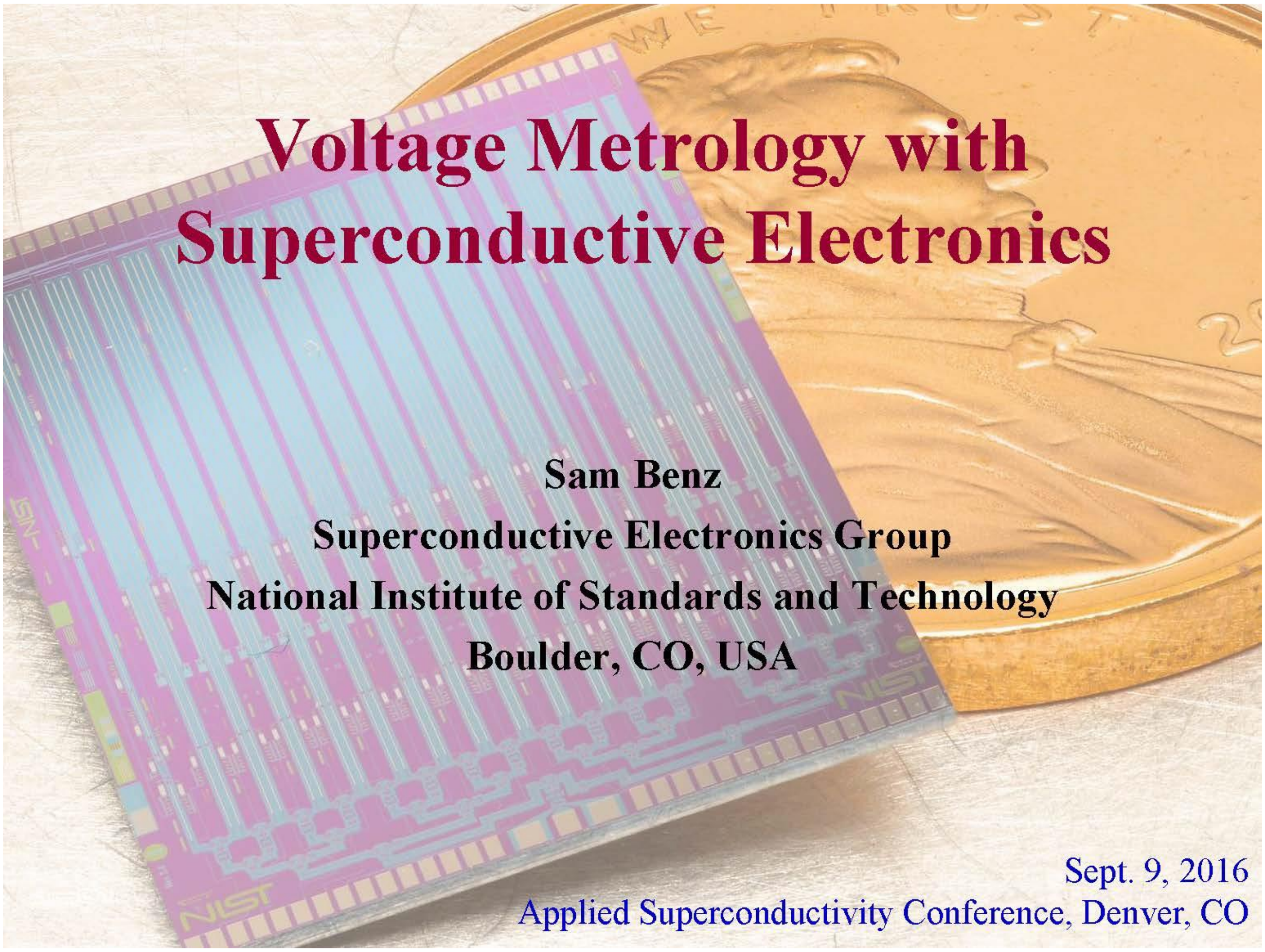


In this talk, I will report primarily NIST results and progress in quantum-based voltage metrology. I want to thank all of the current and former staff, guest researchers and collaborators at NIST, as well as those colleagues and researchers at other national measurement institutes for the work that they've done in the field that provides the foundation for our current research.

Metrology?

NOT
Meteorology

3

When I tell people that I do metrology and standards at NIST, they usually shake their heads in understanding and say, “Oh, so you study the weather and storms?”

No, that is meteorology. In metrology, we study measurement.

In particularly, at NIST and other metrology laboratories around the world, we pursue better measurement and develop new technology and techniques for making better measurements. The staff in my Superconductive Electronics Group at NIST develop voltage standards based on the quantum effects of a device called a Josephson junction. We also exploit the zero resistance state of superconducting wires to reduce measurement uncertainty from voltages produced by currents on resistive leads.

Standard?

Device or system that yields a "repeatable" value when "appropriately" measured

5

What is a standard? It is a device or system that yields a repeatable value when appropriately measured. A quantum standard, such as voltage and resistance standards, exploits quantum effects that enable measurements to be intrinsically accurate so that repeatable values can be achieved in any laboratory using comparable systems, and in fact in any location in the universe. Such quantum- based electrical standards are different from all non-quantum standards for this very reason, and their success has lead the international community to redefine the international system of units and how we assign uncertainty through measurements of fundamental constants. The reproducibility of quantum standards for voltage and resistance through the Josephson and quantum Hall effects are the impetus for these changes. However, there is one caveat, they must be "appropriately" measured using best practices to reveal their accurate values and I will emphasize this important point throughout the talk.

Here are four background references:

J. Niemeyer, Handbook of Appl. Supercond., Vol 2: Applications (IOP, Bristol, 1998), p. 1813.

C. A. Hamilton, Rev. Sci. Instrum., vol. 71, p. 3611 (2000).

R. L. Kautz, Rep. Progr. Phys., vol. 59, p. 935 (1996).

B. Jeanneret and S. P. Benz, "Application of the Josephson effect in electrical metrology," Proceedings of the International School on "Quantum Metrology and Fundamental Constants," Les Houches, France, 1-12 October 2007, eds. F. Piquemal and B. Jeckelmann, published jointly by EDP Sciences and Springer Verlag in *The European Physical Journal Special Topics*, vol. 172, pp. 181-206, June 1, 2009.

NIST-based Josephson Voltage Standards

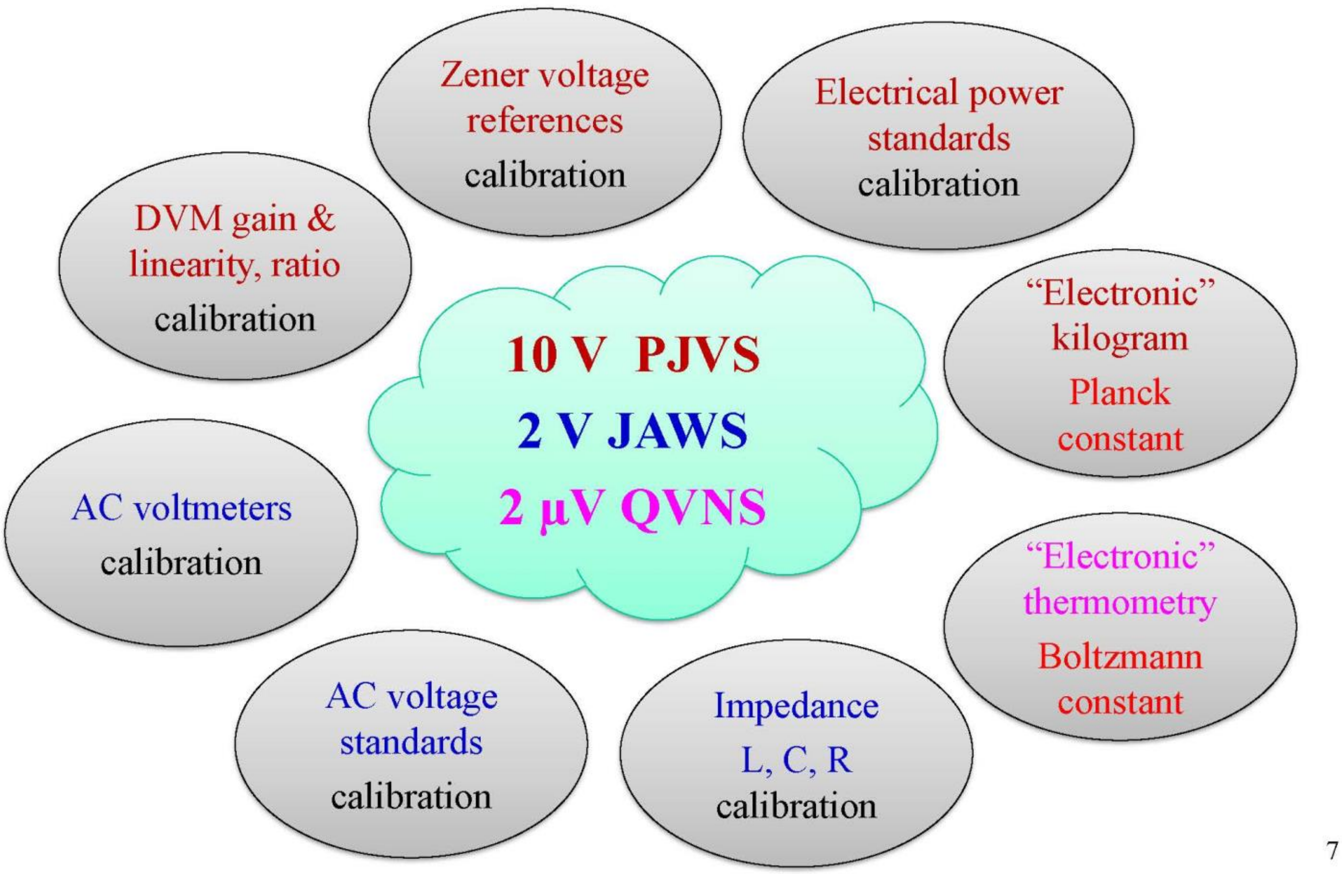
Conventional (CJVS)
Programmable (PJVS)
Josephson Arbitrary Waveform Synthesizer (JAWS)
Quantum Voltage Noise Source (QVNS)

6

For over 40 years, research laboratories worldwide have worked to develop Josephson voltage standard technology for various applications. In this talk, I'm not going to review all the progress and measurement records because there are numerous review papers with all the references. Their have been four main instruments that have been developed at NIST and this map shows the locations of all the NIST-developed systems and chips. Prior to 1995, the conventional Josephson voltage standard was the quantum standard for realizing dc voltages. In this talk, I will focus primarily on the three newest systems that have been developed in order to achieve new capabilities, like ac voltage synthesis. These include the programmable JVS (PJVS), the Josephson arbitrary waveform synthesizer (JAWS), and the quantum voltage noise source (QVNS). These systems are each at different levels of development, and performance.

As a result of decades of development, NIST versions of these 4 devices and instruments now reside on 6 continents.

Applications of JVS systems



Applications of these JVS systems are primarily for calibration measurements of electrical instruments. PJVS systems are used for directly calibrating Zener voltage references. Some calibration labs, for example, will calibrate racks of Zener reference standards and return them to other labs and locations. PJVS systems are also used to measure the gain and linearity of electrical instruments like digital voltmeters and to calibrate electric power standards for low frequency AC. In addition to calibration, PJVS systems are used in a number of precision metrology experiments, such as measuring the kilogram, which is currently the artifact standard for mass. It is also a measurement of Planck's constant. There is a plan to redefine the international system of units, the SI, in the coming years, after which the kilogram mass standard will be replaced with a mechanical and electrical comparison measurement.

So the PJVS are typically at 10 V output level and used for D.C measurements. The 2 V JAWS system is newer and its output voltage used to be only at a quarter voltage. But this technology has dramatically advanced in the last two years, increasing the output by a factor of ten. It's used as an intrinsic ac standard for calibrating meters and other standards. More recently, two 1 V JAWS systems have been used to realize a quantum-based impedance measurement. I'll show one slide of this work.

Finally, there is a very low voltage instrument containing 6 Josephson junctions used as a voltage waveform synthesizer to calibrate low-noise electronics to make a primary thermometer based on measuring the Johnson noise of a resistor. This same quantum voltage noise source (QVNS) is also being used as a precision measurement of Boltzmann's constant. This measurement is very similar to the Planck/ constant/kilogram experiment in that it is a thermal and electrical comparison.

Takeaway Points

- Features of a quantum voltage standard
- Metrology applications
  - DC voltage, and AC power
  - AC voltage and impedance
  - Primary thermometry
  - Future communications
- Measurement performance
  - Measurement techniques and error sources
  - Circuit design and fabrication technology
  - Cryogenic design and packaging
  - System automation

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At the conclusion of this talk, I hope you will have a greater appreciation for the following important point. What are the features of a quantum standard what makes it different from all the other instruments in your labs?

These metrology applications include dc and ac voltage, impedance, primary thermometry, and hopefully in the future radio-frequency communications.

In order to achieve a quantum-accurate voltage measurement, at a minimum, one needs a quantum-based circuit/device, an understanding of the error sources, and a well-characterized measurement technique that minimizes and accounts for those errors.

However, for a person who is neither an expert in superconductivity nor cryogenics to achieve a quantum accurate voltage measurement, they need a practically useful standard instrument that is sufficiently automated, enough to remove those errors. This requires careful circuit design exploiting both superconducting properties and the Josephson effects of Josephson junctions, devices made using a superconductive circuit fabrication process that reproducibly yields nearly identical junctions, cryogenic design and packaging of the devices and cryostats that optimizes thermal management of the circuits and systems, and well-engineered software that enables automation of the system, measurements and error analysis.

