The SI and Quantum Metrology

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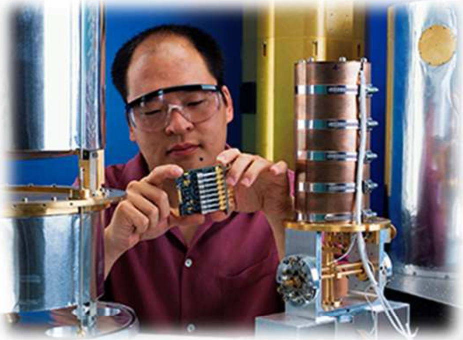

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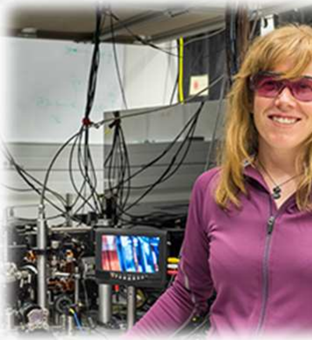

PML
PHYSICAL MEASUREMENT LABORAT

Outline

- NIST and the Physical Measurement Laboratory (PML)
- The Metric System and the SI
- Quantum Standards and Movement Toward Redefining the SI
- Quantum standards and Quantum metrology today
- From Instrumenting the SI to Embedded Measurements
- Implications

Disclaimer: This talk is very "NIST-centric"

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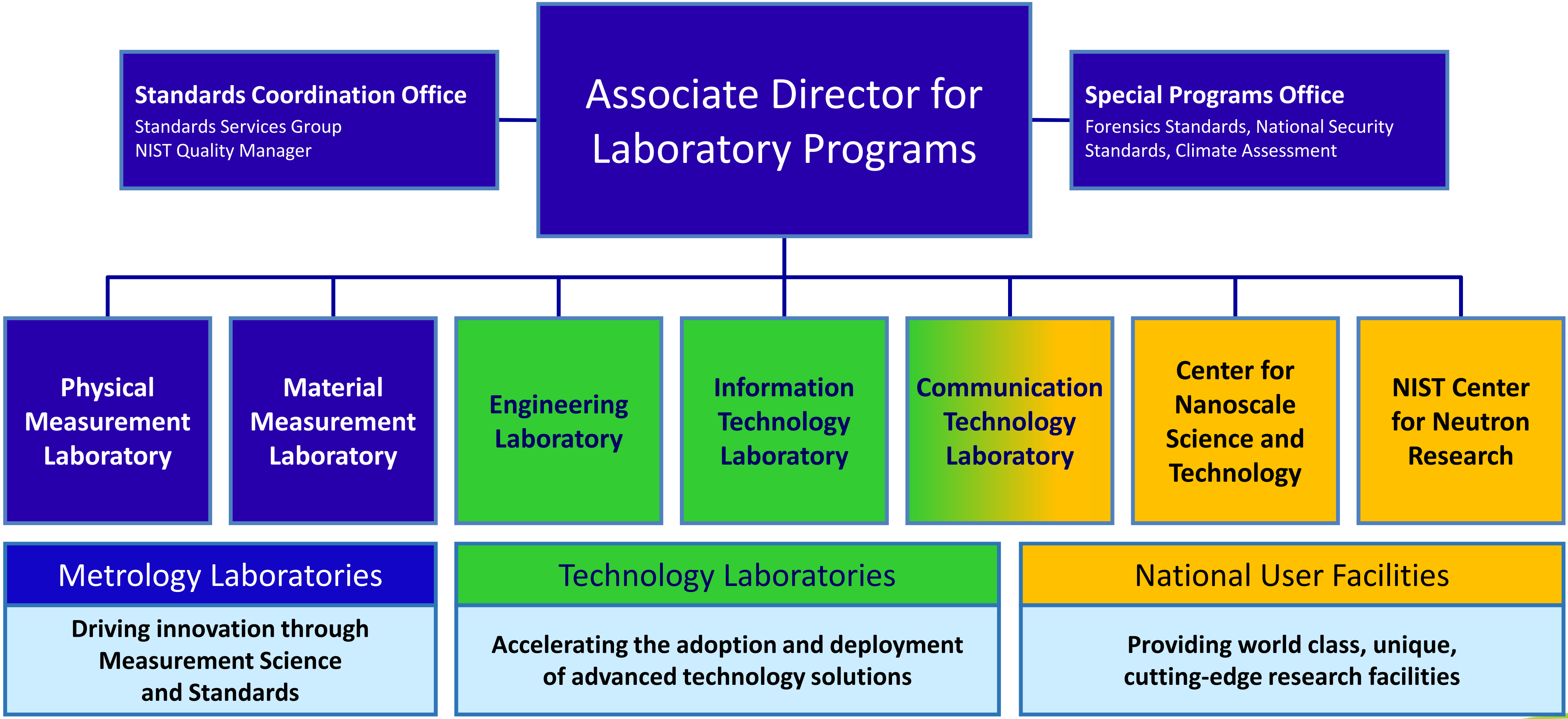
NIST Laboratories and User Facilities



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Physical Measurement Laboratory

Material Measurement Laboratory

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Communication Technology Laboratory

