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A 10 V programmable Josephson voltage standard and its applications for voltage metrology

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Abstract

The concept of a programmable Josephson voltage standard (PJVS) was first proposed in 1997. Since then a significant amount of research and development work has been devoted to the fabrication of the programmable Josephson junction array and its deployment in a voltage standard system. This paper reports the recent development of a 10 V PJVS system at the National Institute of Standards and Technology (NIST) and its voltage metrology applications. The superior stability of the voltage step of the new 10 V PJVS enables it to perform the same tasks as the conventional Josephson voltage standard (JVS) that uses hysteretic voltage steps and to improve the efficiency and effectiveness of a JVS direct comparison. For the first time, a comparison between a conventional JVS and the NIST 10 V PJVS was performed in order to verify the performance of the NIST 10 V PJVS. The mean difference between the two systems at 10 V was found to be -0.49 nV with a combined standard uncertainty of 1.32 nV ($k = 1$) or a relative combined standard uncertainty of 1.32 parts in 10^{10} . Automatic comparisons between the 10 V PJVS and a 2.5 V PJVS at 1.018 V were performed to monitor the long term accuracy and stability of the 2.5 V PJVS and to support the NIST electronic kilogram experiment. By matching the voltages of the two PJVS systems during a comparison, the type B uncertainty can be minimized to a negligible level. The difference between the two PJVS at 1.018 V was found to be -0.38 nV with a combined standard uncertainty of 0.68 nV ($k = 1$) or a relative combined standard uncertainty of 6.7 parts in 10^{10} . Issues encountered during the PJVS comparison and potential challenges for 10 V applications are also discussed.

(Some figures may appear in colour only in the online journal)

1. Introduction

The initial metrological application of the Josephson voltage standard (JVS) was based on a single junction or multiple junctions that used current-biased voltage steps [1–3]. Although the early JVSs were more reproducible than typical standard cells, they were only able to generate voltages of a few millivolts. Levinson in 1977 proposed using

zero current-biased voltage steps, known as zero-crossing steps, to avoid using multiple bias sources for multiple junctions [4]. A breakthrough in array research and fabrication was accomplished in 1984 when researchers at the National Institute of Standards and Technology (NIST) and the Physikalisch Technische Bundesanstalt (PTB) jointly developed a Josephson array with 1474 superconductor–insulator–superconductor (SIS) junctions that used a single bias source for zero-crossing steps to generate a 1 V reference voltage [5]. After a few years, Josephson junction arrays that

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could generate 10 V were fabricated independently at NIST and PTB [6, 7]. There are now approximately 60 JVS systems around the world that use SIS arrays to maintain their national voltage standards and for voltage dissemination. The zero-crossing voltage steps generated by SIS arrays, however, are susceptible to step transitions that are inherent to the junction behaviour or are triggered by electromagnetic interference (EMI). It is very difficult to set the step number of the array to a desired value as required by some applications such as a direct JVS comparison. The development of a programmable Josephson voltage standard (PJVS) based on current-biased voltage steps was proposed as a solution for this problem [8]. Various array fabrication technologies were developed, mainly using the superconductor–normal metal–superconductor (SNS) junction developed at NIST [9] and the superconductor–insulator–normal metal–insulator–superconductor (SINIS) junction developed at PTB [10]. The superior noise immunity and rapid settling time of the PJVS voltage steps led to the PJVS being quickly implemented in applications such as direct JVS comparisons [11, 12], synthesis of low-frequency voltage waveforms for electrical power standards [13–15], and as stable and reproducible references for the electronic kilogram experiment [16].

A number of national metrology institutes (NMIs) have made significant contributions to the research and development of the 10 V PJVS. In 2006, the National Institute of Advanced Industrial Science and Technology (AIST) of Japan and NIST jointly reported the success of a 10 V SNS array that operated at 16 GHz [17]. In 2007, PTB reported the fabrication of a 10 V SINIS junction array that operated at the same nominal frequency used by the SIS array, around 75 GHz [18]. In 2009, NIST made a significant improvement in the optimization of the PJVS array design, especially in the uniformity of the microwave transmission to approximately 250 000 junctions [19]. NIST researchers also recently developed bias electronics and software to operate the 10 V array. This paper describes the implementation of the NIST 10 V PJVS in some metrological applications. For the first time, a comparison between a conventional JVS (known as NIST10) and the NIST 10 V PJVS was performed to verify the performance of the latter. The results have shown the consistency of two JVS systems based on the same operating principle as a frequency to voltage converter, but using different hardware and software. The previous comparison between two 2.5 V PJVS systems was carried out using manual operation which did not enable evaluation of the long-term voltage stability of the PJVS or the long-term agreement between the two PJVS systems. An automatic PJVS direct comparison protocol was developed to automatically control the comparison between the 10 V PJVS and the battery-operated 2.5 V PJVS that supports the NIST electronic kilogram experiment. The comparison between the 10 V PJVS and the 2.5 V PJVS at several different voltages has provided information about long-term accuracy and stability of the 2.5 V PJVS. By matching the voltages of the two PJVS systems during a comparison, the type B uncertainty can be minimized to a negligible level. We will also discuss the experimental challenges encountered during the experiment.