Features of a Quantum Voltage Standard

- Intrinsic accuracy is based on quantum behavior
  - Josephson effect defines the electrical properties of superconducting Josephson junctions
- Always produces an accurate voltage
  - Regardless of environmental conditions or location, which is in contrast to "artifact" standards, and
  - Over a range of all bias parameters and operating conditions, called "flat spots".
  - Flat spots **MUST** be measured to ensure that all junctions are in their quantum states before claiming accuracy.
- Systematic errors must be removed or characterized
  - Measurement leads have thermal voltages
  - Circuit parasitics "leakage" R, L and C have error currents

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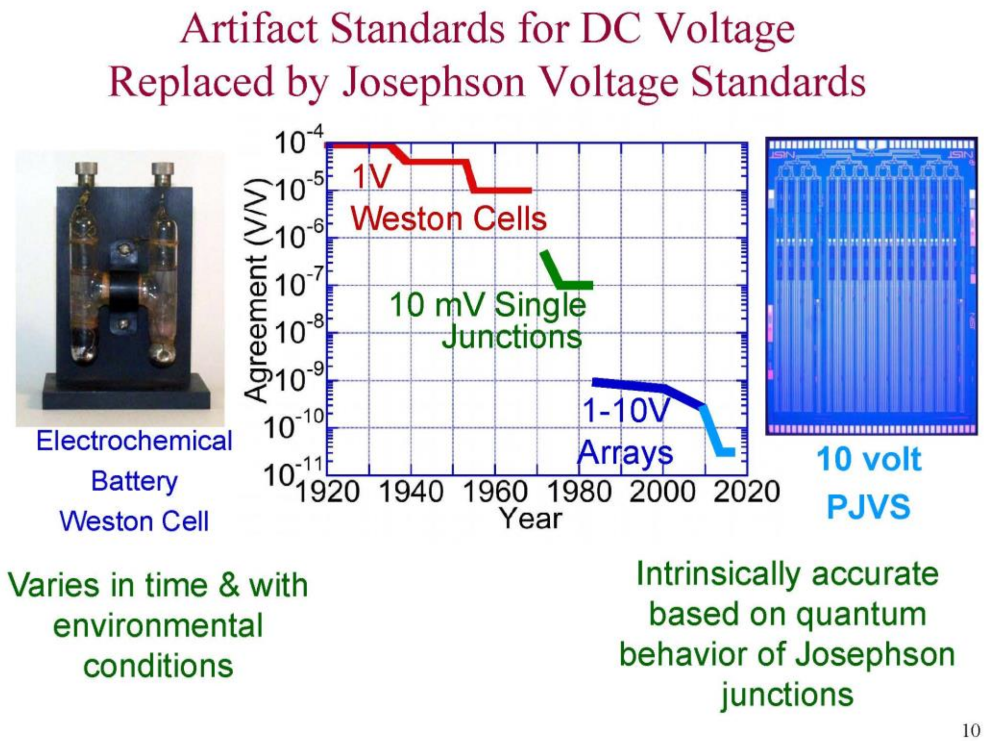
So what are the features of a quantum voltage standard? The intrinsic accuracy must be derived from a quantum behavior. You might already be familiar with the atomic clocks and the quantum Hall effect. The electrical properties of the Josephson effect is the quantum behavior that produces the intrinsic accuracy of voltage standards. A quantum voltage standard always produces an accurate voltage regardless of environmental conditions or location, and thus identical voltages can be reproduced anywhere in the world or in the universe for that matter. This is in contrast to artifacts standards like the kilogram mass, as well as voltage standards based on electrochemical batteries. Such artifact standards were accurate for their time because they were manufactured to be nearly identical and environmentally stable, but their values still depended on manufacturing variations and changed with environmental conditions (temperature, humidity, pressure, etc), and over periods of time (aging). In contrast, a quantum standard generates reproducible and identical values for a range of bias parameters and operating conditions, and its value is insensitive to the environment and aging. Such values that remain constant as a function of varying bias conditions are called "flat spots", and I'll show you some of these for our PJVS and JAWS systems. In order to ensure quantum accuracy, flat spots must be measured repeatedly and regularly to ensure that the devices are in their quantum states before, during and after measurements. So imagine an unchanging value of voltage that results every time you use the standard, or move it between different labs even on different continents.

Nevertheless, there are limitations to the accuracy of quantum standards. For example, thermal voltages generated by resistive leads traversing the cryogenic environment from 4 K to room temperature always affect the measurement of dc voltages. AC voltage errors affecting the JAWS system can arise from frequency-dependent error currents produced by impedance parasitics within the superconducting circuit, or impedances and losses of the measurement leads and the load of the instrument being calibrated. Minimizing systematic errors through optimized design of the instrument and measurement technique is critical and all remaining errors must be understood and characterized.



The values produced by **artifact standards depend on environmental conditions,** although they can be very stable, they will still change with time. **Quantum based standards are intrinsically precise and accurate**. More than 3 order of magnitude improvement in uncertainty with Josephson arrays.

The artifact standard for voltage that was in use for many decades of the last century is a chemical battery called a Weston cell. The technology to duplicate these standards was very good such that their agreement over short periods of time was typically 50 parts in a million provided they were maintained under controlled environmental conditions.

When the Josephson effect was discovered in 1962, metrologists began trying to realize voltage standards made with a few Josephson junctions. There were able to produce small accurate millivolt voltages that immediately improved the agreement between laboratories by two orders of magnitude. Over the next two decades, researchers around the world worked to increase the output voltage of the conventional Josephson voltage standard to achieve practical voltages of 1 V and then 10 V, which led to another 100-fold improvement in agreement.

This required many years of gradually improving fabrication technology for the junctions, microwave designs to bias them, and understanding the physics of chaotic effects. More recently, comparisons of programmable Josephson voltage standards have improved agreement by another 10-fold, primarily because the PJVS produces stable quantized voltage steps that can be measured for longer periods of time thus reducing measurement noise. Thus, metrologists are continually looking for ways to replace artifacts standards with quantum standards for many different applications. Quantum voltage standards, in particular, have improved our ability to measure voltage by over 5 orders of magnitude, which has led to advances in measurements and also the performance of electrical instruments.

C. A. Hamilton, Rev. Sci. Instrum., vol. 71, p. 3611 (2000).

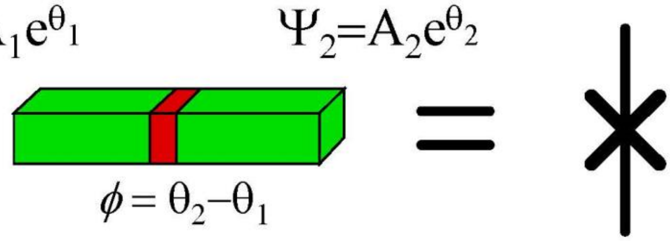
S. P. Benz, “Synthesizing Accurate Voltages with Superconducting Quantum-Based Standards,” IEEE Instr. Meas. Magazine, p. 8 (2010).

A. Rüfenacht et al., "10 volt automated direct comparison of two cryocooled programmable Josephson voltage standards," 30th Conference on Precision Electromagnetic Measurements (CPEM 2016) Digest, presented 10–15 July 2016, Ottawa, Canada, pp. 25. DOI: 10.1109/CPEM.2016.7540474.

What Is A Josephson Junction?

- Weak link between two superconductors

$\Psi_1 = A_1 e^{\theta_1}$ $\Psi_2 = A_2 e^{\theta_2}$



$\phi = \theta_2 - \theta_1$

  - Phase difference determines quantum electrical behavior
- Electrical properties
  - Supercurrent $I = I_c \sin\phi$
  - Voltage $V(t) = \frac{h}{2e}\frac{1}{2\pi}\frac{d\phi}{dt} \quad or \quad V = \frac{h}{2e} f_J$
  - Josephson supercurrents oscillate at frequency f_J

11

A Josephson junction is a weak link between two superconductors, and the weak link is typically either an insulator or a normal non-superconducting metal.

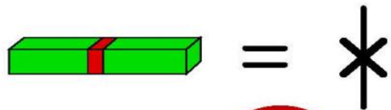
Paired electrons in each superconducting electrode can be described by a many- particle wavefunction that has both an amplitude and phase. This phase can maintain its coherence over macroscopic distances because the superconductor is a macroscopic condensate analogous to the now familiar Bose-Einstein condensate.

Josephson predicted two remarkable effects of such a junction:

(1) a supercurrent will flow through the weak link even at zero voltage difference, where πηι is the phase **difference** between the electrode wave functions, and the critical I_c is the maximum supercurrent that the junction can support.

(2) if a voltage difference is applied across the junction, then the phase difference evolves in proportion to the voltage, where the proportionality constant is the ratio of Planck's constant to twice the electron charge, h/2e. These equations show that the junction's supercurrent oscillates at a frequency exactly proportional to the voltage.

Quantum Behavior of Josephson Junctions



$$V(t) = \frac{h}{2e}\frac{1}{2\pi}\frac{d\phi}{dt}$$

Supercurrent Oscillation Frequency

- One voltage pulse for every 2π phase change

$$\int_0^{\infty} V(t)dt = \frac{h}{2e}\frac{1}{2\pi}\int_0^{2\pi} \phi \, dt = \frac{h}{2e}$$

- Pulse area is always EXACTLY one flux quantum

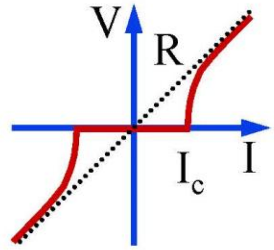
$$\Phi_0 = \frac{h}{2e}$$

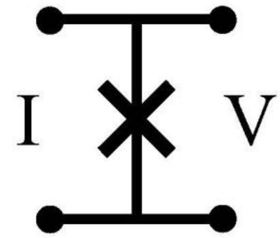
12

Thus a Josephson junction behaves similar to a harmonic oscillator in that the supercurrent oscillates at a frequency precisely proportional to its voltage. More importantly, the phase difference evolves by precisely 2π for each oscillation period and the junction voltage generates exactly one voltage pulse. Equally importantly, the time-integrated area of every pulse is precisely h/2e. Thus, phase periodicity of a junction leads to pulse quantization and voltage accuracy.

Driven Josephson Junction

- DC current bias, I

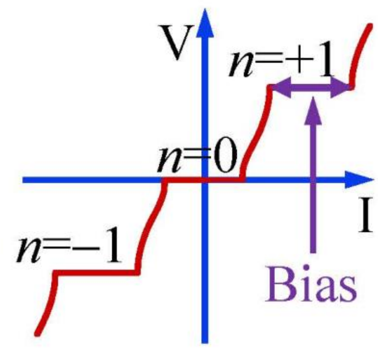




- Continuous microwave or periodic pulse bias
  - Supercurrent oscillations entrain to the drive frequency f
  - Lock at harmonic integers n
  - Generate constant DC voltage steps V_n

$$V_n = n\frac{h}{2e}f$$

  - Over a dc bias current range or **flat spot**



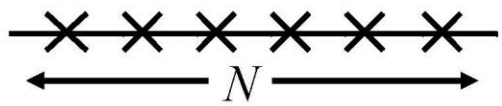
13

A junction biased with a dc remains in the zero-voltage quantum state until the bias exceeds its critical current. This positive and negative current range of this state defines the "flat spot".

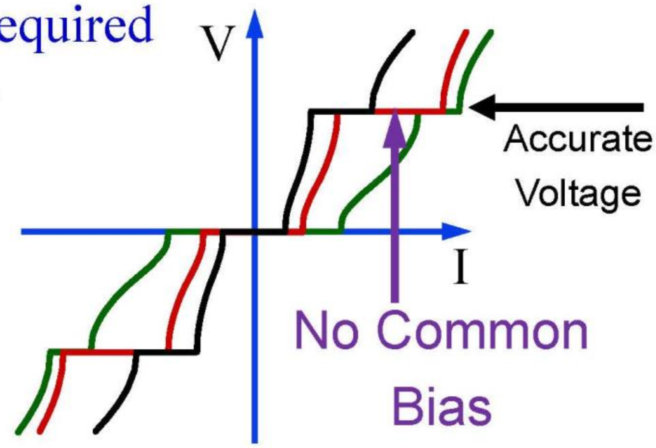
Biased above Ic, the junction continuously pulses and the supercurrent oscillates at a frequency proportional to the voltage. If a microwave signal or a periodic pulse bias is applied, then the oscillations lock and entrain to the frequency of that alternating bias, just like a driven harmonic oscillator. The supercurrent oscillations lock to the drive creating constant voltage flat spots over a range of dc bias. The oscillations also lock at harmonic multiples of the drive frequency, where the junctions generate multiple pulses for each period of the drive. The current range of each flat spot depends on the electrical properties of the junction and the applied ac bias.

Practical Voltages Require Series Arrays

- Single junction voltages ≈ 40 μV $\quad \frac{h}{2e} \approx 2\mu V/GHz$
- 10 V is desired output voltage
- Large series arrays are required



$$V_n = \frac{h}{2e} nNf$$



- Uniform junctions
- Uniform microwave power
- Frequency accuracy derived from atomic clock

Practical Voltages Require Long, Uniform Series Arrays

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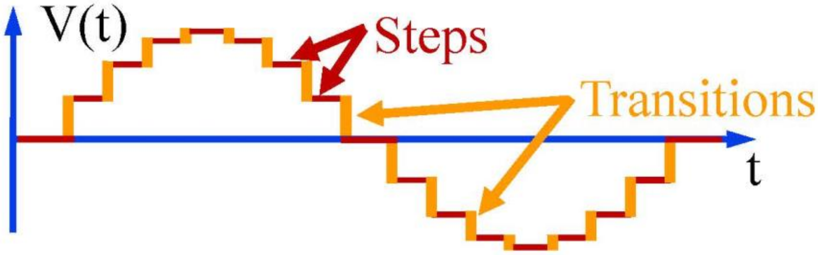
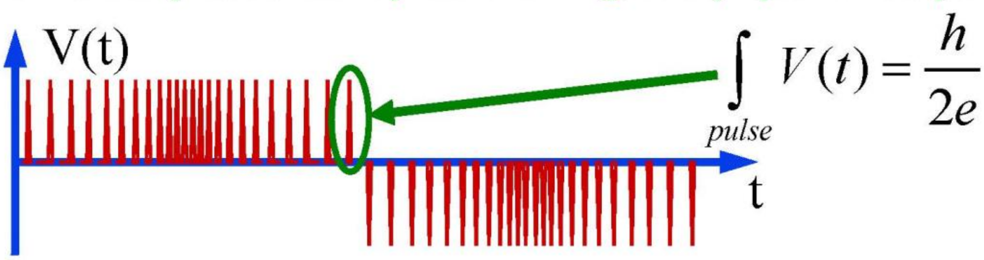
Unfortunately, h/2e is small, about 2 μV/GHz, so that the voltage steps are spaced at about 40 μV for a typical periodic drive of 20 GHz. At least 1 V or 10 V are required for practical calibration of electronic instruments and other voltage standards. Thus, many junctions must be series connected to produce useful voltages. Fortunately, the quantized voltages of each junction will be identical when biased with the same frequency. The challenge, however, is that the current ranges of each step should also be similar so the larger combined voltage of the series- array of junctions can be selected with a common dc bias. This requires excellent junction uniformity and microwave power distribution. Many years of voltage standard development were required to find optimal materials for the junction barriers to achieve the junction uniformity, to improve the fabrication process of those junctions, and to achieve uniform power distribution of the ac biases. In addition to nearly identical current ranges of many quantum states, voltage accuracy also requires that the frequency of the ac bias source be referenced to an atomic clock frequency.