Center for Nanoscale Science and Technology

NIST Center for Neutron Research

Metrology Laboratories

Driving innovation through Measurement Science and Standards

Technology Laboratories

Accelerating the adoption and deployment of advanced technology solutions

National User Facilities

Providing world class, unique, cutting-edge research facilities

PML's Core Mission

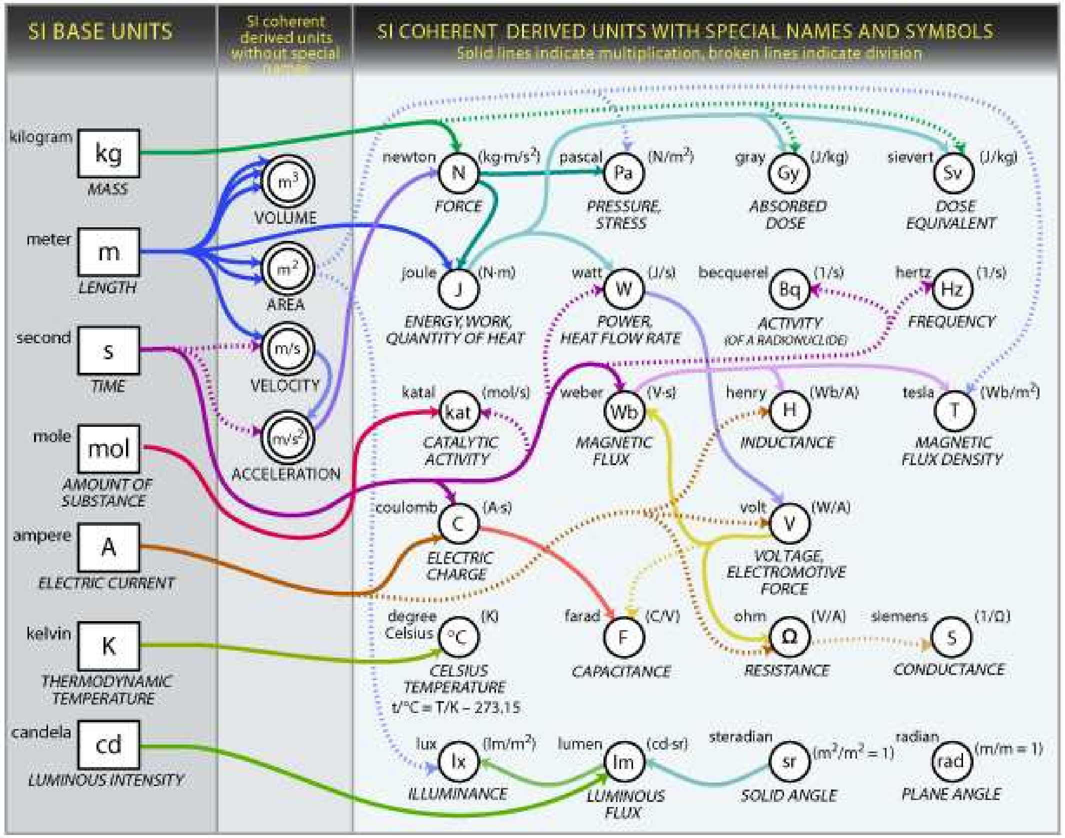
To realize, disseminate, and advance the International System of Units (SI) in the United States

The SI is …

- Scientifically based
- Defined by consensus (CGPM/CIPM)

PML seeks to ensure that in the U.S. the SI is…

- Maintained and improved
- Realized in practice
- Disseminated for routine uses
- Disseminated for new and novel uses



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Origin of the Metric System

Now known as International System of Units (SI)

Adopted by Intl. committee on *December 10, 1799*

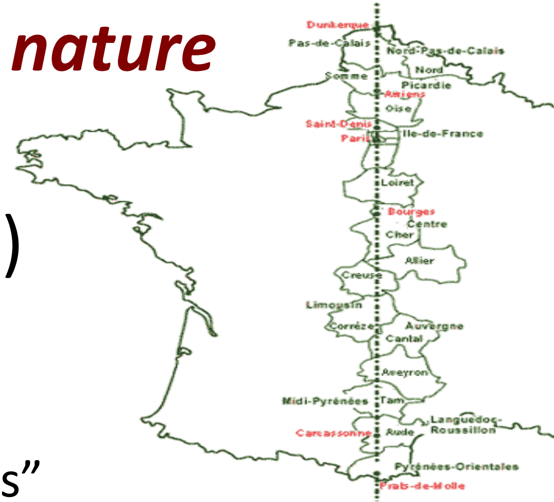
Basic principles: Decimalization, open access, ***based on nature***

Treaty of Meter established 1875 (U.S.:1878)

Originally *only* weights (kilogram) and measures (meter)

In 1921 the Treaty of the Meter is Amended to add:

- Coordinating measures of electrical units
- Establishing and keeping standards of electrical units, and their “test copies”
- Duty to determine the ***physical constants***
- Coordinating “similar determinations affecting other institutions”



Survey of the Meridia
Dunkirk to Barcelon
1792–1799

In 1954 the CGPM *adopts 6 base units* (*meter, kilogram, second, ampere, Kelvin,* and *candela*) giving rise to the modern SI – mole added in 1971

In 1960 adopts the name “Système International d’Unités”

The Metric System

Meant to be *based on nature*

Meter stick was to be 1/10,000,000 of the distance from North Pole to equator along the meridian passing through Paris

- Actual meter is .02% too short (0.2mm) due to a miscalculation of the flattening of the earth (distance ended up being 10,001.9657 km)

The Pt-Ir kg, known as the International Prototype Kilogram (IPK) was based on the weight of 1000 cm^3 or 1 l of water. But what water?

hus, both were in principal *based on nature*, but were in reality artifacts.

oth while artifacts were remarkably good!

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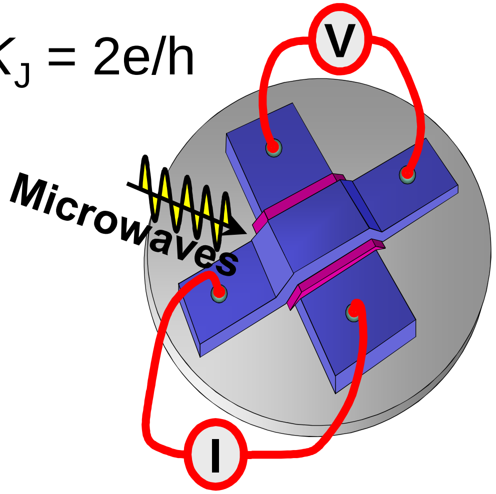
Toward Redefining the SI

