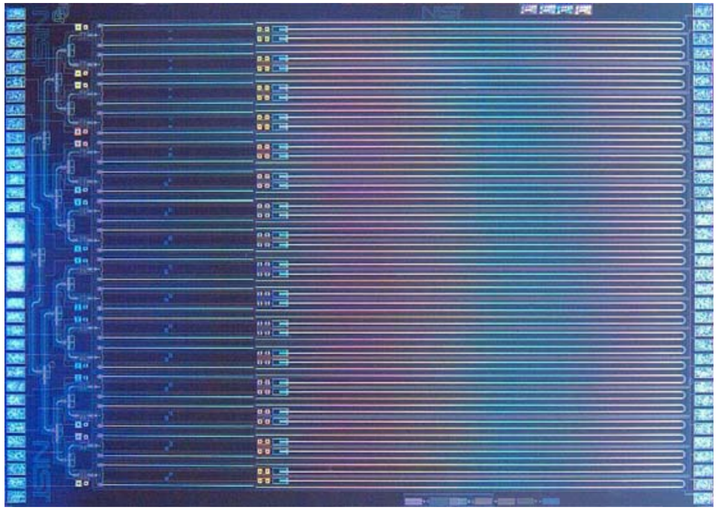
Measurement Capabilities of AC Josephson Voltage Sources



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Encuentro Nacional de Metrología Eléctrica 2009
18-20 de noviembre
- Electromagnetismo
- Temperatura y Propiedades Termofísicas
- Tiempo y Frecuencia

Outline

- Conventional DC JVS review
- Programmable JVS
  - DC and AC applications
  - Stacked Arrays and New Technology
- Pulse-driven ACJVS
  - RMS measurements of thermal converters and transfer standards
  - Arbitrary waveform synthesis
  - ADC measurements
- Quantum Standards for Precision Thermometry

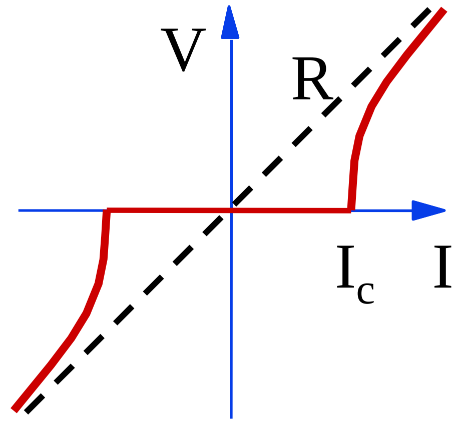
Junctions with Intrinsically Stable Voltages

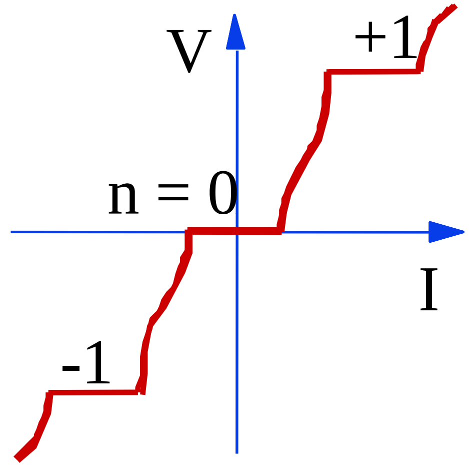
- DC Characteristics
  - Critical Current I_c
  - Normal Resistance R
- AC Characteristics
  - Sinusoidal drive frequency, *f*
  - Constant-Voltage Steps

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

  - Flux quantum

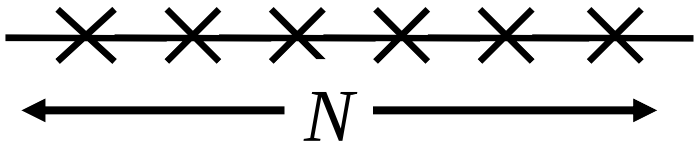
$$\Phi_0 = \frac{h}{2e} = \frac{2.07\,\mu V}{GHz}$$



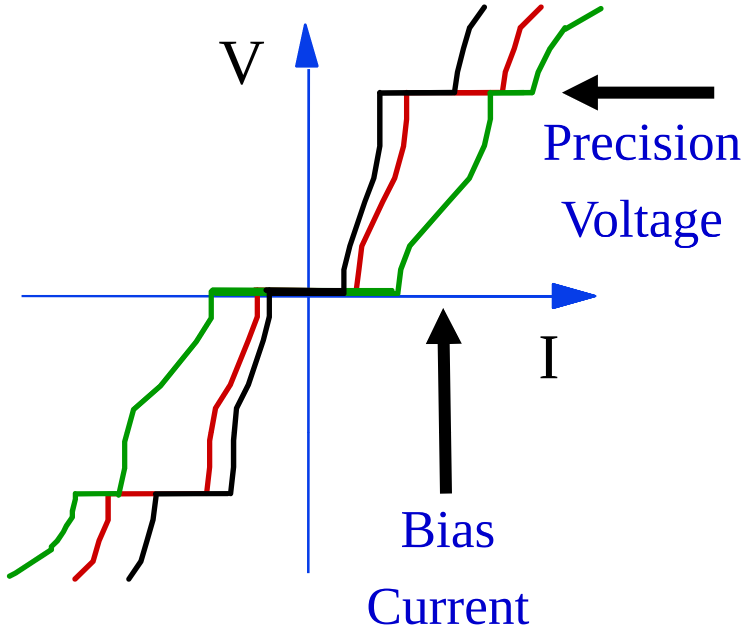


Practical Output Voltage Requires Arrays

- Desired output voltage: 1 to 10 V
- Single junction voltage: typically 20-100 µV
- Need large series arrays



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

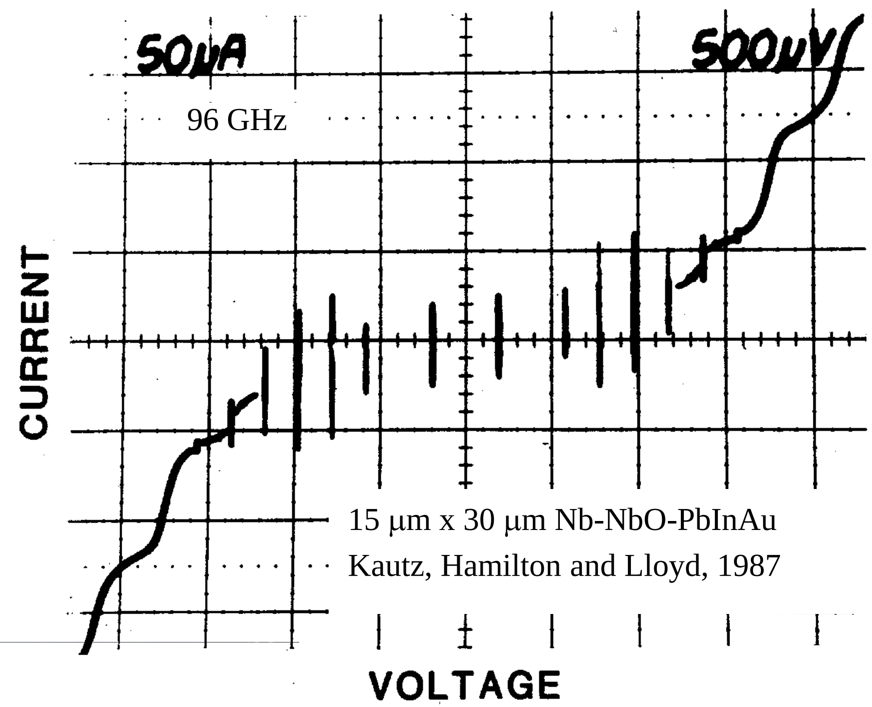


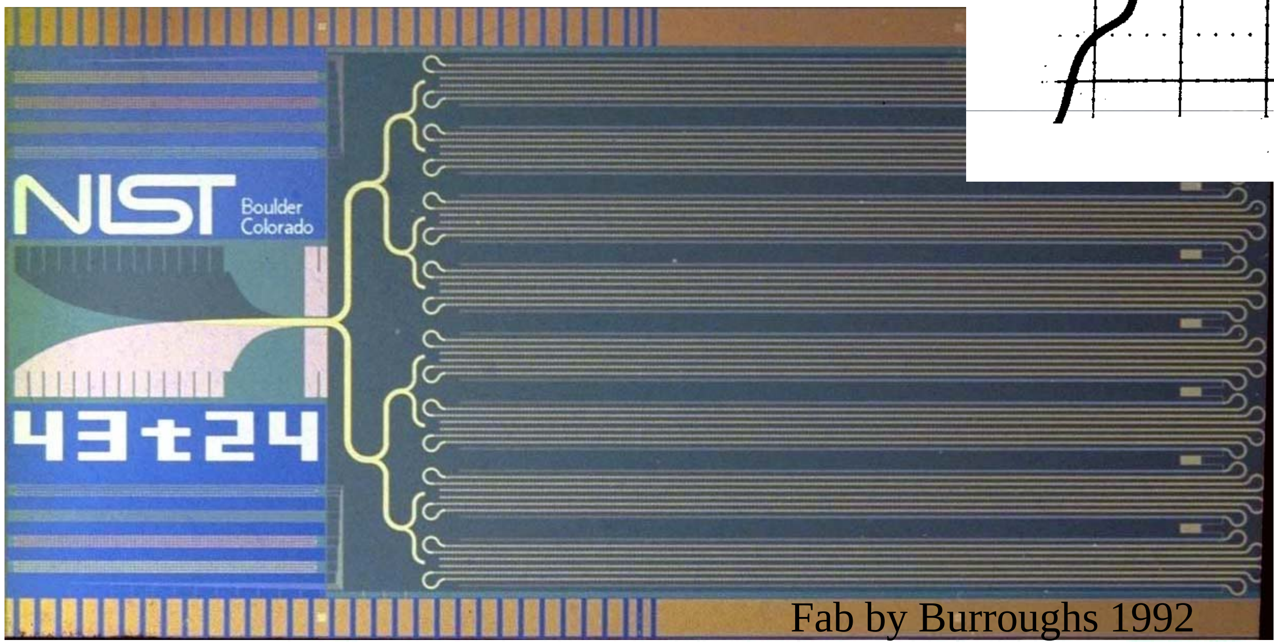
- Uniform junctions
- Uniform microwave power

Practical Voltages require Long, Uniform Series arrays

10 V Conventional Josephson Voltage Standards

- Zero-crossing steps (Levinsen '77)
- Chaotic junction dynamics (Kautz '81)
- Microwave design & uniformity (Niemeyer & Hinken, PTB '83-84)
- First 1 V chip (Niemeyer, Hinken & Kautz, 1984)
  - 1,474 Pb-alloy JJs at 90 GHz
- First 10 V chip (Lloyd & Hamilton'87)
  - 14,184 Nb-Nb2O5-PbInAu JJs, 72 GHz