AC Voltage Synthesis

- PJVS uses step-wise approximated sine waves
  - Transitions between steps compromise accuracy



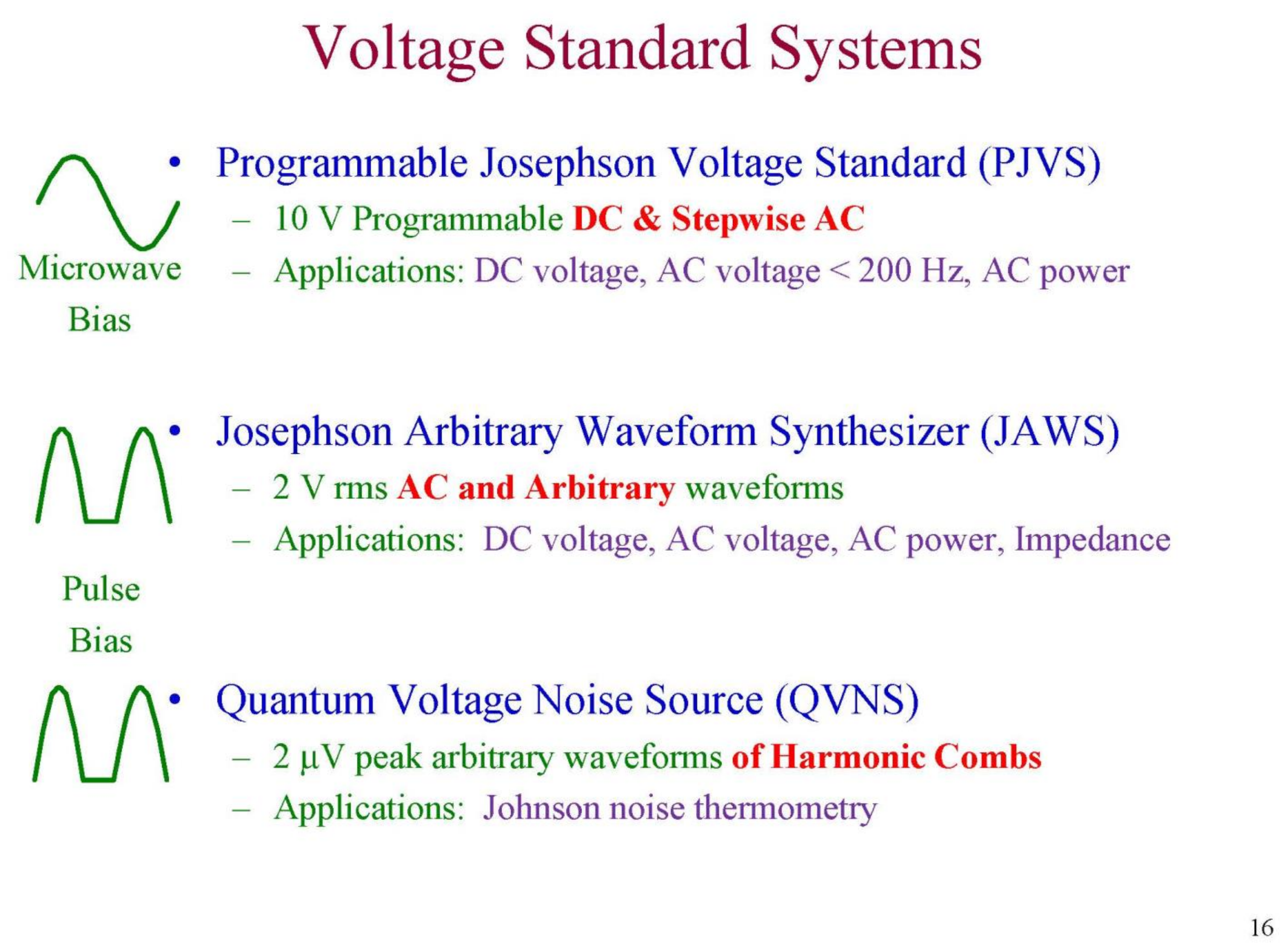
- JAWS direct digital synthesis with current pulse sequences
  - Intrinsically accurate by controlling every quantized pulse



15

The programmable Josephson voltage standard was invented in order to create an ac voltage source with quantum-based accuracy. It’s designed ability to rapidly select different quantized voltage steps enabled the step-wise approximated sign waves to be synthesized. The drawback of this approach was that, although the voltage steps were accurate, the transitions between them were not. Thus, it is not an intrinsic ac voltage source. Differential sampling, which compares these step voltages with other ac signals, has proven to be the best measurement approach for ac signals with frequencies less than 200 Hz and voltages greater than 1 V. This approach is primarily used for calibrating ac power meters.

The Josephson arbitrary waveform synthesizer, on the other hand, is an intrinsic ac voltage standard. It accomplishes this by controlling every quantized pulse in a digitally synthesized waveform, so every junction is always in one of three quantum states, generating either positive or negative pulses, or none. JAWS produces intrinsically accurate sine waves that have proven useful for ac voltage metrology at frequencies below 20 kHz. In addition to sine waves, the JAWS direct digital synthesis with quantized voltage pulses allows intrinsically accurate arbitrary waveforms that can be used for other applications. The quantum voltage noise source is essentially a low-voltage version of JAWS with only six junctions that generates pseudo-noise waveforms having a comb of harmonic tones of equal amplitude spread over bandwidths of a few megahertz.



Here are the features of the three modern voltage standard systems. The PJVS is microwave biased, produces programmable dc voltages up to 10 V and is used for dc voltage calibrations and ac voltage and power calibrations at frequencies below 200 Hz. The JAWS and QVNS systems are both pulse driven circuits that use digital sampling techniques to synthesize dc and ac signals. Recently, a maximum output voltage of 2 V rms was achieved for JAWS. It is an intrinsic ac standard. The QVNS produces arbitrary waveforms with peak amplitude up to 2 μV. A pseudo- noise waveform of harmonic combs of tones of identical amplitude are used as a calibration source for Johnson noise thermometry.

I'll now describe each of these systems in more detail.

Programmable Josephson Voltage Standard

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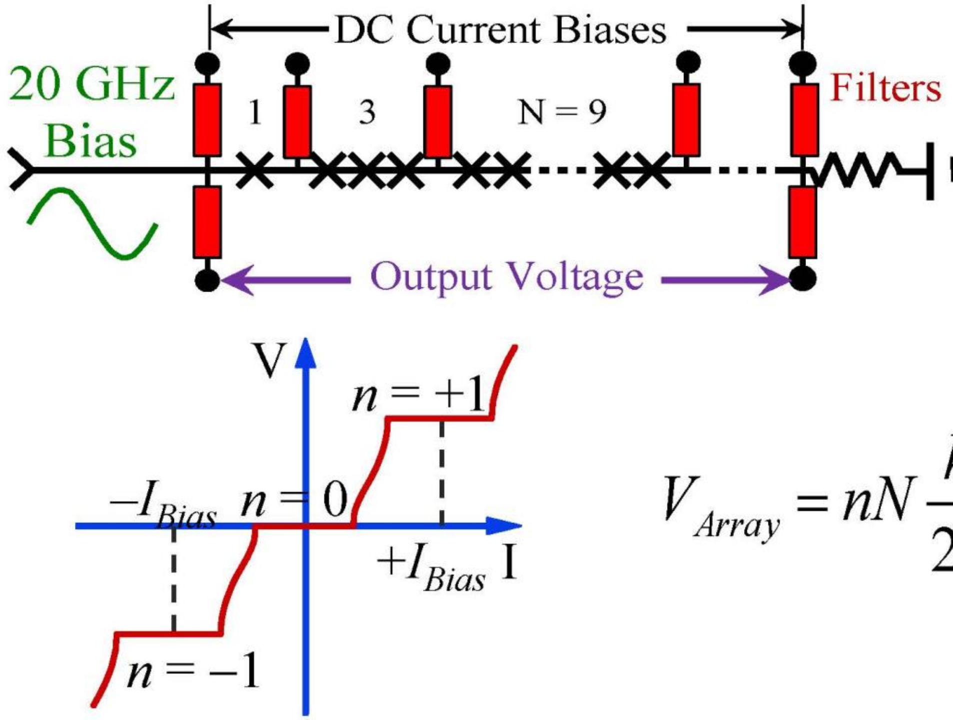
Next, I describe the basic operation, features and applications of the programmable Josephson voltage standard.

Programmable Josephson Voltage Standard



$$V_{Array} = nN\frac{h}{2e}f$$

Hamilton, Burroughs and Kautz, 1995

18

The Programmable Josephson voltage standard was invented in 1995 by Clark Hamilton. The PJVS circuit consists of a long series array of many junctions that is divided into smaller sub-arrays. The output voltage is programmed by individually biasing each array to one of the three quantized voltages. The number of junctions in the smallest arrays typically follow a ternary sequence to optimize voltage resolution with respect to the number of bias leads.

These low-speed bias currents typically switch at a few microseconds.

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, Apr. 1995.

S. P. Benz, et al., "Stable 1-Volt programmable voltage standard," *Appl. Physics Lett.*, vol. 71, pp. 1866-1868, Sep. 1997.

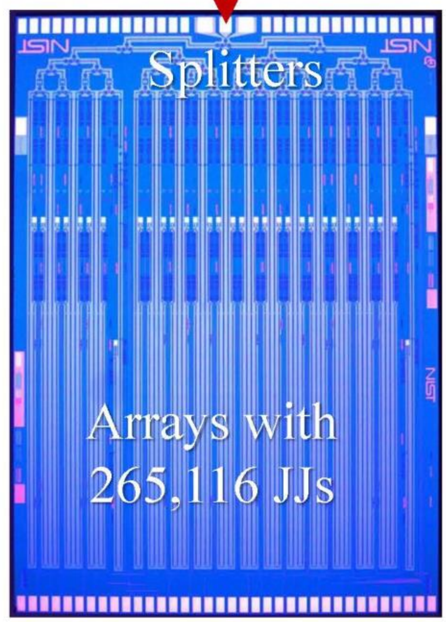
[8] C. J. Burroughs, et al., "1 Volt dc programmable Josephson voltage standard,"
IEEE Trans. Appl. Supercon., vol. 9, pp. 4145-4149, Jun. 1999.

Fabrication & Design of Superconducting Circuits

- Boulder Micro-Fabrication Facility

(12 x 17) mm^2 PJVS Chip

Microwave Input



DC Input/Output Pads

- Superconducting integrated circuits
  - Uniform junctions, barrier materials
  - Power dissipation
- Microwave circuit design
  - Lumped element inductors & capacitors, power splitters, coplanar waveguides
  - Simulation & modelling

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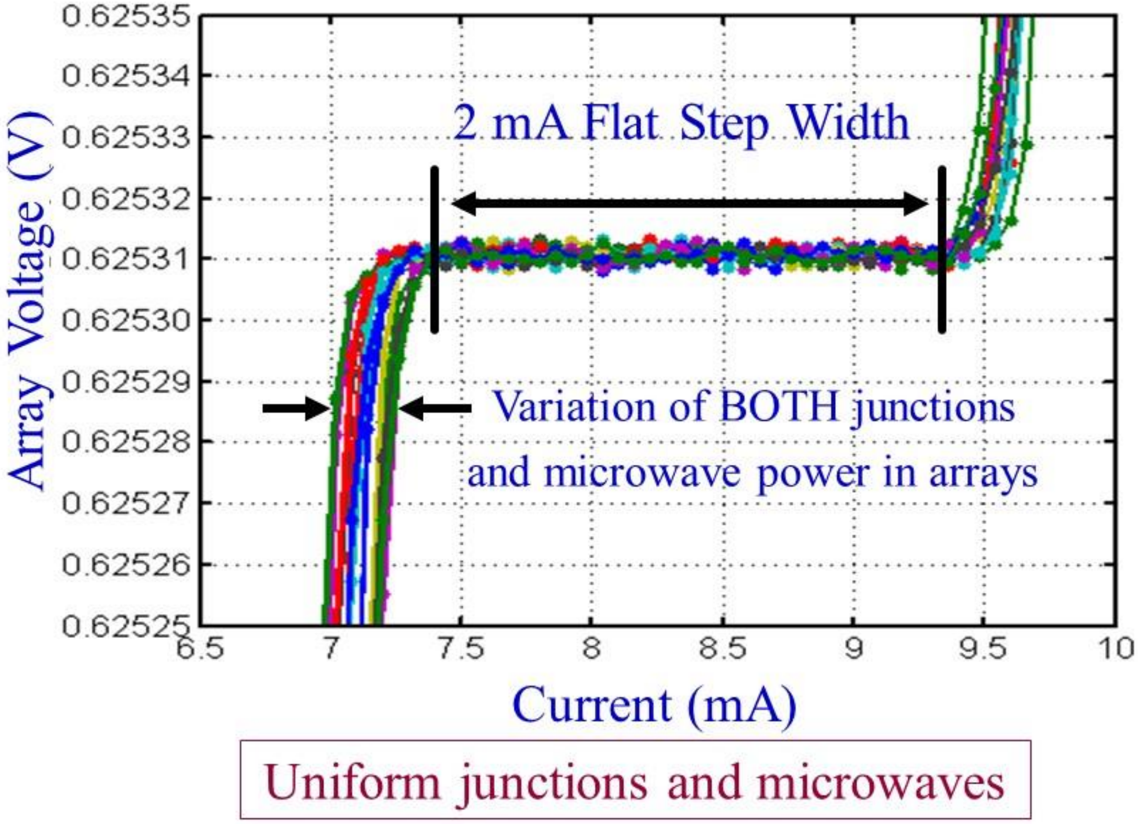
NIST superconducting integrated circuits are fabricated in the Boulder Microfabrication Facility. The 10 V PJVS chips contain over 265,000 junctions on a (12 mm x 17 mm) chip. The junctions consist of niobium superconducting electrodes and conductive barriers made of amorphous niobium-doped silicon. The microwave signal with a typical 20 GHz is supplied to 32 parallel arrays of junctions through a 4-stage power divider circuit consisting of lumped element superconducting inductors, capacitors, power splitters and coplanar waveguides.