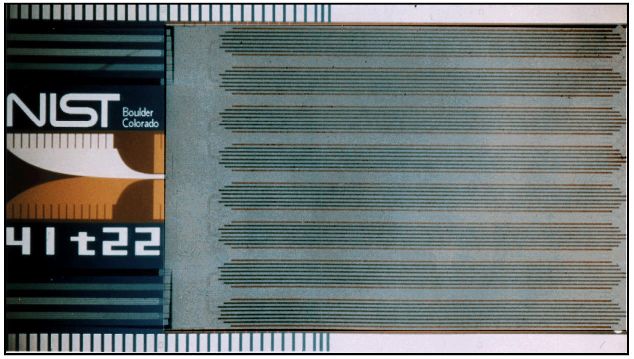
- With the creation of the *SI* in 1960, the process to revise and improve the units in a way that benefits the system as a whole and makes them ***based on nature*** truly begins
- In 1967 the second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom.
- In 1983 the meter was redefined as the length of the path travelled by light in vacuum during a time interval of 1/299,792,458 of a second.
- Where are we and what remains to be done?
- *Are our "current" electrical units part of the SI?*

Standards for Electrical Units Since 1990

Josephson Voltage Standard

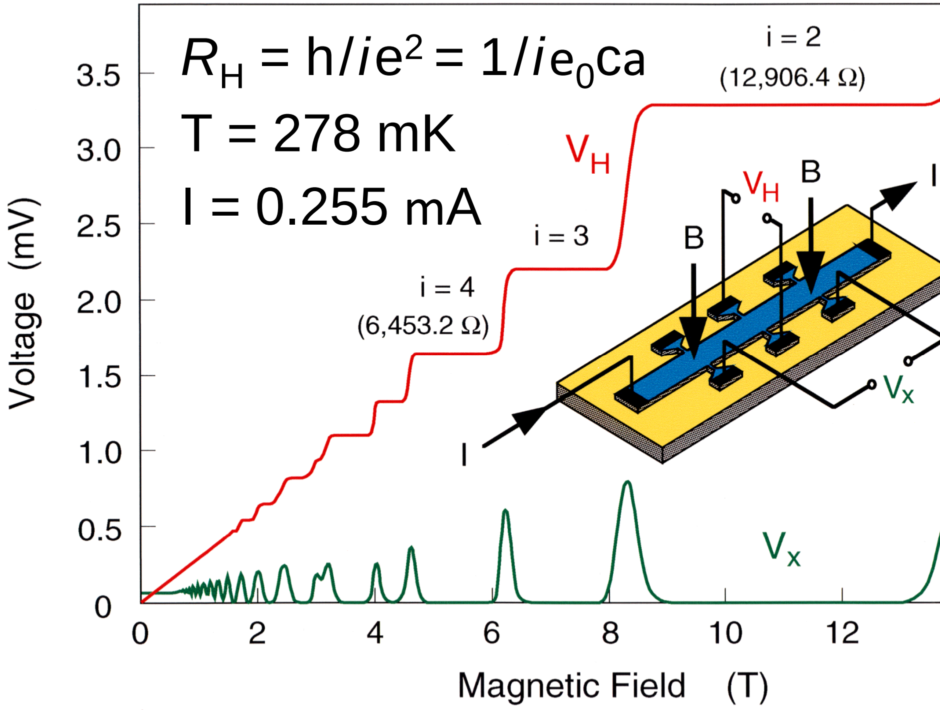
$K_J = 2e/h$





The “volt” realized by Josephson Junction devices, with K_{J-90} = 483,597.9 GHz/V

GaAs Quantum Hall Resistanc



The “ohm” realized by Quantum Hall Effect devices, with R_{K-90} = 25,812.807 Ω

(Graphene QHR underway)

R_K =

or R

e quantum standards, the Josephson effect (1962, Nobel Prize 1973) and uantum Hall effect (von Klitzing 1980, Nobel Prize 1985) are so robust that 37 the CGPM (Resolution 6) established *conventional electrical units!*

Basically, we do not realize the Ampere and we use non-SI units

How new of an idea is the redefined SI?

The two constants [h,k]…which occur in the equation for radiative entropy ***offer the possibility of establishing a system of units for length, mass, time, and temperature*** which are ***independent of specific bodies or materials*** and which necessarily maintain their meaning for all time and for all civilizations*, even those which are extraterrestrial and non-human.

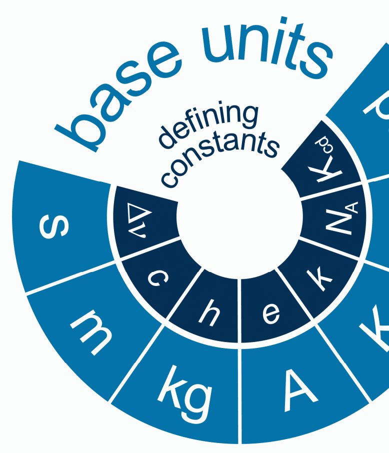
-- Max Planck, 1900

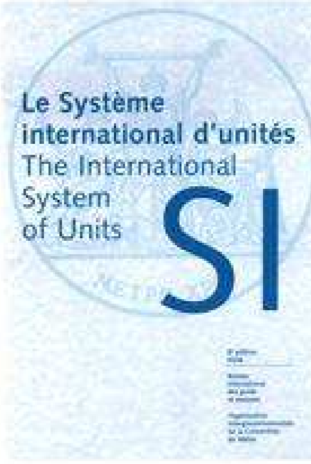
*Planck uses language similar to that used by the Marquis de Condorcet wh he transferred the original French length and mass standards to the Archive de la Republique in 1799. More on the new SI can be found in Dave Newel Physics Today article, July, 2014.

Comparing the Current and New SI

Current SI		New "Quantum" SI	
Base quantity	**Base unit**	**Base quantity**	**Defining Constant**
Time	second (s)	Frequency	$\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$
Length	meter (m)	Velocity	c
Mass	kilogram (kg)	Action	h
Electrical Current	ampere (A)	Electric Charge	e
Therm. Temperature	kelvin (K)	Heat Capacity	k
Amount of Substance	mole (mol)	Amt of Substance	N_A
Luminous intensity	candela (cd)	Luminous intensity	K_{cd}

From: D. Newell, *"A more fundamental International System of Units,"* *Physics Today* **67(7),** July 2014.




