

## Quantum Metrology

**Editors: Richard E. Harris and Jürgen Niemeyer**

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### 9.1 Introduction

*Richard E. Harris and Jürgen Niemeyer*

As thorough readers of this book have begun to discover by this chapter on metrology, the most widely used applications of superconducting electronics involve measurements of electromagnetic phenomena. Unlike most other phenomena used for measurements, superconductivity is also essential for electrical *standards*. Because it is a quantum phenomenon, it can represent voltage in terms of fundamental constants with an amazing precision of a few parts in  $10^{19}$ . In some regards superconducting voltage standards based on arrays of Josephson junctions are the most successful application of superconductivity, considering the numbers of junctions and their worldwide use. While they are conceptually simple, it has taken almost 50 years for their underlying technology to progress from unreliable single junctions to robust, complex, three-dimensional integrated circuits having more than 300,000 junctions and producing precision ac voltages up to 10 V. Here is their story.

As described in other chapters of this book, centimeter-sized superconducting loops can carry a

## 9.8 Quantum-Based Voltage Waveform Synthesis

*Samuel P. Benz*

More than a decade of research and development was required to practically exploit the quantum behavior of superconducting Josephson junctions for ac applications. Sine waves and arbitrary waveforms had to be synthesized with sufficiently large voltage amplitudes; and measurement techniques with appropriate accuracy had to be developed. Two waveform synthesis methods, pulse-driven and stepwise-approximation, have now been implemented in a number of practical systems that are presently being used to calibrate audio-frequency ac voltages and power meters, characterize the stability and linearity of analog components, and as an arbitrary waveform source at the heart of an electronic primary thermometer. Some of the important milestones from these efforts, from my perspective, portray the importance of collaboration as well as the challenges that are typical of technology development. Most importantly, these events have shown how important it is to ensure the accuracy of electrical measurements, even when using quantum-based systems.

The first method that successfully synthesized quantum-based voltage waveforms was the programmable Josephson voltage standard (PJVS), which was conceived by Clark Hamilton in 1991. He proposed synthesizing step-wise approximated sine waves, similar to a multi-bit digital-to-analog converter (DAC), by independently current biasing series-connected arrays on different quantized voltage steps (Shapiro steps). During my postdoc at NIST in September of that year, Clark asked me to research prototype circuit designs. I based the circuit designs on aluminum-oxide-barrier tunnel junctions with external shunt resistors. At the time, many labs, including NIST, were using this junction technology for single-flux-quantum logic circuits, because the junctions were the most reproducible and they were non-hysteretic. PJVS operation required single-valued, stable, constant-voltage steps that were possible with such shunted junctions, which had electrical characteristics very different from those used in the conventional Josephson voltage standard (JVS). I simulated a number of prototype circuits for Clark's PJVS, including circuits in which the microwave bias was inductively coupled to series junctions or series SQUIDs. I chose not to fabricate series arrays with these inductively coupled circuits, since they would have required multilayered wiring, significant chip area per junction, and complicated microwave designs.

The first PJVS prototype circuit that I fabricated used direct-driven series arrays of junctions. In order to further simplify the layout, I chose to shunt each pair of junctions with a single shunt resistor. Although this circuit appeared to work correctly in simulation, the measured current-voltage characteristics (I-V curves) of the prototype circuit showed only half the expected voltage, indicating that only one junction in each shunted pair entered the voltage state. This result taught me the importance of including stability analysis in simulations and the importance of measuring real circuits! Three years later, and after much more research, Clark, Charlie Burroughs and Richard Kautz made and measured the first PJVS circuit with multiple arrays and with all (individually-shunted) junctions contributing to the output voltage. In research and development there usually are many false starts and lessons learned before the correct approach is apparent, as will be seen throughout this chapter.