Many years of research and development, including simulation and modeling, were needed to optimize the materials, fab process, circuit elements and microwave designs.

A. Rüfenacht, L. Howe, A. E. Fox, R. E. Schwall, P. D. Dresselhaus, C. J. Burroughs, and S. P. Benz, "Cryocooled 10 V Programmable Josephson Voltage Standard," *IEEE Trans. Inst. Meas.*, vol. 64, no. 6, pp. 1477-1482, 2015.

Flat Spots of 16 Arrays with 16800 Junctions



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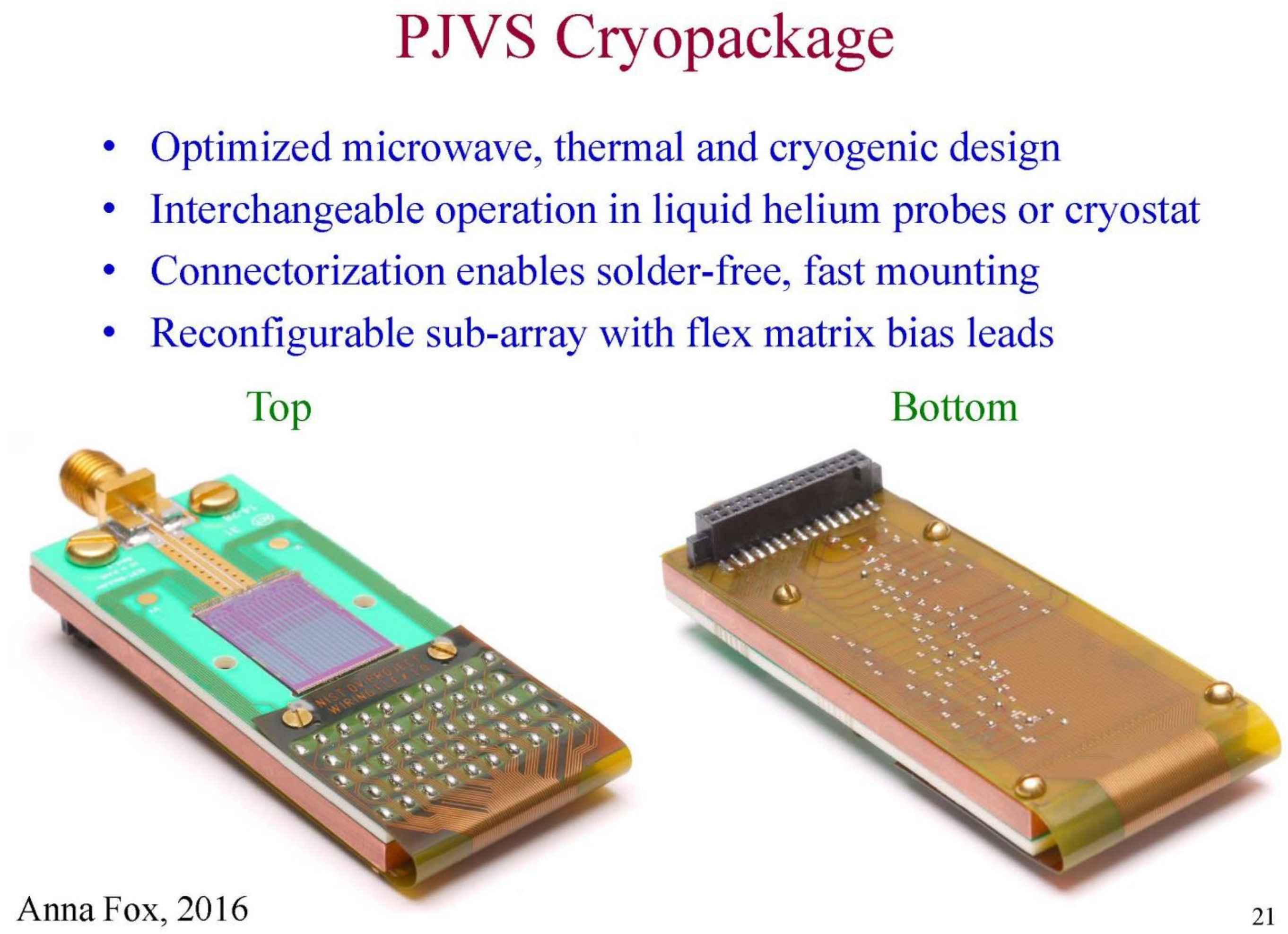
These current-voltage characteristics of 16 identical arrays, having 16,800 junctions each, show that all the junctions in the array can be commonly biased on the same quantized voltage step. Furthermore, the excellent uniformity of both the junctions and the applied microwave biases results in overlapping flat spots covering a 2 mA current range.

A. E. Fox et al., "Junction Yield Analysis for 10 V Programmable Josephson Voltage Standard Devices," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1101505-5, 2015.



New cryopackage features and challenges that were solved include: heat sinking of the chip to a copper header, LHe or cryocooler interchangeability, fast interconnection with socket connections for low-speed biases and output voltage that enables swappable packages, a flexible interconnect matrix that enables reconfigurable sub-arrays to optimize array flat spots by allowing different sub- arrays to be grouped together.

The chip is soldered to the copper block and connected to the pcb via wirebonds. The package is compatible with both 1 inch diameter liquid helium cryoprobes and mounting on a cryocooler cold plate. For the dip probe configuration, a flexible pcb wraps the low speed bias leads to the back of the block, where a solder- configurable matrix enables connections be made between the chip and the connector. This eliminates the need to directly solder to the pcb and encodes the configuration information right on the package.

Optimized thermal management of the cryopackage enhances the resulting system performance by managing heat dissipated on the chip for different bias configurations.

L. Howe, A. E. Fox, A. Rüfenacht, C. J. Burroughs, P. D. Dresselhaus, S. P. Benz, and R. E. Schwall, "NIST 10 V Programmable Josephson Voltage Standard System Using a Low-Capacity Cryocooler," *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, pp. 1400404-4, June 2015.

NIST Cryocooled PJVS System

- Integrated system
  - Bias electronics DC & MW
  - Cryogenics
  - Superconducting devices
  - Turn-key integrated system
  - Automation software
    - Optimize & check quantum states, flat spots
    - Performs measurements
- Specific measurement techniques needed for different applications

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This is the fully integrated NIST PJVS system, including the cryocooler, microwave synthesizer, voltmeter and temp controller, the DACs and an amplifier for DC biases, and a computer.

Operation of the chip in a cryostat allows the system to be fully automated, because a human operator is not required to raise or lower the chip into a liquid helium dewar. It also allows temperature to become a performance optimizing variable so that flat spots can be further optimized as a function of temperature.

Optimization and routine checking of flat spots is fully automated with software. Separate application software is used for different calibration functions, which allows metrologists and engineers to use the system without expertise in either cryogenics or Josephson devices.

NIST has made available identical versions of its PJVS system as a Standard Reference Instrument.

Accuracy vs. Stability

- Reproducible measurements with small statistical uncertainty DO NOT guarantee accuracy
- Error signals that are stable may be present and will still give reproducible results
- **Must check accuracy** (measure constant voltage values or "**flat spots**") by varying ALL biases and changing ground configurations
- Use measurement techniques that reveal or reduce errors
  - DC: voltage reversals remove thermal voltages from contacts & wires
  - AC: use differential sampling with stepwise AC voltage waveforms

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I'd like to say a few things about accuracy and stability. Use of a quantum standard does not ensure accuracy. In addition to known systematic errors, output voltages can be very stable and reproducible, even when circuits are biased off the edge of a **flat spot**, such as when one or a few junctions are not in their quantum states. Such stable, yet inaccurate values can yield measurements with very low uncertainty that give the appearance of accuracy. Thus, the publication of small uncertainties reported for a measurement is not the evidence of accuracy.

It is, therefore, very important to check that the circuits are always operating in quantum states by varying the biases and changing grounding configurations that might redistribute error currents.

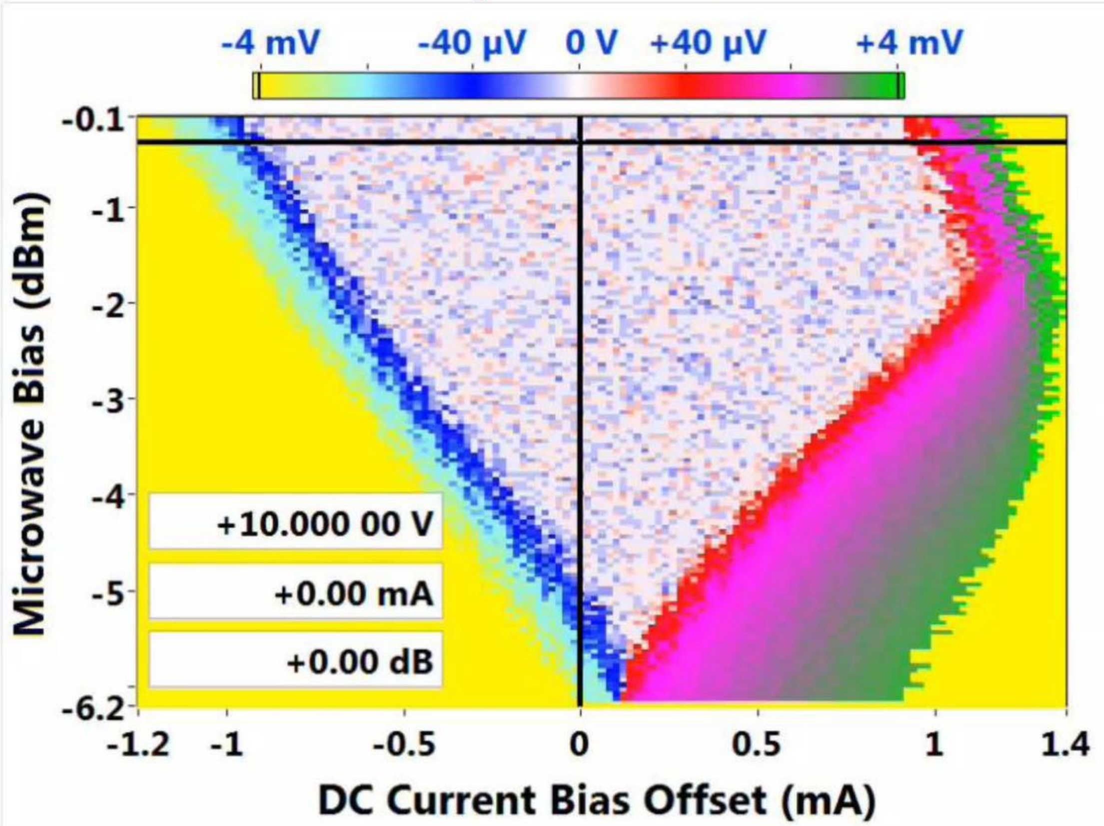
Once again, system automation is an important tool for evaluating the quantum states of the system.

Appropriate measurement techniques are also necessary to measure and account for systematic errors, such as removing thermal voltages by reversing the PJVS dc voltage to opposite polarities, or by use of differential sampling to avoid non- quantized voltages from ac measurements.

A. Rüfenacht, et al., "Precision differential sampling measurements of low- frequency voltages synthesized with an ac programmable Josephson voltage standard," *IEEE Trans. Inst. Meas.*, vol. 58, pp. 809-815, April 2009.

J. Lee et al., "An ac quantum voltmeter based on a 10V programmable Josephson array", Metrologia. vol. 50, p. 612, (2013).

Flat Spots at 10 V



Alain Rufenacht, 2015

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A video showing the how the voltage varies with respect to these two bias parameters is available at:

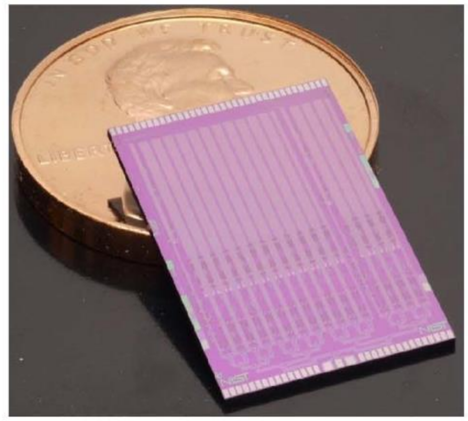
[Quantum State Flat Spots](https://www.nist.gov/pml/quantum-electromagnetics/superconductive-electronics/quantum-state-flat-spots) https://www.nist.gov/pml/quantum-electromagnetics/superconductive-electronics/quantum-state-flat-spots

This slide shows the PJVS 10 V flat spot as a function of both microwave amplitude and common dc bias offset. You can see that the quantization vanishes at the lowest microwave bias shown, and reaches a maximum of about 1.8 mA dc range for applied power greater than -2 dBm. Similar flat spot measurements are typically taken as a function of cryocooler temperature, as well as at different microwave frequencies, to determine the best operating conditions for each device.