Le Système international d'unités
The International System of Units
SI

What do We Mean by "Quantum SI?"

Consider History of the Meter:

1889: Internationa Meter (Artifact)

GOOD

1960: *The meter is t e length al to* 1,650,763.73 *wavelengths in va e radiation corresponding to the transiti the levels* 2p$_{10}$ *and* 5d$_5$ *of the krypton* 8 . **(11th CGPM, Resolution 6)**

BETTER

1983: *The meter is the lengt e path travelled by light in vacuum during val of* 1/299,792,458 *of a second.* **(17th CGP tion 1)**

BEST

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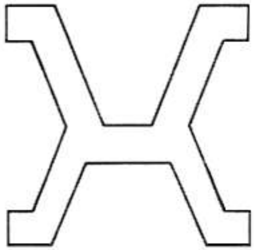
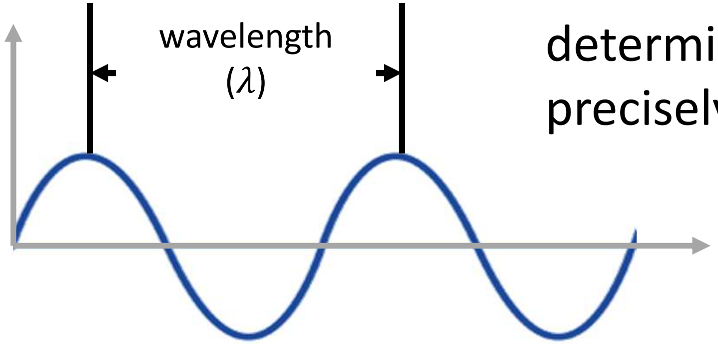
The Meter

Definition of the Meter	Date	Absolute uncertainty	Relative uncertainty
$_{0,000}$ part of one half of a meridian, measurement lambre and Méchain	1795	0.5–0.1 mm	10^{-4}
rototype *Mètre des Archives* platinum bar standard	1799	0.05–0.01 mm	10^{-5}
um-iridium bar at melting point of ice (1st CGPM)	1889	0.2–0.1 µm	10^{-7}
um-iridium bar at melting point of ice, atmospheric pressure, rted by two rollers (7th CGPM)	1927	n.a.	n.a.
,763.73 wavelengths of light from a specified transition in krypton- th CGPM)	1960	0.01–0.005 µm	10^{-8}
n of the path travelled by light in a vacuum in $^{1}/_{299,792,458}$ of a d (17th CGPM)	1983	0.1 nm	10^{-10}

https://en.wikipedia.org/wiki/History_of_the_metre



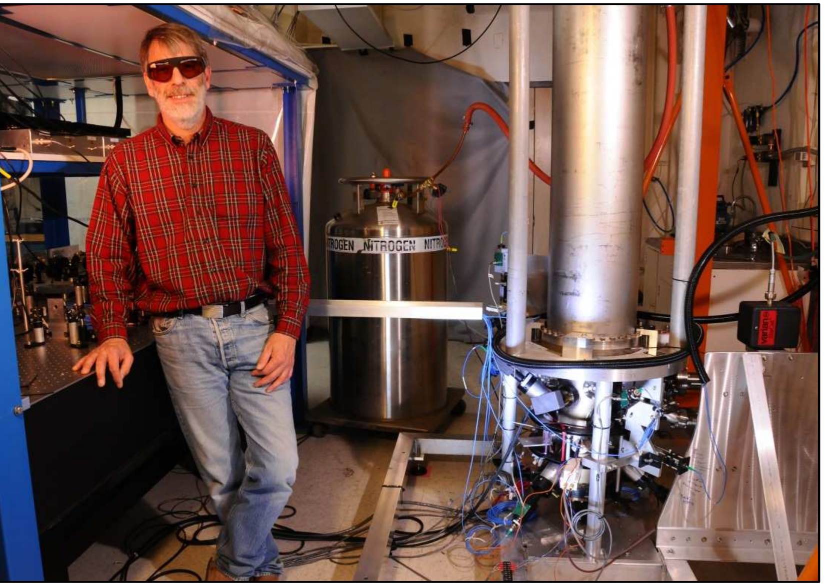


NIST Dimensional Metrology Group realiz the meter to a part in 1

Today, lasers are stable enough that you can ge interference pattern by retro-reflecting a laser the mirror left on the moon. We can measu time very accurately an not for the atmosphere determine the distance precisely.