2. Direct comparison between a conventional JVS and a PJVS

Several 10 V PJVS systems developed at NIST have been deployed in NMIs around the world for voltage metrology research and development, including low-frequency waveform synthesis. A 10 V PJVS using the NIST-fabricated programmable array and recently developed electronics and software was compared with a conventional JVS for the first time in February and March 2012. The primary purpose of the comparison was to examine the equivalency of the two JVS systems that utilize different hardware, software and array technology.

2.1. Direct comparison setup

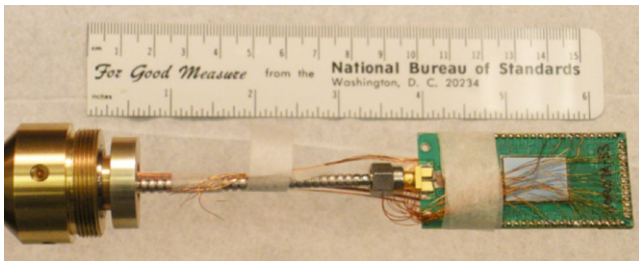
The detailed description of the conventional JVS system is described in a reference document [20]. A brief description of the main features of the systems will be presented here. The NIST 10 V conventional JVS uses an SIS array that was developed at NIST and fabricated by Hypres⁵. The array operates at frequencies near 76 GHz. A microwave assembly, including a Gunn oscillator with 18 dBm power output, an isolator, a splitter and a mixer deliver microwave power to the array. The waveguide is stainless steel with a 12.5 mm diameter and internal silver plating. The attenuation of the waveguide at 76 GHz is 1.5 dB. A 10 MHz reference frequency is provided by a high stability oven-controlled crystal oscillator (OCXO) disciplined with a Global Positioning System (GPS). A 16 bit digital-to-analogue converter (DAC) voltage-bias source enables the SIS array to generate a voltage up to 12 V for either polarity. NISTVolt, the 10 V conventional array software, controls the operation of the SIS conventional array, such as setting the voltage to within 1 mV from the target voltage, performing data acquisition, calculating the voltage of the device under test (DUT) and reporting the uncertainty of the measurement. The system uses an Agilent 34420A⁵ nanovoltmeter to measure the difference between the SIS array and DUT.

The 10 V PJVS was designed and developed at NIST, Boulder [21]. The 10 V PJVS array has a triple stacked structure whose Nb junctions use Nb–Si barriers to improve the junction uniformity. Several variations in the array design have been made. The array used in the NIST Gaithersburg system has the configuration listed in table 1, which includes 23 subarrays ranging from 6 junctions up to 16 800 junctions. The total number of junctions with all subarrays in series is 248 312, so that the circuit is capable of generating 10 V with a frequency of approximately 20 GHz. The advantage of this configuration is that it contains 8 least significant bit (LSB) subarrays (subarray 1 to 8) in a ternary bit configuration that allows the voltage resolution generated by the chip to be 250 μ V at 20 GHz. By slightly adjusting the frequency, the array voltage can be adjusted with nanovolt resolution (for output

⁵ Certain commercial equipment, instruments or materials are identified in this report to facilitate understanding. Such identification does not imply recommendation or endorsement by the NIST, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

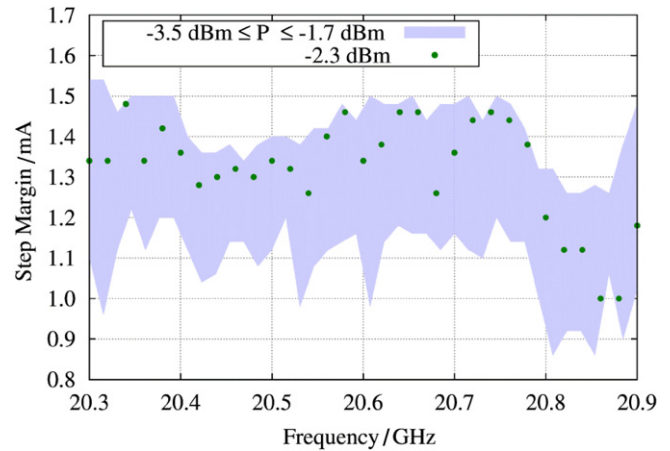
Table 1. 10 V PJVS array configuration.

Subarray	Number of junctions
1	4 374
2	1 458
3	486
4	162
5	54
6	18
7	6
8	8 400
9	16 800
10	16 800
11	16 800
12	8 400
13	8 400
14	16 800
15	16 800
16	16 800
17	16 800
18	16 800
19	16 800
20	16 800
21	14 954
22	16 800
23	16 800

**Figure 1.** The 10 V PJVS array's cryogenic package and bias leads.

voltages greater than 10 mV). The PJVS array bias electronics is a current source with 24 channels that supply bias currents to the 23 subarrays using 16 bit DACs which provide a set point accuracy of ± 0.02 mA. A microwave generator supplies frequencies for array operation at approximately 20 GHz. The source of the 10 MHz reference frequency is identical to that of the conventional JVS system. A microwave power amplifier with 28 dB gain is required to provide sufficient power to drive the array up to 10 V. The microwave transmission line in the cryoprobe is a semi-rigid coax with a corrugated outer conductor, as shown in figure 1, which minimizes the stress on the array assembly during the probe cool-down or warm-up process. The attenuation of the transmission line is 2.5 dB. The system operation is controlled by a LabVIEW program.