A. Rüfenacht, L. Howe, A. E. Fox, R. E. Schwall, P. D. Dresselhaus, C. J. Burroughs, and S. P. Benz, “Cryocooled 10 V Programmable Josephson Voltage Standard,” *IEEE Trans. Inst. Meas.*, vol. 64, no. 6, pp. 1477-1482, June 2015.

PJVS Applications & Best Results

- Stable DC & stepwise AC voltages
  - Calibrate:
    - Zener reference standards
    - DVM gain, linearity
    - Calibrators
    - Power meters
  - Precision Measurements:
    - Electronic kilogram for measuring Planck's constant, *h*



- Uncertainty for different measurement techniques
  - DC to DC comparison of PJVS: 3 x 10^{-11}
  - Differential sampling frequencies < 500 Hz: < 1 μV/V

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This slide reiterates the main applications of the PJVS for calibration and precision measurements. The best comparison between two programmable Josephson voltage standards has shown agreement with an uncertainty of 3 parts in 10^11. For ac measurements of calibration instruments, the measurement uncertainty is less than 1 part in 10^6 for frequencies below 500 Hz.

Arbitrary Waveform Synthesis

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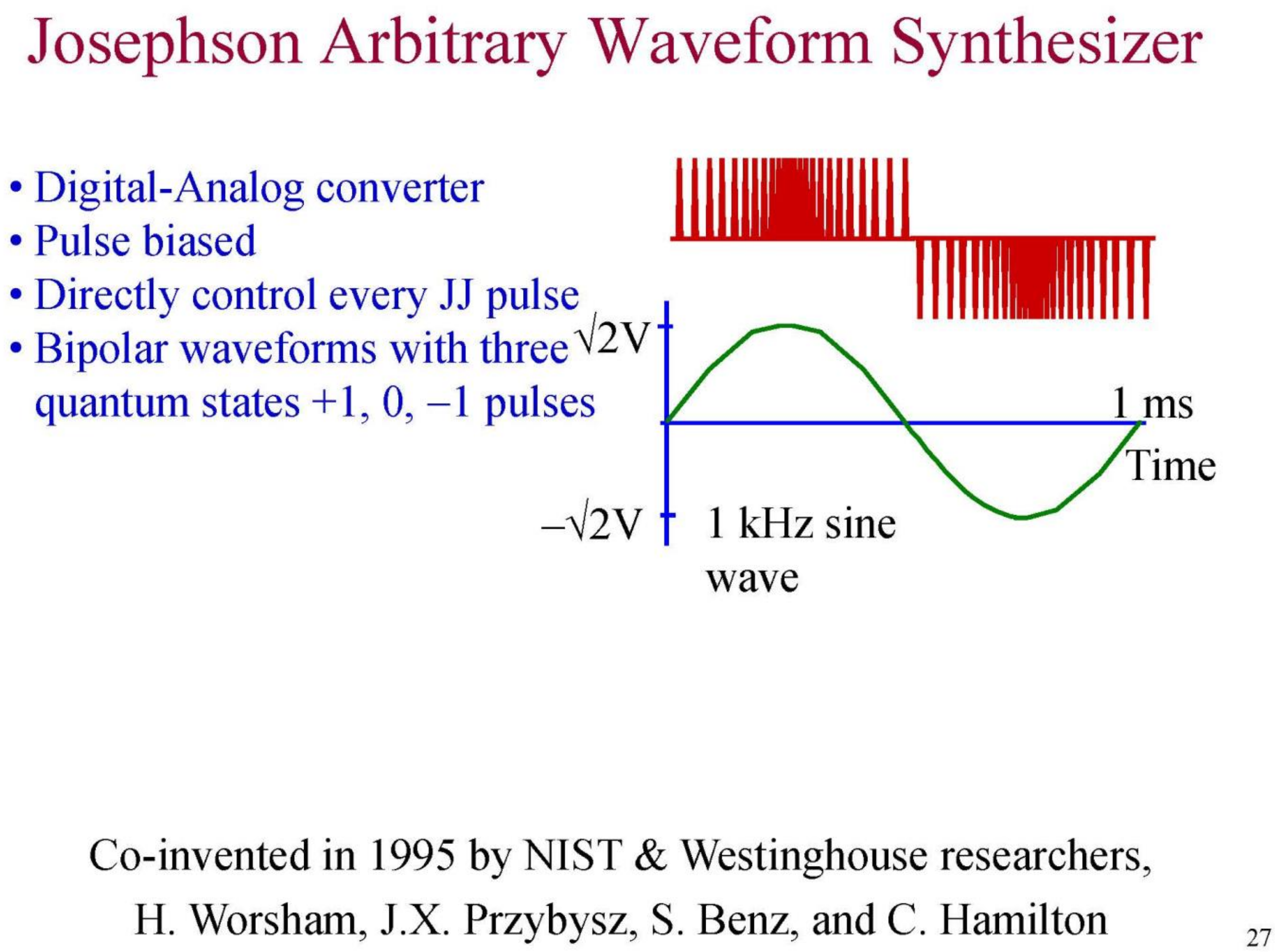
Now we will move on to intrinsic ac voltage standards and arbitrary waveform synthesis.



Synthesis of ac voltages with intrinsic accuracy is possible using the same type of junctions as are used for the PJVS, but biased with pulses instead of microwaves, thereby precisely controlling all quantized voltage pulses at every point in time. The Josephson arbitrary waveform synthesizer is essentially an oversampled three-state digital to analog converter that is clocked at 15 GHz. The three states are pulses of both polarity and zero and they enable bipolar voltage waveforms to be synthesized. JAWS circuits typically synthesize dc and sine wave voltages which are used to calibrate thermal voltage converters and other ac voltage standards. They have primarily been implemented at frequencies below 20 kHz, where frequency- dependent systematic errors are typically less than a part in 10^6. In the past few years, JAWS circuits have achieved record rms amplitudes of 1 V.

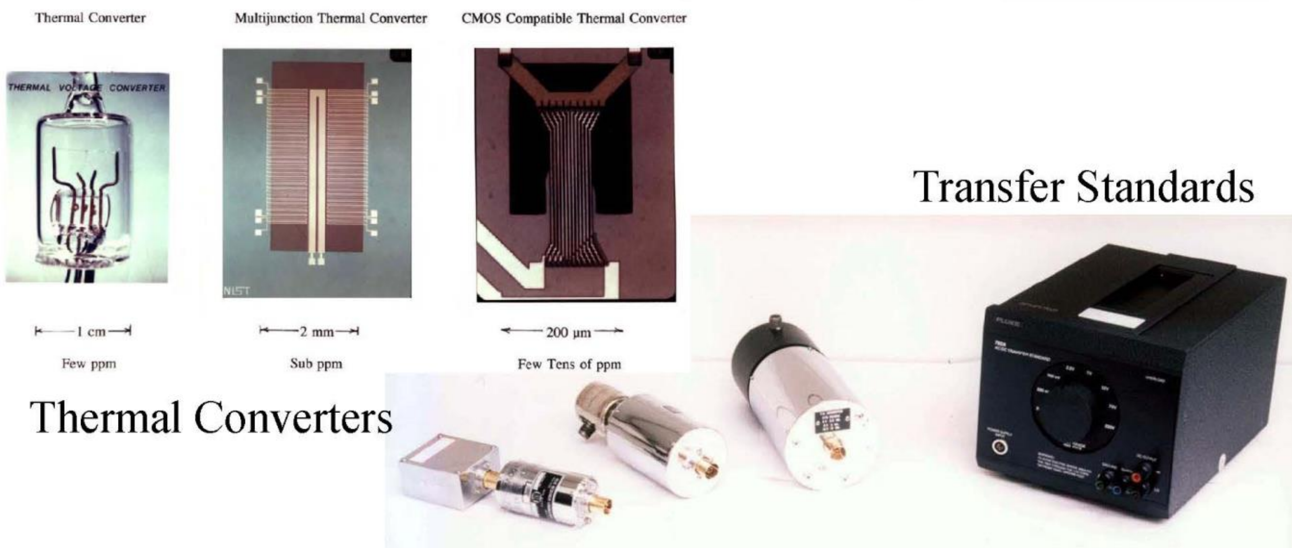
J. Przybysz, A. Worsham , S. P. Benz, and C. A. Hamilton, *Josephson Junction Digital to Analog Converter for Accurate AC Waveform Synthesis*, Pat. No. 5,812,078, Sept. 22, 1998.

S. P. Benz and C. A. Hamilton, *A pulse-driven programmable Josephson voltage standard,* Applied Physics Letters, Vol. 68, pp. 3171- 3173 (1996).

S. P. Benz, C J. Burroughs, C. A. Hamilton, and T. E. Harvey, *AC and DC Bipolar Voltage Source Using Quantized Pulses*, Pat. No. 6,236,344, May 22, 2001.

“Artifact” Detectors vs. “Quantum” Sources

- Conventional AC standards are RMS detectors
  - Thermally compare AC and DC voltage signals
  - “Artifact” standards have similar performance, but <u>NOT identical</u>



- Provide a source based on quantum effects

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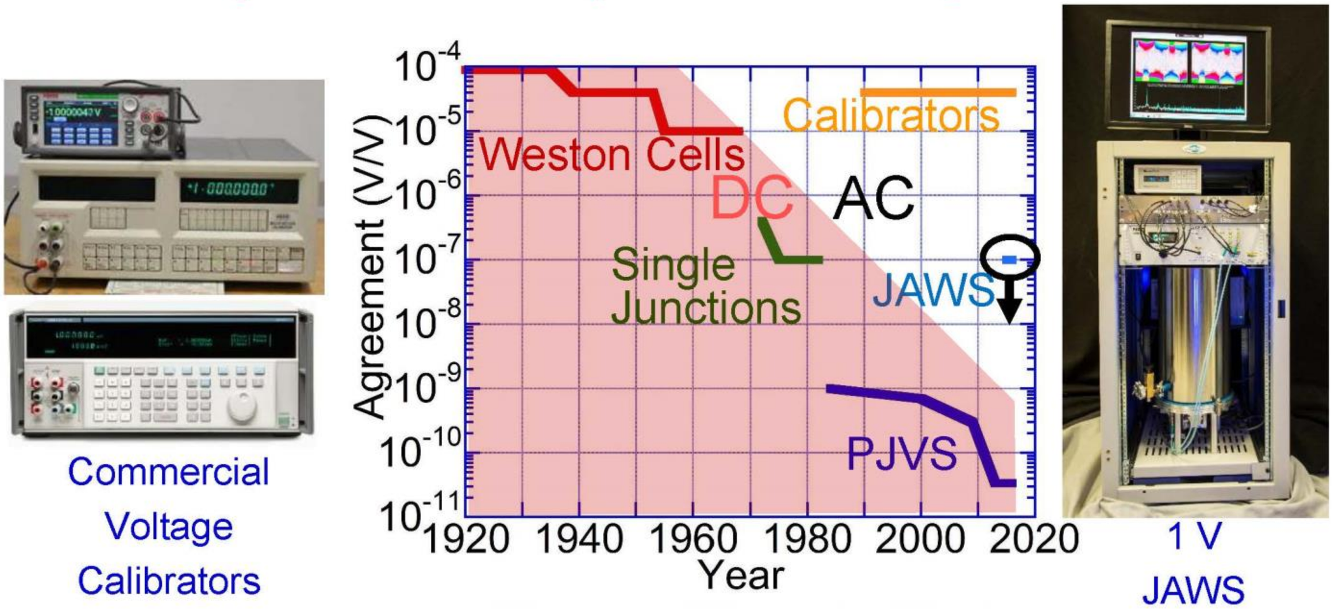
The measurement paradigm for ac voltage is based on rms detectors called thermal voltage converters that thermally compare ac voltages with dc voltages. The ac-dc difference response of these artifact standard detectors depends on frequency and amplitude. Their response is very reproducible and stable with respect to environmental conditions, and they achieve their lowest measurement uncertainties below a part in 10^6 at 1 V. RMS detection also offers the feature of low sensitivity to signals at other frequencies, such as emi.

In comparison, JAWS systems are intrinsically accurate ac voltage sources, not detectors. They have demonstrated three orders of magnitude improvement in measurement uncertainty over thermal converters for small signals below a few millivolts. With the recent achievement of the first 1 V JAWS systems, the first direct comparisons with 1 V calibrators has just recently become possible.

Replace Calibration Sources with Josephson Arbitrary Waveform Synthesizers



Statistical uncertainty below 10^{-7} for 1V JAWS intercomparisons

Systematic errors are ~ 10^{-6} for kilohertz frequencies

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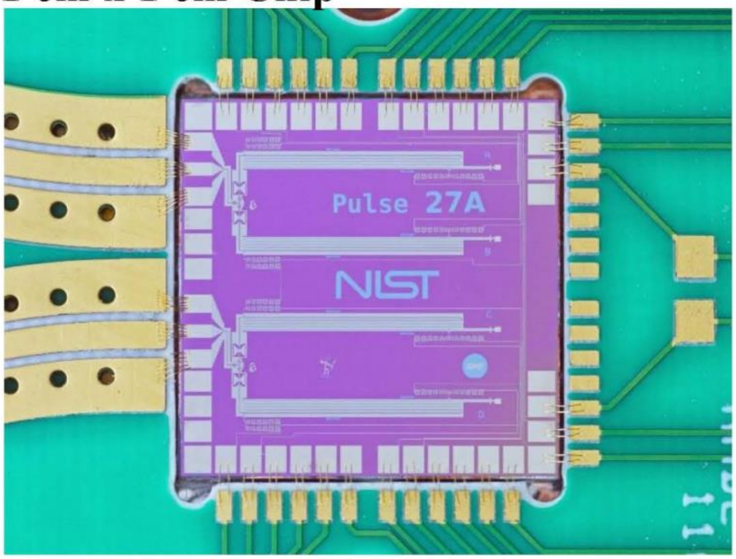
Voltage calibrators are also ac sources and they typically produce voltages with uncertainties of a few parts in 10^5. A recent comparison of 1 V signals synthesized by two JAWS systems agreed to within a measurement uncertainty of a part in 10^7. We expect this agreement to dramatically improve in the coming years.

