A 10 Volt "Turnkey" Programmable Josephson Voltage Standard for DC and Stepwise-Approximated Waveforms

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Abstract: The output voltage of Programmable Josephson Voltage Standard (PJVS) circuits has reached the 10 V benchmark, which was set over twenty years ago by conventional dc Josephson Voltage Standard (JVS) systems. The nonhysteretic Josephson junctions in these next-generation 10 V PJVS systems provide a number of advantages and additional features as compared to conventional JVS systems. Most importantly, the new PJVS system will have comprehensive "turnkey" automation and be able to fully characterize all operating margins of the device without operator participation. Inherent voltage-step stability and large current margins (1 mA), which eliminate the need for output filters, will enable new applications not previously possible with conventional JVS. Rapid settling time (200 ns) will enable the generation of both dc and stepwise-approximated ac voltages that will be metrologically useful up to a few hundred hertz. The lower microwave drive frequency (20 GHz instead of 75 GHz) will reduce cost and improve reliability of the system.

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1. Introduction

Since the development of uniform series arrays of intrinsically shunted Josephson junctions in 1995 [1-3], there has been considerable research demonstrating their use as Programmable Josephson Voltage Standards (PJVS) [4-7]. In addition to applications requiring accurate and stable dc voltages, PJVS systems have also been applied to ac metrology by exploiting their ability to generate waveforms approximated by a staircase series of quantized voltages (usually of equal duration). PJVS systems have been used to produce a variety of arbitrary waveforms. Initially, they were used for fast-reversed dc comparisons between Josephson sources and thermal voltage converters [8, 9], and later as sinewaves for highly accurate ac-dc difference measurements at frequencies up to 1 kHz [10, 11]. In recent years, considerable attention has been given to applying PJVS stepwise-synthesis techniques to the development of quantum-based power standards [12-15]. The goal of these efforts was to improve a significant source of uncertainty in 50 Hz and 60 Hz power calibration, namely the accuracy of the voltage and current sources. PJVS circuits were chosen for this application because they generate stable rms voltages of at least 1.2 V. Development of PJVS circuits and junction technology has been an important component of NIST's efforts to apply quantum-based precision measurement techniques to electrical metrology and fundamental measurements.

PJVS systems are quite different from the ac Josephson Voltage Standard (ACJVS), which is based on high-speed pulse-driven arrays that are useful for synthesizing precision waveforms at much higher frequencies, typically above 1 kHz [16, 17]. The waveform purity and voltage accuracy of the pulse-driven ACJVS are beyond compare, and have been implemented in ac-dc and analog-to-digital converter measurements. The ACJVS can presently synthesize rms voltages up to 0.275 V, and research and development efforts to achieve higher output voltages continue. Although the PJVS systems achieve much higher voltages, their stepwise-approximated waveforms do not produce intrinsically accurate rms voltages. Therefore, sampling measurement techniques (which are described below) have been implemented to achieve the best measurements for ac applications with the PJVS system.

All types of JVS systems require series arrays of Josephson junctions in order to achieve useful output voltages, because individual junctions produce small voltages, which typically range from 30 µV to 150 µV depending on the applied microwave frequency. NIST has focused on developing junctions with superconducting niobium electrodes and various barrier materials such as PdAu, which is purely metallic, and Nb_xSi_{1-x}, which can be tuned from metallic to insulating, depending on the niobium content. When a microwave signal is applied to a single Josephson junction, it will produce perfectly quantized constant voltages $V_n = n\ f\ /\ K_{J\text{-}90}$, where n is an integer, f is the applied microwave frequency, and $K_{J\text{-}90}$ is the Josephson constant (483 597.9 GHz/V). For PJVS circuits, the barriers are chosen so that the junctions have single-valued current-voltage characteristics, and the voltage steps do not share any common current bias range. When a PJVS circuit is operated, the arrays of junctions are biased at a fixed microwave frequency, and the microwave power is chosen to simultaneously produce three constant voltage steps ($n = -1$, 0, and +1), each of which has a current range of at least 1 mA. The voltages of various "sub-arrays", which contain different predetermined numbers of series-connected junctions, are set (or "programmed") to one of the three quantized steps by choice of the appropriate bias current for each sub-array.