Figure 2 shows the positive step margin measurements of subarray 23 at a series of frequencies with different microwave power settings. When a fixed frequency is used, the step margin (positive and negative) decreases with decreasing microwave power. In order to optimize the performance of the array so that it has the largest current range ('flat spot' or 'operating step margin') at 10 V, the current range or 'step margin' of each subarray is determined as a function of frequency and power. The 10 V PJVS array used in these experiments can generate a

**Figure 2.** Subarray 23 positive step margin measurements with different frequencies and microwave power. A total of 700 margin measurements were made ranging in frequency from 20.3 GHz to 20.9 GHz and in power level from -3.5 dBm to -1.7 dBm. All measured points are within the blue shaded band. As an example, the measurements with a power level of -2.3 dBm are shown as points. The microwave power is referenced to the output from the signal generator.

step width (margin) that is larger than 1 mA over a very wide frequency range between 20.3 GHz and 20.8 GHz for power between -0.5 dBm and -2.0 dBm. The microwave design of the 10 V PJVS arrays allows the margin to be relatively constant over this range of microwave frequencies. Microwave power higher than 0 dBm does not produce a substantial increase in the step margin, but it can suppress the zero step and increase the liquid helium usage. In general, it is preferable to operate the system at a lower microwave power and within a frequency range that is not sensitive to the change of the step margins in order to achieve voltages with stable and frequency-tunable step margins and to minimize consumption of liquid helium. For a voltage required by a specific application, several satisfactory working frequency ranges and microwave power ranges can often be found and used.

Figure 3 shows a constant voltage flat spot over a range of dither current using selected subarrays that include most of the largest subarrays and are biased with the sequence 0000000n0np0npnpnp0np where '0' represents a zero step, 'n' is a negative step, and 'p' is a positive step. By definition, the dither current is the current applied across the entire array (all subarrays in series) when each subarray is biased at the centre of the current range that defines their voltage steps. The expected voltage output of the array in this configuration is 0 V, and it is chosen in order to measure the operating margin of the system with the highest voltage resolution and lowest noise on the lowest 1 mV voltage range of the nanovoltmeter. The measurement determines the flat spot or operating margin to be ± 0.35 mA. Satisfactory voltage steps can be generated at frequencies less than 20 GHz with appropriate microwave power, but the output will be less than 10 V. This smaller output voltage can still be useful for other applications such as for comparisons at voltages below 10 V and for measurements of DVM gain. Figure 4 is a block diagram of the 10 V PJVS.

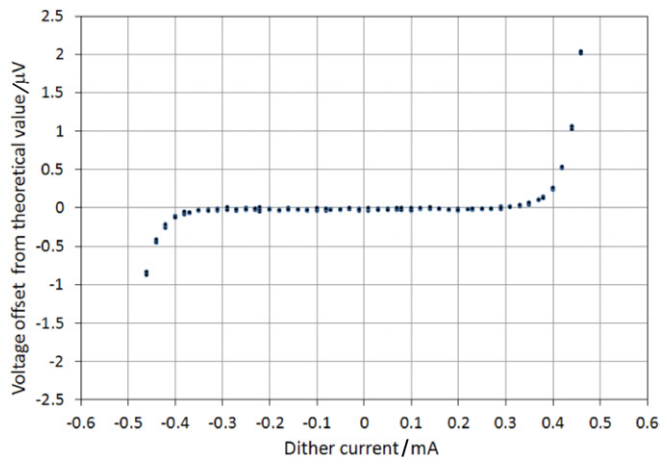


Figure 3. Step flatness test at 20.455 GHz and -1.9 dBm. The array configuration is 000000n0np0npnpnpnp0np starting from subarray 1 and ending at subarray 23 (subarray 12 was disabled). ‘0’ represents the zero step, ‘n’ the negative step and ‘p’ the positive step. The total array output is 0 V, measured by the system nanovoltmeter on the 1 mV range.

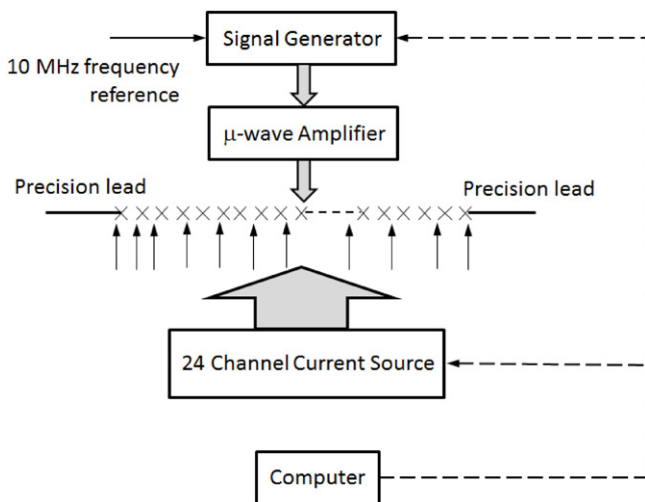


Figure 4. 10 V PJVS block diagram.