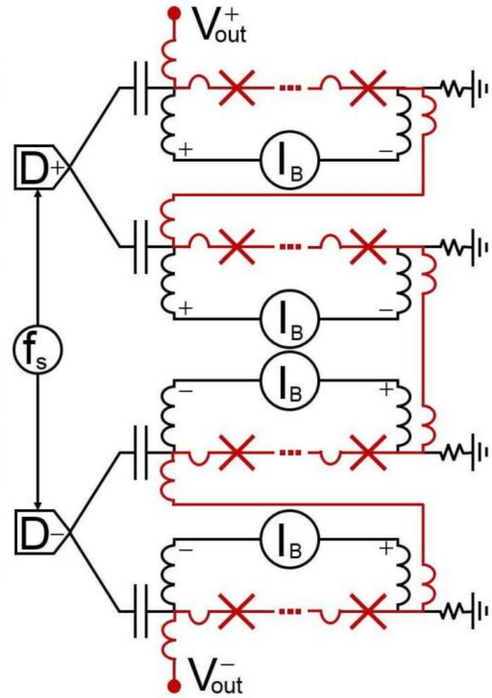
However, important and unwanted systematic errors are present in JAWS systems, and they can reach parts in 10^6 at a few kilohertz and the errors increase with increasing frequency. Research and development of JAWS circuits and JAWS bias techniques have the potential to further optimize the systems and reduce these systematic errors so they can be used at higher frequencies, eventually up to a few megahertz.

N. E. Flowers-Jacobs, A. Rüfenacht, A. E. Fox, P. D. Dresselhaus, and S. P. Benz, "2 volt pulse-driven Josephson arbitrary waveform synthesizer," 30th Conference on Precision Electromagnetic Measurements (CPEM 2016) Digest, presented 10–15 July 2016, Ottawa, Canada, p. 152.

1V RMS JAWS Chip and Circuit

1 cm x 1 cm Chip





- 51,240 total junctions in 4 arrays
- Pulses clocked at 15 GHz
- Controls **770 x 10^{12} quantum states/s**
- Measure spectra with a 24-bit ADC digitizer

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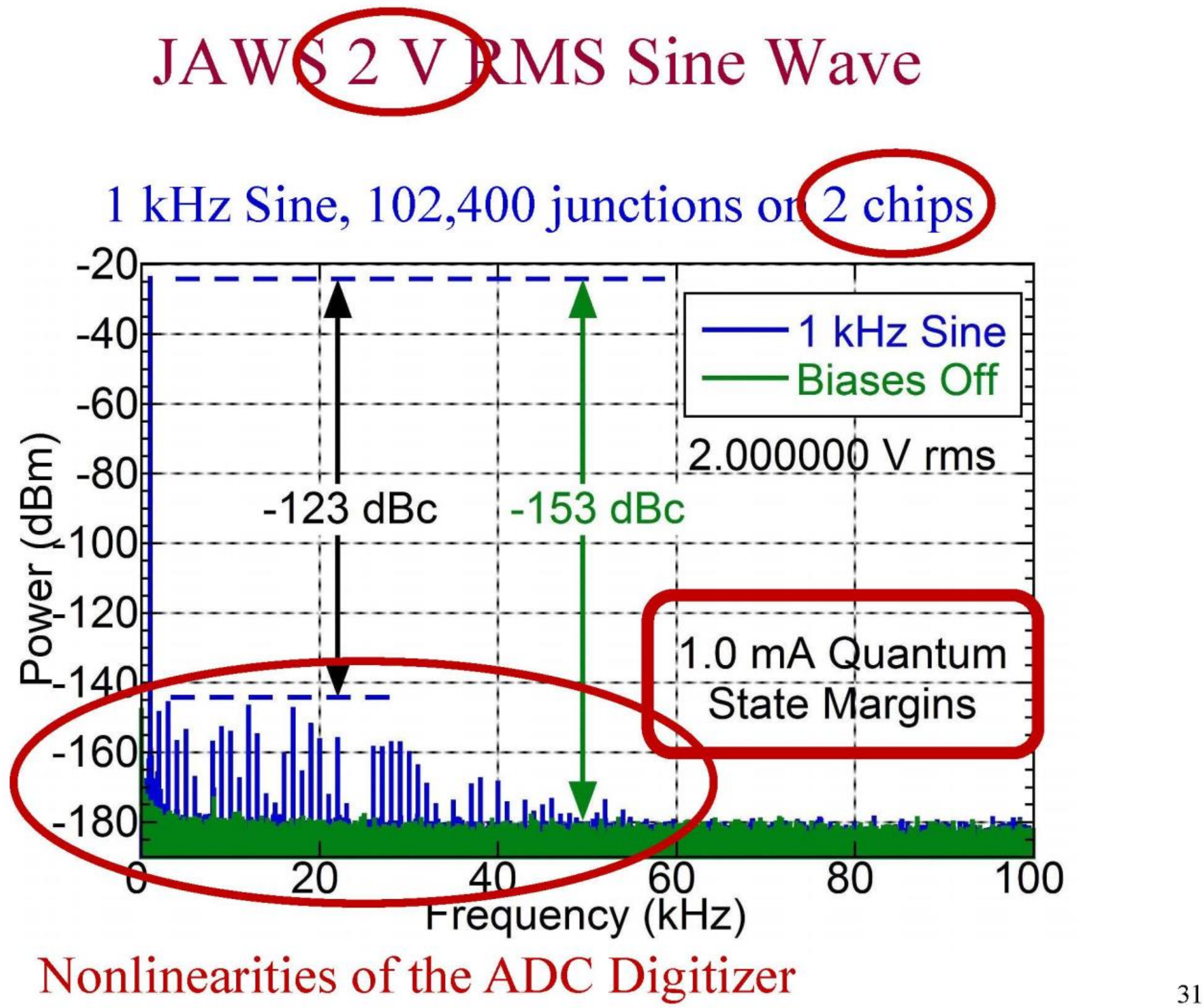
The second one-voltage JAWS chip contained 51,240 total junctions distributed equally into four arrays. Each pair of adjacent arrays was biased with a common high-speed pulse sequence that was divided with a broadband power splitter and ac coupled to each array through on-chip dc blocks. Similar to the PJVS circuit, the arrays are connected in series through inductive low-pass filters. When generating a 1 V sine wave by clocking the bias pulses **at 15 GHz, the JAWS circuit controls 770 trillion quantum states per second**. Thus many quantum states must be quickly controlled to produce quantum-accurate ac voltages with flat spots.

The following examples showing spectra and flat spots were measured with a 24- bit delta-sigma analog-to-digital converter with very low noise and very low intrinsic nonlinearity that produces minimal harmonic distortion.

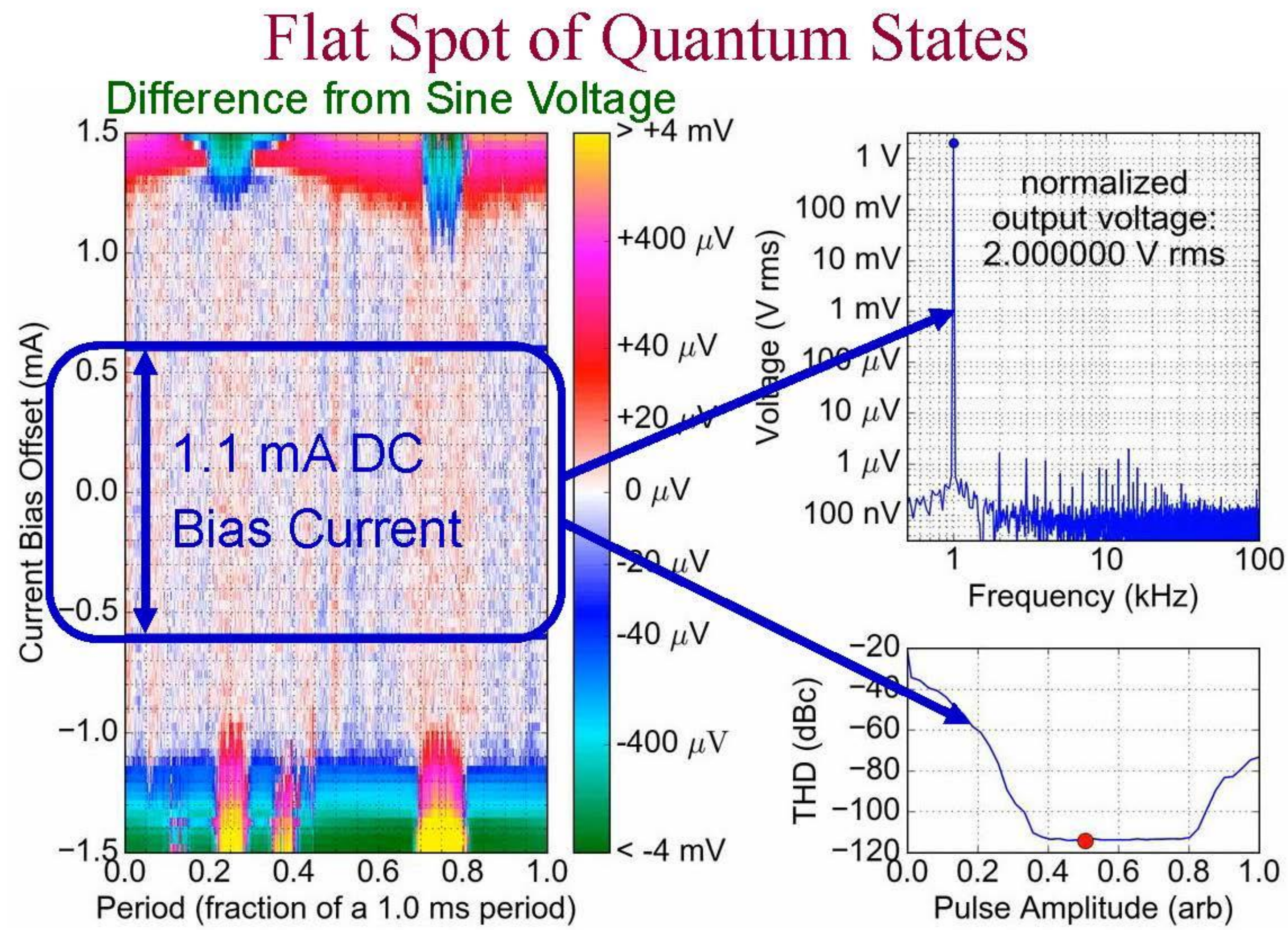
N. E. Flowers-Jacobs, A. E. Fox, P. D. Dresselhaus, R. E. Schwall, and S. P. Benz, "Two-volt Josephson arbitrary waveform synthesizer using Wilkinson dividers," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 6, pp. 1400207-7, Feb. 2016.



This is a spectrum of the first quantum-accurate synthesized waveform of 2 V rms amplitude. The spectrum remains unchanged, showing no harmonic distortion from the JAWS signal over a 1 mA current range (flat spot). The very small (more than 123 dB below the fundamental) and visible harmonic distortion is from measurement ADC, and there are measurement techniques other than the flat spot bias changes that are used to confirm this.

With this record high output voltage, this is the best spectrum with the lowest distortion that we have ever measured with a JAWS signal, probably because the ADC performs better at this higher voltage.

N. E. Flowers-Jacobs, A. E. Fox, P. D. Dresselhaus, R. E. Schwall, and S. P. Benz, "Two-volt Josephson arbitrary waveform synthesizer using Wilkinson dividers," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 6, pp. 1400207-7, Feb. 2016.



Nathan Flowers-Jacobs, 2016

A video showing the how these measured data vary with respect to these two bias parameters (pulse amplitude and current bias offset) is available at:

Quantum State Flat Spots https://www.nist.gov/pml/quantum-electromagnetics/superconductive-electronics/quantum-state-flat-spots

In this slide, we show the flat spots of all the quantum states of the 2 V dual-chip circuit as a function of the waveform period. In one plot we show how flat spot in voltage changes with a common current bias offset through all of the junction. The color shading indicates deviation from quantum accuracy as the difference in the voltage from the 2 V sine wave.

The spectrum in the upper right figure plots the data as measured over a ±0.55 mA range of current bias offset and its inset shows the nominal rms voltage. The spectrum shows the same minimal harmonic distortion of the digitzer as that shown in the previous slide.

The lower right figure, shows the flat spot as a function of the pulse amplitude of the total harmonic distortion (THD), measured also over the 1.1mA total offset range.

When the pulse amplitude is tuned to either edge of the THD flat spot, then the quantum-state shrinks with a bias offset that becomes smaller than the 1.1 mA range. This causes the voltage to deviate from the quantized value and an increase in harmonic distortion (and THD) that scales with the voltage deviation.

N. E. Flowers-Jacobs, A. E. Fox, P. D. Dresselhaus, R. E. Schwall, and S. P. Benz, "Two-volt Josephson arbitrary waveform synthesizer using Wilkinson dividers," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 6, pp. 1400207-7, Feb. 2016.