At any given time, the output voltage of the entire PJVS circuit is digitally programmed by selecting different current biases to the series-connected sub-arrays. The PJVS output voltage is precisely $V = M f / K_{J\text{-}90}$. The digitally programmed step number, M, is the summation of the step numbers (n) for all the junctions in the device. As an intrinsic quantum standard, the accurate PJVS output voltage is determined by choosing M and f. Complete details of PJVS circuits, systems, and bias methods have been described elsewhere [18-20]. The programmable nature of PJVS devices enables them to support a wider range of applications than conventional JVS systems. In the remainder of this paper, a number of important aspects of the "turnkey" PJVS design are described, beginning with the advantages (and limitations) pertaining to automation.

2. Pursuit of a "Turnkey" Josephson Voltage Standard

The amount of automation in present JVS systems is limited by a number of factors, including device technology, circuit performance, and electronics capabilities. Our goal for future systems is that they be completely automated. Next-generation JVS systems, including both ACJVS and PJVS, should be able to automatically perform self-diagnostic tests to verify functionality of all system components, characterize system performance, select and optimize bias parameters, and instruct users on how and when to change electrical connections. An ideal "turnkey" JVS would be one for which a user would require no knowledge of the internal workings of the Josephson system, just like other voltage metrology instruments such as digital voltmeters (DVM) and Zener reference standards. In order to fully achieve this objective, the entire system must be extremely well engineered, and the 4 K operating environment of the superconducting circuit must become transparent to the user by use of cryocoolers.

Over the past twenty years, various JVS systems have been produced at National Metrology Institutes (NMIs) around the world, and they are all significantly automated. However, none have achieved the turnkey status that would make them more prevalent. The majority of JVS systems in the world are "conventional" systems, mostly 10 V devices that are used primarily for dc applications. Although these systems have proven indispensable because of their intrinsic accuracy, their successful implementation in precision measurements requires a highly trained operator to maintain the system and periodically troubleshoot problems that arise with the complex instrumentation. When everything (superconducting circuit, microwave components, etc.) is working properly, a conventional JVS can automatically make round-the-clock calibration measurements, perform some basic diagnostic tests, and perform numerous data recording and analysis functions. However, in order to achieve the necessary step stability, conventional JVS chips require periodic manual adjustment of bias parameters, which can sometimes require significant effort and expertise.

In contrast, the inherent stability of the voltage steps produced by PJVS circuits allows the possibility of complete system automation, because the electrical response (including bias current range and output voltage) of all sub-arrays in the circuit

