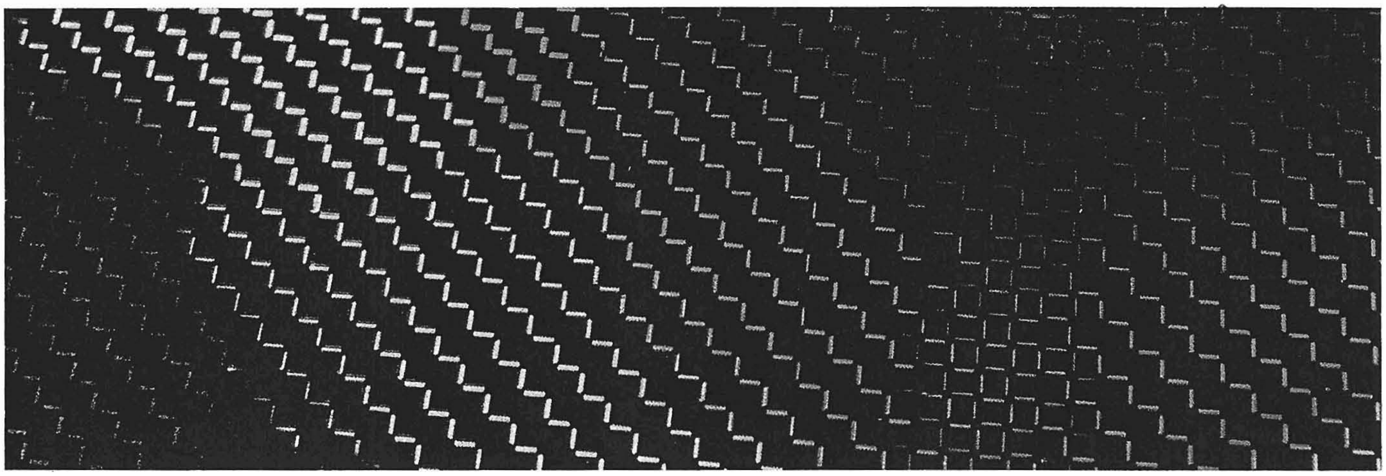

# Implementation of Programmable Josephson Voltage Standard to NIST Voltage Dissemination System

**June E. Sims and Yi-hua Tang**[1]

**Abstract:** For about seventy years, from the establishment in 1901 of the predecessor of NIST, the National Bureau of Standards (NBS), until about 1972, the U.S. legal volt was maintained by groups of electrochemical cells. In 1972, NBS began to exploit the fundamental quantum nature of the Josephson Effect to monitor and correct for the mean drift of these electrochemical cells. Since that time, though the Josephson Effect has formed the basis for the U.S. legal volt, the primary standard cell groups have continued to play a critical role in disseminating the volt through the NIST volt calibration service. This is because the classic Josephson array standards present significant barriers to routine use in a calibration system, and standard cells offer significant advantages, both in their long-term predictability and their lower noise, compared to other types of voltage standards, such as Zener standards. Standard cells, however, are affected by power outage, environmental temperature fluctuation, internal degassing, vibration, etc., sometimes exhibiting permanent voltage shift after such disturbances.

The programmable Josephson voltage standard (PJVS) is based on an improved junction technology and provides a stable output voltage without problems shown by traditional Josephson voltage standards. Their unique properties make it attractive to use the PJVS as a possible replacement for the primary standards cell groups that are still in use in the NIST volt dissemination chain. The implementation of the PJVS will improve both the reliability and the efficiency of the dissemination system. This paper describes the working principle of the PJVS and the present implementation status of the PJVS in the NIST voltage dissemination system.

## 1. Introduction

The volt is a derived unit in the Systeme International (SI) [1]. It is defined as the potential difference between two points on a conductor carrying a current of one ampere when the power dissipated is one watt. Realization and maintenance of SI volt based on this definition is very difficult. The experiment to realize SI volt is time consuming, often resulting in a less than satisfactory uncertainty. In practice, a representation of the SI volt is maintained and disseminated by many national metrology institutes. The uncertainty of the representation relative to SI volt can be determined by various experiments. Once the SI volt has been realized, it is much easier to disseminate the representation of the volt with very high accuracy.

