Improvements for Automating Voltage Calibrations Using a 10-V Josephson Array

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Abstract—**A voltage standard system based on a 10-V Josephson array been completely automated with three novel developments. First, a unique way of connecting Zener voltage standards, a digital voltmeter (DVM), and the array to a commercial standard cell scanner has provided necessary switching flexibility. Second, using a programmable millimeter wave attenuator has greatly simplified the selection of voltage steps. Third and last, programmed error checking, which verifies array steps by comparing measurement scatter to previously characterized system noise levels, has proven more reliable than visual observation. The operation of this new system is simplified enough for an inexpert user while the calibration uncertainty (1σ) is still a few parts in 10^8.**

I. Introduction

FOR the past three years, a 1-V Josephson array system [1]–[3] has been used at NIST as a voltage standard to maintain the unit Volt [4]. A second system based on a 18992 junction Josephson-array with 10-V capability [5] has been recently developed. This new system was designed for a variety of measurements up to 10 V, particularly, calibrating fixed-value Zener references and multi-ranging DVM's. Most significantly, this array system performs these calibrations automatically, with daily reliability, and with nearly the same uncertainty of less than 0.02 parts per million (ppm) as the original 1-V system. An inexpert user, unfamiliar with Josephson array physics, needs only to perform a simple setup sequence for operation. We accomplish this degree of automation by 1) connecting Zener references, a DVM, and the array in a unique way to a commercial standard cell scanner, 2) actively engaging a programmable millimeter wave attenuator in a power cycling procedure that greatly enhances the reliability of the step selection procedure, and 3) ensuring the system accuracy with sophisticated error checking to verify the stability of array steps and to note unexpected results.

II. Switch-to-Instrument Interconnection

In many voltage standard calibration systems, a Data Proof[1] standard-cell scanner satisfies the accepted switching requirements with its low thermal emf contacts and dual channel capability. Briefly described, this scanner has two internal relay networks, each capable of selecting one of many inputs, the first network for channel A and the second as channel B, thus the dual channel connotation. In the normal application of these scanners, voltage references are connected as inputs and the dual outputs have their low sides wired in common, producing an output voltage equal to the difference of the A and B inputs. In the case of many voltage calibration systems, a DVM is connected to the output. But voltmeters have offsets, which can drift too rapidly to be measured at some later time. By taking advantage of this scanner and quickly interchanging the selected input channels, A to B and B to A, the output voltage is reversed relative to the DVM offset for mathematical cancelation. Other offset errors still arise, but irreproducible emfs in switch contacts are small and thermal emfs in the leads to the references are minimized with proper techniques in constructing these connecting wires.

With a Josephson array, there is yet another thermal emf, ever present in the cryoprobe wires connecting the supercooled array to room temperature instruments. However, one unique feature of the array as a voltage standard is that the voltage can be reversed electrically with no loss of accuracy. This reversal virtually nullifies this emf, but *only if the array is connected to unswitched terminals*. This explains our unusual connection of the array to the scanner *output*, as shown in the connection scheme of Fig. 1. Zener references are customarily connected as voltage inputs, so this leaves two valid alternatives for positioning the DVM (aside from internally rewiring the scanner). It could be connected to the output in series with the array. This choice combines the meter offset with the cryoprobe thermal emf, but wires in the same DVM as a rather permanent part of the circuit. Instead we connect the DVM to an input terminal (in anticipation of calibrating several other DVM's). In this case the DVM must also be connected in reverse polarity to a second input to compensate for the DVM offset reversal when the A/B channels are interchanged, and also nullifying any emf's in the DVM connection wires. A short circuit on an additional input terminal benefits both Zener reference and DVM calibrations in a use which is mentioned later.