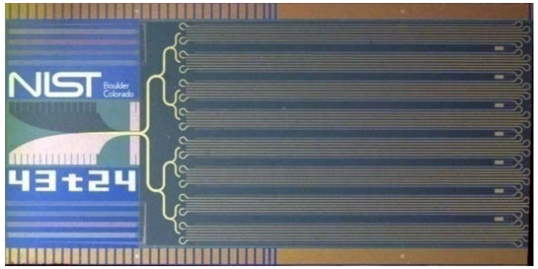
75 GHz drive frequency

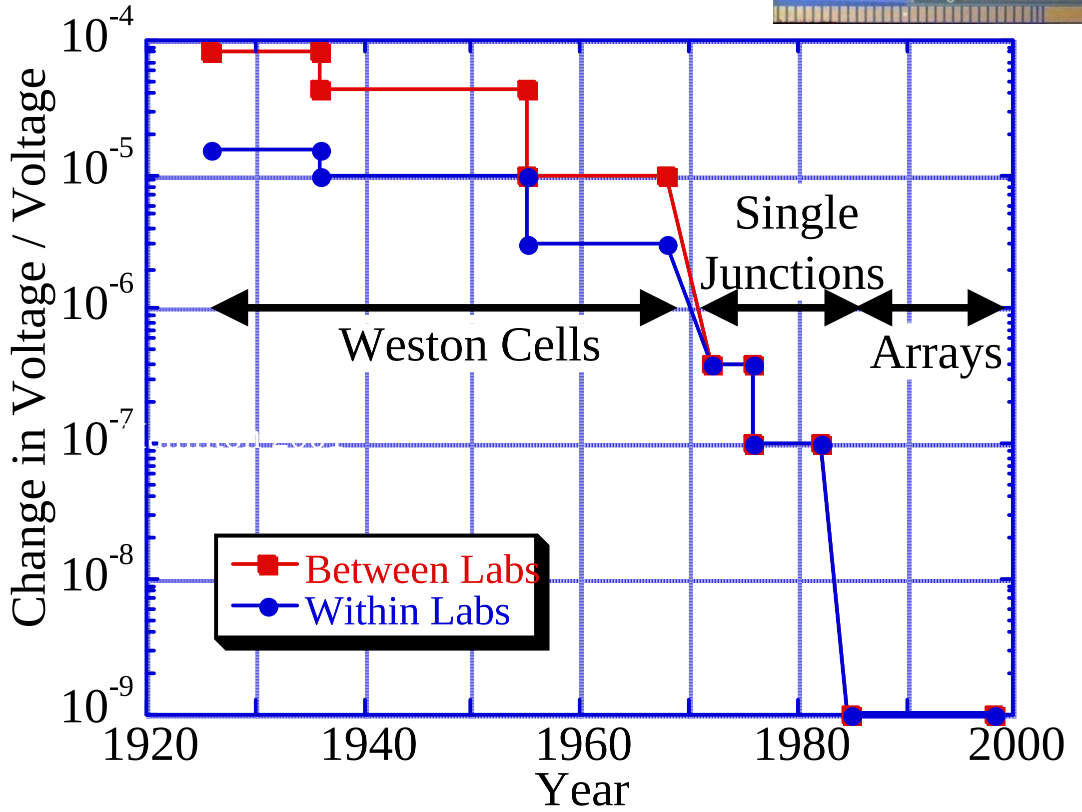
20,208 Nb-Al2O3-Nb junctions

Quantum-based Standards Replaced Artifacts

Weston Cells

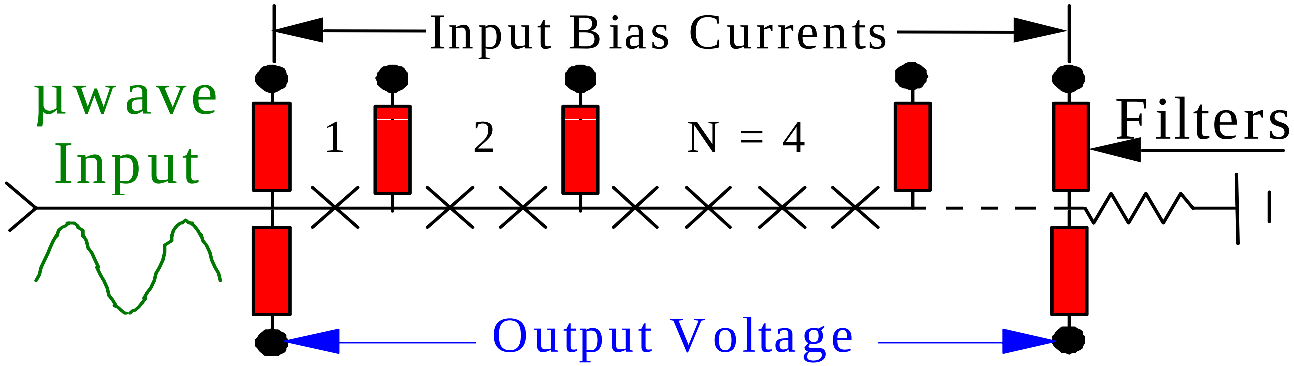
Josephson Arrays





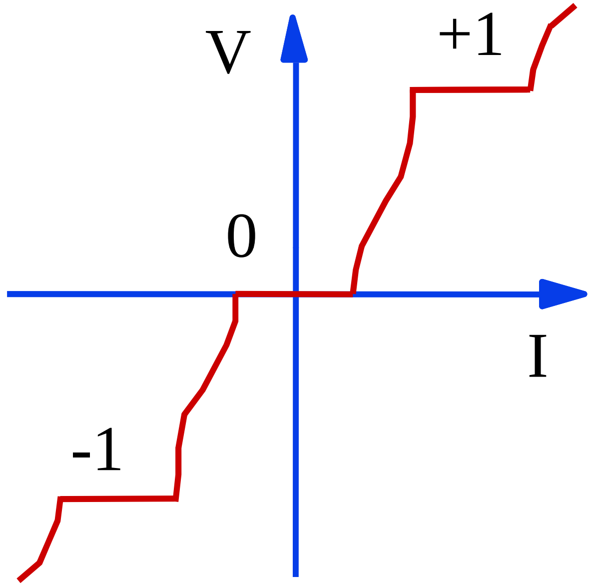
From Bachmair, 1988 and Hamilton, 1998

Programmable Josephson Voltage Standard



- Binary sequence array

  (Hamilton, Burroughs and Kautz, 1995)
  - Non-hysteretic junctions
  - Uses 3 voltage levels, but only needs 2 voltage levels

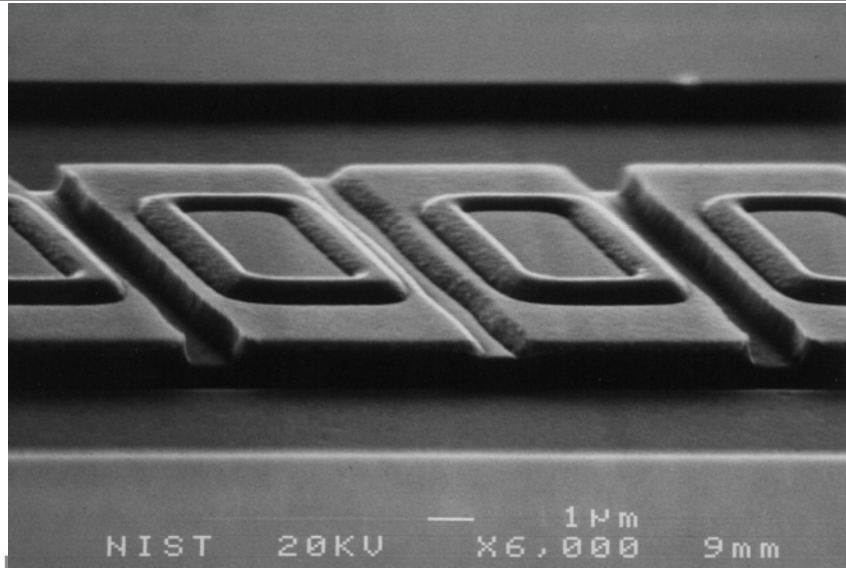


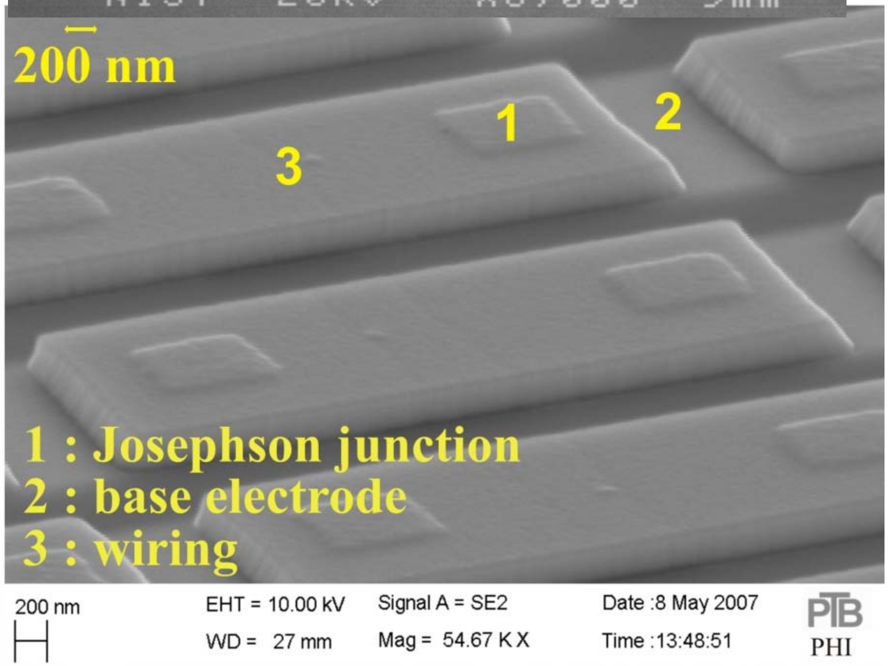
- Voltage of each segment is:

$$V = N \Phi_o f$$

Junction Types & Materials

- Superconductors
  - Nb
    - $T_c = 9$ K
    - Typically operate at 4 K
  - NbN
    - $T_c = 15$ K
    - 10 K cryocooler operation
- Junctions & Barriers
  - SNS Normal metal
    - Barriers: AuPd, TiN_x, HfTi
  - SINIS Adds two insulators
    - Barrier: Al_2O_3–Al–Al_2O_3
  - SCS Conducting Insulators
    - Barriers: Mo_xSi_{1-x}, Nb_xSi_{1-x}





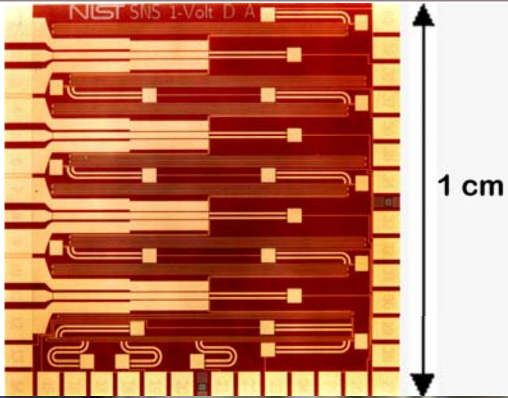
Programmable JVS DC Applications

Intrinsically stable dc steps

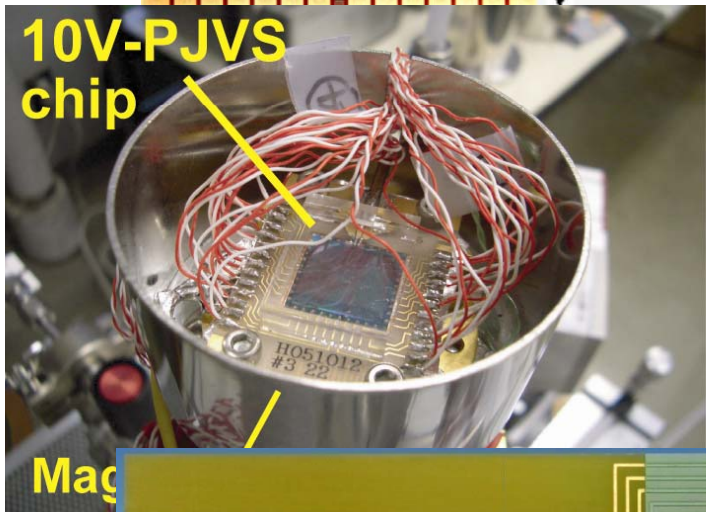
±1 to 10 V programmable

Desired current range >1 mA

< 1 μs settling time

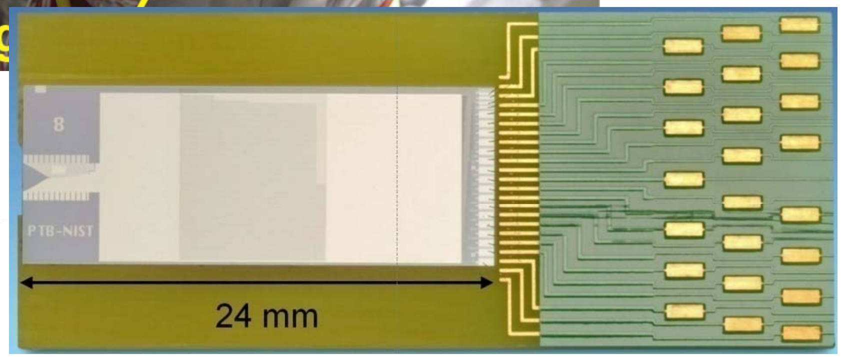


NIST
16GHz
1-5V



AIST
16GHz

PTB-NIST
70 GHz



DC Applications:

Calibrate:

Zener References

Voltmeters

Precision Measurements:

Watt balance (NIST, METAS, BIPM, LNE)