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The Legal Volt maintained by the National Institute of Standards and Technology (NIST), and its predecessor agency the National Bureau of Standards (NBS), is the U.S. representation of the SI volt. From the establishment of NBS in 1901 until 1972, the U.S. Legal Volt was maintained by groups of standard cells. There had been a large effort in the late nineteenth century, which continued into the early twentieth century, to establish reliable standards for electromotive force (emf) based on electrochemical reactions within chemical cells. In 1893, the International Electrical Congress chose the Clark cell, developed by Latimer Clark [2], as the standard electromotive force. In 1894, the U.S. Congress passed Public Law 105, which established the Clark cell as the basis for the U.S. legal unit of voltage [3]. At its establishment in 1901, NBS inherited this definition of the unit. Hence, from 1897 until 1906, the unit of voltage in the United States was maintained by a group of seven Clark cells. However, by 1905 it had become clear that the standard cell developed by Edward Weston had many advantages over the Clark cell. Beginning in 1906, NBS began to base the voltage unit on a group that included both Clark and Weston cells. In 1908, the London International Conference on Electrical Units and Standards officially adopted the Weston cell as the internationally accepted basis for maintaining the volt. Thereafter, the U.S. volt was maintained by a group consisting exclusively of Weston cells. Through the years, the number of Weston cells constituting the national standard has varied. In 1965, the National Reference Group of Standard Cells consisted of 44 saturated Weston cells that were kept in an oil bath whose temperature was stabilized within 0.001 °C. Before the introduction of the Josephson effect, it was very difficult to provide incontrovertible evidence regarding the long-term stability of saturated standard

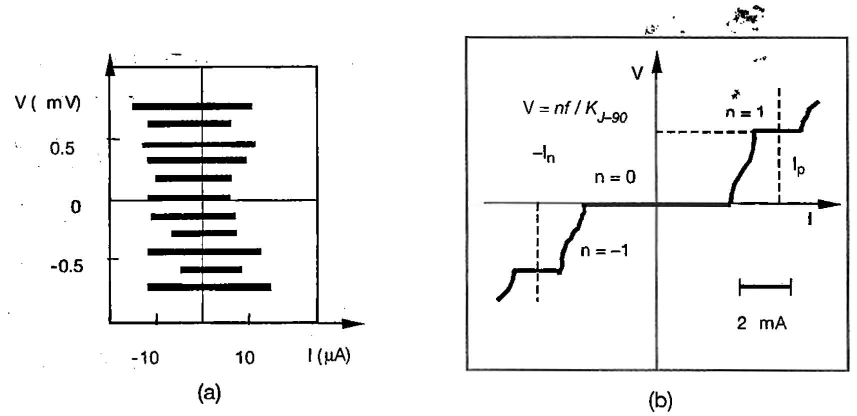


**Figure 1.** Voltage steps of (a) zero current biased Josephson junction array, (b) programmable Josephson junction array.