Calibrating an unknown Zener reference involves a more complicated switching and measurement procedure than DVM calibrations, so a complete description of the scanner switch configurations and the four circuit equations is presented here. Two of the scanner's internal configurations are schematically pictured in Fig. 2. The voltages involved are: four DVM readings ($V_{1,2,3,4}$), the Zener reference voltage (V_Z), a DVM offset voltage (V_o), and the calculated array voltage plus its associated probe thermal emf ($V_a^{\pm} + V_t$). The polarity of the array is defined (+ or −) relative to the A output terminal on the scanner. Thus, selecting channels A4 & B1 as in Fig. 2(a), yields

$$V_1 = \{(V_a^- + V_t) + V_z\} - V_o. \quad (1)$$

Selecting channels A5 & B1 yields the complementary equation

$$V_2 = -\{(V_a^- + V_t) + V_z\} - V_o. \quad (2)$$

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[1]Brand names are used only for purposes of identification. Such use implies neither endorsement by the National Institute of Standards and Technology nor assurance that the equipment is the best available.

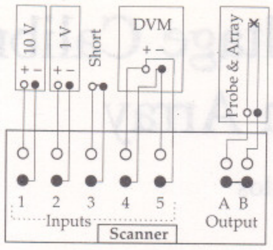

Fig. 1. An illustration of the array system connections at the back panel the scanner. Inputs 1 and 2 are Zener references, 3 is short, and 4 and 5 are DVM connections reversed relative to each other. The array within its cryoprobe circuit is at the output terminals; the common output terminals are shorted.

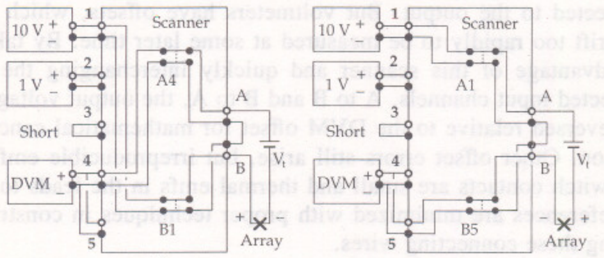

Fig. 2. A simplified internal wiring schematic illustrating two different switch configurations. (a) Selections A4 and B1. (b) Selections A1 and B5. To maintain the DVM polarity of the first circuit but interchange the array and 10-V source, the reverse DVM of channel 5 must be used.

The DVM offset can be eliminated by subtracting expression (2) from (1). Switching between this pair of measurements doesn't usually require another step selection. Next, after interchanging the Zener reference and DVM by selecting A1 & B5 (B5 to again make the DVM positively oriented, see Fig. 2(b)) and electrically reversing the array polarity, the voltage measurement is

$$V_3 = \{(V_a^+ + V_t) - V_z\} - V_o. \tag{3}$$

And finally, choosing A1 & B4 yields

$$V_4 = -\{(V_a^+ + V_t) - V_z\} - V_o. \tag{4}$$

An independent value for the Zener reference arises directly from these four measurements and the computed array voltage,

$$V_z = (0.25)\{(V_1 - V_2) - (V_3 - V_4)\} + V_a. \tag{5}$$

Of course, the array voltage is calculated from the step number n, millimeter wave frequency f, and the Josephson constant K_J,

$$V_a = nf/K_J. \tag{6}$$

The frequency and the step number are chosen at the start to match V_a with an initial approximating measurement of the Zener reference. In our procedure, the millimeter wave frequency remains constant, and although each array voltage may be a different step number, it is a simple matter to mathematically adjust each V_n reading so they all correspond to the same step number. This measurement set is repeated in a pattern that reduces the skewing effects of any linear drift—(1,2,3,4)(3,4,1,2) (1,2,3,4)(3,4,1,2). Calculation of the standard deviation of the mean of these four independent points is straightforward.

A premeditated advantage to this wiring scheme is that another measurement procedure, calibrating DVM's directly against the array, can be performed without any wiring reconfiguration. Indeed, any number of DVM's can be attached as single inputs for workload calibration. Simply selecting channels A4 & B3 (the short) links the DVM directly to the array. No further switching is needed, so irreproducible thermal emf's from multiple switch closings are avoided. The thermal emf's and DVM offset are directly measured by setting the array to zero volts. The basic details of the routine and calculations are similar to those reported elsewhere [5], [6]. In brief, various array steps are generated from zero to the DVM's full scale. From each DVM reading, the step number can be calculated for the precise test voltage, thus resulting in a point-by-point DVM calibration curve.