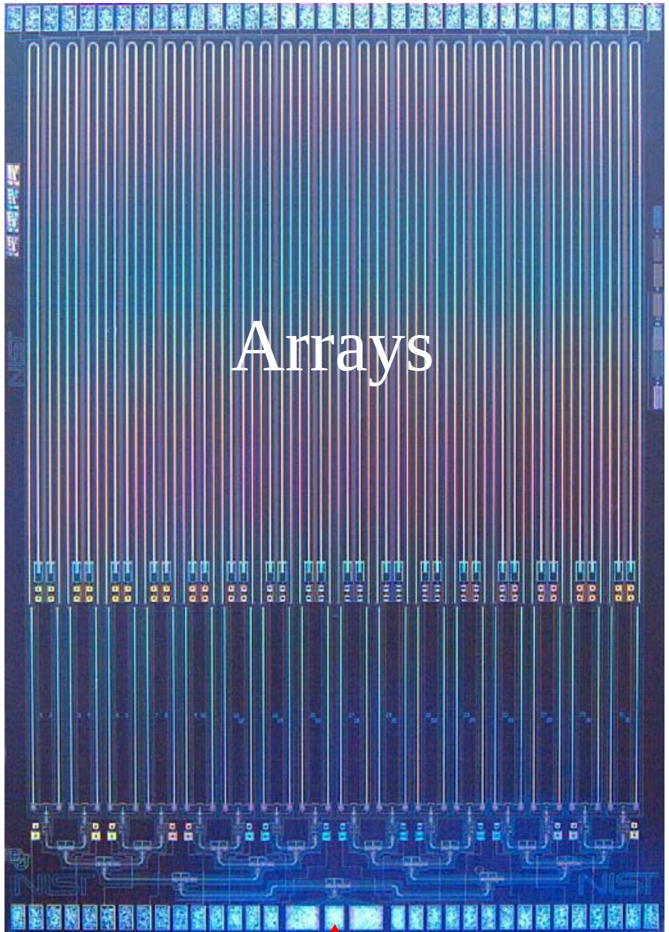
Quantum Metrology Triangle

$R_K – e – K_J$

NIST 10V PJVS Results

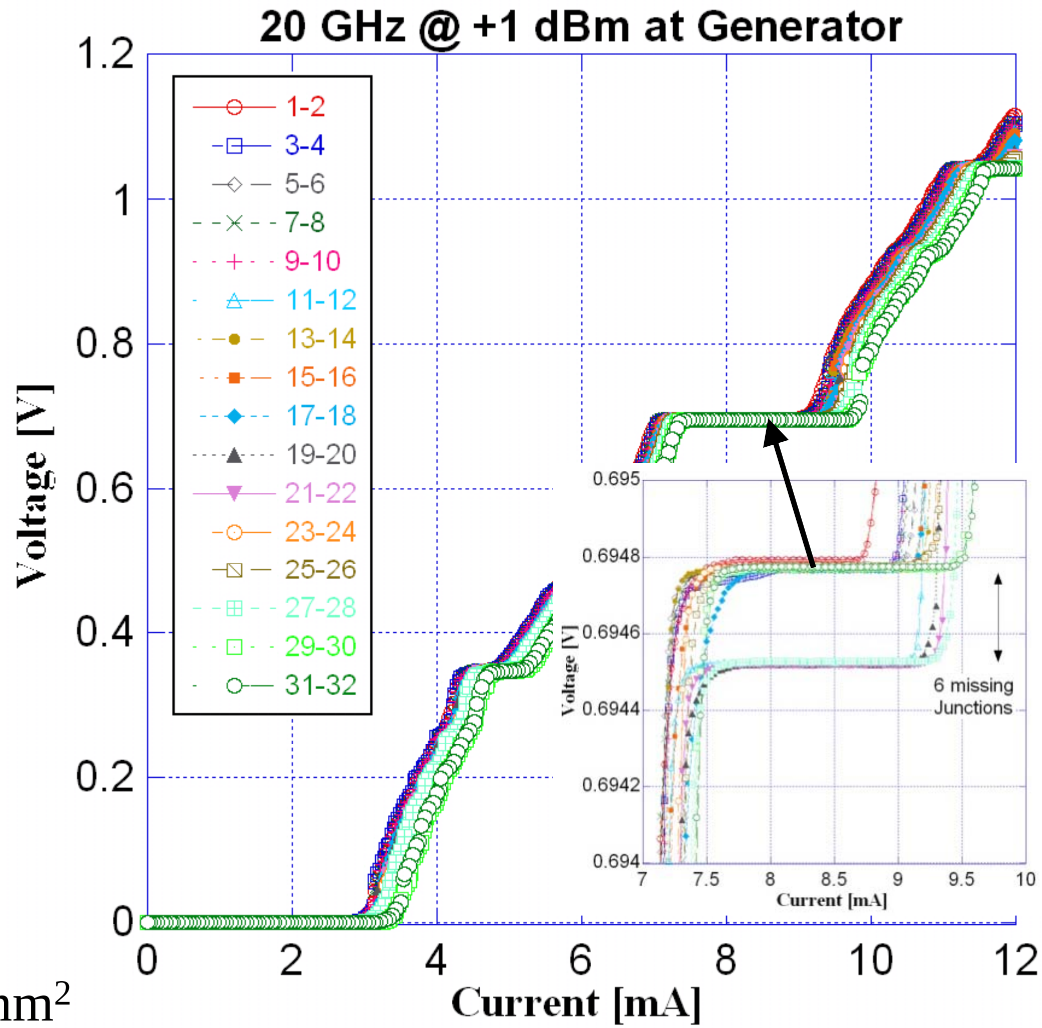
32-way split, 339,264 junctions, 20 GHz bias

Input/Output Taps



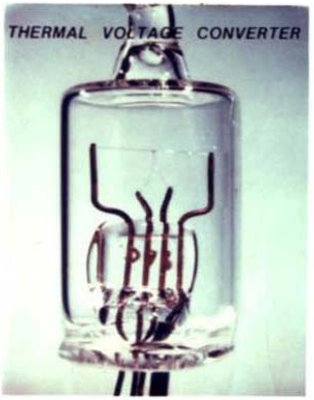
12x17 mm^2

Microwave Input & Splitters

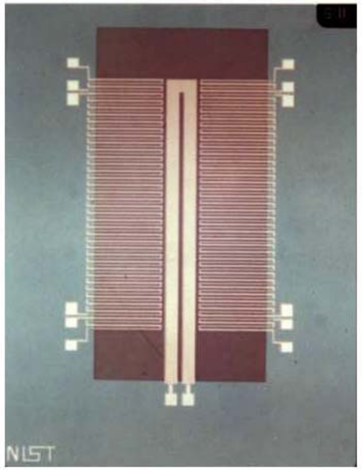


Conventional AC Standards

Thermal Converter



Multijunction Thermal Converter



⇤— 1 cm —⇥

⇤— 2 mm —⇥

Few ppm

Sub ppm

RMS detectors

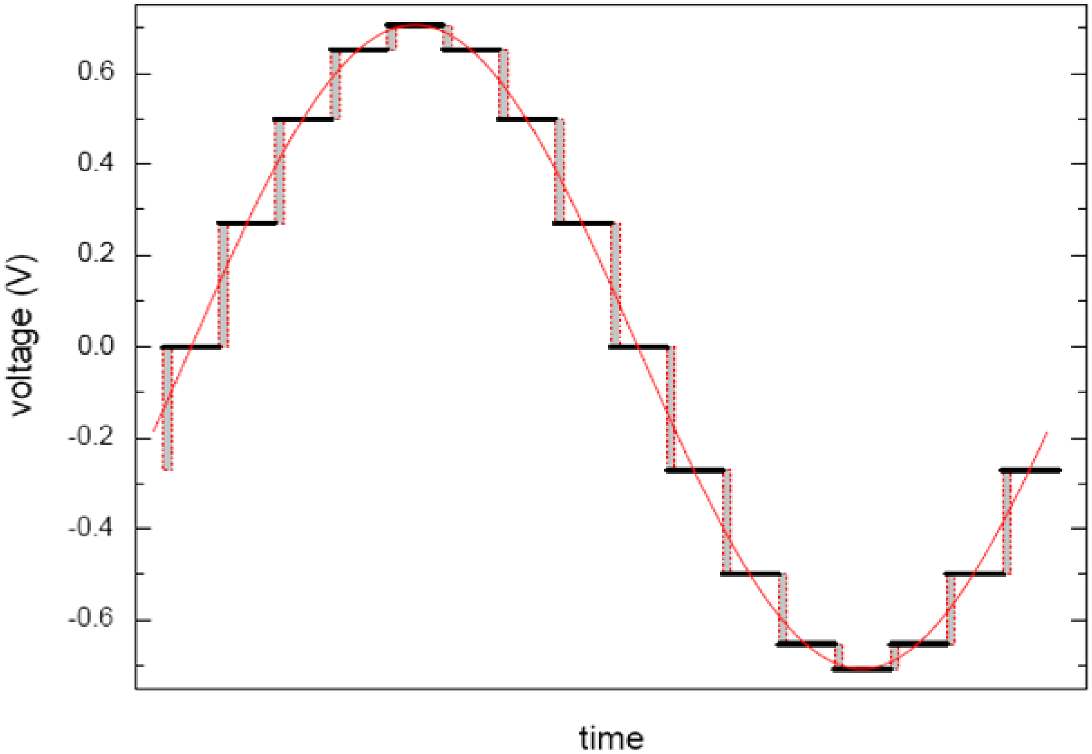
Calibrate sine wave signals

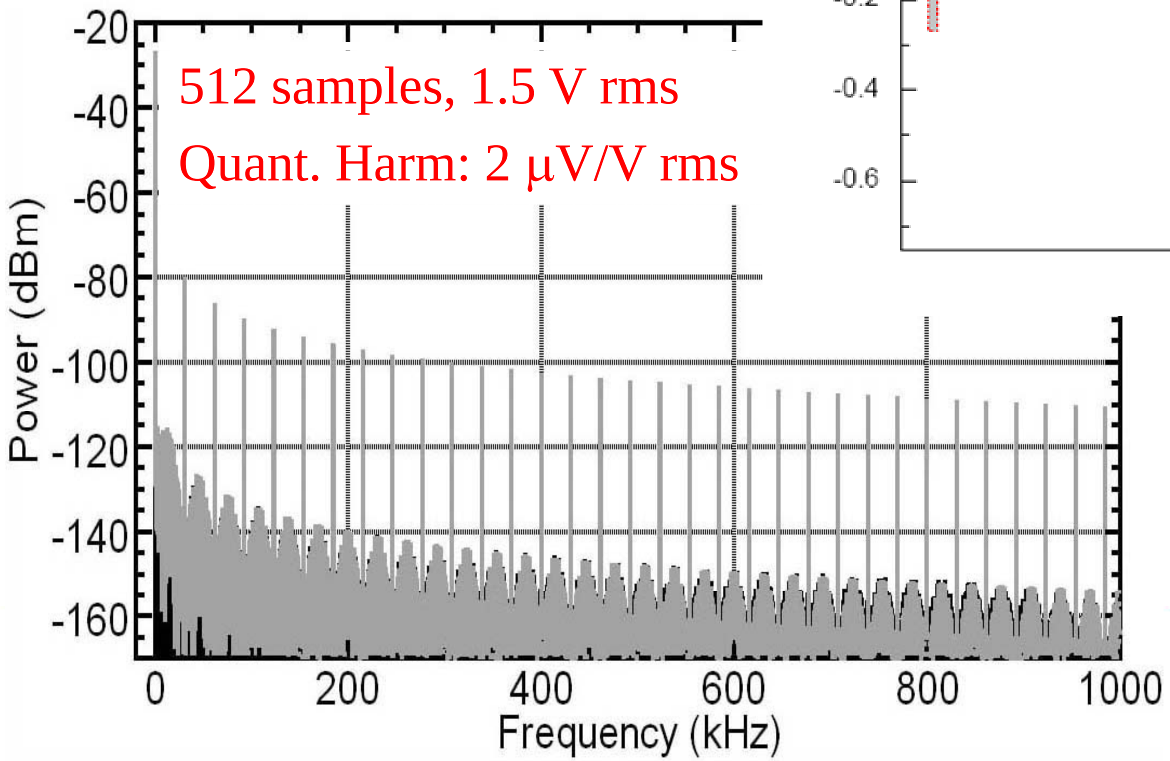
1 V rms typical amplitude

Optimized for various frequency ranges 50 Hz to > 10MHz

ACPJVS as a Multi-bit DAC

- Step-approximated waveforms by switching between voltages
- NOT intrinsic standard for ac synthesis