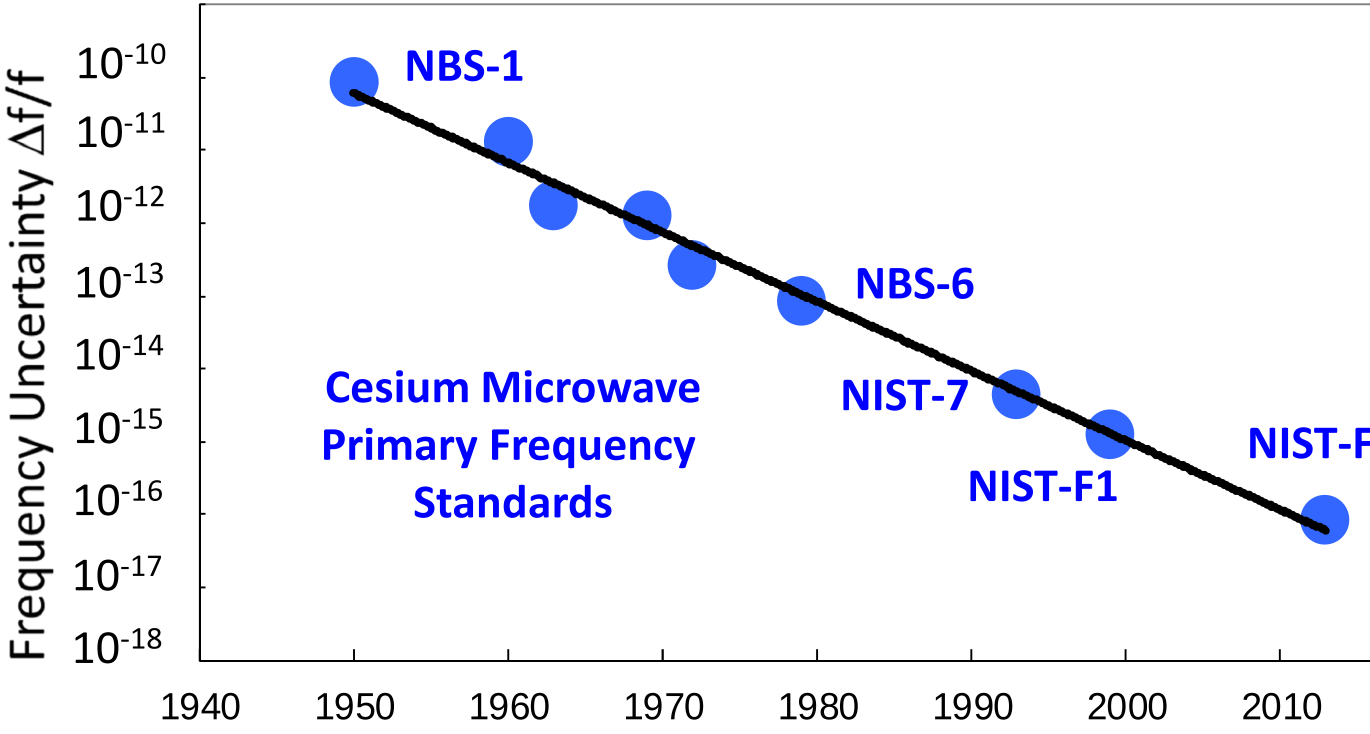
The Power of One Quantum Bit: NIST-F2

second is defined as the duration of ,192,631,770 cycles of the cesium yperfine transition.

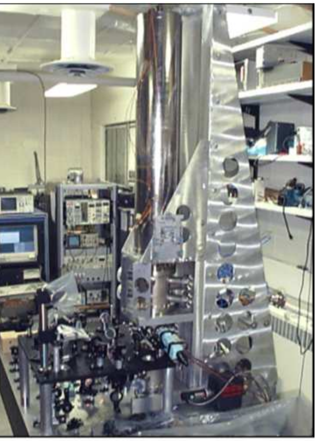


IST-F2 laser-cooled fountain standard atomic clock

- Frequency uncertainty: $\Delta f/f = 1 \times 10^{-16}$
- 1 second in 300 million years.
- Enabled by laser cooling and trapping.



Comparison of Primary Frequency Standards



NIST-F1 Cesium Fountain Standard

T-F1 commissioned 1999

tial $\Delta f/f$ = 17 x 10^{-16}

imate $\Delta f/f$ = 3 x 10^{-16} by 2009

T-F2 commissioned 2013:

ryogenic drift tube.

ther improvements.

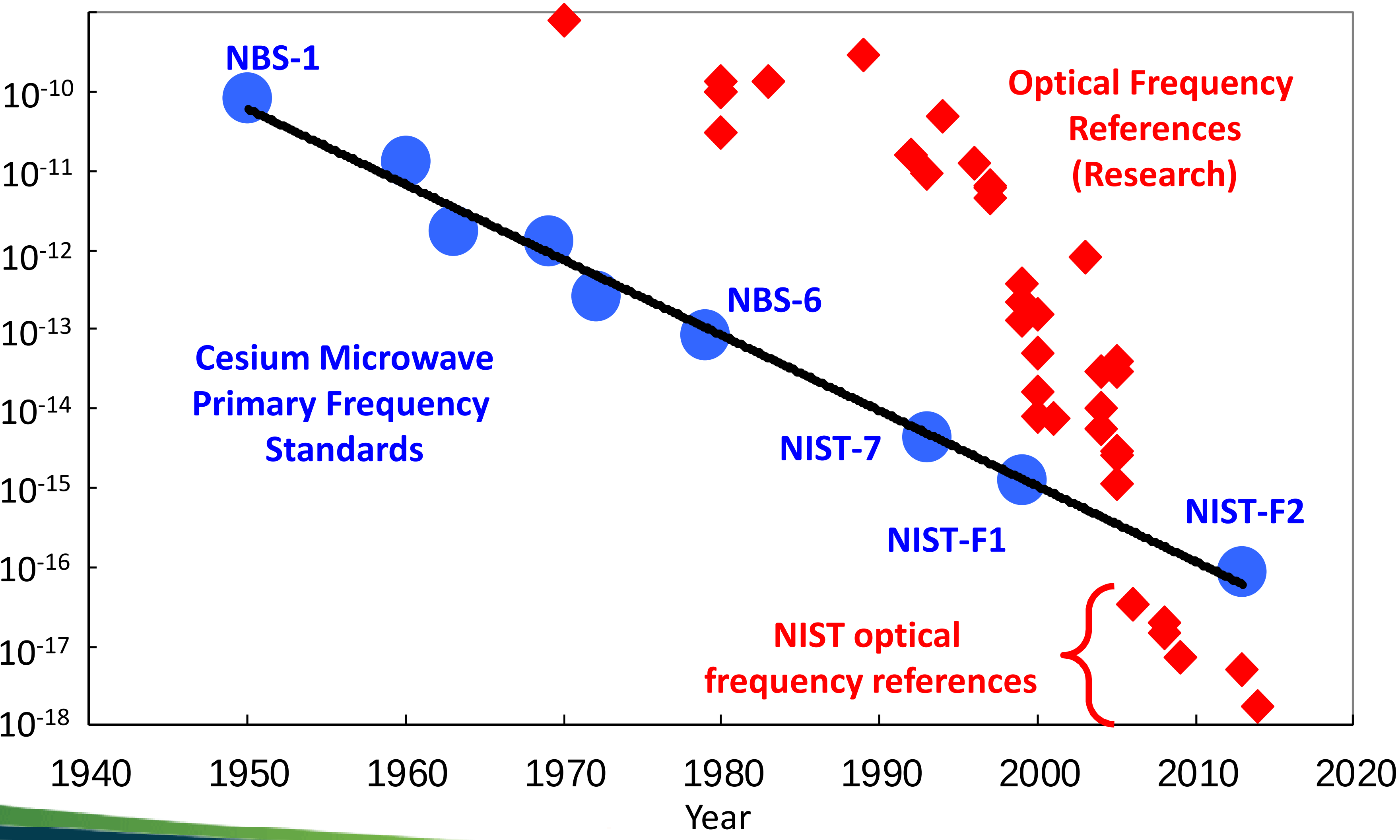
	Nation	Fountain	Uncertainty (10^{-15})
1	NIST (US)	NIST-F2	0.11
2	Italy	IT-CsF2**	0.18
3	UK	NPL-CsF2	0.23
4	France	SYRTE-FO2	0.23
5	NIST (US)	NIST-F1	0.31
6	France	SYRTE-FORb	0.32
7	France	SYRTE-FO1	0.37
8	Germany	PTB-CsF2	0.41
9	Russia	SU-CsFO2	0.50
10	Germany	PTB-CsF1	1.4
11	China	NIM5	1.4
12	India	NPLI-CsF1	2.5
13	Japan	NMIJ-F1	4.0