III. Array Step Selection

Generating stable array steps at specifically targeted voltages is an unavoidable prelude to any measurement, yet this procedure long retained a "personal touch" resistant to efforts of standardization. In most systems, operators still peer at oscilloscope displays and manually adjust the millimeter wave power in coordination with coarsely setting the target value, then use large triangle wave oscillations or short pulses of higher magnitudes to acquire each step. The procedure is made more complicated by other considerations: frequency sources with variable power output, array coupling efficiencies, different array designs, and voltages ranging from 1 mV to 10 V for DVM calibrations. From a historical perspective, the original attempts at computerized step selection employed only voltage manipulations. In one method, the bias was swept in small voltage increments and step jumps were recorded to map out the edges of several array steps in order to return to a bias point at the center of a step. A more reliable method was to mimic a real operator using triangle waves and pulses [4]. All of these "bias only" routines were limited in that they needed tailoring to specific voltage values and individual array characteristics. Their automated reliability often failed at lower voltages because the attenuator needed some fine adjustment. Although we have no explanation as yet, our experience indicates that there is a more complex array response to a change in the bias voltage when the step number is less than about two times the number of junctions, i.e., less than step number 6000 with a 3000 junction array.

Fortunately, there is no longer any barrier to automated step selection. We have found an improved and flexible algorithm to generate stable steps using a programmable attenuator as an active component. The procedure is based on two observations: 1) enough millimeter wave power to generate high-voltage steps will generate usable steps at any voltage, and 2) gradually ramping up to this "optimum" power *after* voltage biasing will almost invariably generate *stable* steps. The algorithm works for all arrays tested so far (1500, 2000, 3000, and 19 900 junctions) and at all voltages up to each array's maximum. An "optimum" power level is as yet manually set for each array in a standard routine: bias the array to its highest, stable voltage step and apply just enough power to start overdriving the array, i.e., decreasing the step current. Although this power level varies with the drive frequency and array design, any satisfactory combination of attenuation and frequency are constant from day to day.

The millimeter wave attenuator of this system is a 0–50 dB rotary vane design. It is calibrated and reproducible to 0.1 dB. This is important to recovering the "optimum" power level at the end of the attenuation ramping. Also, because the dial rotations has an asymptotic response and the usual setting is no more than about 3 dB, this attenuator is less sensitive to vibration than smaller, slide dielectric-damper designs. This mechanical stability is a serious concern, since power fluctuations can cause array instability.

Another vital instrument for the step-selection procedure is the bias controller, a digitally-programmable voltage calibrator with a 1-ppm resolution and a low noise, low impedance output. The electrical circuit, with a slight modification, and the biasing manipulations are the same as described elsewhere [4]. In this new system, the bias controller is wired directly to the array with a shielded, twisted pair cable, instead of passing through an oscilloscope plug-in. The series impedance is a balanced configuration of two 5-Ω series resistors (in addition to a similar resistance from the wires and rf filters in the cryoprobe). The voltage measurement lines are also shielded, twisted pairs. All the shields are connected, but grounded at only one place in the circuit.

A summary of the step selection algorithm follows. The goal is to select a step at some target voltage. First, the power is attenuated by about 20 dB and the array is biased with an estimated target voltage. For convenience, we define this kind of offset bias setting as a static voltage, to distinguish it from several types of dynamic waveforms also generated by the controller. Next, the attenuator ramps back to the preset "optimum" setting. The resulting voltage is checked directly to verify the step quality and to compare its voltage against the target value by a routine described in the next section. If it is not a good step or this first try does not closely match the target voltage, then some electrical stimulation is tried. The first stimulus is a triangle wave superimposed upon the static voltage, starting at 2-mV amplitude and gradually subsiding to a new static voltage which has been adjusted to correct the difference between the array and the target voltage. This increases the probability of settling on a step near the new static voltage and also nearer the center of a large step. (Note that 2 mV across 10 Ω bias impedance is far more current than a step's maximum of about 50 μA.) A second stimulus of a slightly larger pulse voltage, about 10 mV beyond the static voltage, sometimes works to push the array onto a step. As necessary, the routine loops back to the attenuator cycle or the triangle wave. 10 attenuation cycles or 20 triangle wave oscillations are generally enough to find a good step; any more usually indicate some array stability problem.

