical cell references at the 1.018-V level.

MAP PROCEDURE

The transfer loop began at NIST/Gaithersburg and then included the various participating laboratories to which a standard reference was hand-carried or shipped overnight. To test the efficacy of the various measurement techniques that have evolved over the last several years, the laboratories followed their normal procedures in measuring the reference voltage. This is similar to a round-robin 10-V test performed in 1986 [6]. Room temperature and relative humidity were recorded for each day, though no corrections to the reference were possible. Each laboratory performed a series of at least ten measurements on the standard, generally within three weeks. Since two of the laboratories have fully automated array systems, their participation in the MAP meant only a little added work time for the operator. But even for the rest of the laboratories, the complete measurement time for this transfer standard was 1-2 hours a day. All data were sent to NIST for analysis. It is important to note that the cell output values were not revealed to each laboratory until after the initial information was transmitted for analysis, and the drift rate was not disclosed until after the data set was complete. Thus, the accuracy of each recorded point was unknown to the operators and "better" measurement points could not be selected.

The transfer standard itself was a new model Zener reference. It contains four Zener-diode-based reference cells, each one powering a 10-V output. As with chemical cell standards, the numerical average of the four Zener cells showed less scatter and more predictability, so this value was chosen as the relevant number for the entire standard. Every average value was compared to a predicted value, based on a linear drift rate for the reference from data accumulated at NIST over 3.5 months. Each set of comparative differences was in turn averaged to express each labs' result as its total variation from the NIST predicted value.

VERIFICATION RESULTS

Although the transfer loop was barely completed at the time of this writing, it seems safe to say that the MAP has proved to be a reassuring success in verifying the array systems. The reference has been returned to NIST, and the initial measurements indicate little change in the drift rate and thus the predicted value. With this caveat, the averaged variation from the predicted drift line for each laboratory is presented in Table 1, where the uncertainty is the standard deviation of the mean. The graphic representation of the results in Fig. 1 is most striking. It probably depends on the readers' point of view as to which conclusion should be drawn. One conclusion is that six voltage standard systems, variously constructed and operated, agree with the reference's linear drift to within 0.045 parts per million (ppm) with all the random uncertainties less than 0.015 ppm (1σ). Conversely, an alternate conclusion is that a commercial, transportable voltage standard (a "noisy Zener" reference) has actually drifted linearly over nearly a year despite transport and changing environmental conditions, while its scatter stayed within 0.04 ppm. For either point of view, the close agreement among all the laboratories is the most interesting result of this MAP because it illustrates the potential for higher calibration accuracies.

Two specific comments about array system verification stem from these results. First, the extremely small variations between the laboratories and NIST indicate that the several known causes of systematic errors have been minimized in each of these systems. As stated earlier, array systems can be very accurate, but systematic errors can reduce this accuracy while not increasing the random scatter. The most obvious things to check for systematic errors are the frequency reference, leakage resistance, and thermal emfs in either the switch contacts or the connection wires. Based on the smallness of the variations, there are no total systematic errors larger than 0.045 ppm. Though small relative to 10 V, thermal emfs occurring in the connection wires would cause the most likely systematic error. It was hoped that extra measurements of the thermal emfs for each wire would be unnecessary for this experiment, and this seems to have proven true.

Laboratory	Location	Variation	Uncertainty
Army TMDE Redstone	Huntsville, AL	0.015 (ppm)	0.010 (ppm)
Hewlett-Packard LID	Loveland, CO	-0.006	0.009
Navy Prim Std Lab	San Diego, CA	-0.017	0.014
Navy Gauge &Std Dept	Pomona, CA	-0.010	0.008
Lockheed M & S Co.	Sunnyvale, CA	-0.043	0.006

Table 1. The laboratories using a 10-V Josephson array, in the order of receipt of the MAP transfer standard. Included are the preliminary results, showing each lab's variation from NIST and the random uncertainty of the measured points. The largest variation coincides with some unusual temperature changes and a minor battery power problem for one of the cells. The largest uncertainty coincides with some temperature fluctuations and a noisier system digital voltmeter.