2.2. Measurement results

Direct JVS comparisons at 1.018 V and 10 V were performed in February and March 2012. Both arrays were floating from ground during the comparison. The 10 V PJVS acted as the DUT when measured by the conventional JVS. A fixed voltage of 9.999 999 999 V was generated by the PJVS using the frequency 20.309 852 589 GHz with 238 110 total junctions. The margins for all the PJVS subarrays and the flat spot at the target voltage were determined before starting the comparison to ensure the bias parameters were optimized. The conventional JVS was biased with a microwave frequency of approximately 76.435 GHz. The 10 V PJVS was measured with the same NISTVolt software that was used for the NIST-BIPM 10 V conventional JVS comparison [22]. The polarity change of the conventional JVS array during the comparison was made electronically via software control. The polarity change of the 10 V PJVS array was made electronically as

Table 2. Cryoprobe leakage resistance and correction.

Probe	Voltage/V	Leads' resistance/ Ω	Leakage resistance/ $10^{11} \Omega$	Correction Δ /nV
PJVS	10	3.7	10.0	0.04
JVS	10	14.2	1.32	1.08
JVS	1.018	14.2	0.57	0.25

well, but by operator's manual control. An Agilent 34420A⁵ digital nanovoltmeter was used as a null detector on the 1 mV range to minimize the noise and to avoid a change in gain when different ranges are used. Four sets of 10 points in a sequence of polarity of $+ - + -$ were taken, with each point being the mean of 5 DVM readings for 10 powerline cycles. The NISTVolt software performed the data acquisition and analysis. A situation where the difference between the two arrays is larger than 1.2 mV will cause the conventional JVS bias electronics to automatically reset the array until it produces a step voltage that is within 1.2 mV of the 10 V produced by the PJVS system.

The leakage resistances between two 10 V PJVS precision leads, and the precision lead to the ground (probe body) were measured at 10 V without the array mounted using the same setup for the NIST-BIPM 10 V JVS comparison [22]. The leakage resistance of the conventional 10 V JVS cryoprobe was also measured at 10 V and 1.018 V to determine the corresponding corrections. Table 2 lists the results and corresponding corrections for the comparison. The PJVS cryoprobe has about 10 times higher leakage resistance than that of the conventional cryoprobe because no capacitive filter is installed in the PJVS probe. The leakage resistance of the PJVS bias electronics to ground was measured using a method described previously [23], and found to be $1.5 \times 10^{10} \Omega$. The leakage resistance to the ground at the various nodes of the voltage measurement loop (such as from the conventional JVS precision voltage leads and DVM to the ground) is five times this value (or more). When there is no direct connection from the measurement loop as in this comparison, the voltage error caused by the leakage current through the PJVS precision voltage leads to the ground is determined by the ratio of the leads' resistance and the leakage resistance from the leads to the ground. Therefore, for this measurement configuration the PJVS source leakage does not contribute significantly to the overall uncertainty analysis.

Table 3 is a summary of the comparisons at 10 V and 1.018 V. The difference between the two systems is calculated by

$$\delta = V_{\text{JVS}} - V_{\text{PJVS}} + \Delta_{\text{JVS}} - \Delta_{\text{PJVS}}, \quad (1)$$

where V_{JVS} is the reported voltage for the PJVS measured by the conventional JVS, V_{PJVS} is the theoretical value of the 10 V PJVS which can be calculated from the number of junctions, frequency and the Josephson constant $K_{\text{J-90}}$, Δ_{JVS} is the correction for the conventional JVS due to the leakage, and Δ_{PJVS} is the correction for the 10 V PJVS due to the leakage at the voltage listed in table 2. Figure 5 shows the comparison results at 1.018 V. The average time to perform

Table 3. Summary of a direct comparison between the conventional JVS and the 10 V PJVS at 10 V and 1.018 V. The difference between the conventional JVS and 10 V PJVS has been adjusted by application of the probe leakage corrections.

Date	PJVS /V	δ /nV	Points	STDEV /nV	SD of mean /nV	Student t	Type A 95% /nV
22 February	9.999 999 9999	−0.15	27	2.86	0.55	2.06	1.13
23 February	9.999 999 9999	−0.85	22	2.73	0.74	2.08	1.53
2 March	9.999 999 9999	−0.54	20	6.80	1.52	2.09	3.18
24 February	1.017 939 9042	−0.14	39	3.81	0.61	2.02	1.24