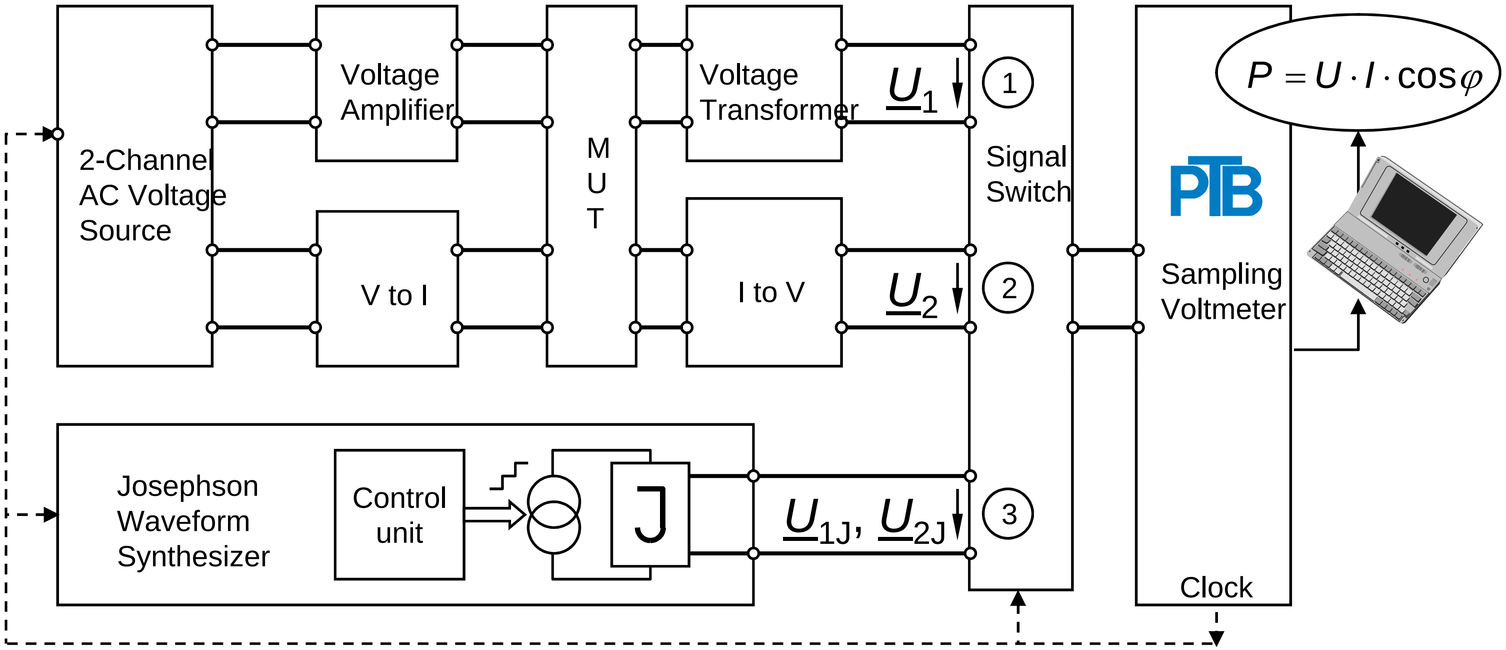
- Quantization harmonics
  - Contribute to rms
  - Depend on number of samples

AC PJVS

- RMS voltage reference for low frequencies < 1 kHz
  - Uncertainty limited by transitions (a few nanoseconds) of bias electronics
    - < 0.5 µV/V at 50-60 Hz
    - > 2 µV/V at 1 kHz
  - THIS is an “ADJUSTABLE” AC voltage standard
    - It can appear to have stable, reproducible RMS voltages that are not quantum accurate
- AC-Reference voltages with digital “differential” sampling
  - Measure voltage difference between ACPJVS and a waveform generator, including sine waves
  - 60 Hz AC power – “Quantum Watt” (NIST system operating in May 2007)
  - Uncertainty 0.1 µV/V at 50-60 Hz (dominated by secondary ref)
- Various systems and approaches at various NMIs and EU PROVOLT program

ACPJVS for Power Meter Calibrations

- PTB Approach
  - Direct sampling
  - Calibrate sampling voltmeter
- NIST Approach
  - Differential sampling
  - Calibrate divided-down voltages



System measurement uncertainties reduced below 1 µV/V

L. Palafox et al, *IEEE Tr. Instrum. Meas.* **56**, Apr. 2007

B. Waltrip et al, *IEEE Tr. Instrum. Meas.* ***58*** p. 884, Apr. 2009

Pulse-driven Josephson DAC
AC Josephson Voltage Standard (ACJVS)

Josephson Arbitrary Waveform synthesizer

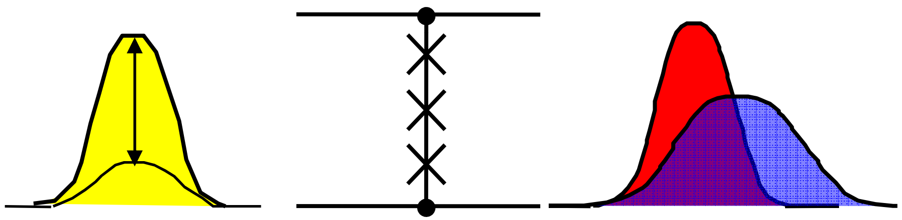
- Quantum-based voltage source
- Arbitrary waveform synthesis
- <u>Calculable</u> accurate voltage
- Applications
  - AC & DC voltage standards
  - Programmable source for broadband ADCs & amplifiers
  - Precision audio, rf and noise references