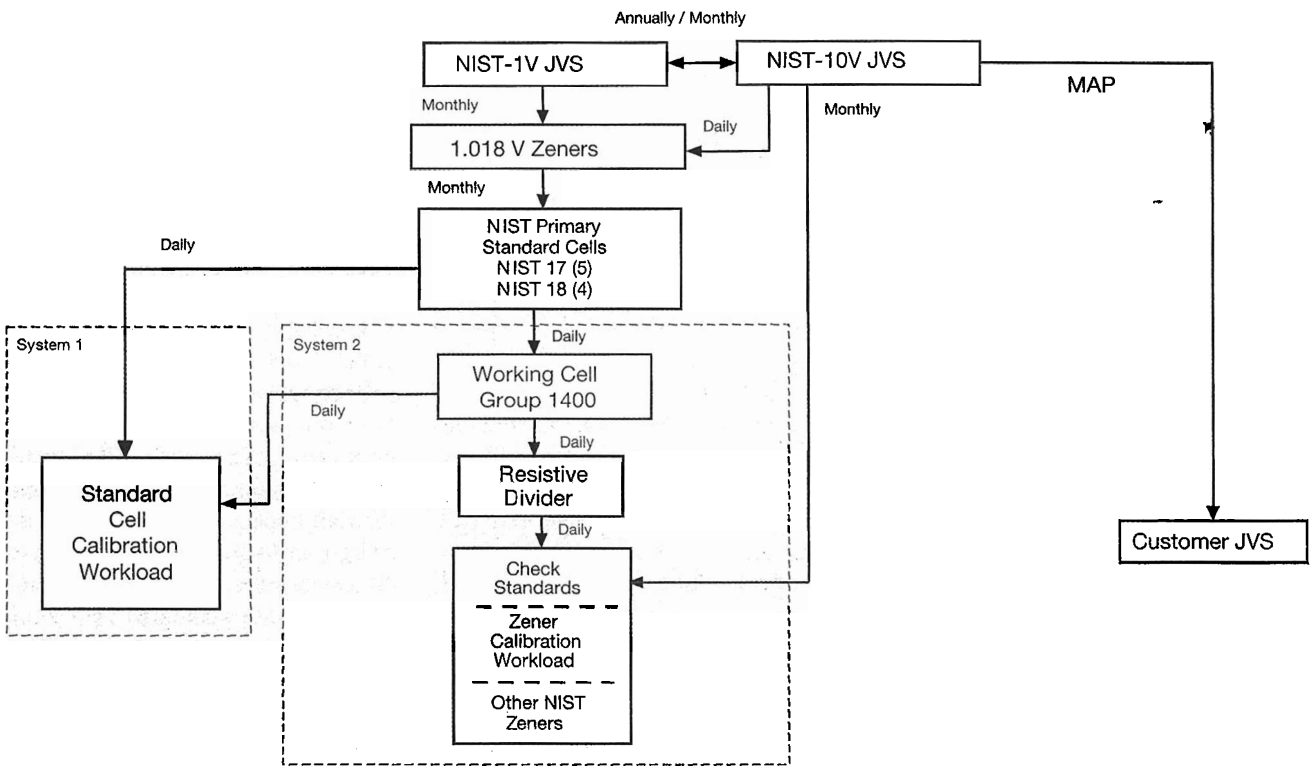


**Figure 2.** NIST dc voltage dissemination chain. The primary standard cell groups play an important role in transferring the volt from the NIST JVS systems and disseminating the volt to calibration customers.

cells; nonetheless, by the middle 1960's there was considerable evidence to suggest that from the early 1900's to the 1960's the National Reference Group of Standard Cells was drifting at a rate of about 1 part in $10^7$ per year.

The discovery of the Josephson Effect, along with the implementation of workable voltage references based on this effect, led to conclusive evidence of the long-term drift of the National Reference Group. It also provided the basis for a voltage reference that, because it is based on fundamental quantum properties of nature, is globally consistent and time invariant.

The Josephson Effect works like an essentially perfect frequency to voltage converter [4]. To realize the Josephson Effect, a Josephson junction (two superconductors separated by a very thin insulator) is irradiated by microwave radiation, resulting in the development of an exactly calculable voltage difference between the two superconductors. The value of the developed voltage, V, is simply proportional to the microwave frequency, $V = nf / K_J$, where n is a quantum step number, $f$ is the microwave frequency, and $K_J$ is the Josephson constant. The value of this constant depends only on the fundamental electron charge $e$ and the Planck constant, $h$, via the expression $K_J \equiv 2e/h$. Because neither $e$ nor $h$ is determined with sufficient accuracy to meet the needs of the international metrology community, a 'convention value' was adopted in 1990 by the international community, $K_{J-90}$ = 483 597.9 GHz/V, and this value is used worldwide to determine the unit of voltage [5].

| Segment | Number of junctions | V (mV) |
|---|---|---|
| 1 | 8800 | 327.810 |
| 2 | 8800 | 327.810 |
| 3 | 8798 | 327.736 |
| 4 | 8800 | 327.810 |
| 5 | 8794 | 327.587 |
| 6 | 8800 | 327.810 |
| 7 | 8792 | 327.512 |
| 8 | 3888 | 144.833 |
| 9 | 1296 | 48.278 |
| 10 | 16 | 0.596 |
| 11 | 48 | 1.788 |
| 12 | 144 | 5.364 |
| 13 | 432 | 16.093 |

**Table 1.** Construction of a programmable Josephson junction array and its voltage output with microwave frequency 18.014588 GHz.

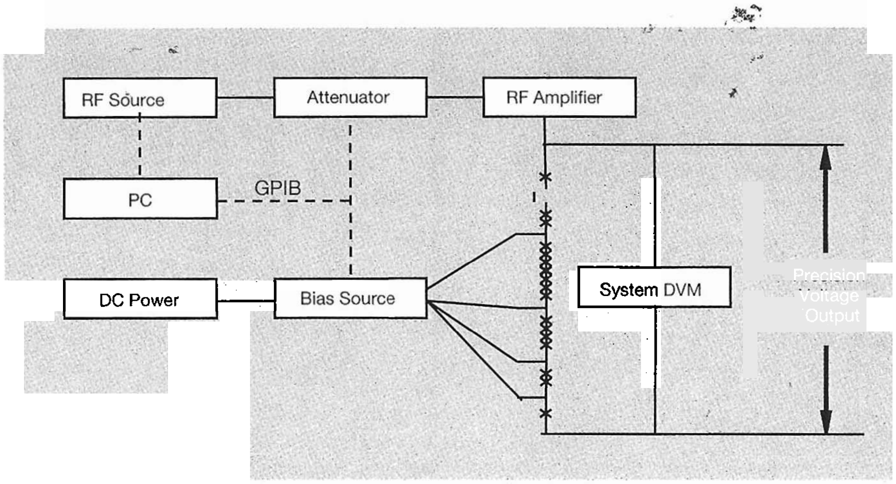


**Figure 3.** PJVS block diagram.

This paper describes the NIST voltage dissemination system and the implementation of a programmable Josephson voltage standard (PJVS) in the dissemination chain. The application of a PJVS using biased voltage steps can improve system reliability and efficiency.