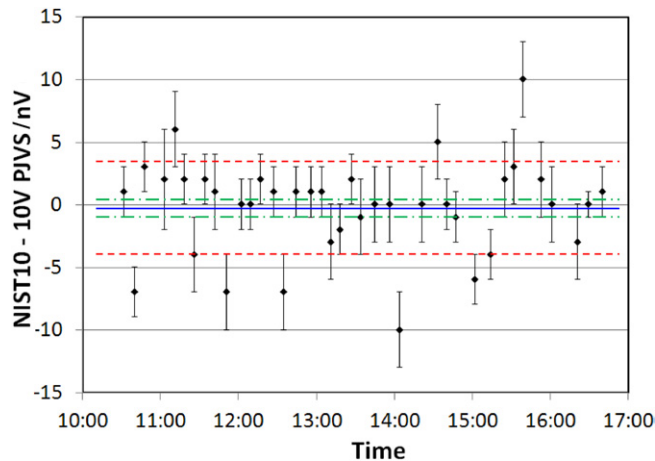


Figure 5. The results of a direct comparison between the NIST conventional JVS and 10 V PJVS at 1.018 V. The error bars represent the type A uncertainty based on 4 sets of data for each point. The solid line represents the mean difference of 39 points. The dotted–dashed line is the standard deviation of the mean, and the dashed line is the standard deviation.

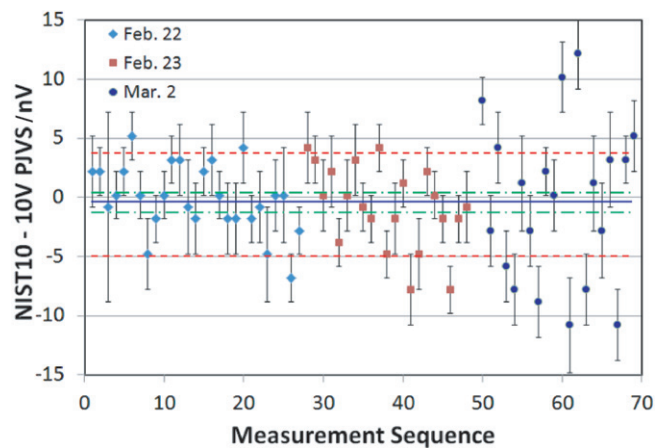


Figure 6. The results of a direct comparison between the NIST conventional JVS and 10 V PJVS at 10 V on three days. The error bar represents the type A uncertainty based on 4 sets of data for each point. The solid line represents the mean difference of 69 points. The dotted–dashed line is the standard deviation of the mean, and the dashed line is the standard deviation.

one measurement point was approximately 9 min. Figures 6 and 7 are the comparison results at 10 V and the histogram that includes all of the measurements performed on three days. The standard deviation of the measurements performed on 2 March was higher than those for the other days. The reason for this discrepancy was not determined.

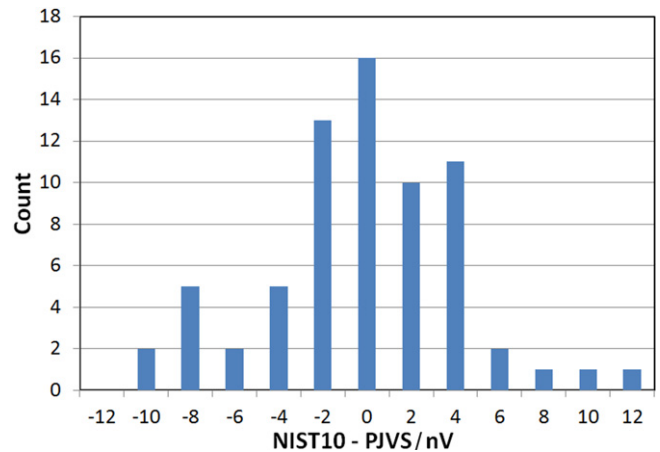


Figure 7. The histogram of the comparison between the conventional JVS and 10 V PJVS at 10 V. The data are from the measurements performed over three days.

Table 4. Type B uncertainty components of conventional JVS and 10 V PJVS for comparison at 10 V. The contribution from the frequency reference is counted only once because the two JVS systems share the same frequency reference.

Component	Conventional JVS /nV	10 V PJVS /nV
Frequency reference	0.01	0.01
Counter	1.08	
Leakage correction	0.22	0.01
Null detector	0.50	

2.3. Uncertainty analysis

The 10 V comparison measurements were performed on three days. The mean standard deviations were 0.55 nV, 0.74 nV and 1.52 nV. The 69 measurements were grouped together and the mean difference between the two systems was calculated to be -0.49 nV and the standard deviation of the mean to represent the type A uncertainty ($k = 1$) was 0.54 nV. (Note that the Allan deviation measurement of the DVM with serial number 578206 for this comparison has shown that the $1/f$ noise floor is below 0.5 nV. It is valid to use the standard deviation of the mean to express the type A uncertainty in this case.)