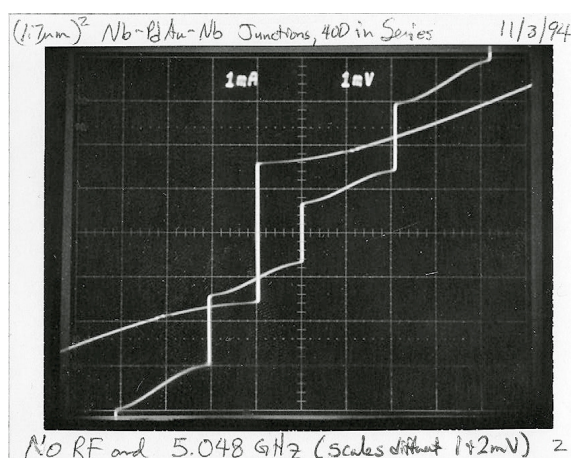
During the early 1990s, a number of laboratories around the world were working on intrinsically shunted junctions with high-temperature superconductors (HTS). It was clear that the PJVS circuit would be much simpler and have higher junction density if the junctions were intrinsically rather than externally shunted. At that time, and it remains so today, it was difficult in HTS technology to fabricate a large number of junctions with sufficient uniformity to produce practical voltages. During my graduate research with Chris Lobb and Mike Tinkham, I had gained experience

with superconductor-normal-superconductor (SNS) junctions. With the help of Martin Forrester and Horst Rogalla, I fabricated two-dimensional (2D) arrays of SNS in-line Josephson junctions with thin-film niobium islands patterned on top of a copper film. The Nb was deposited with a magnetron sputtering head that Horst built in Giessen. The Nb islands were patterned using a custom-made reactive-ion etching chamber. Having observed interesting quantum effects in these 2D circuits with planar SNS junctions, which were not particularly uniform, I was optimistic that planar trilayer SNS junctions might produce sufficiently uniform series arrays for the PJVS because the barrier would be defined by the normal-metal film thickness instead of a lithographically defined Nb gap having length of about  $1\text{ }\mu\text{m}$ . However, most of my more experienced colleagues, including Richard Harris, were much less optimistic, and one expert insisted that SNS junctions simply would not work. This pessimism was well founded because the current density of SNS junctions depends exponentially on the barrier thickness.

Richard Kautz calculated in April, 1994, that SNS junctions would be feasible with regard to appropriate electrical characteristics. He showed that high  $I_c R_n$  products would be difficult to achieve with AuPd and noted that higher resistivity materials would be needed for operation at frequencies of at least 70 GHz, the frequency typically used for the conventional JVS. I used AuPd as the barrier material in my first Nb-based SNS junctions, because I had recently implemented it as the resistor material for our single-flux-quantum (SFQ) digital circuits, because it had higher resistivity than that of InAu. Two challenges with producing these junctions were (a) modifying the wet aqua regia<sup>86</sup> gold etch to adequately remove the Pd, and (b) increasing the current density of the Nb wiring contacts to the junction's Nb counter electrode. By November, 1994, I successfully fabricated a wafer of test chips that had series arrays of junctions

with different areas and uniform electrical characteristics. Figure 9.24 shows I-V curves of the first uniform arrays that produced constant voltage steps with an applied microwave bias. The Shapiro steps are greater than 1 mA and are surprisingly flat<sup>87</sup>, even though the junctions were not embedded within a microwave circuit and the microwaves were radiatively coupled to the test circuit with a wire coil in close proximity. Sometimes research and development produces unexpectedly favorable results.

The first 1 V PJVS circuit based on SNS junctions was demonstrated in 1995. It contained 32,768 junctions and implemented coplanar waveguide microwave designs, including filters and impedance-matching elements, and custom DAC bias electronics. The intrinsically stable steps were a unique feature, which allowed us to conceive, for the first time, of a turn-key Josephson voltage standard that could be fully automated to produce arbitrary voltages. For the next ten years at NIST,



**FIGURE 9.24:** 1994 photo of the oscilloscope I-V curves of the first “uniform” 400-junction SNS array of Nb-AuPd-Nb trilayer junctions with (2 mV/div) and without (1 mV/div) microwave bias. The I-V curve without microwaves was exposed after moving the origin and changing voltage scale (1 mV/div).  $I_c = 1.5\text{ mA}$ ,  $R = 5.5\text{ m}\Omega/\text{JJ}$ ,  $(1.7\text{ }\mu\text{m})^2$ , and 43 nm thick AuPd.