## 2. NIST Volt Dissemination Chain

The dc voltage standard laboratory at NIST is operated under the supervision of the Quantum Electrical Metrology Division, in the Electronics and Electrical Engineering Laboratory. Its responsibility is to maintain the U.S. representation of the SI volt and to disseminate the volt to the U.S. scientific and industrial communities. Two Josephson voltage standard (JVS) systems, named NIST-1V and NIST-10V, operate equivalently as U.S. representations of the SI volt. The NIST-1V system uses a 1 V Josephson array consisting of 3000 junctions in series. The NIST-10V system uses a 10 V Josephson array consisting of more than 20 000 junctions. The voltage steps of these arrays are all biased at zero current as shown in Figure 1a. The step margin of such arrays is usually around 20 μA, which is generally sufficient for stable operation. However, electromagnetic interference in the typical measurement circuits can be large enough to trigger voltage step jumps during the measurement. The microwave frequency used for the zero current biased array is typically around 75 GHz, corresponding to a 155 μV voltage difference between adjacent steps. Hence, the array voltage can change by a few millivolts when step jumps occur. If such a jump were to occur while a standard cell is directly connected to the JVS for calibration, the abrupt voltage change could very likely cause an unrecoverable change in the cell's voltage. Consequently, voltage is transferred at NIST from the JVS to primary standard cell groups via the 1.018 V outputs of a set of solid-state Zener standards. This transfer has typically been performed monthly. It usually takes several hours to complete the transfer and is performed with a one-standard-deviation uncertainty of 2.3 parts in $10^8$. This uncertainty has been adequate to support the NIST volt calibration services.

The NIST dissemination chain for dc voltage is illustrated in Figure 2 [6]. The primary standard cell groups NIST 17 (including 5 cells) and NIST 18 (including 4 cells) are used to perform daily standard cell calibrations – the assignment of the daily value of the working standard cell group 1400 used as a reference standard in System 2, and the direct calibrations of the standard cell workload connected to System 1. The working standard cell group 1400 is used to calibrate a resistive divider in System 2. The resistive divider is then used to calibrate the Zener calibration workload. The primary standard cell groups at NIST have been well maintained in enclosures with very stable temperature control. The variation or noise of these cell groups is smaller than the noise of Zener standards. The cell groups exhibit very linear drift characteristics so their output value at time of use can be predicted very accurately between transfers from NIST JVS systems. By contrast, Zener standards, which are affected by changes in the atmospheric pressure, ambient temperature and relative humidity, exhibit behaviors that are much more difficult to predict with high accuracy [7]. Because of the good transportability and easy maintenance, Zener standards have replaced standard cells in most industrial laboratories. But their performance has not been sufficiently high to form the basis of the NIST calibration services. Thus, for the last three decades, since the advent of Josephson-based voltage references, the NIST primary standard cell groups have continued to play a critical role in disseminating the volt to calibration customers. The cells in the NIST primary cell groups are aging and some can exhibit erratic and unpredictable behavior, which requires reconfiguration of the cell groups to exclude poorly performing cells. The supply of high quality standard cells around the world is very limited and is decreasing. Hence, finding a suitable backup or replacement for the NIST primary standard cell groups has become a high priority task that must be completed to maintain a healthy national dissemination system.