Short duration, high voltage pulses are no longer used as electrical stimuli. We have found that pulses are reliable only under special conditions. Although stable steps can generated with them, the array's response to a pulse is unpredictable; sometimes no further steps can be generated without resorting to ramping the attenuator. For best effectiveness, a pulse must force the array well beyond the total gap voltage, but for practical reasons this requires a second bias supply to avoid having to change ranges on a single one. Also, a pulse anywhere near the 10-V array gap value of 60 V will usually produce a current generating enough magnetic field to allow flux trapping, or could even break down the array's dielectric layers.

This step selection procedure's flexibility in hitting any target voltage deserves extra discussion. Applying bias corrections in successive trials becomes important if an exact voltage match is required or large series impedances are used in the bias circuit. Even with a low 10-Ω series impedance, several voltage steps not only coexist with a single bias setting, but they limit all bias corrections to a set of discrete values. Thus, the difference between the target and the array voltages may have neither the sign nor magnitude needed for the next correction. The solution is to weight the correction values in inverse proportion to the number of triangle-wave stimuli trials. Although this "learning curve" works very well, the rigorous selection of a particular step is eased in normal operations by accepting any voltage steps ranging within 1 mV of the target value. This speeds step selection considerably, gives the array freedom to settle onto a more stable step for a given millimeter wave power, yet still limits any uncompensated DVM error to 1% of the full scale gain correction on the 100-mV range. Also, the array target voltage is very flexible. It can be a near-zero reading on the DVM during a Zener reference calibration or a specific voltage for a DVM calibration. The special case of finding the exact zero-voltage step is quite simple. The attenuator is set to the maximum 60 dB and the bias is set to zero volts. The array step is checked against the shorted scanner input (0.0 V) in place of the reference. (By zeroing the array, the DVM can measure the Zener reference directly to provide the initial bias estimate and the step number.)

IV. Step Errors and Accuracy Checks

Filling in the details is certainly the most tedious part of creating any system program. This system's programming for automated array calibrations of either Zener references or DVM's addresses user friendliness as well as accuracy, speed, and reliability, but only aspects which are specific to the Josephson array are discussed here. The main problems in automating an array calibration can be summarized as follows: checking the characteristics of the array voltage step, confirming the stable behavior of the step during the measurement, assuring the DVM accuracy, and affirming the overall consistency of the measurement.

The first two of these problems deal with the most complex procedures in either manual or computerized operation, checking voltage steps. Fundamental to any measurement is confirmation that an array voltage is indeed a Josephson current-independent step. However, any observations might themselves cause another common headache, step instability. By itself or from electrical stimuli, a step can jump to a different quantum number and cause a large and easily noticed voltage change, or it can temporarily jump and return, causing the tiniest fluctuation. Since an ideal array step is virtually noiseless, our solution was to establish a baseline of voltage noise from all the instruments involved in the system and compare the noise of any measurements against the "ideal" baseline, using minimal or no stimuli. So in checking whether the array is unstable or not producing steps at all, the routines simply look for a higher than expected level of voltage noise. In actuality, the step checking routines examine the standard deviation of a series of DVM readings. If a measurement exceeds the baseline scatter by a chosen acceptance limit, individual points or whole calibration runs are rejected. Therefore, success comes from finding an acceptable rejection rate by setting a lower limit based on a low and fuzzy baseline in order to achieve reliable operation with the best calibration uncertainty in a reasonable measurement time.

This step recognition method should work for a variety of instruments, but designing a system to maintain a low noise level is a vital consideration. The selection criteria for this system's instrumentation included commercial availability, ease of programming, and low noise characteristics. Minimizing the noise baseline reduces measurement uncertainty, but also helps keep the array stable. A higher noise baseline (or shorter measurement time) requires an increased ac bias stimulus to detect a bad step reliably. This trade off can eventually lead to disaster, because the array step has a finite current limit, and disturbances of any sort destabilize the array.