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

Josephson Pulse Quantizer

Variable Input

Quantized Area h/2e



Co-invented in 1995 by NIST & Westinghouse researchers,

H. Worsham, J.X. Przybysz, S. Benz, and C. Hamilton

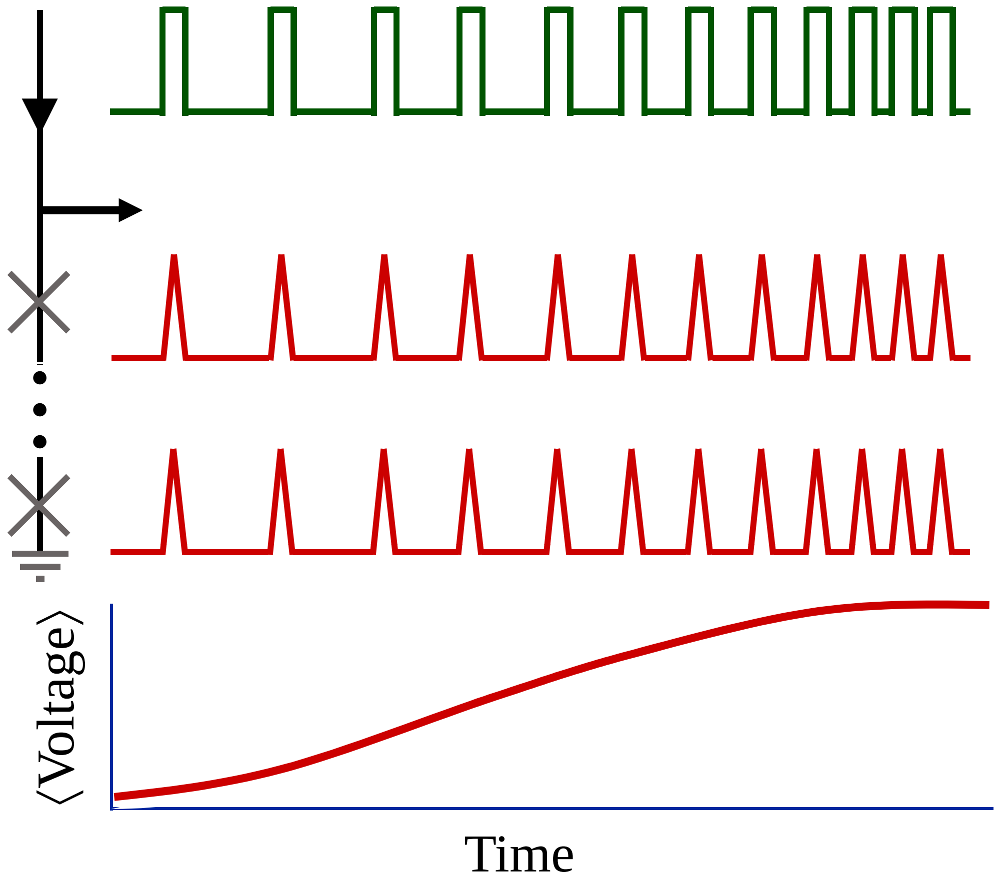
Digital-to-Analog Conversion

Digital Code Bit Pattern 0010001000100100100100101010101011

Commercial Semiconductor
Pulse Pattern Generator

Array Output Voltage

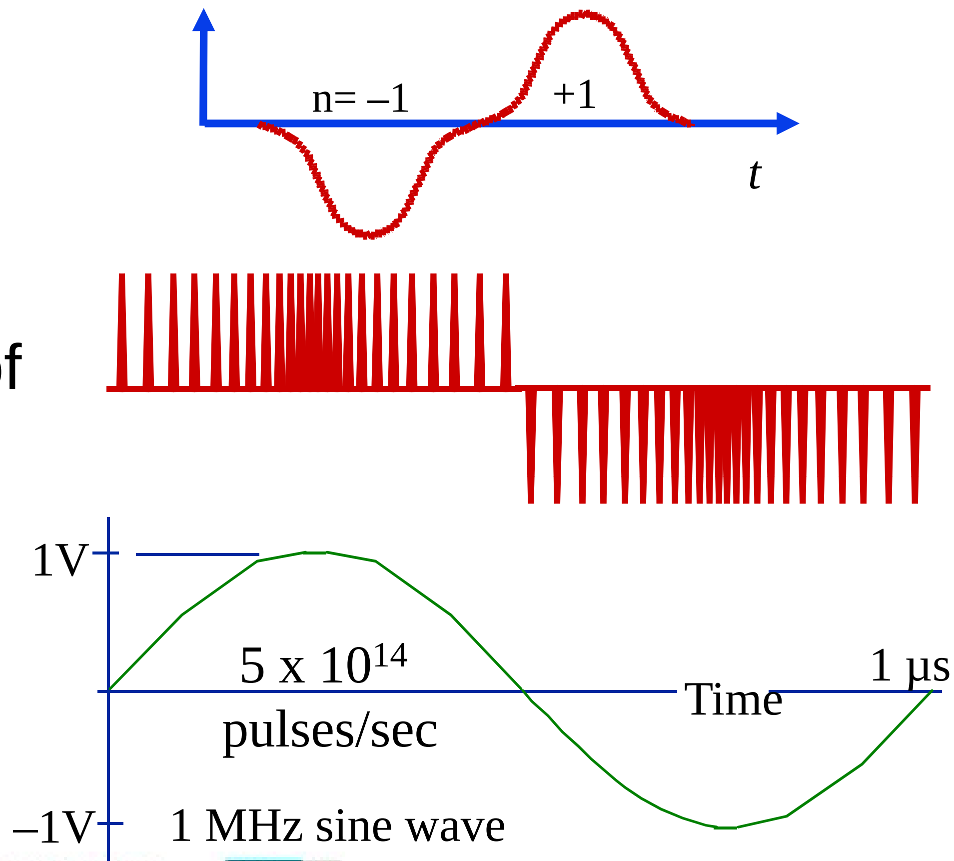
Time-integrated
Average Voltage



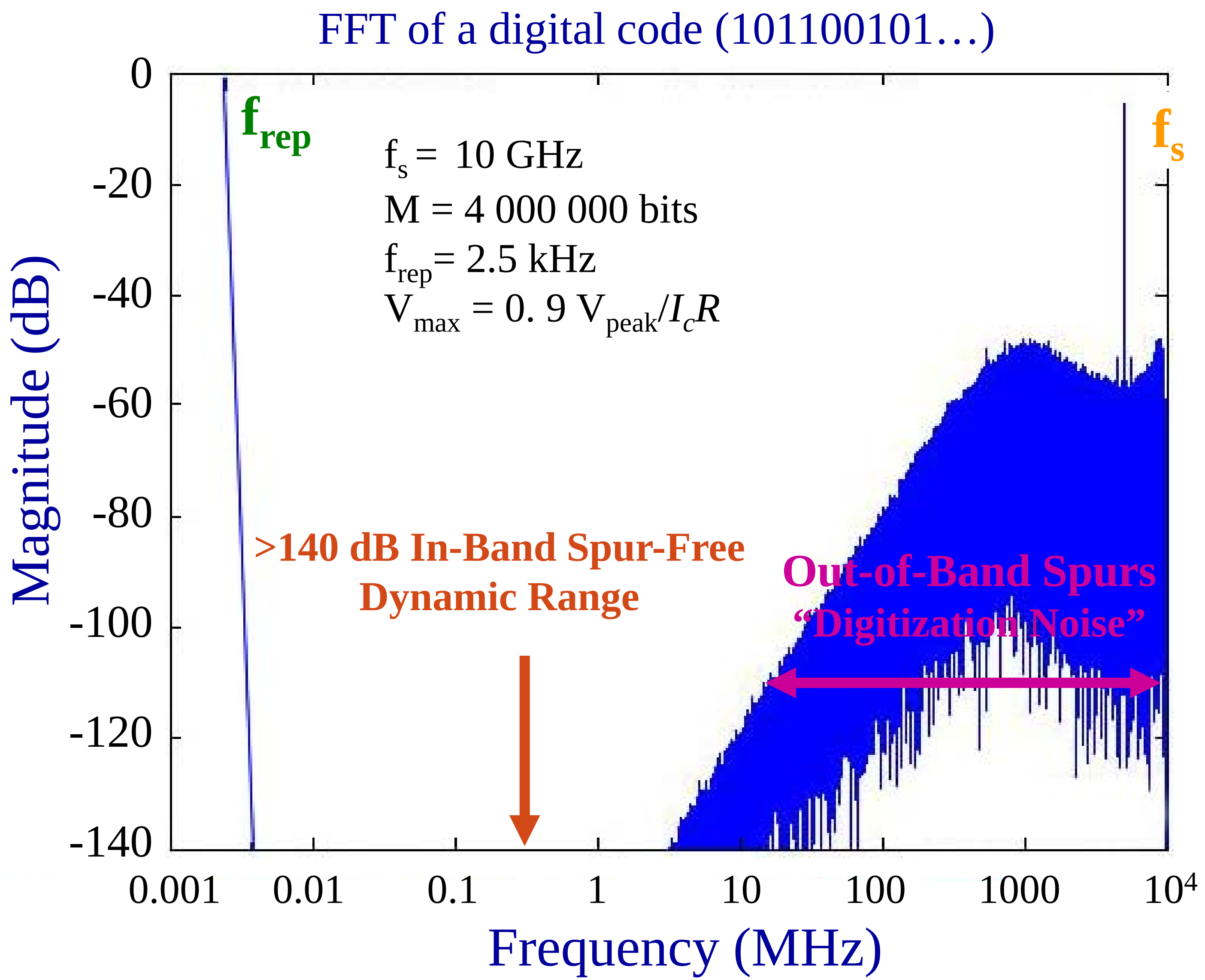
Bipolar Digital Waveform Synthesis

- Two Approaches
  - Single-bit, 2-level, 10 GHz drive, combined with 15 GHz
  - 3-level bitstream generator (developed by VSL Netherlands and Sympuls Gmbh)
- Direct control of JJ pulses of both polarities
- Timing and polarity precisely determine the voltage waveform and accuracy

Perfectly Quantized Pulses



Delta-Sigma Digital-to-Analog Conversion



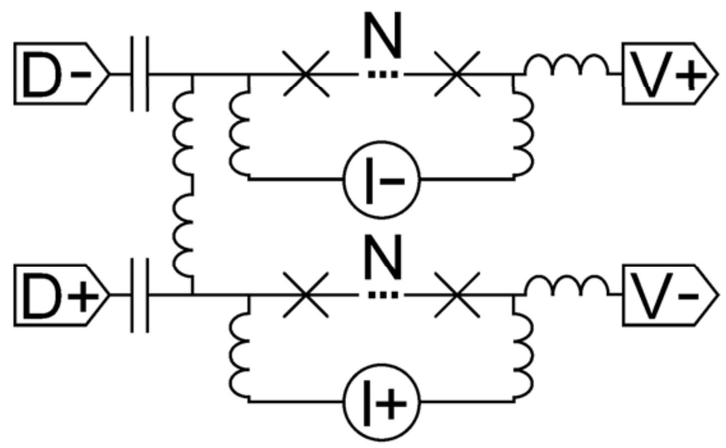
- Sampling Or Clock frequency, $\mathbf{f_s}$
- Pattern repetition frequency

  $\mathbf{f_{rep}} = f_s/M$
- Signal frequency

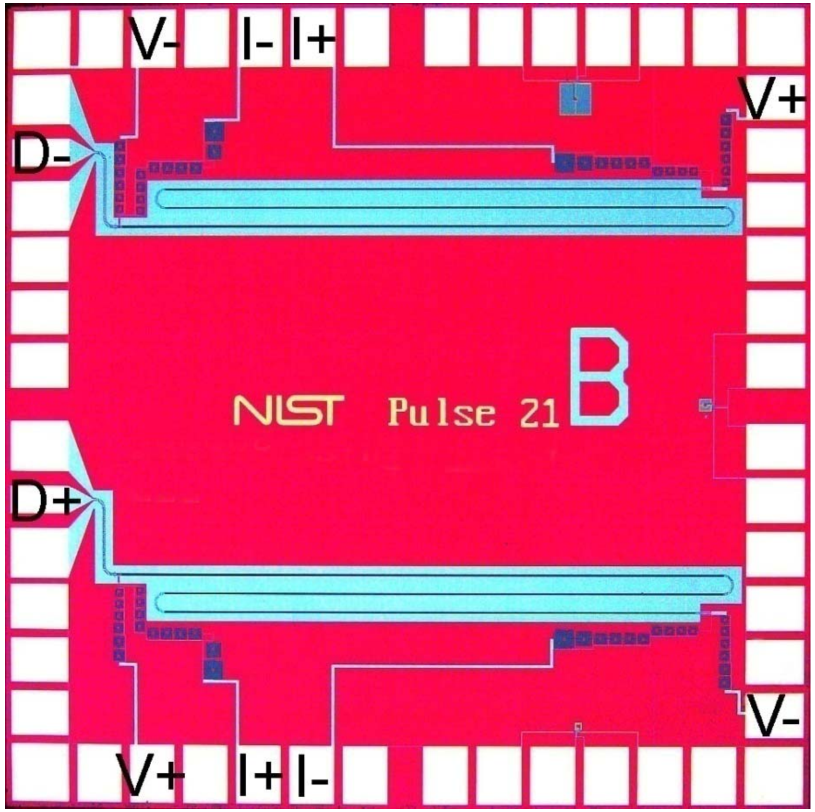
  $\mathbf{f} = n\mathbf{f_{rep}}$

  where *n* is the number of periods

Dual AC-Coupled Arrays



- 275 mV rms ACJVS
- *N* = 12 800 double-stacked junctions



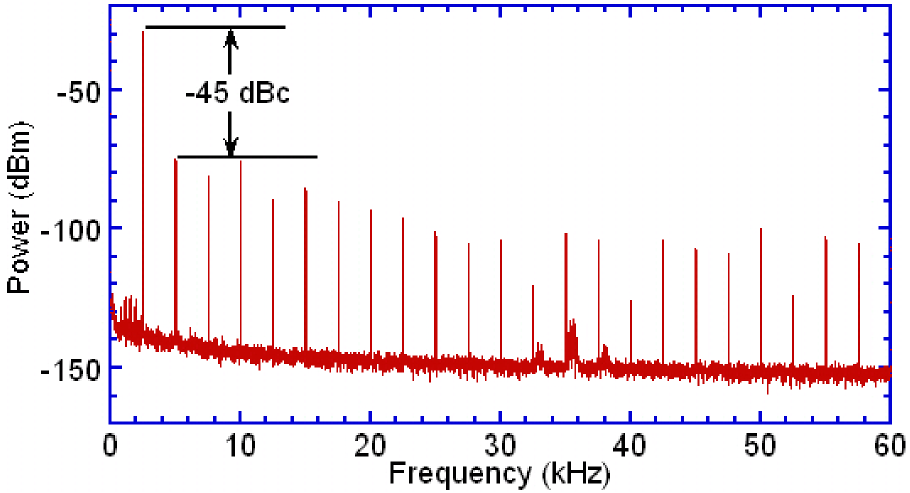
1 cm x 1 cm Chip

- RMS AC-DC measurements with thermal converters or Fluke transfer standard

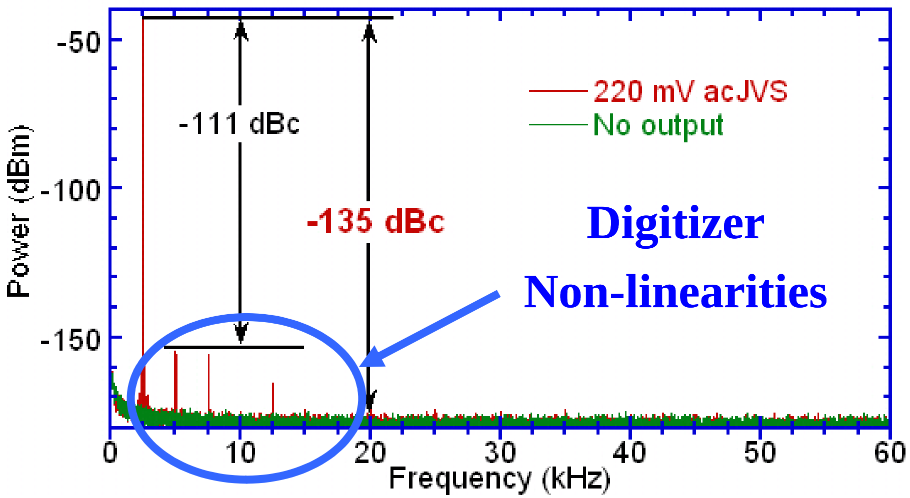
Pulse (D) and AC (I) biases → Grounded JJ Array → RMS Detector → Digital Voltmeter

Perfect Quantization Demonstration

Semiconductor Code Generator Output



Josephson Junction Array Output



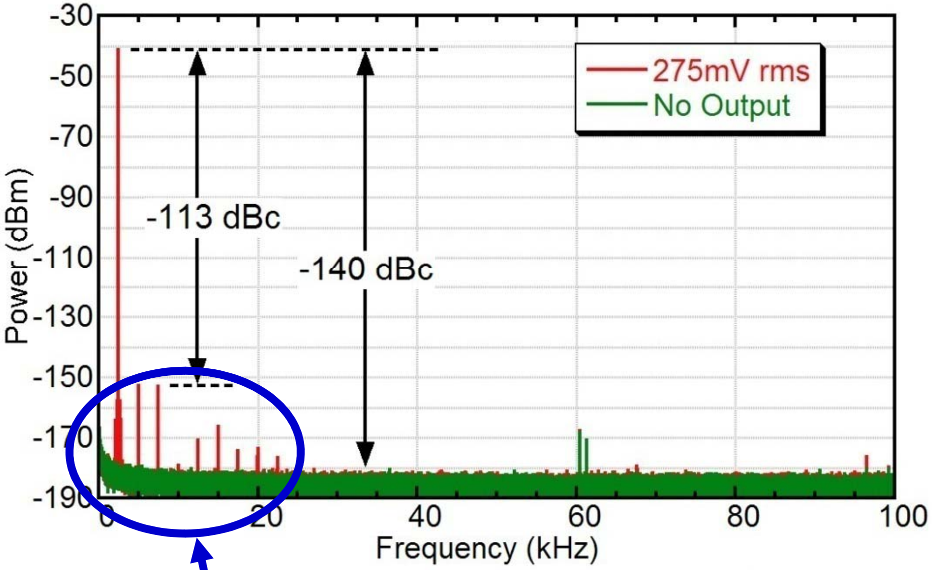
- Sine Wave Synthesis
  - 2.5 kHz tone
  - 4,00,000 bit code length
  - 15 GHz sine, 10 GHz clock
- Semiconductor code generator
  - **-45 dBc** Harmonic distortion
- 2 ac-coupled arrays in series
  - 10,240 junctions
  - 220 mV rms voltage
  - **-135 dBc** Harmonic distortion