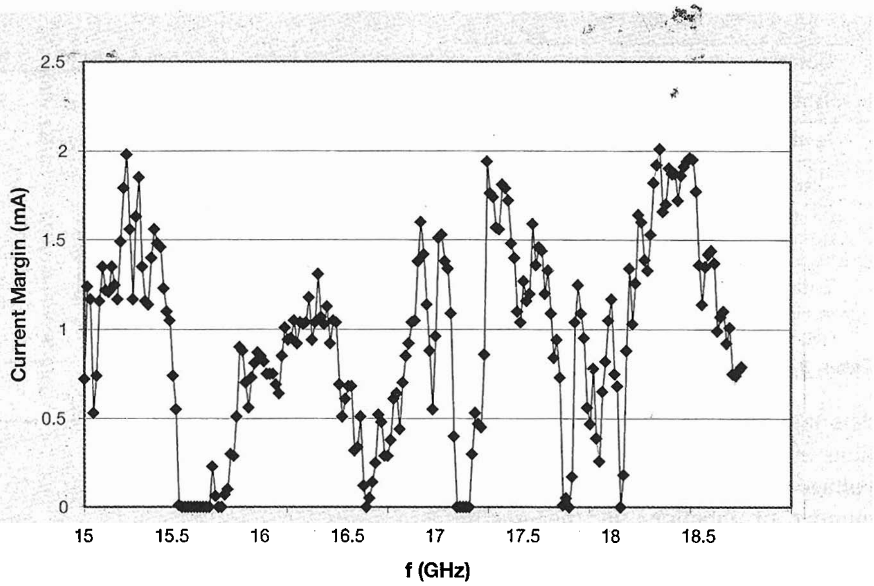


**Figure 4.** Frequency characteristics of a programmable Josephson junction array.

### 3. Working Principle of Programmable Josephson Voltage Standard (PJVS)

A new type of programmable Josephson voltage standard (PJVS) was developed in 1997 at NIST using the superconductor-normal metal-superconductor (SNS) junction [8]. The disadvantage of the zero current biased Josephson junction array, shown in Figure 1a, is the step number n cannot be uniquely specified by any operating parameter in the system. Hence, the output voltage can exhibit spontaneous jumps triggered by noise in the measurement circuit or electromagnetic interference from the surrounding environment. By contrast, PJVS biased at non-zero current, leading to a non-hysteretic junction that has distinct voltage values depending on the bias current, as shown in Figure 1b. Unless the bias current changes, the voltage output of a junction is set to be stable for an infinitely long time. In the present PJVS design, only three bias currents, $-I_n$, 0, $+I_p$ are used, leading to steps of $n = -1, 0,$ or $+1$, which of course implies dc voltage outputs of $-V$, 0, or $+V$. In the PJVS, the array junctions are grouped into segments, with all junctions in a segment being biased by a common bias current, and each segment having a number of individual junctions taken from a binary sequence. Hence, each segment can be individually programmed to one of the three operating states by setting its bias current. Thus, the output voltage of the full array can be digitally programmed by applying the appropriate combination of bias currents to the various segments.

The PJVS can be programmed to provide a stable output anywhere between $-V_{Max}$ and $+V_{Max}$, where $V_{Max}$ is

| Segment | Number of junctions | Ip | In | pHEIG | zHEIG | nHEIG |
|---|---|---|---|---|---|---|
| 1 | 8800 | 13.22 | −13.22 | 2.11 | 8.27 | 2.11 |
| 2 | 8800 | 12.84 | −12.77 | 2.18 | 6.97 | 2.17 |
| 3 | 8798 | 13.40 | −13.39 | 1.95 | 8.48 | 1.96 |
| 4 | 8800 | 13.14 | −13.05 | 2.14 | 8.32 | 2.15 |
| 5 | 8794 | 13.15 | −13.12 | 1.91 | 7.75 | 1.90 |
| 6 | 8800 | 13.03 | −13.02 | 2.22 | 8.22 | 2.24 |
| 7 | 8792 | 12.67 | −12.64 | 1.87 | 6.34 | 1.86 |
| 8 | 3888 | 12.92 | −12.93 | 2.31 | 8.74 | 2.30 |
| 9 | 1296 | 12.79 | −12.80 | 2.38 | 9.05 | 2.37 |
| 10 | 16 | 12.13 | −12.19 | 3.16 | 9.72 | 3.16 |
| 11 | 48 | 12.59 | −12.67 | 2.74 | 10.14 | 2.77 |
| 12 | 144 | 12.73 | −12.81 | 2.95 | 9.93 | 2.95 |
| 13 | 432 | 12.82 | −12.87 | 2.78 | 10.09 | 2.80 |

**Table 2.** Bias currents and voltage step margins. All currents in mA.

| Component | (nV) |
|---|---|
| Time base | 0.001 [10] |
| Leakage | 0.015 |
| Leads thermal voltage, RF induced offset and noise in the circuit | 3.9 |
| Total uncertainty | 3.9 |