<sup>86</sup> Aqua regia is a highly corrosive mixture of nitric and hydrochloric acids.

<sup>87</sup> Flat means constant in voltage over a large current range, which is called the “operating margin”.

we applied the PJVS primarily to applications requiring stable and accurate dc voltages, such as supporting the watt balance experiment for measuring Planck's constant (see the next section) and helping Yi-Hua Tang build a new dc voltage dissemination chain, which allowed NIST to retire its traditional electrochemical standard cells.

With regard to ac synthesis with the PJVS, continued research on the SNS and the resistively shunted junction circuits showed that the slow  $\sim 300$  ns rise times of the transitions between the quantized voltage steps limited the uncertainty of root-mean-square (rms) voltage measurements with the PJVS multi-bit stepwise-approximated waveforms, especially for the target frequencies above 1 kHz that were of primary interest for ac-metrology. However, interesting and useful rms measurements were performed at lower frequencies by Hitoshi Sasaki and Burroughs and separately by PTB researchers, who used SINIS-junction PJVS circuits<sup>88</sup> (see the preceeding section by Kohlmann). Both experiments characterized the frequency response of a thermal converter<sup>89</sup> with the fast-reversed dc method that used simple waveforms with only three voltages, which minimized the transient effects.

On the morning of July 26, 1995, John Przybysz and Hodge Worsham, superconducting electronics colleagues from Westinghouse Research and Development Center in Pittsburgh, visited NIST, Boulder. They presented to Clark and me their interests in developing DACs and analog-to-digital converters (ADCs) for U.S. Navy applications. I remember that the discussion began with the concept of waveform synthesis by switching between two Josephson voltage levels, similar to what we had demonstrated with the PJVS system, but with much faster sampling rates. We already knew that perfect quantization was compromised in stepwise waveforms, due to transients. However, we were all involved in research on SFQ digital circuits, which controlled the movement of SFQ through superconducting integrated circuits and changed their quantum states with properly timed junction pulses. Clark pointed out that waveform synthesis would be intrinsically accurate if the quantized voltage pulses of the junctions were exactly controlled and the resulting voltage would be proportional to the pulse spacing. It was typical to use "average voltage" measurements to characterize the time-dependent pulsed-voltage outputs of SFQ circuits. Semiconductor pattern generators were suggested as a possible bias signal because they could produce pulse waveforms by programming either of two voltages, depending on a digital pattern stored in memory. We realized that Josephson arrays could produce quantum-accurate waveforms by biasing them with a digitally controlled pulse waveform.

I was thrilled to have participated in this creative process, which required complementary expertise from all parties, and generated a potentially useful and important new idea. That afternoon I hunted for and found an HP8082A pulse generator<sup>90</sup> with an appropriately short, 2 to 10 ns pulse width that was capable of 10 to 250 MHz pulse repetition rates. The next morning I successfully produced quantum-accurate dc voltages with 100  $\mu$ A margins by pulse biasing an SNS array circuit from a prototype PJVS design. It was very exciting to have experimentally realized the pulse-driven bias technique within 24 hours of conception. This was a critical first step toward demonstrating accurate ac waveform synthesis. I was also able to show that the step voltage changed with pulse period and that the current range of the step decreased with wider pulses, due to the frequency response of the junctions. Only the smallest array (the PJVS least significant bit) with 512 junctions (each having  $I_c = 1.9$  mA,  $R = 4.4$  m $\Omega$ , and  $(2 \mu\text{m})^2$  area) showed steps because of insufficient uniformity of the pulse signal in the longer arrays.

<sup>88</sup> A SINIS junction is formed with layers of superconductor-insulator-normal metal-insulator-superconductor.

<sup>89</sup> Thermal converters are rms detectors that determine the equivalence between alternating current (ac) signals and direct current (dc) signals by measuring the difference in their heating values.