Perfect quantization produces intrinsically accurate waveforms

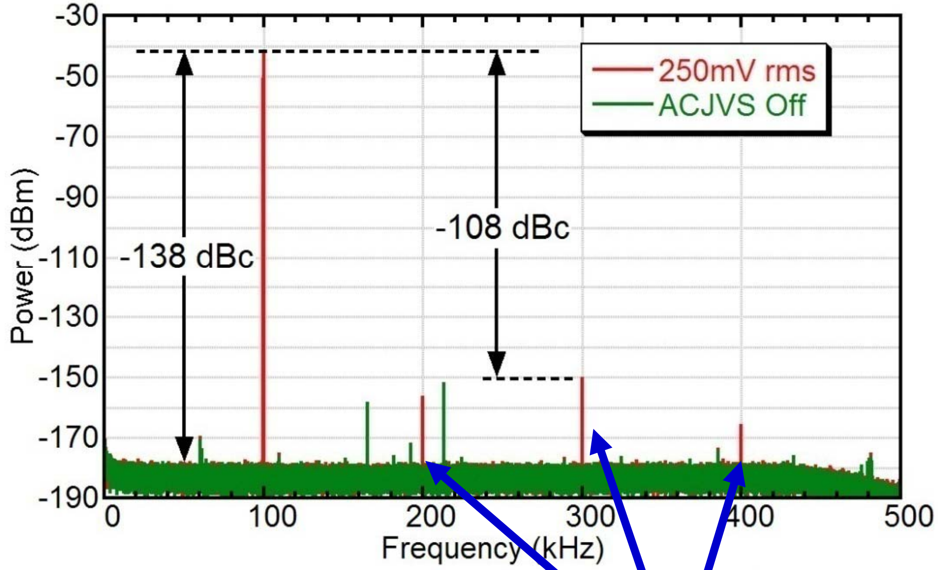
Precision Measurements

Find non-linearities in the ADC Digitizer

2.5 kHz



100 kHz



Digitizer Non-linearities

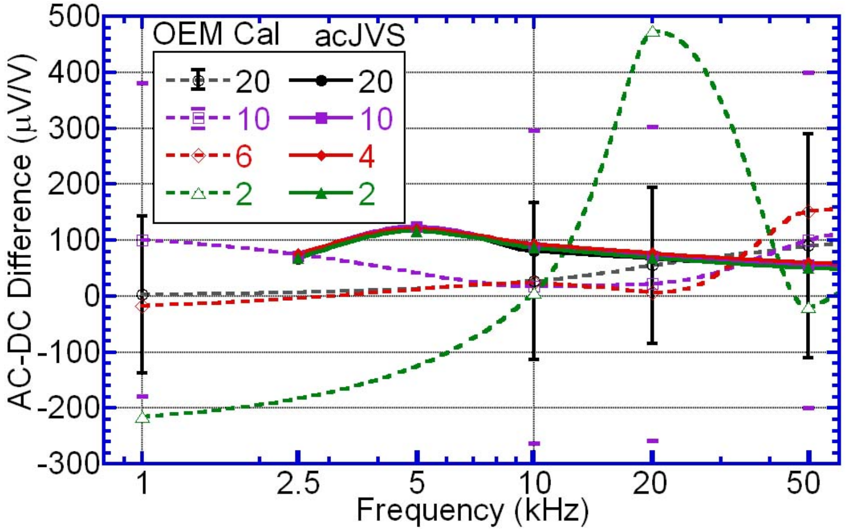
Frequency (kHz)	Array Circuit	RMS Voltage (mV)	Distortion (dBc) Meter Range 10V	2V
2.5	Both	275	-113	-122
2.5	Both	250	-114	-120
2.5	Single	125	-122	-114
100	Both	250	-108	-110
100	Single	125	-112	-108

Digitizer Non-linearities

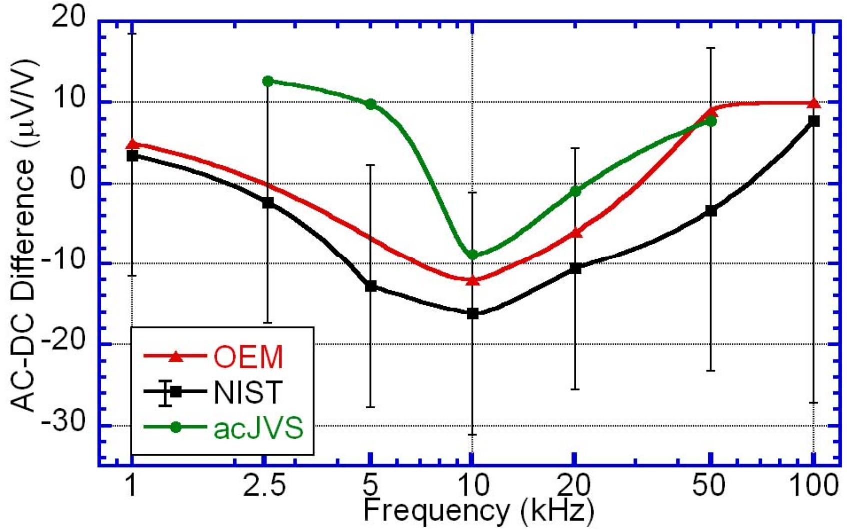
Comparison with Conventional Calibrations

RMS AC-DC Difference Measurements

2, 4, 10 and 20 mV
on the **22 mV** Range



100 mV
on the **220 mV** Range



Manufacturers Spec. Uncertainty:

20 mV ± 140 µV/V
10 mV ± 280 µV/V
2 mV ±1600 µV/V

Uncertainty:

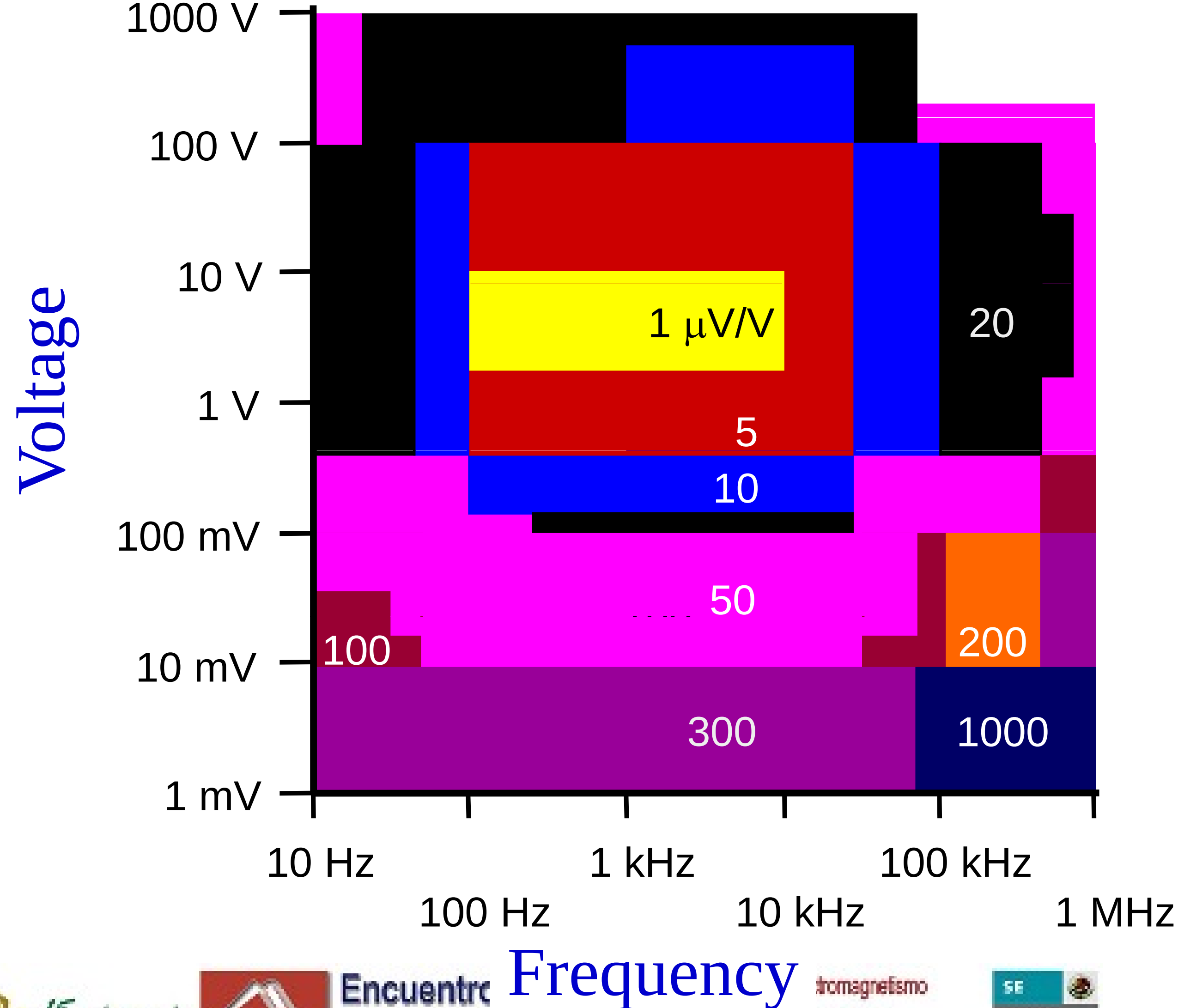
NIST ±15 µV/V
Fluke ±50 µV/V

ACJVS measurements have 10X lower uncertainty

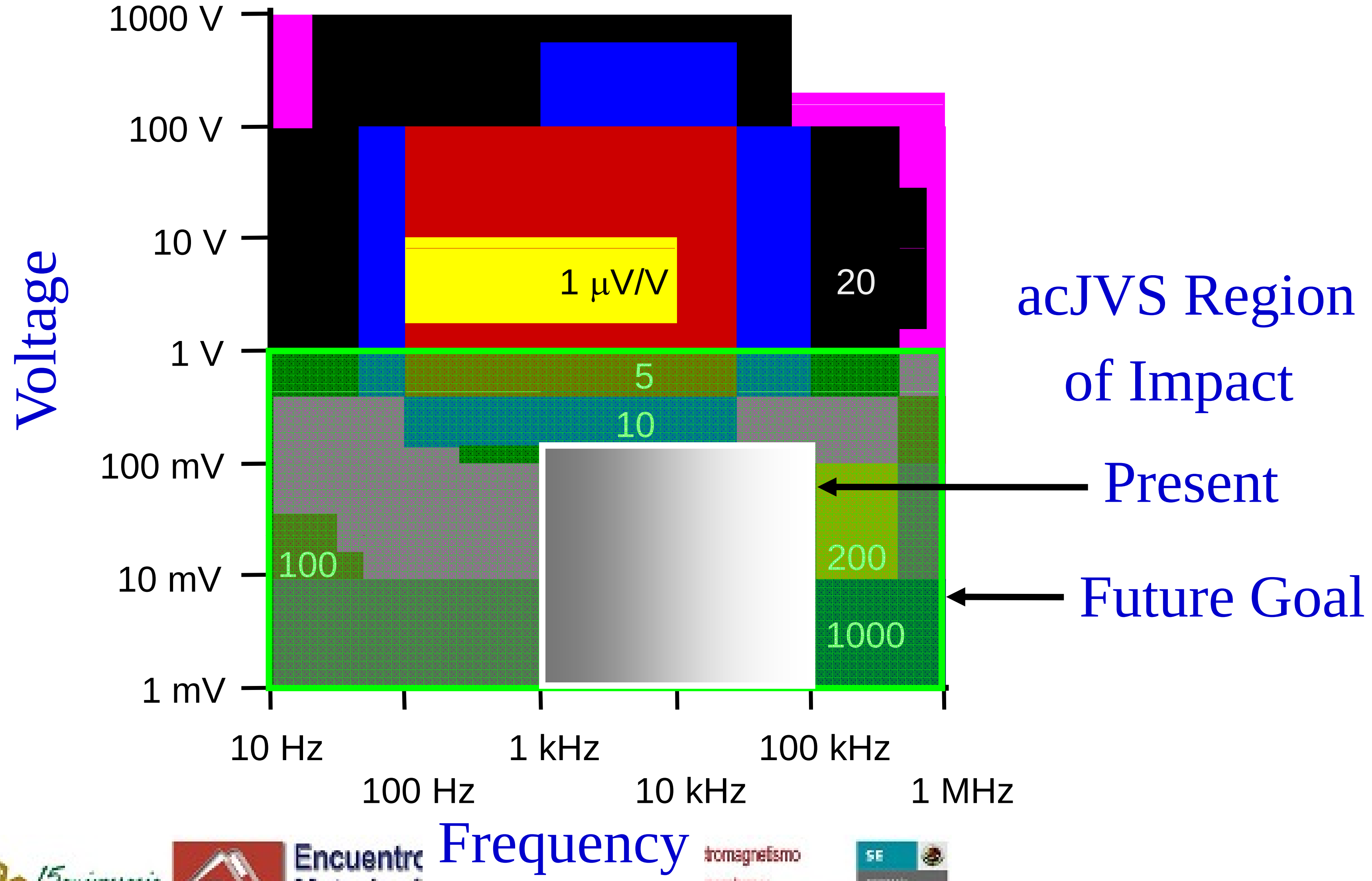
Metrology Impact of ACJVS Synthesis

- A quantum-based source with intrinsic accuracy
  - Provides a new method for ac metrology (<100kHz, 275mVrms)
  - Intrinsic linearity is a powerful tool and allows direct ac to ac comparisons
  - Lower uncertainty for AC-DC rms comparisons
    - 10x to 1000x lower uncertainties, esp. for low voltages
- Challenges
  - Systematic errors from transmission line inductance can be measured and accounted for
  - Transmission line effects and filtering reduce accuracy of RMS measurements at frequencies above 10 kHz