**Table 3.** PJVS uncertainty at 1 V.

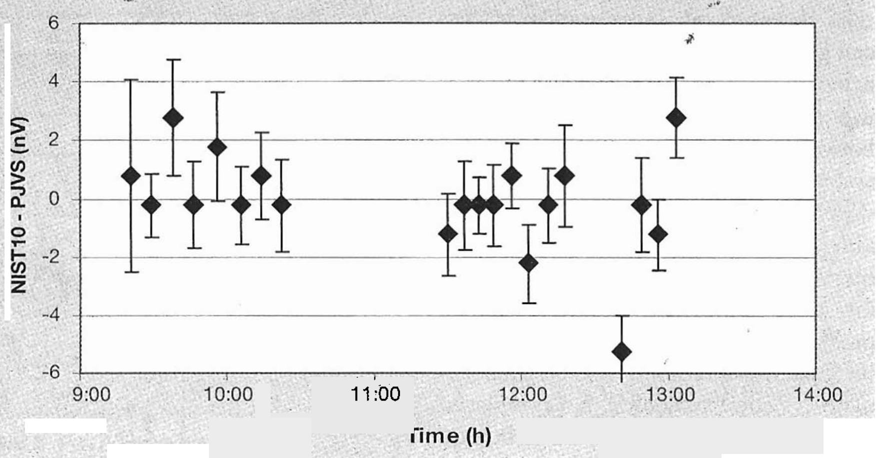


**Figure 5.** Direct comparison between the zero current biased array and the programmable Josephson junction array at 1.018 V.

determined by the total number of junctions in the array. The resolution of the voltage output is determined by the number of junctions in the smallest segment. A state-of-the art array design can contain more than 67 000 junctions on a two-layer structure with 16 junctions in the smallest segment [9]. Table 1 shows the construction of a programmable Josephson junction array used in the NIST volt dissemination system. By programming a combination of segments and their bias currents, a stable voltage up to 2.6 V can be generated.

Figure 3 shows the block diagram of a PJVS system. The bias source provides bias currents for each of the segments in the array. The bias current for an individual segment can be positive, negative or zero depending on whether the voltage output required is positive, negative or zero. In order to avoid electromagnetic interference from AC power coupling to the bias circuits, the bias source electronics uses DC power supplied by lead-acid rechargeable batteries. Microwave radiation for the array is provided by a microwave source with an attenuator and RF amplifier to obtain the optimum RF power level for array operation. A PC through a GPIB interface controls all the electronics.

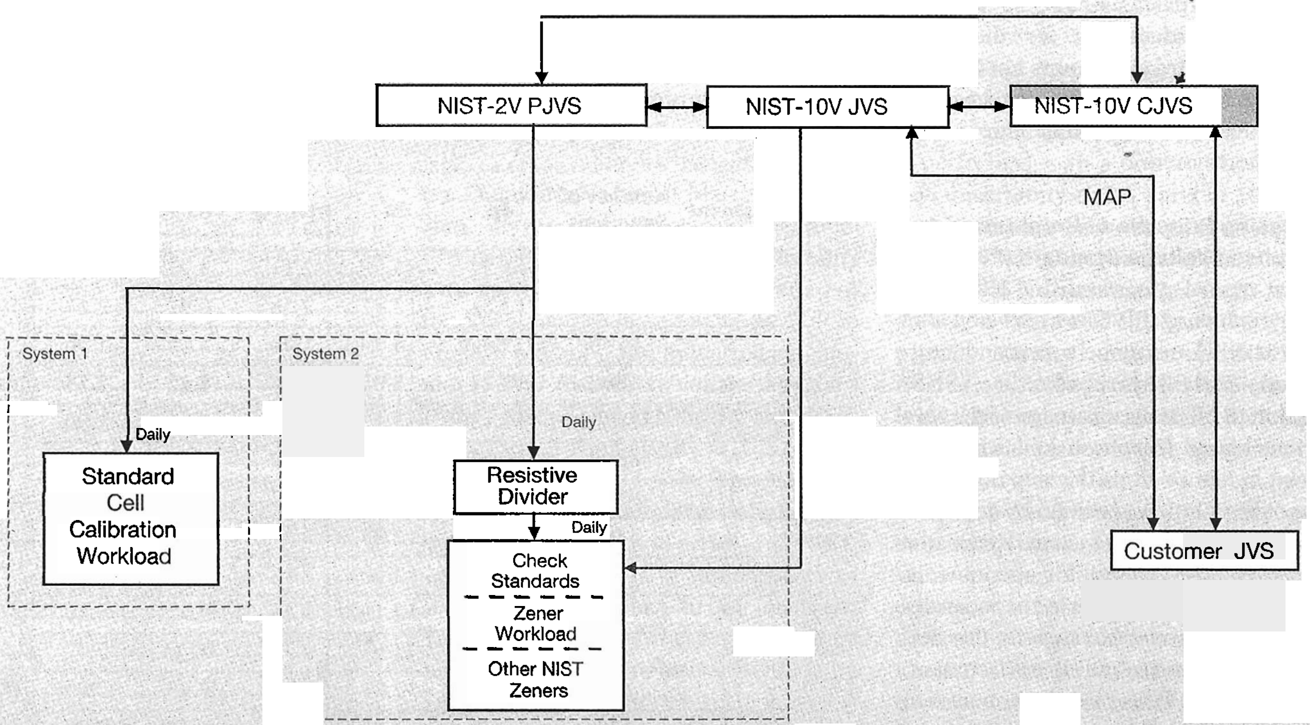


**Figure 6.** Streamlined NIST volt dissemination chain, where NIST-10 JVS is a 10 V lab system and NIST-10 CJVS is a 10 V compact JVS.