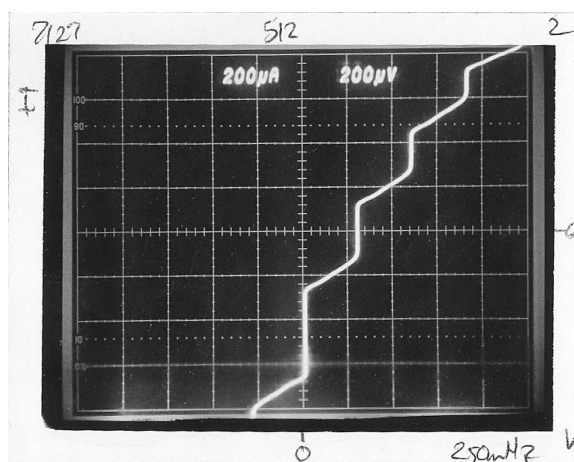
<sup>90</sup> Commercial instruments are identified in this paper only to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the NIST, nor does it imply that the equipment identified is necessarily the best available for the purpose.

Figure 9.25 shows the first  $265\ \mu\text{V}$  voltage step that was produced with the pulse-driven array at the fastest 250 MHz pulse rate. The pulse amplitude was adjusted to center the first constant-voltage step on the zero-current axis. The voltage was correct for the number of junctions and the pulse frequency, and corresponded to exactly one quantized Josephson voltage pulse for every input pulse. The higher voltage steps are for higher order quantization ( $n = 2$  and 3 Josephson pulses for every input pulse).

Flat steps were larger than expected, for two reasons. First, the 250 MHz pulse frequency was much slower than the 4 GHz junction characteristic frequency, so that the current ranges of the steps were inherently small, due to the junction response. Second, the pulse waveform reaching each junction was probably not uniform because the PJVS circuit had multiple bias taps with filters designed for 11 GHz. This PJVS circuit was intentionally chosen because it didn't contain on-chip blocking capacitors, which would have blocked the low-speed pulse drive. Sometimes your best available resources (such as the circuits and pulse equipment, in this case), can still produce useful results.

A few days later, I discovered the 1996 paper by Maggi that showed his simulations of pulse-driven junctions. For many months, we were unaware of a related 1990 paper by Monaco. Both of these researchers were interested in "step-width" enhancement of zero-crossing steps, not waveform synthesis, for increasing the current range of dc voltages. Maggi's simulations gave us confidence that our experimental results were reasonable. I began my own simulation investigation of pulse-driven junction dynamics by modifying one of Kautz' FORTRAN programs<sup>91</sup> and characterizing the junction response with different pulse-drive and junction parameters, including different pulse shapes. Research then shifted to understanding digital waveform synthesis (with Richard Schreier's delta-sigma modulator Matlab programs) and oversampling techniques, and characterizing the performance of state-of-the-art commercial pattern generators. This research gave me an acute appreciation of the broadband nature of our pulse-drive waveforms and how significantly more challenging it would be to ensure that all junctions receive the same pulse bias as compared with the single-frequency continuous-wave (CW) biases of both the PJVS and conventional JVS. It became necessary to develop lumped-element filters and other microwave circuit techniques that were appropriate for broadband waveforms and our specific applications.

Increasing the rms voltage to at least 100 mV was the greatest challenge to making the ACJVS a useful system. At lunch one day in the NIST cafeteria, Charlie Burroughs and I were discussing different schemes to produce bipolar pulses. On a napkin we sketched I-V curves and pulse waveforms. We considered combining the two-level pattern generator signal with a CW microwave signal and speculated that pulses of both polarities might be possible if the CW frequency were  $3/2$  that of the pattern generator's clock. Charlie arrived the next morning with calculated combined waveforms that showed bipolar pulses. Experimentally combining the two bias waveforms required creativity, such as minimizing attenuation of the two-level pattern generator signal by using a microwave coupler (in reverse). Developing techniques to optimize the phase and amplitude of the two bias signals



**FIGURE 9.25:** First pulse-biased SNS array I-V curve of 512 series-connected junctions showing flat steps that indicated reasonable pulse uniformity.