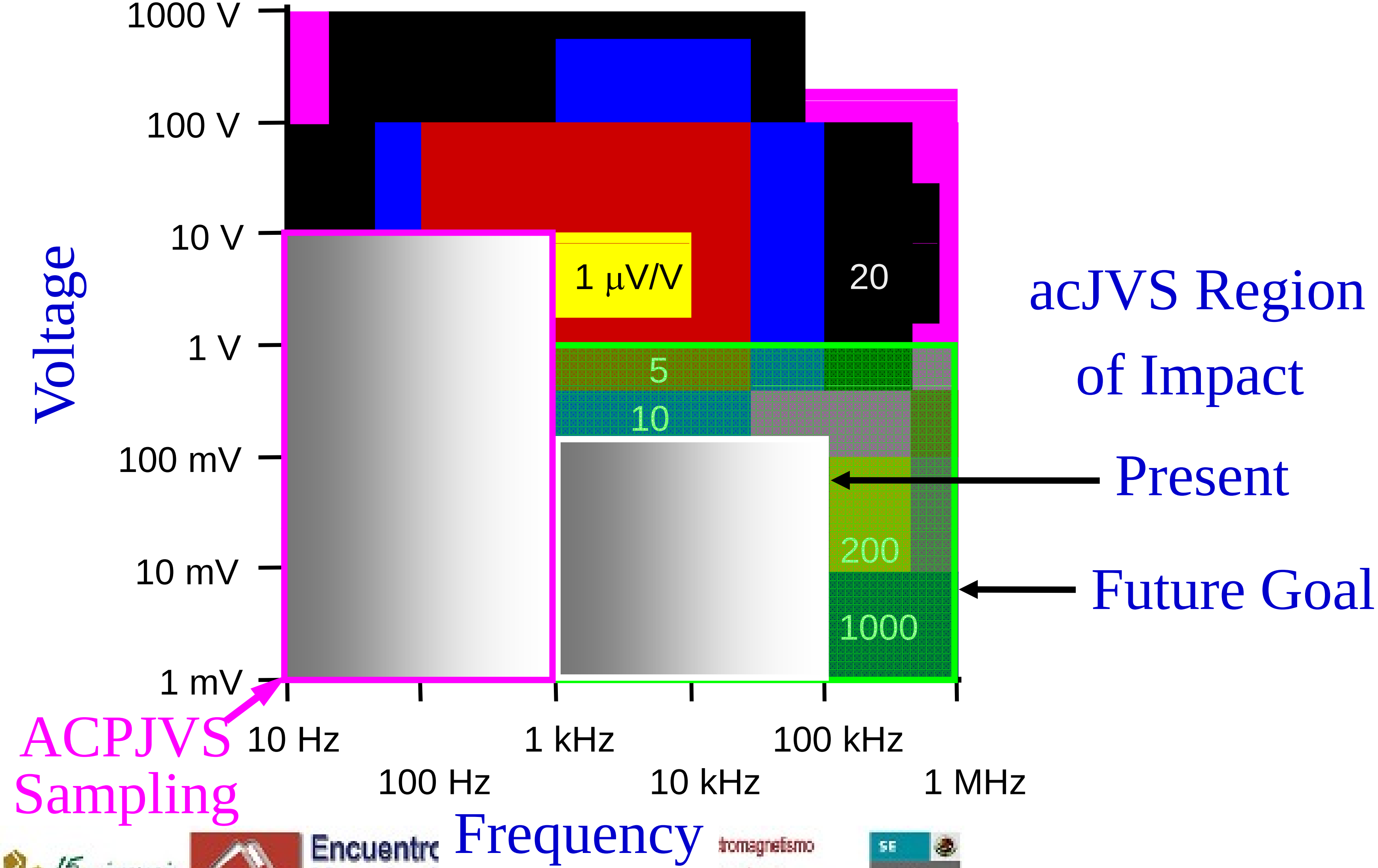
NIST AC Voltage Uncertainty



NIST AC Voltage Uncertainty



NIST AC Voltage Uncertainty



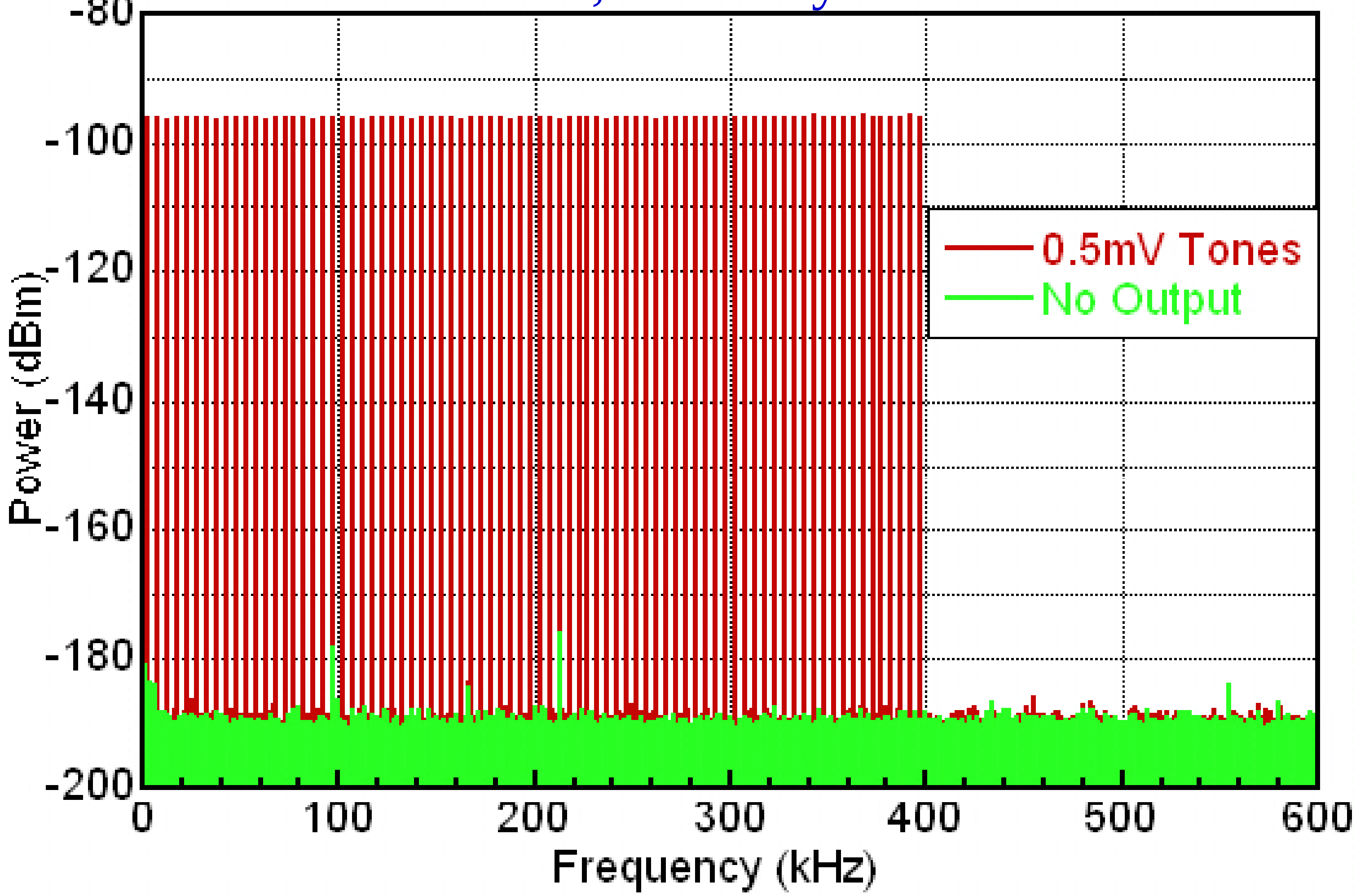
Summary

- PJVS
  - 1V-5V range typical and common for DC applications
    - 10V chips with yield and a few systems have been realized (PTB, AIST/NMIJ, NIST)
  - Implemented 3V ACPJVS for 60 Hz power calibration standard
    - Commercial power meters have been calibrated (NIST)
  - Useful AC synthesis up to 500 Hz is possible
- AC JVS
  - Four fully operational 275 mV systems (2xNIST, NRC, VSL)
    - Automated ac-dc calibrations and lower uncertainty ac measurement for NIST Voltage Calibration Lab
    - Precision measurements with arbitrary waveforms to 400kHz
  - Demonstrated practical 275 mV RMS (388 mV_{peak}) ACJVS
  - Research to increase performance to 1 V and 1 MHz

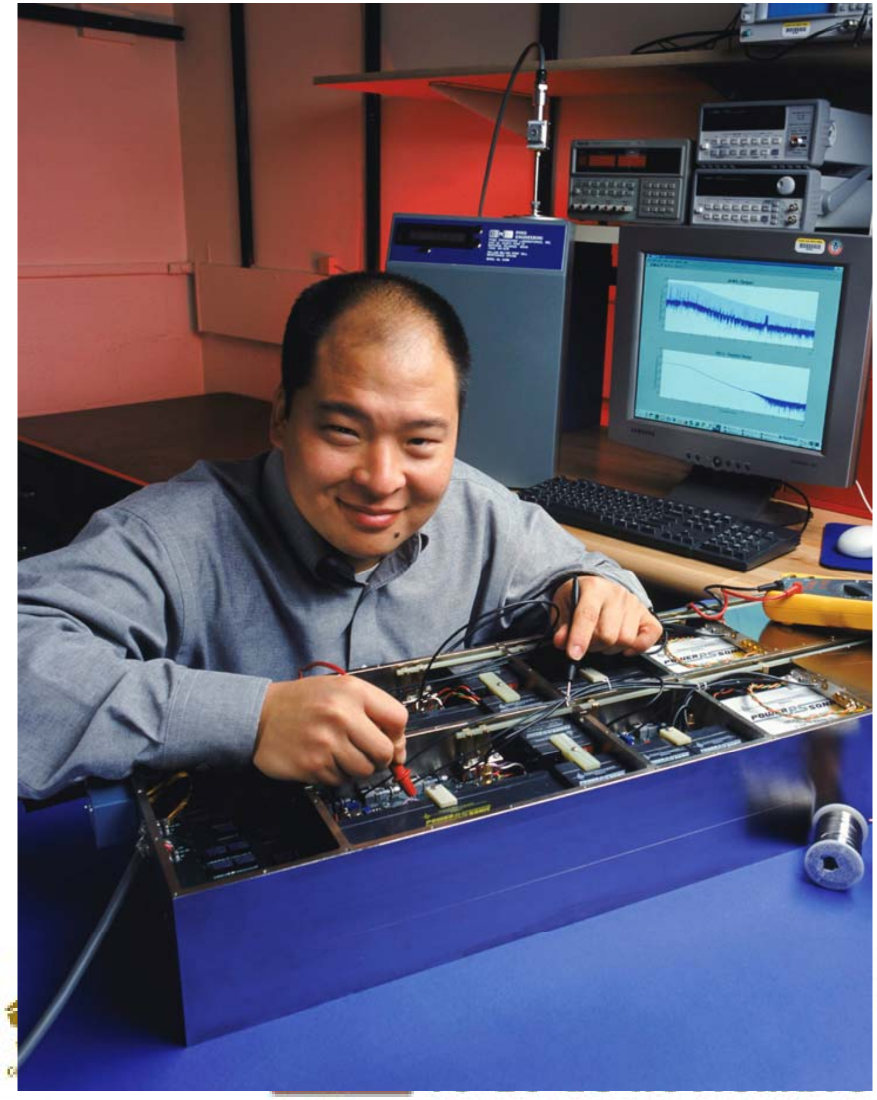
Accurate Pseudo-noise Waveforms

Constant 0.5 mV_{rms} Amplitude

Random Phase, Odd-only Harmonics



Quantized Voltage Noise Reference for Johnson Noise Thermometry



Quantum Voltage Project
and
Sae Woo Nam (NIST-EEEL)
W. Tew (NIST-CSTL)
D.R. White (IRL)

INDUSTRIAL RESEARCH LIMITED

NIST

- Electromagnetismo
- Temperatura y Propiedades Termofísicas
- Tiempo y Frecuencia