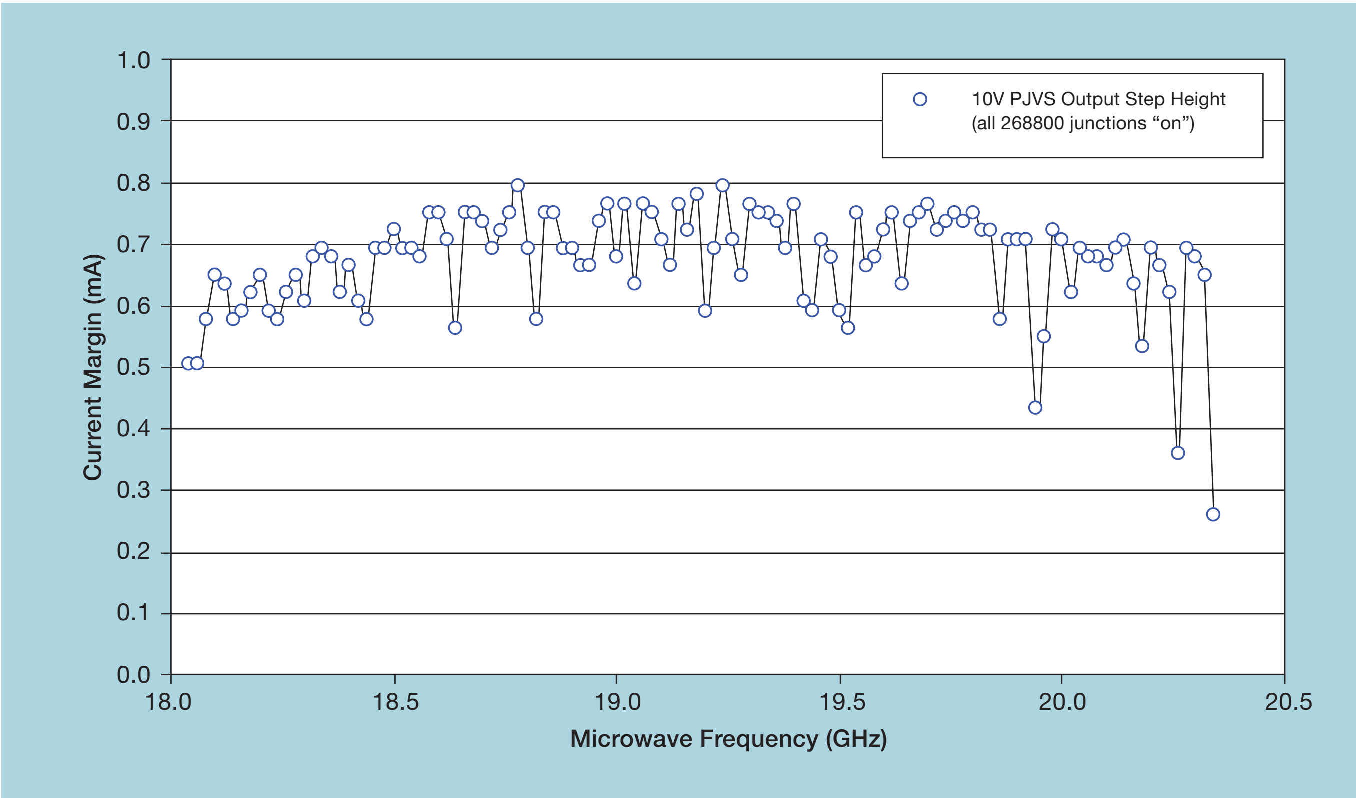

Figure 1. Measured operating current range for a 10V PJVS circuit (with all 32 sub-arrays at nonzero voltage steps) at numerous microwave frequencies over a 2.3 GHz range. This PJVS circuit operates with a current margin greater than 0.5 mA for all frequencies between 18 GHz and 19.8 GHz. At 19.8 GHz and above, the current margin could actually be made 20 % to 30 % larger if the microwave power had been increased. These current margins are smaller than those of our 2.5 V devices, which are typically 2 mA. The lower current range is due partially to the lower critical current of the 10V chip (roughly half that of the 2.5 V devices), which was intentionally chosen to reduce the circuit's total power so that its heat load would be more compatible with cryocooler operation.

can be precisely controlled. Because the current ranges of the quantized voltage steps produced by PJVS circuits are generally 20 to 30 times larger than those produced by conventional JVS circuits, the steps are significantly less sensitive to noise. The quantized steps of PJVS arrays can typically be produced over significantly larger ranges of microwave power and frequency. Recent microwave design improvements [21, 22], which have been implemented in new 10 V PJVS circuit designs, use on-chip splitters that enable operation at arbitrary microwave frequencies within a wide (multi-gigahertz) range, as illustrated in Fig. 1.

All of the above features have made fully automated chip characterization of PJVS circuits significantly easier than for conventional JVS circuits. In fact, since the mid 1990's, fully automated evaluations of PJVS circuits have been routine. The automated evaluation includes nanovoltmeter measurements of the bias-current ranges of the Josephson steps for each sub-array at hundreds of different operating points (microwave power and frequency), and recording of all that information for later analysis. From these data, the computer can automatically determine the best operating parameters for each sub-array in the PJVS circuit. The results have also proven to be useful for optimizing the circuit design and fabrication process to improve the device performance. Other capabilities that the stability of PJVS devices allows is precise verification of step flatness and detailed characterization of the shape of the current-voltage characteristics at the corners of the steps. Figure 2 shows a typical step-flatness measurement for a 10 V device with all cells activated, demonstrating a measured voltage that is flat over ±0.35 mA, with a ±41 nV uncertainty in the slope ($k = 2$). This step-flatness verification is difficult to directly measure for a conventional JVS, because the device is likely to switch steps when the bias current approaches the step edges.

The same characteristics that enable PJVS circuits to be completely automated also make the devices suitable for a number of applications that conventional voltage standards cannot perform. Their rapid settling time (typically 200 ns) enables PJVS systems to produce stepwise-approximated ac voltages (most often sinewaves) that can be useful for metrology at frequencies up to a few hundred hertz. Among the ac applications mentioned in the introduction, perhaps the most powerful and successful demonstrations to date have been the measurement techniques that utilize sampling methods to assign a precise value to a secondary reference waveform [23, 24]. In this approach, the sampling technique gives the necessary measurement accuracy by using only the samples on the quantum-accurate voltage steps of the PJVS waveform, and discarding the step-transition portions of the waveform. With regard to rms-based ac measurement techniques, PJVS systems appear to have limited usefulness because the rms voltage accuracy is limited by transients and by contributions from digitization harmonics [14, 25, 26, 27].