Since detailed knowledge of the noise baseline is so crucial, establishing this baseline is a continuing project. System instruments from various manufacturers have been used, along with different procedures involved in the two operating modes, Zener reference or DVM calibrations. For example, the characteristic noise of each DVM model depends upon the integration time, resolution, range, and the voltage level, all parameters which change in a single calibration. Fig. 3 shows noise plots of two $8\frac{1}{2}$ digit DVM models as functions of two of these variables, range and voltage input (as a ratio of full scale). Zener references are also noisy, depending upon the model and voltage level. Based on measurements like those of Fig. 3, an empirically determined equation or set of conditions describes the baseline for the step checking routines. The acceptance limit is set tightly at about two times the baseline estimate.

Some error checking routines used in this system have been mentioned elsewhere [4], [7], and have not been changed significantly. The following section details only the major error traps encoded recently. They are as generalized as possible for either calibration mode, but some check procedures differ between the two. These are indicated by stars (*). As mentioned before, in one mode the DVM measures the voltage difference between the Zener reference and the array, and in the other mode, the DVM measures the array voltage directly.

Check of DVM calibration*: A Zener reference calibration begins with a DVM reading of the unknown reference directly, with the array set to zero volts. From this voltage, the array's corresponding step number and an operating frequency are calculated and set, so that successive voltage difference measurements should be very nearly integer step voltages or zero volts. A discrepancy of more than half the step voltage between the preliminary DVM reading and the final calculated reference value is generally caused by an uncalibrated DVM. Thus, extreme DVM calibration errors or offsets are trapped.

In the DVM calibration mode, the test points start at low voltage and proceed to full scale, with a correction value calculated for each DVM reading and applied to the next highest value. This prevents miscalculation of the step number if the DVM gain error surpasses the half step value. By choosing appropriately spaced points, corrections accumulate slowly enough so even DVM's with large errors can gain be calibrated automatically.

Step check—direct: Each array voltage is checked with a 1-2 μA bias oscillation, applied as a 10 μV square wave. Six DVM readings are recorded over about 1 s, asynchronously with the square wave. This amplitude provides enough current to boost the noise level of a resistively sloped step by about a factor of three, yet not enough to disturb a good step of 30–60 μA. Also, this can force a step jump if the step happens to be biased near an edge, which will prevent any bias drift during the measurement from causing a jump later. (In practice, "bad steps" are retested in case the step jumped to a more stable one during the first check. Minimizing needless step searches means less time between array or DVM reversals and more efficient offset nulling.)

Step check—inferred: Because we prefer not to apply any test signal to the array during the actual measurements used in

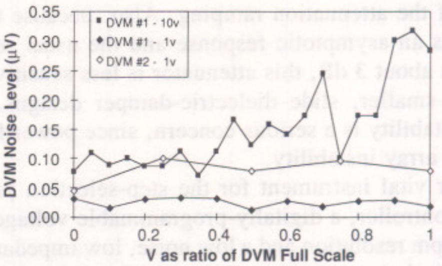

Fig. 3. A graph showing the noise levels in μV as calculated from the standard deviation of 10 DVM readings integrated over about 30 s. The x-axis is V as a ratio of full scale for various array voltages applied as input to the 1-V and 10-V ranges. Two different DVM models are represented. The noise level for both meters on the 0.1 V range is the same as that of DVM #1 on the 1-V range.

reference calibrations, the state of the step can only be inferred by assuming that if the scatter is small and random, the step is good. Before recording voltages for calibration purposes, two DVM readings are taken at integration times of about 5 s each. (This is also a built-in time delay to allow for switch contact emf equilibration.) A tolerance of ± 250 nV or ± 750 nV for 1- or 10-V Zener references, respectively, centered on this average value sets an acceptance interval for six further readings. Triggering a remeasurement when this interval is exceeded saves some of the 30 s total measurement time by providing for immediate detection of small thermal emf drifts from poor switch closures or large step jumps. The problem is more subtle if the array loses coherence after the step has already been checked directly. The array then shifts to the bias voltage, a change which will usually extend beyond the acceptance interval. The array can also be at exactly zero current and thus equal to the bias voltage, but then the bias supply only adds noise, not voltage error. In DVM calibrations, the limited resolution of 1 and 10-V ranges makes the confident detection of non-Josephson voltages more difficult. Ten or more DVM readings comprise a measurement point in this mode and the standard deviation is closely compared to a complex baseline formula specific to the DVM, as mentioned earlier. Fully integrated points with a standard deviation more than about two times the baseline noise level is rejected. The penalty for this redundant checking is lost from completing the measurement of bad-step points or retaking ones that may be only have had randomly high noise.