Table 4 lists the type B components of both systems. Both systems use the same 10 MHz frequency reference. The measured Allan deviation of the OCXO oscillator disciplined by GPS for an integration time up to 10 min was 1×10^{-12} , corresponding to the error of 0.01 nV at 10 V [24]. This is a very insignificant contribution to the total type B uncertainty. For the uncertainty in the frequency counter we use the manufacturer's specification of ± 15 Hz with an assumed rectangular distribution. For the comparison at

10 V the frequency uncertainty is dominated by the counter and its standard uncertainty contribution in the array voltage is 1.08 nV [25]. The final reported difference between the two systems includes the correction due to the leakage resistance of both cryoprobes. However, the uncertainty of the leakage resistance measurement also contributed to the type B uncertainty. We estimated the component was 20% of the leakage correction. The gain of the nanovoltmeter on the 1 mV range was measured using the 10 V PJVS as 3.0 parts in 10^6 . We did not adjust the raw data in the comparison measurements. Instead, a type B component for the DVM gain and linearity was estimated based on the mean polarized null voltage (MPNV) measurements [22]. The average of the 69 MPNV measurements was 167 μ V, with the type B uncertainty component due to the DVM gain and linearity error determined to be 0.50 nV. The combined type B uncertainty of 1.21 nV was calculated from the root mean square of all the components (the frequency reference component was used once, because the same reference is used for both systems). The combined standard uncertainty was then calculated to be 1.32 nV or the relative standard uncertainty of 1.32 parts in 10^{10} .

Similarly, for the 1.018 V comparison the difference between the two systems was found to be -0.14 nV with a combined standard uncertainty of 1.35 nV or a relative standard uncertainty of 1.33 parts in 10^9 .

3. Direct comparison between two PJVSs

A 2.5 V PJVS is used to measure voltages in the electronic kilogram experiment at NIST. The PJVS directly measures the voltage generated from a coil in spite of the coils' noisy signal [16]. The data acquisition in the electronic kilogram experiment is often continuous, lasting hours or days. We have developed an automatic protocol for the PJVS comparison between the 2.5 V PJVS and the 10 V PJVS to monitor the long-term voltage stability and accuracy for the PJVS system used for the electronic kilogram experiment.

3.1. The experimental setup

The 2.5 V PJVS was developed in 2005 at NIST [26]. The Josephson junctions used in this particular array were fabricated in double stacks and with MoSi_2 barriers. The circuit consists of 13 subarrays with total of 67 410 junctions. The bias electronics is powered by two sets of lead–acid batteries for isolation from ground, which is critical for the electronic kilogram experiment. The computer and software for the 2.5 V PJVS system were recently updated so that it is controlled by the same LabVIEW program as the one used for the 10 V PJVS system. The setup for the automatic comparison between the 10 V PJVS and 2.5 V PJVS is shown in figure 8. A third computer (the controller) was implemented to communicate with the two computers that controlled the two PJVS systems via a local area network (LAN). The controller program transmits the commands to set the voltages and polarities to the two PJVS control computers. The difference between the two array voltages is measured by a nanovoltmeter.

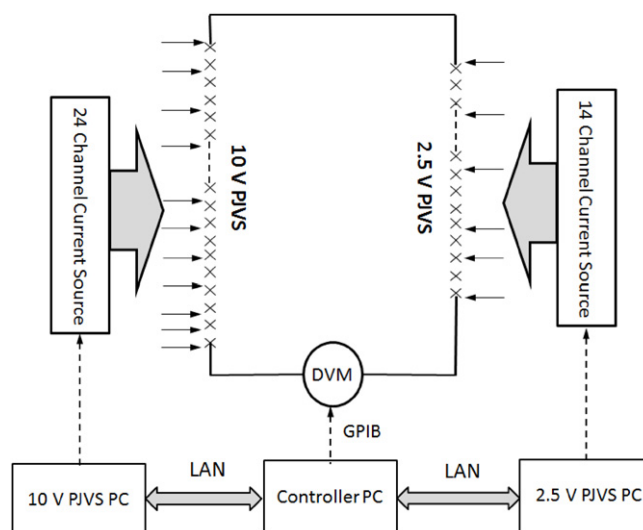


Figure 8. Two PJVS automatic comparison setup (microwave parts are not shown).

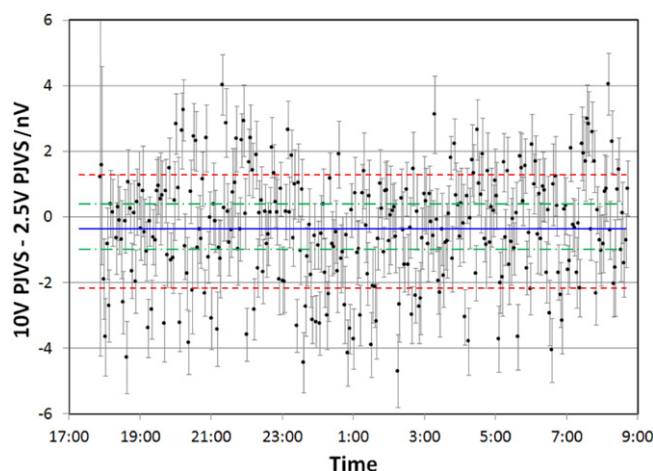


Figure 9. Automatic comparison between two PJVS at 1.018 V. The error bar represents the pooled standard deviation based on 4 data sets of each point. The solid line represents the mean difference of 299 points. The dashed line is the standard deviation. The dotted–dashed line is the type A uncertainty based on the DVM $1/f$ noise floor measurement.