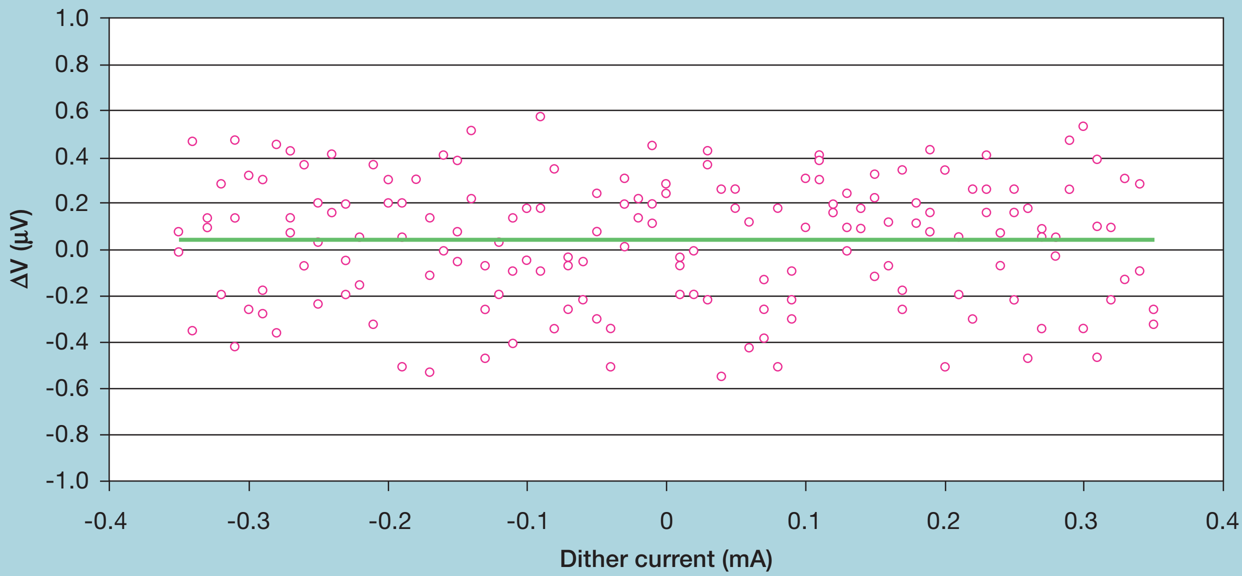

Figure 2. Measured output voltage deviation from the expected quantized dc voltage vs. dither current for a 10 V PJVS with all cells active (half the device positive and half the device negative, to yield a small net voltage that can be measured on a low voltage range, microwave frequency is 19.3 GHz in this plot). The total usable step height is 0.7 mA, and the dither current flows simultaneously through all cells. The calculated slope is –9 nV ± 41 nV ($k = 2$), which is an uncertainty of ±4 parts in 10^9 for 10 V. The measurement uncertainty could be reduced further by using a lower voltage range and averaging more data.