## 4. Implementing the PJVS into NIST Volt Dissemination Chain

### 4.1 Characterization of PJVS

Before a PJVS can be used for calibrating the device under test (DUT), it must be optimized for its operation. This includes finding the best operating microwave frequency and power level, and characterizing the working parameters for each segment such as bias current, step margin, etc. The operating frequency for the programmable array is designed to be between 15 to 18 GHz. The optimum operating frequency range is determined by scanning the frequency and finding the maximum current margin for the voltage steps. Figure 4 is an example of array frequency characteristics, which shows that the best operating frequency is between 17.82 GHz and 18.03 GHz. The current margin corresponding to the frequency varies between 1.7 mA and 2.0 mA. The rich frequency response structure is unique to each individual array chip and is due to interference between eight microwave transmission lines that distribute microwave power to the junctions. Since the frequency characteristics vary from array to array, it is necessary to characterize the frequency response for each array to ensure the best performance at its voltage output.

In order to maintain a stable voltage step, the segments must be biased at the center of the steps as shown in Figure 1(b). The optimal bias current for each segment is slightly different, and each optimal current can be slowly shifting due to the changes in the liquid helium level in the Dewar. It is important to characterize the PJVS at time of use to determine the bias currents for each segment. This process has been completely automated and is performed by an instrument control program for the PJVS and takes approximately 10 min. to complete. Table 2 lists the parameters of a programmable Josephson junction array containing 13 segments, where $I_p$ is the bias current for a positive voltage step, In is the bias current for a negative voltage step, pHEIG is the current margin of a positive voltage step, nHEIG is the current margin of a negative voltage step, and zHEIG is the current margin of a zero voltage step, where the current margin is defined as the current amplitude of a voltage step. For example, if segment 1 is chosen, the bias current for a positive voltage output is 13.22 mA.