<sup>91</sup> FORTRAN is a programming language widely used for scientific computing, especially in the previous century.

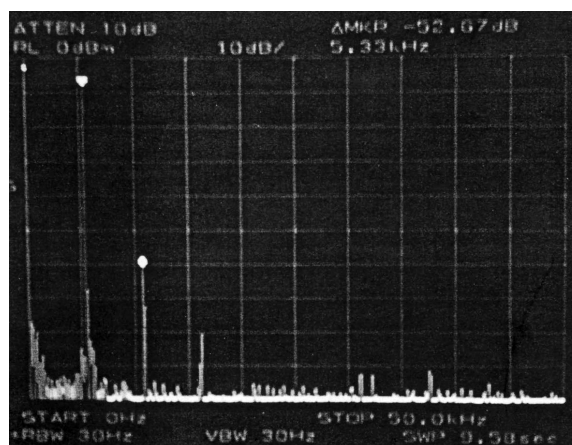
was also challenging. After many failed attempts to achieve operating margins, we finally synthesized the first bipolar pulse-driven sine wave with quantum-based accuracy, as shown in Figure 9.26. We found that the  $-52.7$  dBc second harmonic and lower-amplitude third harmonic were due to nonlinearities of the differential preamplifier and spectrum analyzer measurement instruments. Every junction in this array produced exactly one quantized voltage pulse for every input pulse, so that the first perfect bipolar sine wave was synthesized with no measureable distortion above the noise floor (more than 90 dB below the fundamental tone).

It took many more years of technology development in fabrication, microwave circuit design, and bias techniques before circuits were able to produce useful 100 mV sine waves. Automating the ACJVS for ac-dc difference measurements enabled the first quantum-based ac voltage calibrations in 2007. Also during these many years of development Paul Dresselhaus, Yonuk Chong, Nicolas Hadacek, and many other collaborators helped improve the fabrication process and experimented with new barrier materials. The barriers we found that produced the most uniform and reproducible junctions were high-resistivity metal-silicides. These barriers enabled us to increase output voltage for both the ACJVS and PJVS circuits. The maximum rms output voltage of the ACJVS is currently 275 mV. We also worked with a number of collaborators and com-

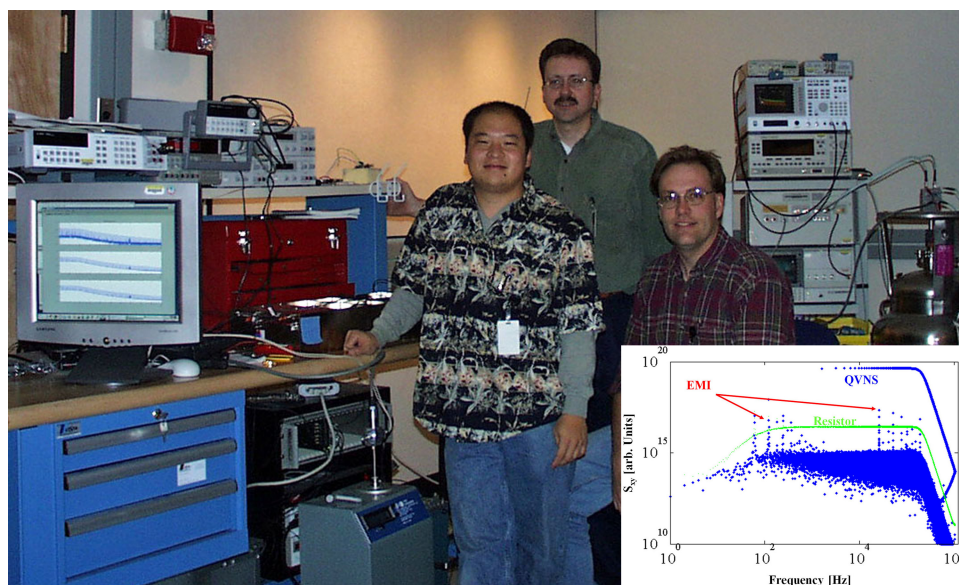
panies to produce custom pattern generators that had more memory and performance optimized for the ACJVS. A German company, Sympuls LLC, now makes a ternary pulse pattern generator that directly generates bipolar pulse waveforms, which they developed in collaboration with our metrology colleagues at the NMi Van Swinden Laboratory in The Netherlands.