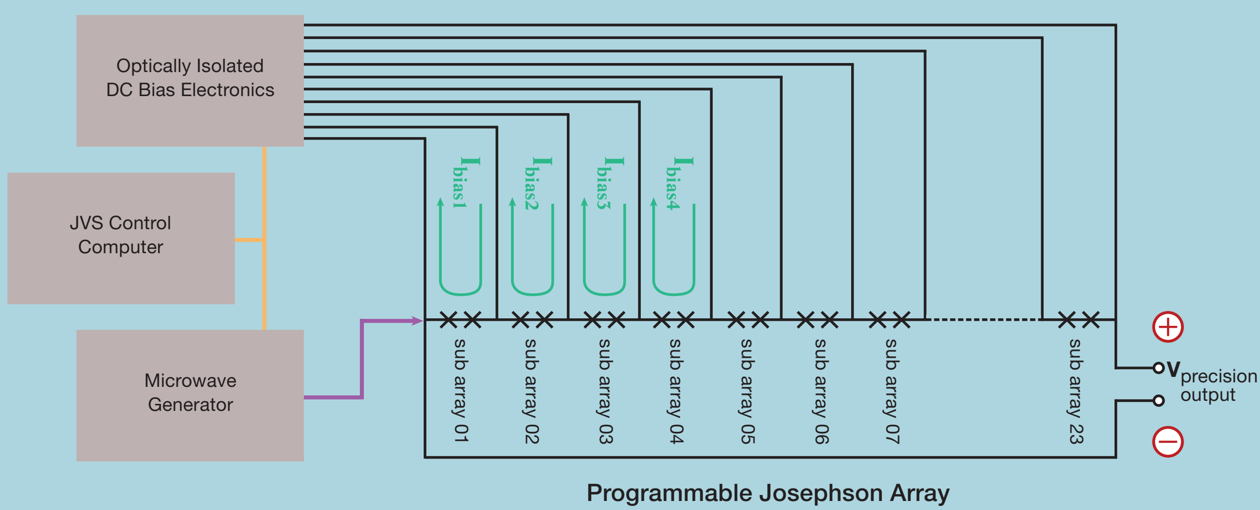

Figure 3. System block diagram for the new “turnkey” 10 V PJVS.

3. PJVS System Design Requirements

To realize the goal of an ideal “turnkey” PJVS, NIST is constructing a new system based upon our newly developed bias electronics module that is capable of operating 10 V PJVS chips. The system will be able to produce both dc and stepwise ac (up to a few hundred hertz) voltages. The electronics will consist largely of commercially available components, which permits the number of drive channels to be easily expanded to accommodate more sub-arrays for future higher-resolution circuits. The initial bias electronics configuration provides 24 channels (for 23 PJVS sub-arrays) whose outputs are amplified by a custom amplifier board that converts the DAC signals into the appropriate bias currents required by each sub-array. The principal components of the new turnkey system are illustrated in Fig. 3. Our PJVS devices were designed for operation at 18 GHz to 20 GHz, so that the microwave generator and amplifier are

Bias Electronics Design Specifications		
Design Parameter	**Requirement**	**Resulting Set-point Deviation (each individual channel)**
DAC resolution	16 bits	0.004 mA/LSB
Output Resistor Tolerance	±0.05 %	±0.01 mA
Cryoprobe Line Resistance	±0.05 Ω	±0.01 mA
Output Stage Gain Uniformity (channel to channel)	±0.02 %	±0.02 mA
Output Stage DC Offset Stability (channel to channel)	±0.05 mV (*max*)	±0.005 mA

Table 1. Required tolerances on each channel for the primary design parameters. When the performance of every channel falls within the "requirement" range in the second column, then the bias electronics will never need calibration to guarantee a set-point accuracy within ±0.05 mA (i.e., the sum of the entries in the third column, which is the absolute worst case). The bias electronics must meet these requirements at any operating temperature that it experiences.

significantly less expensive (and more reliable) than the higher frequency components, typically 70 GHz, presently used in conventional JVS systems.

PJVS chips are current-biased devices, and the calculations necessary to "program" the total output to different quantized voltages are relatively straightforward [18]. However, actually *delivering* the intended calculated bias current precisely to all PJVS sub-arrays simultaneously (in all potential measurement environments) requires some careful attention to the design of the bias electronics. Additionally, it is desirable to have bias electronics with sufficiently tight component tolerances that they never need to be calibrated, and those critical design considerations are shown in Table 1. A target for bias set-point accuracy of ±0.05 mA (absolute maximum) on each channel was chosen, so the sum of all five values in the rightmost column of Table 1 must not exceed this worst-case limit. This limit was chosen by assuming a 1 mA minimum step current range for every sub-array, and by our desire to have ten discrete points on each step. The resulting step increment of 0.1 mA allows a sufficient number of points on each step to ensure that the set-points are properly centered, and to carefully measure PJVS step flatness and step-corner behavior. Since the values in Table 1 are worst case, it is anticipated that the typical set-point deviations will generally be a little more favorable (possibly within ±0.03 mA to ±0.02 mA) which will be helpful when characterizing Josephson steps smaller than 1 mA.