JAWS Applications

- Calibrations:
  - Voltage calibrators
  - AC-DC transfer standards
  - Thermal converters
- Characterize analog and digital electronics:
  - Gain, linearity, and distortion of analog-to-digital converters (ADCs) and amplifiers
- Impedance comparisons
- Primary thermometry and precision measurement of k_B
  - Johnson noise thermometry with QVNS

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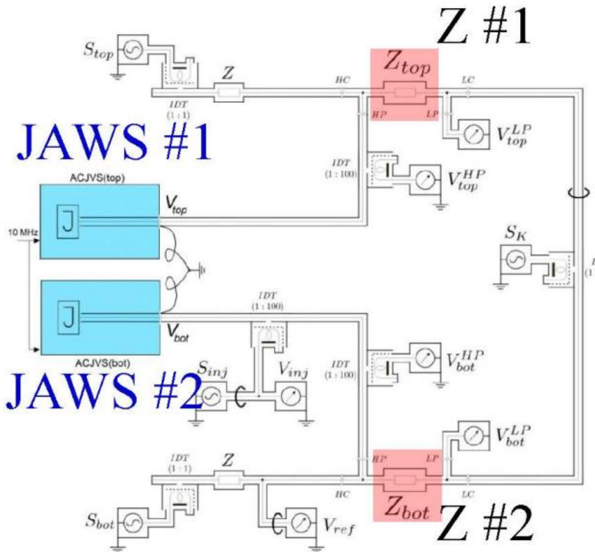
The JAWS applications are summarized here for ac voltage calibration of standards, converters and calibrators. The programmability and intrinsic accuracy of JAWS systems is also useful characterizing the gain and linearity of many other electronic instruments, like ADCs and amplifiers. Very recently, the two 1 V JAWS systems enabled the first application of quantum ac voltage metrology to impedance calibrations. The arbitrary waveform capability of JAWS has been exploited for over a decade to characterize the analog electronics used to measure Boltzmann's constant. I will briefly describe these two applications in the remaining slides.

Impedance Comparisons with 2X JAWS



- Voltage ratio can be set to any desired value and frequency
  - Don’t need different transformers to match different impedance ratios
  - Allows direct comparison between the decadal scale and AC-QHE, 10:12.906
- Any impedance in the complex plane can be calibrated
  - Because the phase between the JAWS sources can be adjusted to any value

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Traditional bridge measurement methods for electrical impedance rely on calibrated transformer ratios and inductive voltage dividers. Such methods require many unique hardware configurations, one for each impedance ratio and impedance type (typically 1:1, 10:1, or quadrature ratios). A METAS (Swiss Federal Institute for Metrology) and NIST collaboration demonstrated a new quantum-based system using a full digital bridge and two 1 V JAWS systems. The JAWS programmability and accuracy, for the first time, enable impedance ratio measurements over the full complex impedance plane at any ratio and without needing any hardware modifications. This bridge also allows impedance ratio measurements to be performed over a larger frequency range (50 Hz to 50 kHz) because the JAWS systems have perfect linearity, high resolution, and the ability to adjust their relative phases. The system also eliminates the need for component calibration because it doesn’t require calibrated transformers or inductive dividers such as those required for conventional impedance bridges. It will greatly simplify dissemination of the impedance scale because it can directly compare any complex impedance (R, L, or C) to the dc quantum Hall resistance value (12.906 kΩ), or to any other complex impedance.

F. Overney et al., "Josephson-based full digital bridge for high-accuracy impedance comparisons,” *Metrologia*, vol. 53, p. 1045, June 2016.

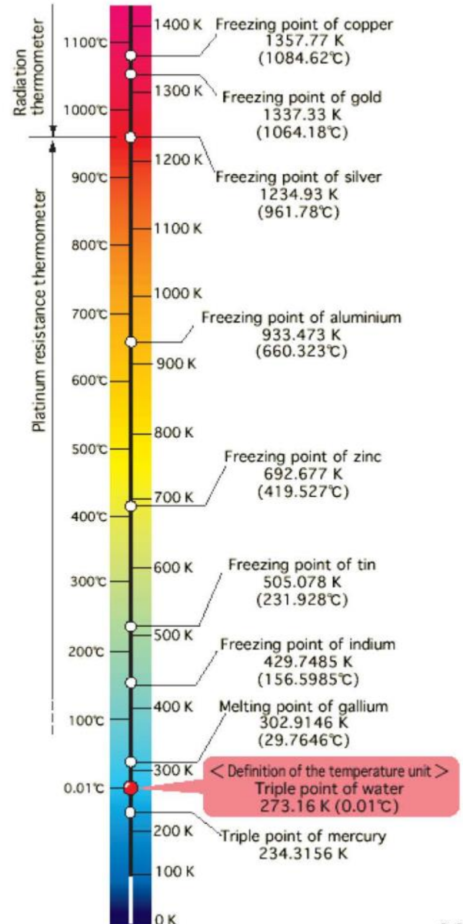
Quantum Voltage Noise Source

35

Finally, I'll briefly describe the quantum voltage noise source (QVNS) that is being developed as a primary temperature standard and is currently being used for an electronic measurement of Boltzmann's constant.

Artifact Standards in Thermometry

- ITS-90 scale of fixed points
- K defined by triple point of water
- Scale is designed to "represent" thermodynamic temperature
- Interpolation required for temps between fixed points



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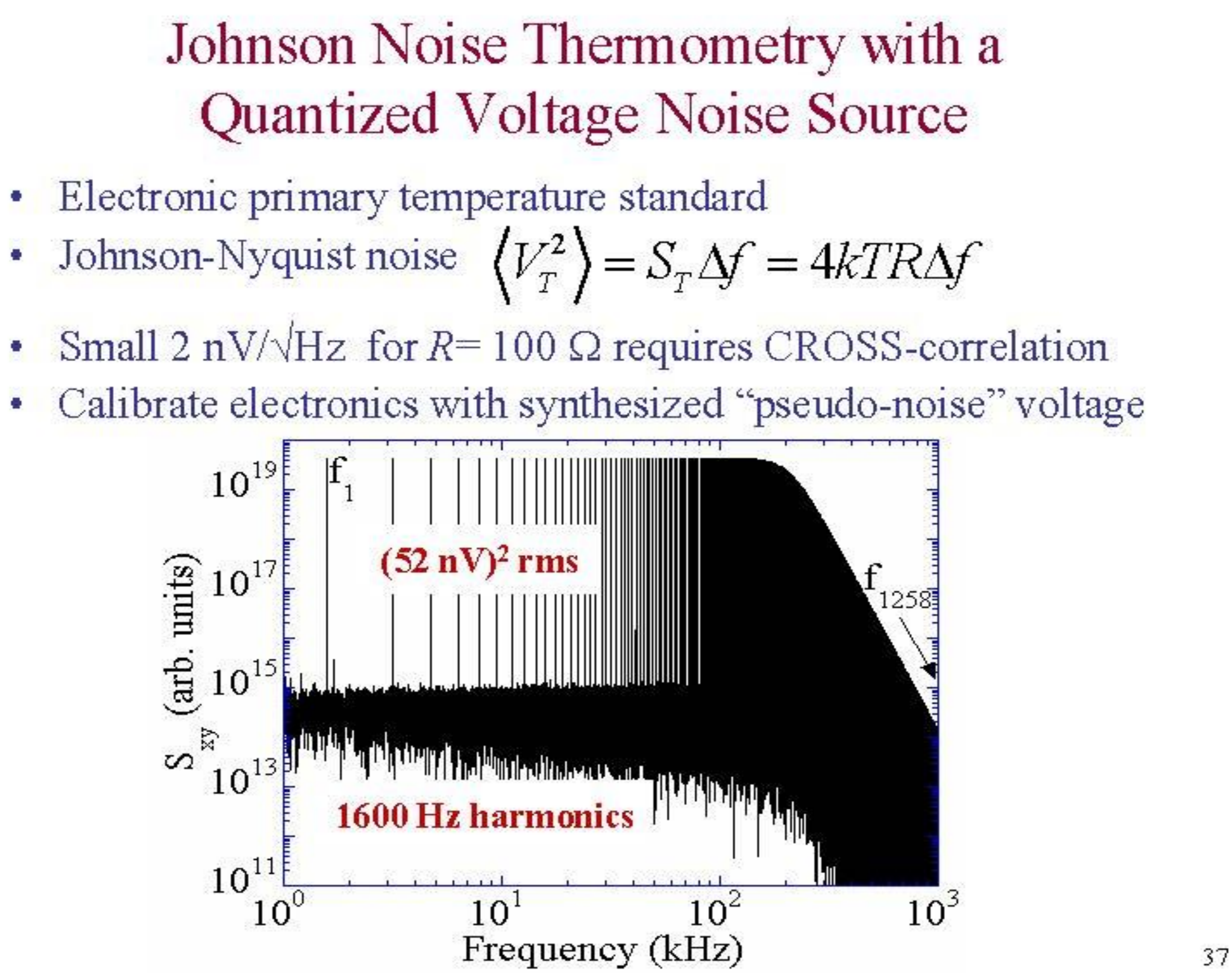
The Kelvin, one of the seven base SI units, is defined by an artifact standard, namely the triple point of water, whose temperature is set to 273.16 K. In addition, there are fixed-point artifact standards for 14 defined temperatures covering the International Temperature Scale of 1990 (ITS-90) from 0.65 K to 1,357.77 K. In 2000, additional points were added that extend the scale to millikelvin temperatures. The scale is designed to "represent" thermodynamic temperature and temperatures between the fixed points must be interpolated. A reproducible, scalable, primary thermodynamic standard is needed and an electronic one is being developed that is based upon quantum voltage synthesis and Johnson noise thermometry (JNT).

NIST first developed its QVNS-JNT system to investigate deviations of the International Temperature Scale of 1990 (ITS-90) from thermodynamic temperature at temperatures in the range of 505 K – 933 K, which overlaps the ranges of both acoustic gas-based and radiation-based thermometry. The success of these measurements led to its use as an "Electronic Kelvin" that links the SI kelvin to quantum-based electrical measurements, which produced an electronic determination of Boltzmann's constant.

The international metrology community plans to fix the value of the Boltzmann constant, which would then redefine the Kelvin as part of a larger effort to link all units to fundamental constants. This approach would be the most stable and universal way to define measurement units, essentially eliminating all remaining artifact standards, such as those based on physical objects or substances like triple points.

D. R. White and J. Fischer, "The Boltzmann constant and the new kelvin," Metrologia, Vol. 52, No. 5, pp. S213–S216 (Aug. 2015). doi:10.1088/0026-1394/52/5/S213



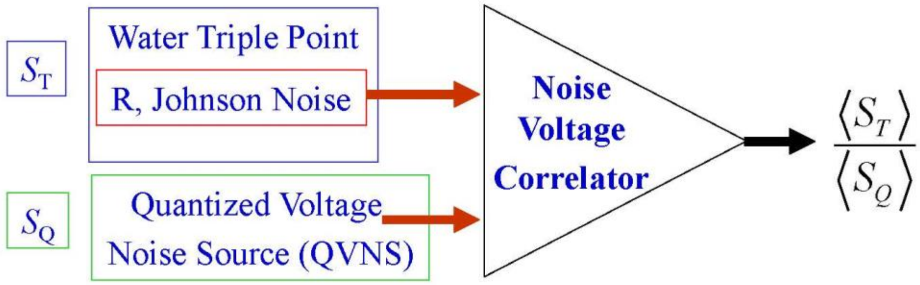
A number of researcher teams are developing JNT precision measurement systems and voltage synthesizers whose waveforms are based on the quantized voltage pulses generated by Josephson arrays. The QVNS developed at NIST is one of these synthesizers. This intrinsically accurate voltage calibration source is the heart of an electronic-based JNT, which determines temperature from the Johnson-Nyquist noise of a resistor. Typically, a 100 Ω resistor at the triple point of water is used to produce an extremely small ~1.2 nV/Hz½ noise voltage. Since this voltage is comparable to the noise of typical low-noise amplifiers, cross-correlation electronics must be used to measure the small voltage noise signals, and is typically measured over a 600 kHz bandwidth and integrated for many days in order to reduce the statistical measurement uncertainty below a part in 10^5. The QVNS synthesizes accurate, reproducible multitone waveforms that are intentionally designed to be comparable to the white noise of the resistor noise source. These pseudo-noise waveforms are constructed by summing many sine waves of different harmonic frequencies that have identical amplitudes but random relative phases.

QVNS quantum-accurate signals are used to characterize the amplitude-frequency response and the nonlinear behavior of electronic components, such as the multiple amplifier stages and the analog-to-digital-converters.

S. P. Benz, J. M. Martinis, S. W. Nam, W. L. Tew, and D. R. White, "A new approach to Johnson noise thermometry using a Josephson quantized voltage source for calibration," in: Proceedings of TEMPMEKO 2001, the 8th International Symposium on Temperature and Thermal Measurements in Industry and Science, B. Fellmuth, J. Seidel, and G. Scholz, Eds., Berlin: VDE Verlag, April 2002, vol. 19, pp. 37-44.

Johnson Noise Thermometry

- Compare thermal and electrical noise powers



- Temperature is determined by noise ratio, measured resistance R, fundamental constants h, k and R_k, and QVNS constants D, N, f_{clock} and M)

$$T = \frac{h}{k}\frac{\langle S_T \rangle}{\langle S_Q \rangle}\left(\frac{R_k}{R}\right) f_{clock}\frac{D^2 N^2 M}{16}$$

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Similar to the Watt balance that compares mechanical and electrical power to measure Plank’s constant h and the kilogram, the NIST QVNS-JNT system measures very small electrical noise in a resistor that resides in water triple point cell. “Johnson noise” is created by the random motion of electrons and the generated noise voltage is directly proportional to temperature. The electronic devices measuring the noise are calibrated with voltage signals synthesized by the QVNS, whose accuracy derives from the quantized pulses and the quantum mechanical behavior of the Josephson effect. This unique feature enables the JNT system to match electrical power and thermal-noise power at the triple point of water, and assures that JNT systems with comparable quantum-based voltages will produce identical results.