Johnson Noise Thermometry

- Nyquist Relation

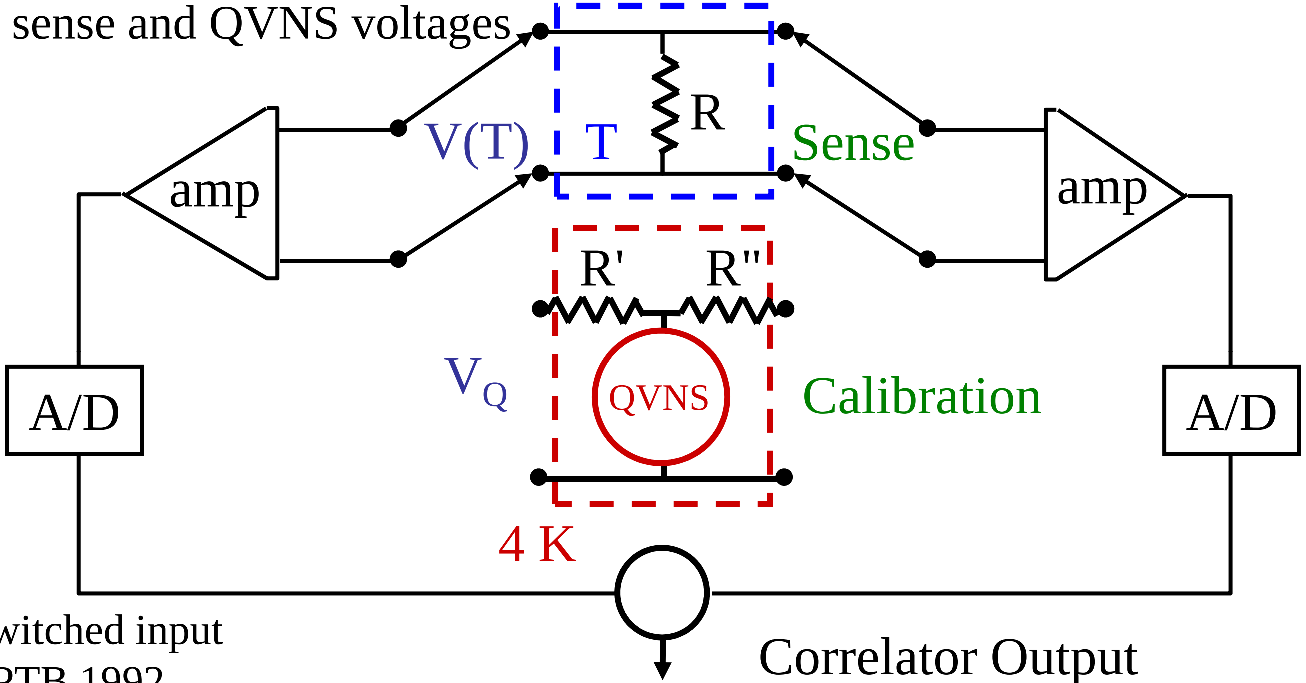
$$\boxed{\left\langle V^2(T) \right\rangle = 4kTR\Delta f}$$

- Challenges
  - Small magnitude ~1.26 nV/sqrtHz at 273 K
  - Need cross-correlation technique
    - Long integration times
  - Minimize errors in electronic measurement system
    - Calculable voltage noise reference/source

Calibrate with a Quantized Voltage Noise Source

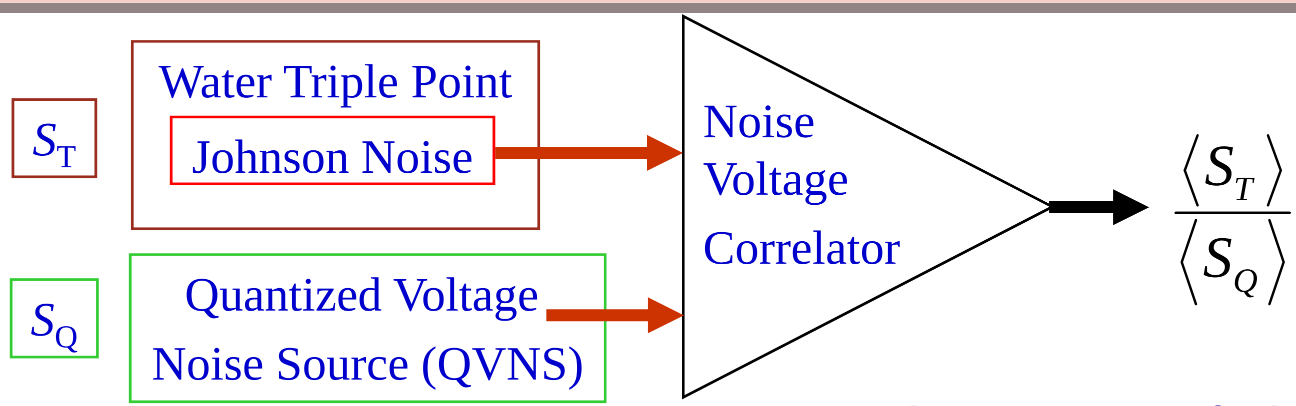
- Calculable pseudo-noise waveform
- Absolute temperature calibration
  - MATCH V_{calc} to ANY sense T and R
  - Matched, uncorrelated resistors R', R“
  - Measure sense and QVNS voltages

$$\left\langle V^2(T) \right\rangle = 4kTR\Delta f$$



H. Brixy et al. “switched input correlator JNT”, PTB 1992.

Electronic measurement of Boltzmann's Constant



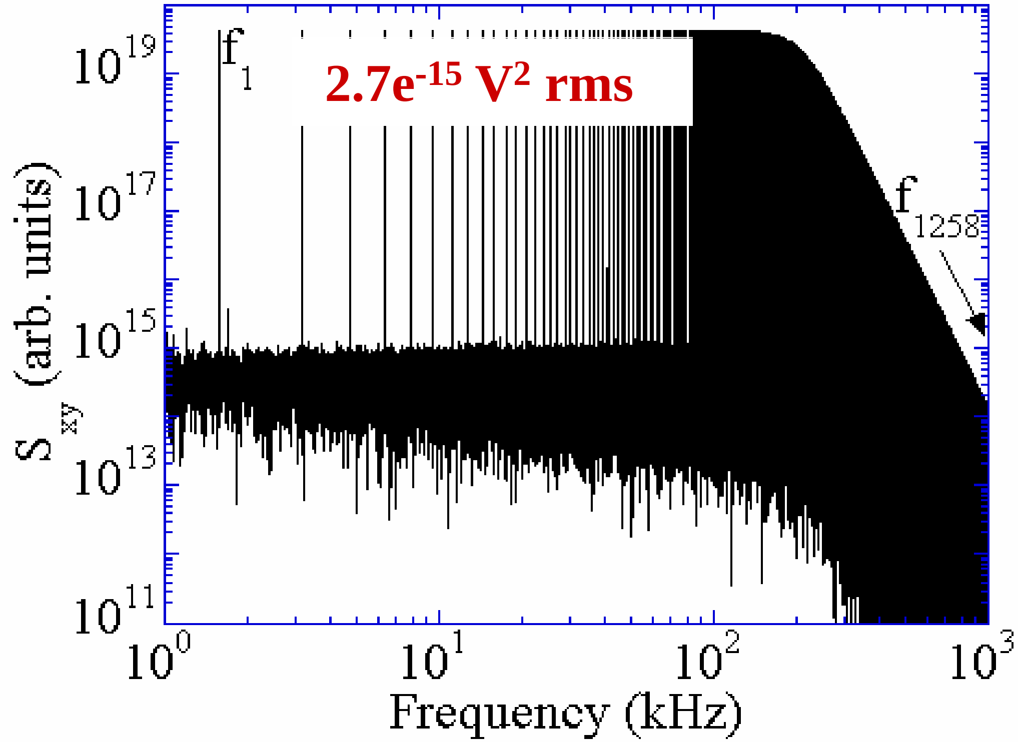
- Measure Johnson noise of a resistor

$$\boxed{\langle V_T^2 \rangle = S_T \Delta f = 4kTR\Delta f}$$

- Random-phase multi-tone waveforms calibrate X-corr electronics
- Compare thermal to electrical noise power

$$\boxed{\frac{k}{h} = \frac{\langle S_T \rangle}{\langle S_Q \rangle} \frac{D^2 N^2 f_s M R_{k-90}}{16TR}}$$

Measured Cross-correlation Spectrum



Pseudo-Noise Waveform

- Pattern repetition frequency

  Choose M bits

  $f_1 = f_s / M$

- Add *random phase* harmonics

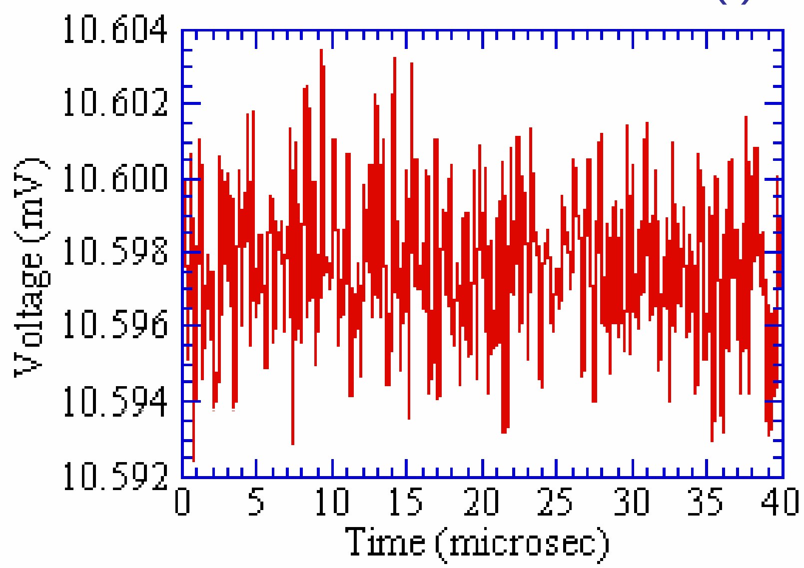
  n = 1258

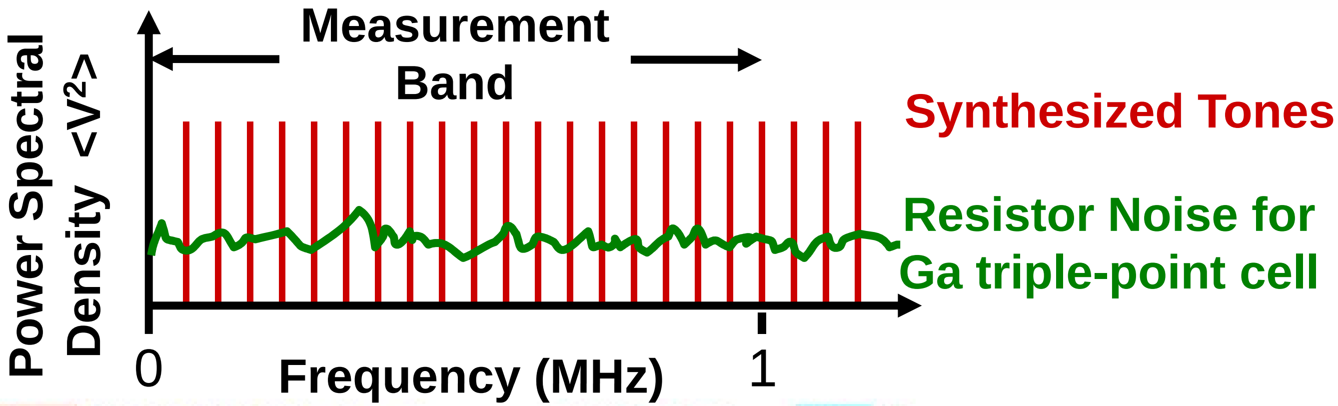
- Match voltage to resistor PSD

  $V_{rms} = (4kTRf_1)^{½} = 51.55$ nVrms

  for T = 302.916 K, R = 100 Ω

Desired Pseudo Noise V(t)





JNT Summary

- Best result is still 2007 measurement:
  - Measured temperature is consistent with SI-assigned temperature: +3 μK/K $\pm$ 25 μK/K
  - Recent ratio measurement is +50 μK/K $\pm$ 19 μK/K
- Primary efforts:
  - Determine sources of systematic error
  - Measure all contributions to uncertainty budget
  - On track to complete 4-channel 600 kHz bandwidth system
  - Expect 5 μK/K statistical uncertainty in 7-10 days of integration
- Goal to contribute to redetermination of the Boltzmann constant at 6 μK/K