4. Conclusions

Now that the first 10 V programmable Josephson voltage standard devices have been successfully demonstrated, NIST is developing a prototype 10 V PJVS system for use in dc and ac voltage metrology. The system is aimed at applications that require frequencies up to a few hundred hertz, and utilizes sampling comparison measurement techniques to discard transients in the stepwise-approximated waveforms. This next-generation Josephson voltage standard system will more closely resemble "turnkey" operation, because it will exploit the advantages of non-hysteretic junction technology and incorporate more system automation. Ultimately, NIST will strive to develop systems that do not require users to know any more about the internal workings of a PJVS than of other metrology instruments. Additionally, it is anticipated that the lower microwave frequency (20 GHz) will improve long-term reliability and reduce system cost. It is hoped that these developments will make PJVS systems more affordable to purchase and maintain, easier to deploy, and more widely used in the voltage metrology community.

5. References

[1] S. P. Benz, "Superconductor - normal metal - superconductor junctions for programmable voltage standard," *Appl. Phys. Lett.,* vol. 67, pp. 2714–2716, 1995.

[2] H. Schulze, R. Behr, F. Müller, and J. Niemeyer, "Nb/Al/AlO/Al/AlO/Al/Nb Josephson junctions for programmable voltage standards," *Appl. Phys. Lett.,* vol. 73, pp. 996–998, 1998.

[3] H. Yamamori, M. Itoh, H. Sasaki, A. Shoji, S. P. Benz, and P. D. Dresselhaus, "All-NbN digital-to-analog converters for a programmable voltage standard," *Supercond. Sci. Technol.,* vol. 14, pp. 1048–1051, 2001.

[4] C. A. Hamilton, C. J. Burroughs, and R. L. Kautz, "Josephson D/A converter with fundamental accuracy," *IEEE Trans. Instrum. Meas.,* vol. 44, no. 2, pp. 223–225, April 1995.

[5] S. P. Benz, C. A. Hamilton, C. J. Burroughs, T. E. Harvey, and L.A. Christian "Stable 1-Volt programmable voltage standard," *Appl. Physics Lett.,* vol. 71, pp. 1866–1868, September 1997.

[6] H. Schulze, F. Müller, R. Behr, J. Kohlmann, J. Niemeyer, and D. Balashov, "SINIS Josephson junctions for programmable Josephson voltage standard circuits," *IEEE Trans. Appl. Supercond.,* vol. 9, pp. 4241–4244, 1999.

[7] M. Ishizaki, H. Yamamori, A. Shoji, P. D. Dresselhaus, and S. P. Benz, "Programmable Josephson voltage standard circuits using arrays of NbN/TiN/NbN/TiN/NbN double-junction stacks operated at 10 K," *IEEE Trans. Instrum. Meas.,* vol. 54, no. 2, pp. 620–623, 2005.

[8] C. J. Burroughs, S. P. Benz, C. A. Hamilton, T. E. Harvey, J. R. Kinard, T. E. Lipe, and H. Sasaki, "Thermoelectric transfer difference of thermal converters measured with a Josephson source," *IEEE Trans. Instrum. Meas.,* vol. 48, no. 2, pp. 282–284, April 1999.

[9] T. Funck, R. Behr, and M. Klonz, "Fast reversed dc measurements on thermal converters using a SINIS Josephson junction array," *IEEE Trans. Instrum. Meas.,* vol. 50, no. 2, pp. 322–325, April 2001.

[10] R. Behr, J. M. Williams, P. Patel, T. J. B. M. Janssen, T. Funck, and M. Klonz, "Synthesis of precision waveforms using a SINIS Josephson junction array," *IEEE Trans. Instrum. Meas.,* vol. 54, no. 2, pp. 612–615, April 2005.

[11] R. Behr, L. Palafox, J. Schurr, J. M. Williams, and J. Melcher, "Quantum effects as a basis for impedance and power metrology," in *Proc. of the 6th International Seminar in Electrical Metrology,* pp. 11–12, September 21-23, 2005, Rio de Janeiro, Brazil.

[12] L. Palafox, G. Ramm, R. Behr, W. G. K Ihlenfeld, and H. Moser, "Primary ac power standard based upon programmable Josephson junction arrays," *IEEE Trans. Instrum. Meas.,* vol. 56, no. 2, pp. 534–537, April 2007.

[13] J. Kohlmann, F. Muller, O. Kieler, R. Behr, L. Palafox, M. Kahmann, and Y. Niemeyer, "Josephson series arrays for programmable 10-V SINIS Josephson voltage standards and for Josephson arbitrary waveform synthesizers based on SNS junctions," *IEEE Trans. Instrum. Meas.,* vol. 56, no. 2, pp. 472–475, April 2007.