Understanding the limitations (and especially the systematic errors) of Josephson voltage standard systems is extremely important, and influences the measurement techniques used for a particular application. The most important step in ensuring that a Josephson system is producing an accurate voltage is demonstrating that it produces the same voltage for a range of values for every bias parameter. Even if a measured voltage appears repeatable and can attain a low uncertainty, it can still be inaccurate! The accuracy also depends on systematic errors, such as thermal voltages (for dc signals) and ac signals from other sources (electromagnetic interference or bias-related signals) or unexpected circuit paths (especially for frequencies greater than 100 kHz). Other effects that compromise the accuracy of measured voltage waveforms include the frequency response of the output transmission line, voltages induced from bias signals driving the inductance of the superconducting wiring between the junctions, nonlinearities from wiring connections (that produce distortion), and signals produced by the digitization process, which are particularly detrimental in rms measurements.

Some of the above challenges to measurement accuracy were reinvestigated beginning in 2005 as researchers again attempted to make rms measurements of PJVS stepwise waveforms at frequencies up to 2 kHz. It was hoped that a bias source with a faster 100 ns rise time that enabled shorter transients would reduce rms measurement uncertainties. Burroughs and other NIST colleagues showed



**FIGURE 9.26:** First spectrum (2/25/1998) that demonstrated operating margins of an ACJVS-synthesized bipolar sine wave and with the largest amplitude to date of 13.4 mV rms — 95 % of peak amplitude waveform, 1000 junctions biased with a 6.44 GHz clock and 9.66 GHz microwave drive.



**FIGURE 9.27:** First (November, 2001) cross-correlation measurement (left monitor display) with NIST Johnson noise thermometry electronics (on bench). Pictured are Sae Woo Nam, Wes Tew, and Sam Benz. The sense resistor probe is in the water cell inside the thermoelectric cooler (on the floor). The ACJVS system is in the upper right. Inset shows the first published spectra of the resistor and QVNS signals and challenges with EMI.

that the uncertainty of rms measurements of stepwise waveforms, even with rise times as short as 20 ns, was still limited by bias offsets and also by other bias parameters that influence the shape of an array's I-V curve, such as the applied microwave power. These “flat spot” measurement results convinced most researchers to focus on sampling measurement techniques, which can eliminate transient and bias-related errors when stepwise waveforms are measured.

In parallel with the rms investigations, Waldemar Kürten Ihlenfeld and Luis Palafox and colleagues used stepwise waveforms and direct sampling to calibrate the digital voltmeter and demonstrated the technique for power calibration. In 2005, Ralf Behr et al. proposed a differential sampling method with a PJVS voltage reference. Alain Rüfenacht and collaborators optimized and demonstrated this differential sampling technique by characterizing ac sources. At frequencies up to 200 Hz, the lowest uncertainty for a commonly used commercial voltage source was a few parts in  $10^7$ , which was limited by the stability of that source. An order of magnitude lower uncertainty was found when comparing the multilevel stepwise waveforms of two PJVS signals (one source and one reference). In 2008, Waltrip et al. developed a new power calibration system for NIST that used differential sampling and an integrated PJVS as the voltage reference. The most challenging research aspects for this system were developing the stable semiconductor synthesized source, the permuting dividers, and the differential measurement technique. Frequently, when implementing a quantum system in a new application, the challenges may lie in integration or other instruments or components required for the measurement.