Johnson Noise Thermometry Applications

- Electronic determination of Boltzmann's constant, k

$$\frac{k}{h} = \frac{\langle S_T \rangle}{\langle S_Q \rangle}\left(\frac{R_k}{R}\right)\frac{f_{clock}}{T_{TPW}}\frac{D^2 N^2 M}{16}$$

  – Uncertainty results
    - 12×10^{-6} (5ppm Type A in 10 days) NIST USA, 2010
    - 4×10^{-6} (3ppm Type A in 34 days) NIM China, 2015
    - (9ppm Type A in 7 days) AIST Japan, 2016

  – Goal $< 3\times10^{-6}$

- Electronic primary thermometer
  – Perfect voltage and temperature linearity

    ⇒ Eliminate fixed-point "artifacts

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The Boltzmann constant relates energy to temperature for individual particles such as atoms. The accepted value of this constant has been based primarily on a 1988 NIST measurement performed using acoustic gas thermometry, with a relative standard uncertainty of less than 2 parts per million (ppm). The technique is highly accurate but the experiment is complex and difficult to perform. To assure that the Boltzmann constant can be determined accurately around the world, scientists have been repeating the gas-based measurements and also developing different measurements with improved uncertainty.

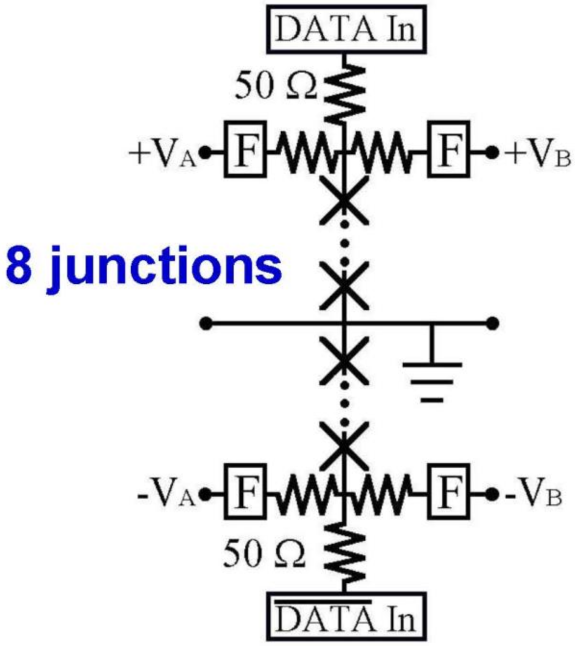
The first QVNS-JNT measurement of Boltzmann's constant in 2010 found agreement with the conventional value to within an uncertainty of 12 parts in 10^6. However, 10 days of continuous signal integration was required to reduce the statistical uncertainty (cross-correlate out the amplifier noise) to 5 parts in 10^6. Unfortunately, there combined uncertainty was much larger due to a systematic error caused by variations in the measured frequency response. The measured value k/h should be independent of frequency (another flat spot!), as well as with respect to pulse amplitude and resistor value. In 2015, NIM's (National Institute of Metrology, China) QVNS-JNT system yielded a measurement with a combined uncertainty of 4 parts in 10^6 after 34 days of integration. AIST's (National Institute of Advanced Industrial Science and Technology, Japan) JNT system uses quantum-based voltage waveforms synthesized by a direct digital synthesizer. Their system has a achieved a statistical measurement uncertainty of 9 parts in 10^6 in 7 days of integration. Improvements are being made to all three system with the expectation to produce reduced measurement uncertainties by July 2017, with the goal of a combined uncertainty of 3 parts in 10^6.

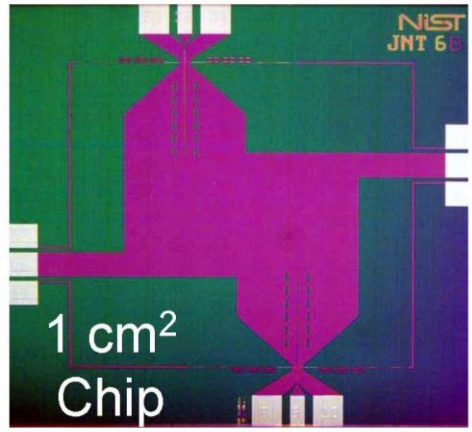
S.P. Benz, et al., "An Electronic Measurement of the Boltzmann Constant," Metrologia, vol. 48, pp. 142-153, March 2011.

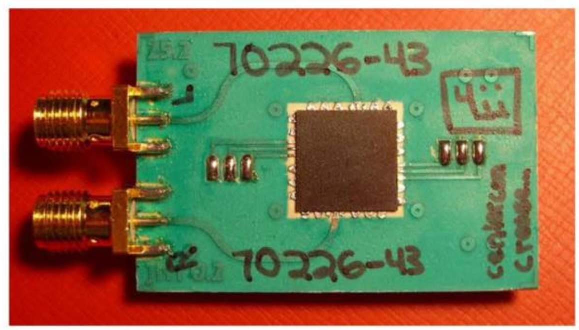
Jifeng Qu, S. P. Benz, A. Pollarolo, H. Rogalla, W. Tew, R. White, and Kunli Zhou, "Improved electronic measurement of the Boltzmann constant by Johnson noise Thermometry," *Metrologia*, vol. 52, pp. 441-451, June 2015. stacks.iop.org/Met/50/441, doi:10.1088/0026-1394/50/5/441

C. Urano et al., "Johnson Noise Thermometry Based on Integrated Quantum Voltage Noise Source," *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, pp. 1800305-5, Apr. 2016.

Quantum Voltage Noise Source QVNS



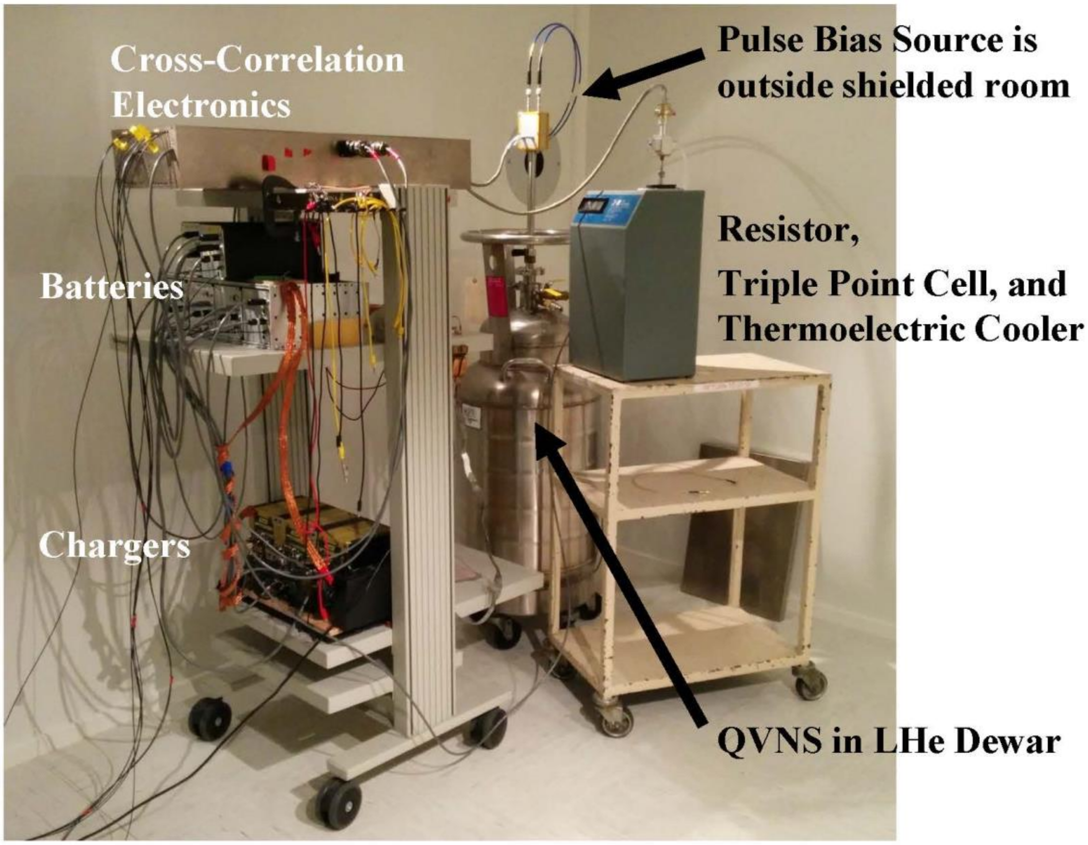




Cryopackage

The QVNS is a low-voltage realization of the JAWS. Since the amplitude of the pseudo-noise waveforms are small (<1 μV peak), the QVNS only requires a few Josephson junctions, typically 8 junctions are used. A typical 1cm x 1 cm chip consists of two 4-junction arrays connected in series to a common ground. Two sets of three-wire leads transmit the grounded differential signal to each of the two cross-correlation measurement channels.

NIST Johnson noise thermometer



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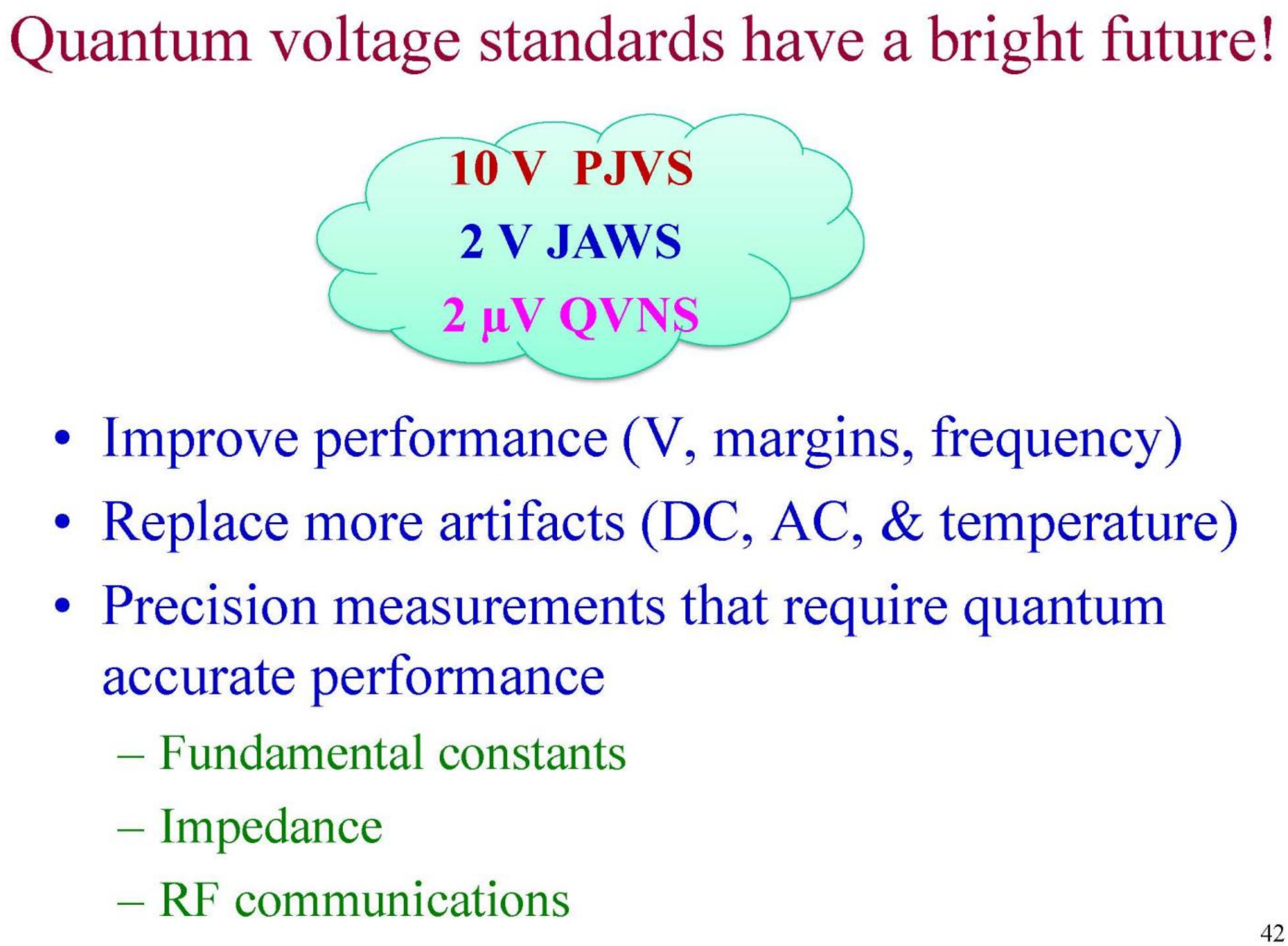
The instrument is simpler and more compact than that of other methods for measuring the Boltzmann constant. This picture shows the measurement configuration inside an rf shielded room, including (1) the thermoelectric cooler containing the triple point that holds the sense resistor, (2) the 30 L liquid helium storage dewar containing the cryoprobe that holds the QVNS (pulse bias source is external to the room), and (3) the cross-correlation measurement system, which is powered by sets of Li-ion batteries alternately switched between charging and operation.

A. Pollarolo, H. Rogalla, A. E. Fox, K. J. Coakley, W. L. Tew, and S. P. Benz, "Improved spectra aberration in Johnson noise thermometry," 30th Conference on Precision Electromagnetic Measurements (CPEM 2016) Digest, presented 10–15 July 2016, Ottawa, Canada, pp. 331-2. DOI: 10.1109/CPEM.2016.7540777.



In conclusion, the Josephson effect has played an important role in creating quantum-based voltage standards. The perfectly quantized pulses produced by Josephson junction, combined with the zero-resistance properties of superconducting wires and enabled the development of quantum-based voltage standards. Josephson voltage standards have successfully replaced the electrochemical cell as the dc standard for dc voltage and have demonstrated measurement systems with improved performance for ac voltage, power, impedance and primary thermometry.

Superconductive Electronics Group in Boulder, Colorado

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Thank you from our Superconductive Electronics Group in Boulder, Colorado.