Cesium fountain primary frequency standards

- NIST-F2 world's most accurat primary frequency standard
- NIST-F1 was world's most accurate during most of its tenure
- However, optical clocks are now showing better fractiona uncertainty

**Note: IT-CsF2 is a copy of NIS F2 built for INRIM

Optical Frequency Standards



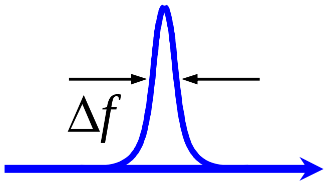
Since 2005 optical
frequency standard
have shown better
fractional uncertaint
and estimated
systematic uncertain
then primary standa

Possible redefinition
time now being
discussed for 2026

Benefits of Optical Clocks

$$\frac{f_0 \text{ optical}}{f_0 \text{ microwave}} \approx \frac{10^{15}}{10^{10}} \approx 10^{5}$$

requency uncertainty ~ $\dfrac{\Delta f}{f_0} \cdot \dfrac{1}{\sqrt{\tau}} \cdot \dfrac{1}{\sqrt{N}}$



Atomic Resonance

τ = observation time

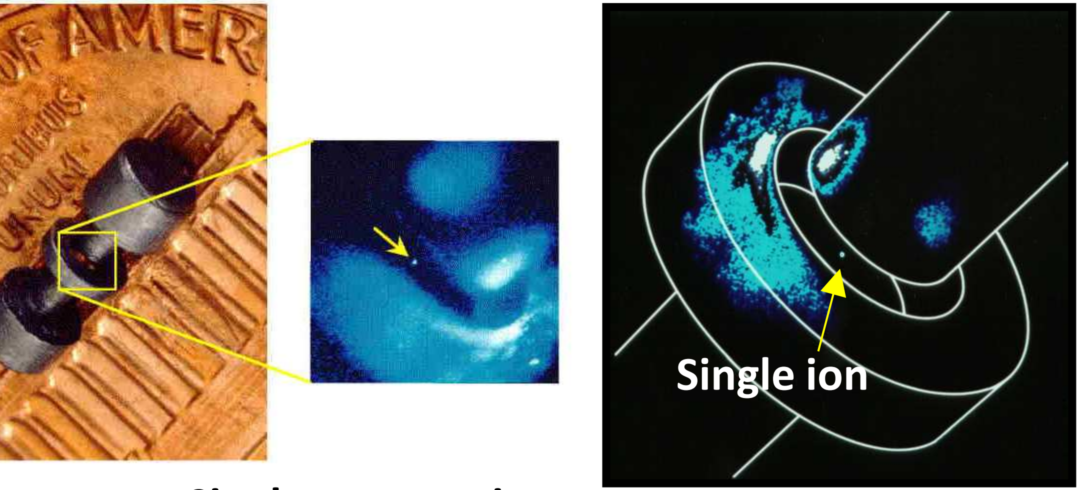
N = number of atoms

NIST research atomic clocks

Al^+	1124 THz (1124 x 10^{12} Hz)	Optic
Hg^+	1064 THz	
Yb	520 THz	
Ca	456 THz	
Sr	429 THz	
Cs	0.0092 THz	Microw

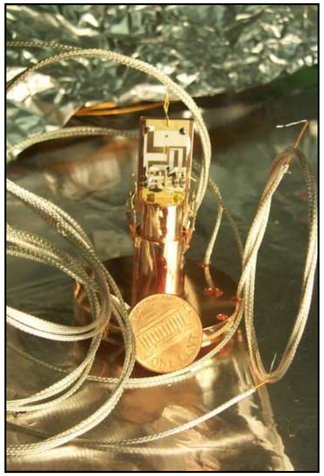
Optical Frequency Standards

$\Delta f/f \sim 10 \times 10^{-18}$



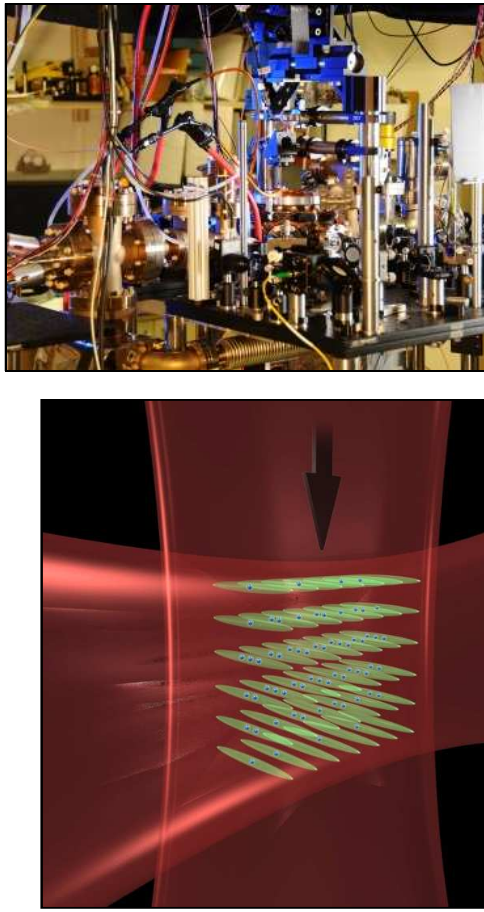
Single mercury ion trap

$\Delta f/f \sim 8 \times 10^{-18}$



Aluminum ion logic clock

$\Delta f/f \sim 2 \times 10^{-18}$



Strontium or Ytterbium optical lattice clocks

- High-frequency optical clocks outperform microwave (cesium) clocks.
- Potential to perform ~100 times better than best cesium clocks
- Many years before SI second redefined to optical standard(s) *(est. now 2026)*