Consistency check*: Neither the direct nor the inferred step checks will catch every deceptive trick the array may try, so the standard deviation of the mean for the four Zener reference calibration points is compared to the historical value of past calibrations. The acceptable limit for our two similar systems is 0.02 ppm. This seems to catch all the unexpected errors for which the previous checks are insensitive, yet allows for variations in Zener reference noise levels. For the corresponding check in the DVM calibration mode, the scatter of three zero voltage measurements interspersed within a complete DVM calibration helps detect offset drifts over the longer time span of this process.

V. Observations and Discussion

The regular operation of our 10-V array system testifies to the tremendous value of the Josephson array and the utility of reliable automation. About 20 Zener reference calibrations are performed daily and several DVM models are characterized periodically. A 16 channel scanner was recently replaced with a

32-channel model to accommodate an increasing workload. As a result of improvements described in this paper, the uncertainty of the system has not been compromised by increasing the automation. Random or Type-A uncertainty is 0.004–0.02 ppm, varying with Zener reference models. Measurement periods are 10–15 min each. Systematic or Type-B uncertainty is dominated by the thermal emf's of the scanner relays, measured to be less than 50 nV. Full range DVM calibration curves have included as many as 83 points recorded in less than 2 h. DVM linearity errors of a few tenths of a ppm have been reproduced over many months to within about 0.05 ppm, a compliment as much to the DVM manufacturers as to the array system.

Research on this system has resulted in a greater understanding of array and instrumentation characteristics, from both the anticipated errors and the errors that have been caught by the programming itself. The most dramatic example of the latter appeared as a "last resort" consistency check error, which successfully flagged an array which was producing intermittently distorted steps with sloped segments of about 0.02 Ω. (In fact, this occurred on the 1-V system, which requires manual switching and produces oscilloscope images of the array steps. This slope was nearly invisible even to the "expert" operator.) Similarly, a large scatter in the zero voltage readings of DVM calibrations immediately brought our attention to a more general problem, that DVM's can have significant, nonlinear offset drifts of about 1 μV for up to 30 min after a self-calibration. We have avoided this problem by reversing the DVM quickly during high precision reference measurements. These offsets are caused by thermal emf's settling after internal DVM relays were switched during the self-calibration. In comparison, small thermal emf's in the cryoprobe are typically 200 nV and vary more slowly, about ± 25 nV per day. Because we calculate these emf's separately from the DVM offset and routinely check them, they act as telltales for items which need periodic maintenance: low liquid helium levels, wire degenerated by the severe thermal cycling, or dirty connector contacts at the top of the cryoprobe.

Studying baseline noise limits has produced data indicating that, as quiet as our array measurement system is, the noise from certain Zener references at the 1.018-V level is still less or about the same. This is an indirect conclusion based on the surprising observation that some Zener references are not measurably 10 times noisier at 10 V than at 1.018 V. This seems to be noticeable only at very short integration times (30 s); the scatter does scale consistently when averaged over many days. The noise structure exhibited by DVM's (see Fig. 3) reveals that front-end amplifier noise dominates at low voltages, but the internal Zener reference noise begins to dominate proportionally as the DVM circuitry analyzes input voltages nearer to 10 V. Clearly, the minimum noise we can directly measure is about 10 nV per 30-s integration time, given the particular instruments of this array system.

It is difficult to overemphasize how crucial the attenuator ramping cycle has proven in automating the step selection. By consistently generating steps that are stable it reduces the frequency of step searches and obriates the need to find the "right" power level for each voltage. Once the voltage bias supply is accurately calibrated for close initial estimates, then no additional electric biasing is usually needed. This speeds the time of step selection to 8–20 s, faster than a human operator can achieve, seemingly limited only by the speed of the rotary attenuator motor. Failures of the complete step selection routine within the last year were all from correctable problems: low liquid helium levels, insufficient power due to waveguide obstructions, excessive rf noise from poor bias cable shielding, an instrument's power supply noise or vibration, or in one case, a physically deteriorating array.

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