In order to minimize the impact of the DVM's gain error and non-linearity, both PJVS systems use the same operating frequency of 18.014 588 GHz and 27 330 junctions. The target voltage of the comparison was chosen to be 1.018 074 499 6 V for both PJVS systems, which is comparable to the voltages that are measured during the electronic kilogram experiment.

3.2. Results and uncertainty

Figure 9 shows a typical overnight automatic comparison between the two PJVS systems at 1.018 V from 17:30 on 14 February to 9:00 on 15 February. This time period is comparable to an overnight electronic kilogram measurement. Two hundred and ninety-nine measurements were collected in approximately 15 h. The error bar of each point shown in figure 9 is the pooled standard deviation of 4 data sets of each measurement point. The solid line is the mean difference, the

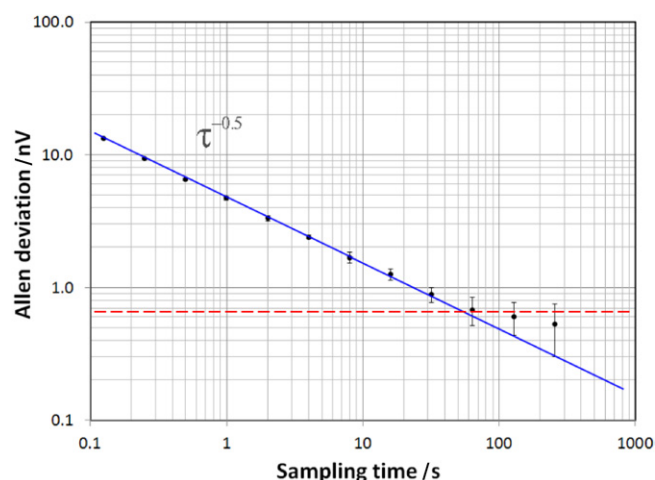


Figure 10. $1/f$ noise measurement of DVM with a shorted input. The error bar is the standard deviation of 12 repetitive measurements. For the sampling time up to 30 s, the Allan deviation varies as $\tau^{-0.5}$ where τ is the sampling time. This is the white noise regime.

dashed line is the standard deviation of all the measurements and the dotted–dashed line is the type A uncertainty using the DVM $1/f$ noise floor of 0.67 nV. The difference between the 10 V PJVS and 2.5 V PJVS was found to be -0.38 nV.

When analysing nanovoltmeter measurements, stochastic serial correlations are sometimes ignored and the type A uncertainty is assumed to be the experimental standard deviation of the mean. For the large number of measurements acquired from the two PJVS systems during the automatic comparison at 1.018 V, the standard deviation of the mean was found to be 0.10 nV, which was much smaller than the $1/f$ noise floor of the DVM. We have measured the Allan deviation of the DVM (serial number 611366) using the method described in [27] with a shorted input and a total sampling period from 0.12 s to 255 s, as shown in figure 10. For sampling periods up to 30 s, the Allan deviation varies nearly as $\tau^{-0.5}$, where τ is the sampling period. The Allan deviation in this white noise regime is equivalent to the standard deviation of the mean. A single measurement consists of 4 data sections $+ - - +$ with 2 polarity reversals. For each data section, 10 voltage measurements were taken; each measurement was the average of 5 readings with an integration period of 10 power line cycles. The average time for a single point was approximately 180 s taken in the following sequence: 22.5 s of data acquisition for each section, and 22.5 s of delay period between the sections. This delay was chosen to stabilize the transient voltage between the polarity changes. It was also applied between the sections having no polarity changes. The standard deviation of each section was about 2 nV. The Allan deviation for the sampling period of 22.5 s was about 1 nV as shown in figure 10.

The measured standard deviation for the comparison was higher than the Allan deviation because the Allan deviation measurement for the DVM was made with a shorted input, while the standard deviation of each section data during the comparison was also affected by the noise in the measurement circuit, such as thermal voltage fluctuations from the leads. For the comparison data, the sampling period at each polarity

Table 5. Type B uncertainty components of two PJVS systems for comparison at 1.018 V.

Component	10 V PJVS/nV	2.5 V PJVS /nV	DVM/nV
Frequency reference	0.001	0.001	
Leakage correction	0.01	0.01	
Null detector			Negligible

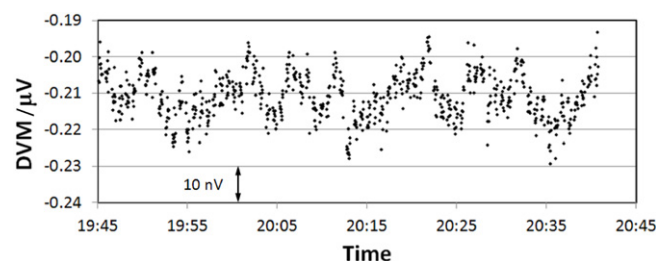


Figure 11. A snapshot of the DVM cyclic drifting during the automatic PJVS comparison between 19:45 and 20:45 on 14 February 2012.

including two data sections was 45 s, which falls into the $1/f$ regime, as shown in figure 10. The standard deviation of two sections together with the same polarity (about 2 nV) was higher than the Allan deviation for the same reason mentioned above. Nevertheless, the $1/f$ noise floor represents the best uncertainty achievable with the settings used in this comparison. The $1/f$ noise floor is calculated as the mean Allan deviation for the sampling time of 30 s and above. The 0.67 nV noise floor represents the lower limit of the type A uncertainty obtained with the DVM for this comparison.