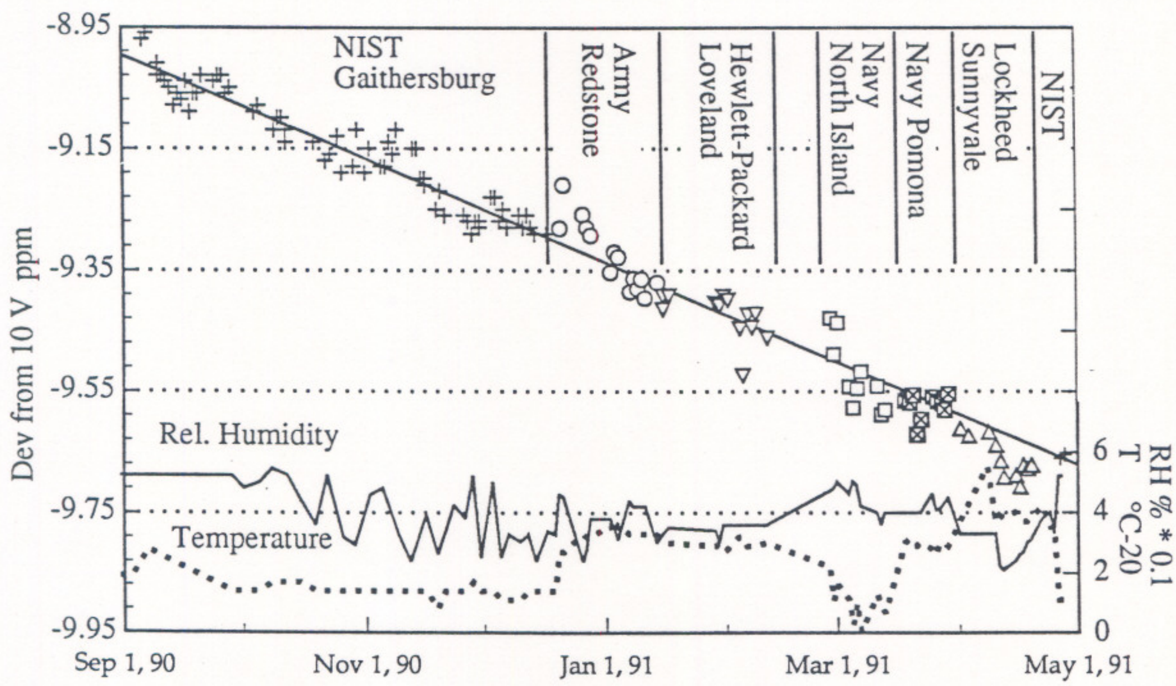

Figure 1. The graphic results of the measurement points compared to the predicted line for the Zener reference. The labels above delimit the data sets. The left scale is the deviation from a nominal 10 V in ppm. The right scale represents the relative humidity in percent times 0.1 and the laboratory temperature deviation from 20 °C.

A second comment relates to the unexpected wide range of array system operating techniques encountered during the MAP. Apparently no method is significantly more accurate. The levels of precision also seem similar, but this is not as clear, because the precision of each array system combines with the stability of the Zener reference to affect the random uncertainty. This reference did not show a noticeable relation between day-to-day noise and environmental fluctuations, and yet there seem to be short-term changes within the data sets. This may indicate a slight environmental sensitivity of some other component in the array system or a delayed response of the reference. Further testing is needed to decipher this result. Also, it should be noted that each laboratory reported their "within-run" standard deviation, or uncertainty. Since the numerical methods for calculating this number varied between laboratories and the values were in every event ten times smaller than the day-to-day scatter, the relevance of this number needs to be examined.

MAP AND ARRAY LIMITATIONS

As stated earlier, the results of this MAP can be viewed two ways, either as an estimate of the accuracy of array systems, or as proof that a predictable Zener reference has been produced. This dichotomy highlights a basic problem in designing any MAP, choosing a transfer standard which is stable and predictable enough to provide a sufficiently accurate test case. Thus, there were two reasons to examine this particular reference for over three months before the MAP was started. One reason was to accumulate enough data on the drift rate to predict its behavior during the time frame of the MAP. But just as important was studying the noise level and how it reflected the reference's sensitivity to the environment or to physical handling. It is estimated that this noise level adds an extra component of 0.01 - 0.02 ppm to the uncertainty of this MAP data. Thus, these MAP results cannot put a definitive limit on the potential accuracy and precision of array systems.

However, there were some temporary but gross measurement errors that arose in the course of this MAP that could have added some giant uncertainty components. Two different laboratories reported an initial data point which was in error by 15 ppm, equivalent to one array voltage step! This type of error spotlights the low precision aspect of array systems. To start a measurement, a value for the reference voltage must be estimated to within half the step voltage. This predetermination requires close operator scrutiny or cross checking procedures within the system software.

There were several other observed "bad points". In a close inspection of the reference's scatter within the set taken in late January, one of these, a particularly outlying point can be seen, as in Fig. 1. This point was 0.1 ppm below the prediction, unusual because its difference was more than 3σ from the full set's simple standard deviation of 0.031 ppm and *the shift was identical on three of four cells*. Yet, the "within-run" standard deviation was 0.004 ppm! Although Zener references have exhibited this type of sudden shift, this represents an improbable coincidence, especially since this reference has been well behaved. Unfortunately, the raw measurement data was not saved, limiting any further investigation. The frequency reference was suspected, but no direct cause could be found for this anomaly, so it is not clear whether or not this array system experienced an error. But the difficulties encountered in analyzing this problem leads to two recommendations to users of array systems. One, save the raw data in case an error must be traced, and two, don't blindly trust the system if accuracies better than 0.1 ppm are desired, regardless of the short-term uncertainty calculations. These caution flags should remind managers and operators that Josephson array systems are still in the the early stages of development. Operating software is currently being developed with sophisticated menu features, internal checks, and reliability, but due to the lack of standardization of system instrumentation, this software is not yet available nor can it be easily converted for use on all systems.

CONCLUSIONS

It seems beyond a doubt that this experimental MAP transfer was successful in verifying Josephson array systems to the limits of the reference standard. The variations on the order of

±0.04 ppm between the laboratories and NIST are almost ten times less than the best uncertainty (3σ) specified in the NIST voltage calibration service. After further measurements at NIST, the reference's drift curve will be updated and the calculated variations between the other laboratories and NIST may decrease slightly. However, discrepancies did occur. There were large ones as well as small ones, which being near the level of 0.1 ppm, were more subtle and difficult to analyze in spite of being fairly easy to spot. Finally, the purpose of this MAP was to verify array systems which were expected to have high accuracies, but the results also portend an increase in the calibration specifications and capabilities of newer electronic instrumentation. Laboratories may eventually have to upgrade their voltage capabilities considerably to meet higher specifications but a wider access to array systems, new metrology equipment, and greater participation in MAPs will hopefully ease the process while also spurring these improvements.

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