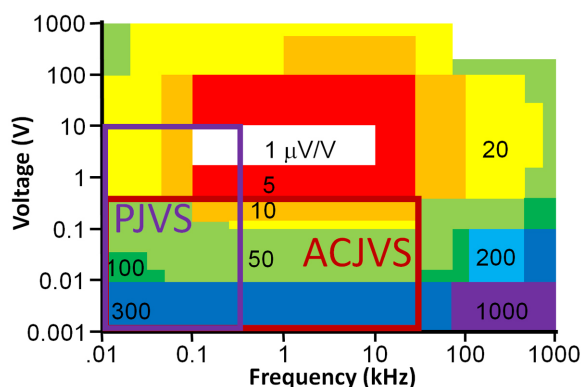
Finally, I would like to mention my favorite application of quantum-based waveform synthesis. It is my favorite because it has been and continues to be challenging, has required many smart and capable collaborators, and exploits quantum-accurate waveform synthesis in a completely new area for me, namely thermometry. In 2000, John Martinis conceived of improving Johnson noise thermometry (JNT) with quantum-based waveforms because they could provide a calculable, accurate, pseudo-noise voltage reference. Rod White (Measurement Standards Laboratory, New Zealand)



and Wes Tew (NIST) provided the thermometry expertise for our collaboration. Sae Woo Nam, with Martinis, constructed the cross-correlation electronics. The initial experiments were designed to demonstrate the new approach to JNT and to investigate differences between thermodynamic temperature and the ITS-90 temperature scale, which has been characterized primarily by gas and radiation thermometry. In Figure 9.27, Sae Woo Nam, Wes Tew and I pose with the JNT apparatus after the first measurements. More recently, we focused our JNT research toward producing an electronic measurement of Boltzmann's constant  $k_B$  at parts in  $10^6$  uncertainty.

The unique aspect of our JNT measurement technique is the use of a low-voltage version (only eight junctions) of the ACJVS, called a "quantized voltage noise source" (QVNS), which is used to synthesize a waveform constructed from harmonic tones of identical amplitudes and random relative phases. This quantum-accurate "pseudo-noise" waveform is used to characterize the amplitude-frequency response of the JNT electronics over its 1 MHz Nyquist measurement bandwidth. We have also used two-tone and multi-tone waveforms synthesized with both the QVNS and the ACJVS to uncover, characterize, and reduce nonlinearities by revealing the distortion in both active and passive electronics components, the input transmission lines and wiring, and the sampling ADCs. As with the power calibration system, the most difficult aspects of the JNT experiment are the non-Josephson components, namely, improving the low-noise measurement electronics. Horst Rogalla (University of Twente, the Netherlands), Jifeng Qu (National Institute of Metrology, China), Alessio Polarollo (Istituto Nazionale di Ricerca Metrologica, iNRI) and Chiharu Urano (AIST/National Metrology Institute of Japan) are recent guest researchers working on the NIST JNT experiment and their improvements are now yielding a measurement of Boltzmann's constant with an uncertainty less than  $12 \mu\text{K/K}$ .

In conclusion, there are two different quantum-based ac voltage sources that produce either step-wise approximated waveforms (PJVS) or perfect digital-to-analog conversion (ACJVS). New measurement techniques that use these systems have been developed and demonstrated for ac voltage and power applications. These systems and measurement techniques have the potential to shift the paradigm for measuring ac signals from one based on rms detectors to one based on intrinsically accurate voltage sources. The present region of impact in ac voltage metrology for each of the two systems is indicated in Figure 9.28. The uncertainties displayed in this plot, which are based primarily on rms detection with thermal converters, are those offered in 2010 by the NIST ac voltage calibration service, which is used for calibrating thermal converters and voltage sources. The Josephson systems should be able to improve upon these uncertainties by at least an order of magnitude, and this has already been demonstrated at a number of frequencies and voltages. In order to fully realize the paradigm shift to quantum-based voltage sources, additional technology development will be required to improve the Josephson systems and measurement techniques, particularly in bias electronics and system automation. I am optimistic that the remaining technical challenges will be overcome, as usual, through collaborative interactions between the metrology and superconducting electronics researchers working in this field.



**FIGURE 9.28:** Voltage vs. frequency plot showing the uncertainty boundaries (in units of  $\mu\text{V/V}$ ) for ac voltage calibrations at NIST (courtesy of T. Lipe and J. Kinard, NIST). Boxes indicate regions presently impacted by the PJVS and ACJVS quantum-based voltage sources.