All of the type B components are listed in table 5. The advantage of using two PJVS systems for the comparison is that we were able to match the theoretical voltages for both PJVS. The DVM reading range during the data acquisition was approximately $0.2 \mu\text{V}$, mainly due to the thermal voltages in the leads of both cryoprobes. The DVM gain was measured to be 1.000 016, or -16 parts in 10^6 for the correction, before the PJVS comparison using the 10 V PJVS. The error caused by the DVM in this setup was determined to be negligible. The type B uncertainty components corresponding to the frequency reference and leakage correction were also insignificant. The total type B uncertainty in this comparison was about 0.02 nV and the combined standard uncertainty for the automatic PJVS comparison at 1.018 V was found to be 0.68 nV or a relative uncertainty of 6.7 parts in 10^{10} , dominated by the DVM $1/f$ noise floor.

Figure 11 shows a noticeable cyclic drift in the DVM voltage that was observed during the automatic PJVS comparison. The peak-to-peak variation was around 20 nV with a 5 min cycle period. The data acquisition time for each polarity was 45 s, the delay time between each data section was also 22.5 s as described above. We concluded that the slower DVM cyclic voltage drift did not significantly impact the comparison. We have investigated a number of possible causes for the DVM cyclic voltage drift, such as environmental conditions, and liquid helium Dewar pressure. A definitive explanation for this effect was not determined. Further investigation will need to be conducted.

Automatic comparisons between the two PJVS were also carried out at 0 V and 2.511 V. The differences were found to be 0.04 nV and -0.23 nV, respectively. The uncertainty of the comparisons at these voltages was also dominated by the DVM $1/f$ noise floor. A similar DVM cyclic voltage drift was also observed at these voltages.

4. Discussion

A majority of the JVS systems are operated by NMIs and industry for maintaining a voltage reference that is based on the SIS array and a voltage-bias source. The main application of these systems is to disseminate the voltage reference by calibrating secondary voltage standards such as a solid state voltage standard (Zener). To ensure the consistency of these JVS systems, vital JVS comparisons have been carried out within the framework of the BIPM Key Comparison and a regional supplemental comparison. Some comparisons failed to obtain optimum results due to array instability caused by EMI. The 10 V PJVS provides an alternative system for performing JVS comparisons using a current-bias source. When compared with the SIS arrays that have a typical step margin of $20\text{ }\mu\text{A}$ without a bias current, the 10 V PJVS can generate a step margin of at least 0.6 mA with a bias current that provides superior noise immunity to EMI during a JVS comparison. The PJVS is an alternative that can endure EMI signals that make conventional JVS measurements difficult and sometimes impossible to perform, such as the large amounts of EMI typically present in the electronic kilogram experiment. PJVS systems may significantly improve the uncertainty of JVS comparisons.

For critical and sometimes sensitive applications such as voltage measurement for the electronic kilogram experiment, long-term monitoring of the PJVS performance can be verified with a second PJVS. By exactly matching the voltages of the two PJVS systems, the type B uncertainty can be minimized to a negligible level and the total uncertainty of the comparison can be improved.

5. Conclusion

The 10 V PJVS developed at NIST that uses an array with triple stacked SNS junctions and a frequency near 20 GHz has been compared at 10 V with a conventional JVS whose array uses SIS junctions. The difference between the two JVS systems at 10 V was found to be -0.49 nV with a combined standard uncertainty of 1.32 nV or a relative standard uncertainty of 1.32 parts in 10^{10} . The 10 V PJVS provides superior noise immunity to electromagnetic interference because of its huge (approximately 30 times larger) step current margin when compared with that of the conventional SIS array. PJVS systems may perform better in JVS comparisons that occur in an environment with substantial EMI where the conventional JVS may experience difficulty.

An automatic comparison protocol was developed to perform PJVS to PJVS comparisons for monitoring long-term voltage accuracy and stability. The 10 V PJVS was compared with the 2.5 V PJVS that is used for the electronic kilogram

experiment. The difference between the two PJVS systems at 1.018 V was found to be -0.38 nV with a combined standard uncertainty of 0.68 nV or a relative standard uncertainty of 6.7 parts in 10^{10} . The 10 V SNS array contains 8 least significant bit subarrays which enable it to generate almost any voltage up to 10 V with a resolution of 1 nV (above 1 mV) by tuning the frequency. This feature may be used to minimize the type B uncertainty to a negligible level for a PJVS comparison by matching the PJVS voltages.

Similar comparisons between the 10 V PJVS and the conventional JVS or the 2.5 V PJVS were also performed at different voltages. All results were consistent within the measurement uncertainty among the various systems using different electronics, software and three different types of Josephson array circuits, each having Josephson junctions with different barrier materials and microwave frequencies.

A cyclic drift was observed in the DVM during the comparison. The cause of the cyclic drifting is still under investigation.

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