[14] C. J. Burroughs, S. P. Benz, P. D. Dresselhaus, B. C. Waltrip, T. L. Nelson, Y. Chong, J. M. Williams, D. Henderson, P. Patel, L. Palafox, and R. Behr, "Development of a 60 Hz power standard using SNS programmable Josephson voltage standards," *IEEE Trans. Instrum. Meas.,* vol. 56, no. 2, pp. 289–294, April 2007.

[15] R. Behr, L. Palafox, G. Ramm, H. Moser, and J. Melcher, "Direct comparison of Josephson waveforms using an ac quantum voltmeter," *IEEE Trans. Instrum. Meas.,* vol. 56, no. 2, pp. 235–238, April 2007.

[16] S. P. Benz and C. A Hamilton, "Application of the Josephson effect to voltage metrology," *Proc. of the IEEE,* vol. 92, pp. 1617–1629, October 2004.

[17] S. P. Benz, C. J. Burroughs, P. D. Dresselhaus, N. F. Bergren, T. E. Lipe, J. R. Kinard, and Y. H. Tang, "AC-DC transfer standard measurements with an ac Josephson voltage standard," *IEEE Trans. Instrum. Meas.,* vol. 56, no. 2, April 2007.

[18] C. J. Burroughs, S. P. Benz, T. E. Harvey, and C. A. Hamilton, "1 Volt dc programmable Josephson voltage standard," *IEEE Trans. Appl. Supercon.,* vol. 9, pp. 4145–4149, June 1999.

[19] Y. Chong, C. J. Burroughs, P. D. Dresselhaus, N. Hadacek, H. Yamamori, and S. P. Benz, "Practical high resolution programmable Josephson voltage standards using double- and triple-stacked $MoSi_2$ barrier junctions," *IEEE Trans. Appl. Supercon.,* vol. 15, no. 2, pp. 461–464, June 2005.

[20] C. J. Burroughs, P. D. Dresselhaus, Y. Chong, and H. Yamamori, "Flexible cryo-packages for Josephson devices," *IEEE Trans. Appl. Supercon.,* vol. 15, no. 2, pp. 465–468, June 2005.

[21] M. M. Elsbury, P. D. Dresselhaus, N. F. Bergren, C. J. Burroughs, S. P. Benz, and Z. B. Popović, "Broadband lumped-element integrated n-way power dividers for voltage standards," *IEEE Trans. Microwave Theory and Techniques,* vol. 57, no. 8, pp. 2055–2063, August 2009.

[22] P. D. Dresselhaus, M. M. Elsbury, and S. P. Benz, "Tapered transmission lines with dissipative junctions," *IEEE Trans. Appl. Supercon.,* vol. 19, no. 3, pp. 993–998, June 2009.

[23] A. Rüfenacht, C. J. Burroughs, and S. P. Benz, "Precision sampling measurements using ac programmable Josephson voltage standards," *Review of Scientific Instruments,* vol. 79, pp. 044704-1 to 044704-9, April 2008.

[24] A. Rüfenacht, C. J. Burroughs, S. P. Benz, P. D. Dresselhaus, B. C. Waltrip, and T. L. Nelson, "Precision differential sampling measurements of low-frequency voltages synthesized with an ac programmable Josephson voltage standard," *IEEE Trans. Inst. Meas.,* vol. 58, no. 4, pp. 809–815, April 2009.

[25] C. J. Burroughs, A. Rüfenacht, S. P. Benz, and P. D. Dresselhaus, "Systematic error analysis of stepwise-approximated ac waveforms generated by a programmable Josephson voltage standard," *IEEE Trans. Inst. Meas.,* vol. 58, no. 4, pp. 761–767, April 2009.

[26] C. J. Burroughs, A. Rüfenacht, S. P. Benz, P. D. Dresselhaus, B. C. Waltrip, and T. L. Nelson, "Error and transient analysis of stepwise-approximated sinewaves generated by programmable Josephson voltage standards," *IEEE Trans. Instrum. Meas.,* vol. 57, no. 7, pp. 1322–1329, July 2008.

[27] C. J. Burroughs, A. Rüfenacht, S. P. Benz, P. D. Dresselhaus, B. C. Waltrip, and T. L. Nelson, "Error and transient analysis of stepwise-approximated sinewaves generated by programmable Josephson voltage standards," paper 5F-2 in (CD) *Proceedings of the 2007 NCSLI Workshop and Symposium,* St. Paul, MN, July 29-August 2, 2007.