Frequency Combs: Enabling Optical Clocks

ical standards at NIST:

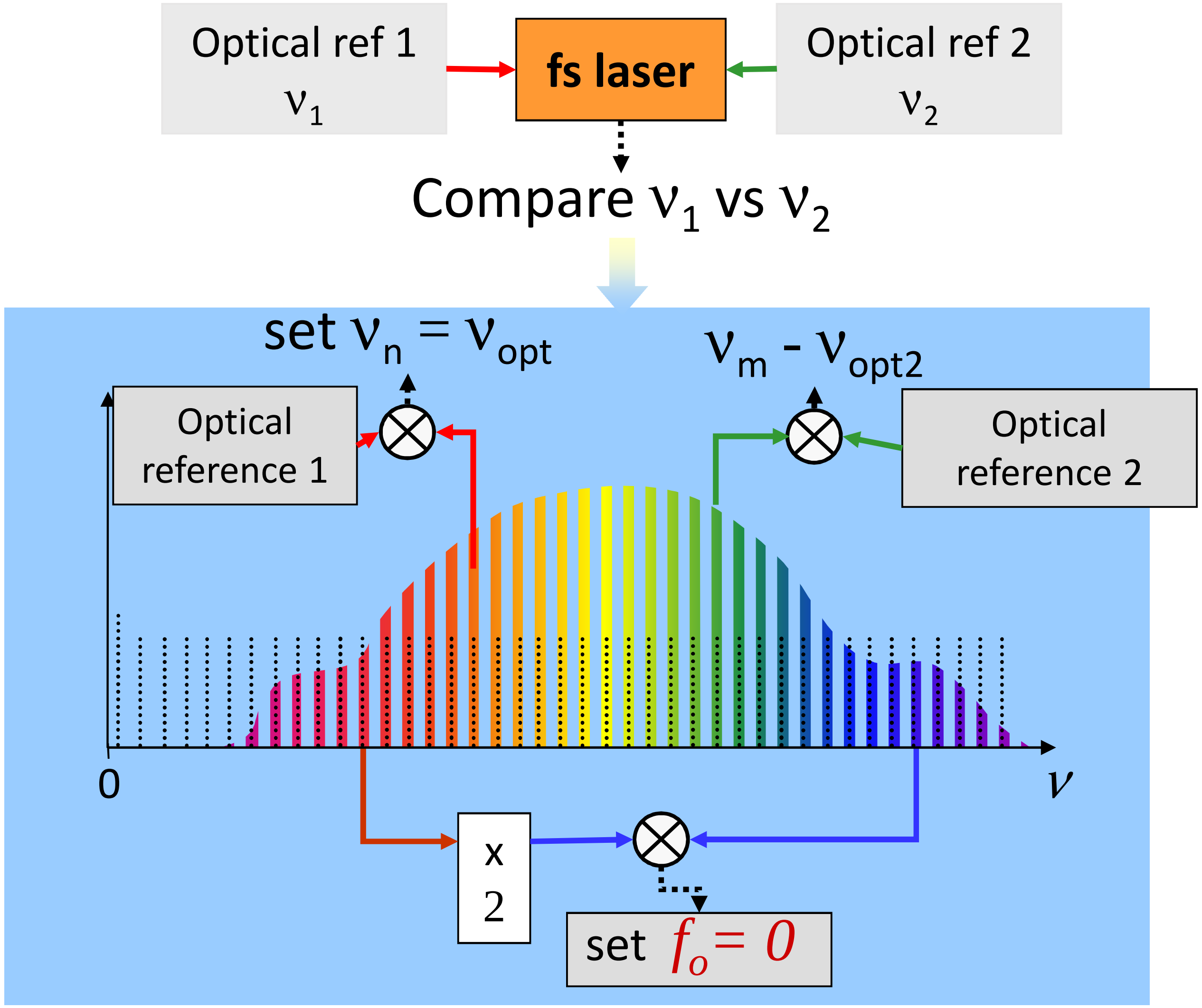
$^+$ (1124 THz)

g$^+$ (1064 THz)

eutral Yb (520 THz)

(429 THz)

irect comparison to Cs (0.0092 THz)



Optical ref 1 ν_1

fs laser

Optical ref 2 ν_2

Compare ν_1 vs ν_2

set $\nu_n = \nu_{opt}$

$\nu_m - \nu_{opt2}$

Optical reference 1

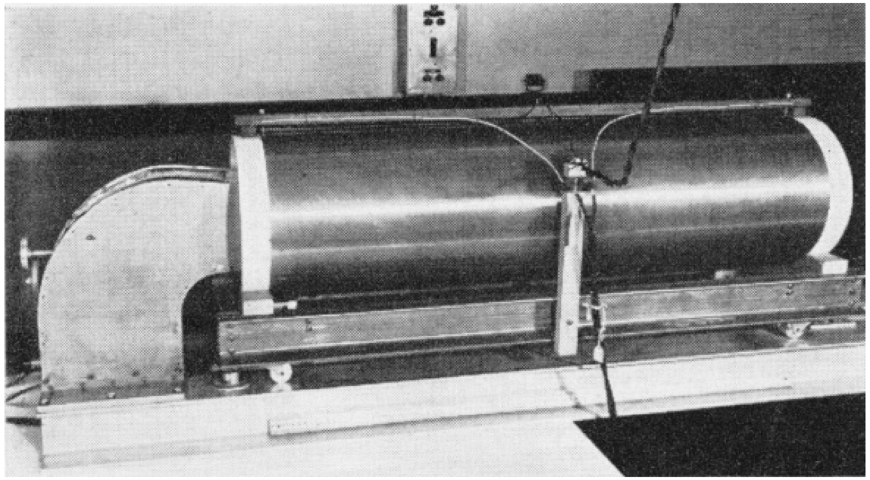
Optical reference 2

x 2

set $f_o = 0$

The Ampere

1946: *The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to* 2×10^{-7} *newton per meter of length*. (9th CGPM, Resolution 2)