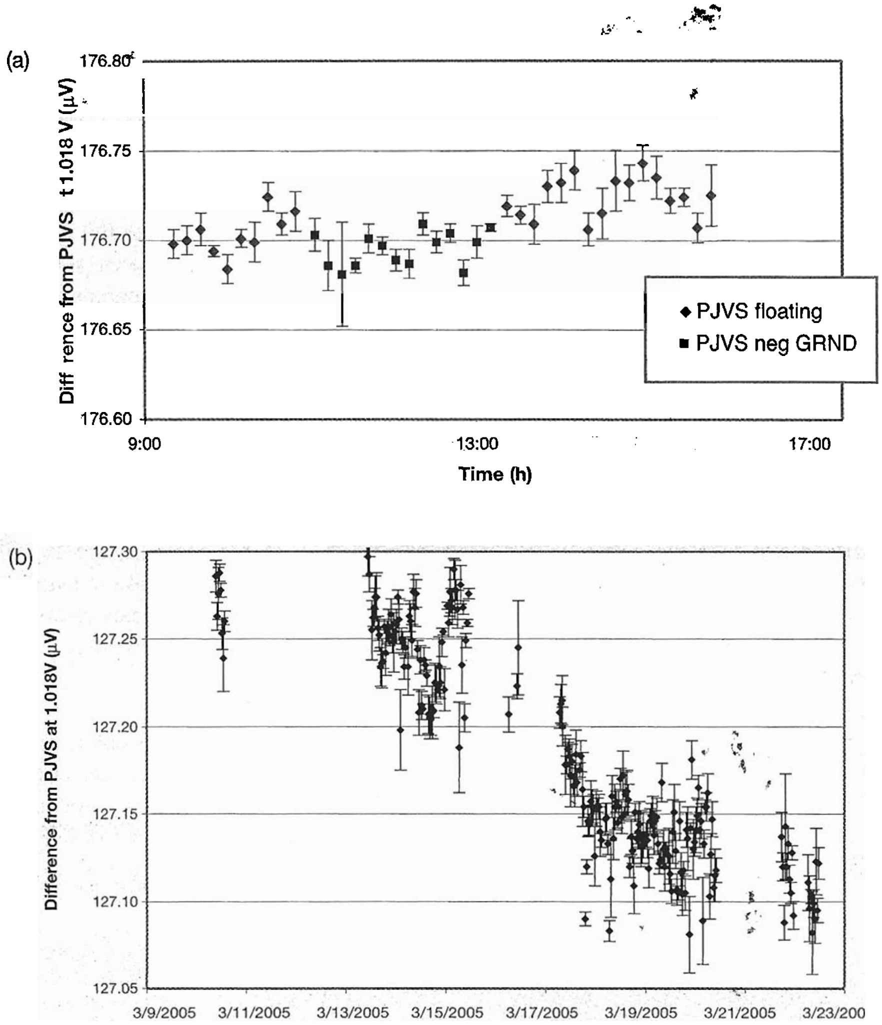


**Figure 7. (a)** Results of Zener calibration at 1.018 V against PJVS directly and **(b)** results of a standard cell calibration at 1.018 V against PJVS showing the short-term noise and drift of the cell.

### 4.2 Verification of PJVS operation

Uncertainty sources of PJVS come from the frequency reference, leakage resistance of cryoprobe, thermal voltage fluctuation in the leads, RF induced offset and noise in the measurement circuit. The uncertainty in voltage measurement caused by the frequency reference is proportional to noise of the frequency reference, which can be measured using the Allan deviation. For most frequency standards, such as a cesium clock, disciplined GPS or other types of high performance frequency references, the Allan deviation is between a few parts in $10^{11}$ and a few parts in $10^{12}$. The measured leakage resistance between the two precision leads is 6.5 x $10^{11}$ Ω. With a lead resistance of about 10 Ω, the uncertainty caused by the leakage resistance is negligible. We have also measured the combined uncertainty contributed by the thermal voltage in the leads, RF induced offset and the noise in the measurement circuit. In approximate 15 min the standard deviation of short measurements at the operating frequency and power level for the PJVS was found to be 3.9 nV. This is the most significant component in PJVS uncertainty budget. Table 3 summarizes the uncertainty components of the PJVS for a 1 V output. The total uncertainty of the PJVS at 1 V thus is 3.9 nV or 3.9 parts in $10^9$ (one standard deviation). When the PJVS is used for calibrating Zener standards or standard cells, other uncertainty components such as thermal voltage from switches should be included.

Extensive comparisons have been made between a conventional JVS (NIST10) using the zero current biased array and a PJVS using a programmable Josephson junction array, where the two arrays were directly connected via a low noise digital volt meter (DVM). The difference between the two voltages can be measured by the DVM. Figure 5 shows the result of such a comparison at 1.018 V. The average difference between the two systems is 0.09 nV with an expanded uncertainty of 0.83 nV or 8.3 parts in $10^{10}$ at 95 % confidence.

### 4.3 Streamlined NIST Volt dissemination chain

The superior stability of the voltage output from the PJVS makes it an attractive backup and potential replacement for the NIST primary standard cell groups. Figure 6 shows the streamlined NIST voltage dissemination chain. Several steps in the dissemination chain shown in Figure 2 have been eliminated because the PJVS can make direct calibrations at 1.018 V using a Zener standard or a standard cell. The PJVS can also calibrate a ratio divider from 1.018 V up to 10.18 V, which provides for the calibration of 10 V Zener standards. The streamlined dissemination chain also has improved the reliability, efficiency and uncertainty of the voltage dissemination process. Figure 7 shows the results of measurements of a Zener standard and standard cell at 1.018 V against the PJVS. For a Zener standard which is highly electrically isolated from the ground, the calibration against the PJVS yields a consistent result whether the PJVS is floating or grounded at one terminal as shown in Figure 7(a). The uncertainty of the calibration in this case is mainly determined by the Zener noise level. Figure 7(b) shows an example of measurements of a standard cell at 1.018 V against the PJVS over a period of about 13 days. In all these measurements the uncertainty of the PJVS is negligible compared to short-term noise of the standard cell. The streamlined voltage dissemination chain reduces the calibration uncertainty by reducing the required number of voltage transfer steps between the primary reference and the DUT.

There are other advantages obtained by incorporating the PJVS into the dissemination chain to replace the primary standard cell groups. Because the temperature change of the enclosure for standard cells can cause permanent voltage shift, strict temperature control and 100 % reliability of laboratory power are essential to maintain stable working environment for standard cells. These requirements in the streamlined dissemination chain can be much reduced. A stable temperature is still required in general for making satisfactory measurements, but, excursions do not lead to permanent problems.

## 5. Summary

The new programmable Josephson junction array, which is based on current biased junctions, provides substantial advantages compared to traditional zero current biased arrays, primarily due to the stability of its voltage steps. A PJVS using the current biased array is being implemented into the NIST voltage dissemination chain to replace the primary standard cell groups. The new dissemination chain will have substantially improved reliability, efficiency, and uncertainty.

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