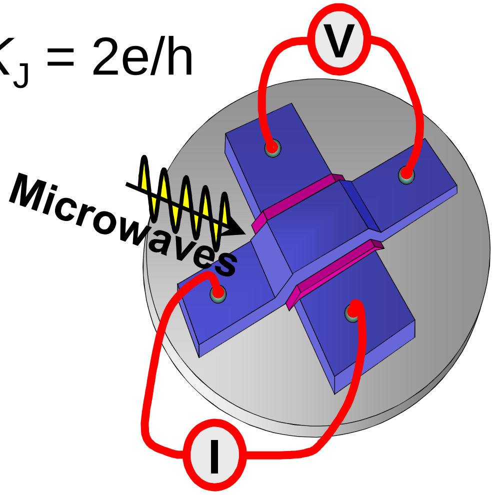
From R. L. Driscoll, “*Measurement of Current with a Pellat-Type Electrodynamometer,*” Journal of Research of the National Bureau of Standards, 60(4), April 1958

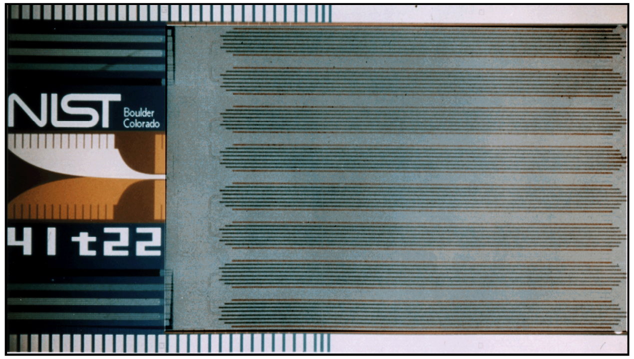
The Ampere has mostly not been realized. It is a definition that is *infinitely* complex. Approaches to realizing it have been demonstrated and new ones exist.

Standards for Electrical Units Since 1990

Josephson Voltage Standard

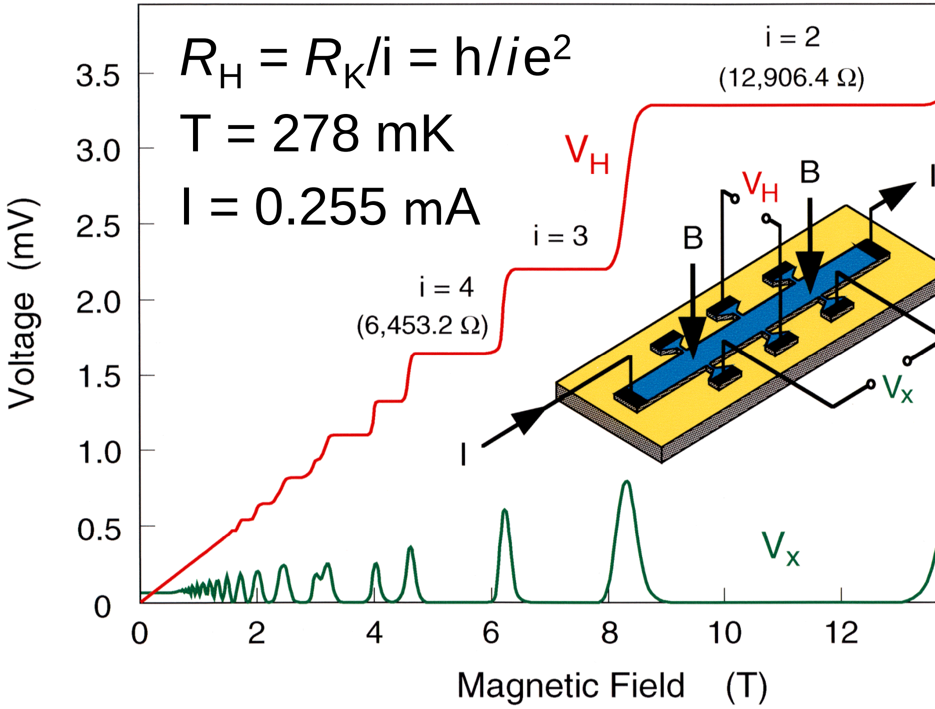
$K_J = 2e/h$





The "volt" realized by Josephson Junction devices, with K_{J-90} = 483,597.9 GHz/V

GaAs Quantum Hall Resistanc



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(Graphene QHR underway)

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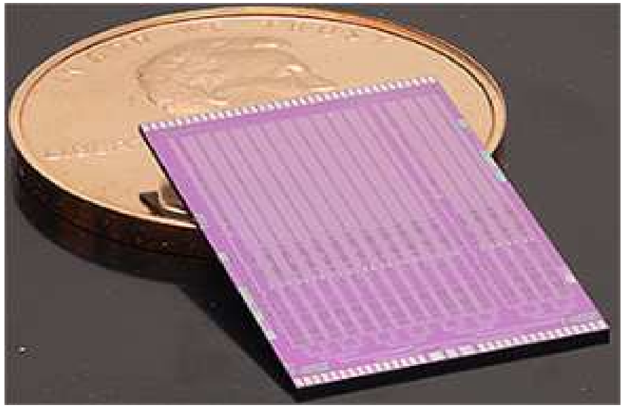
Quantum-Based Voltage Standards

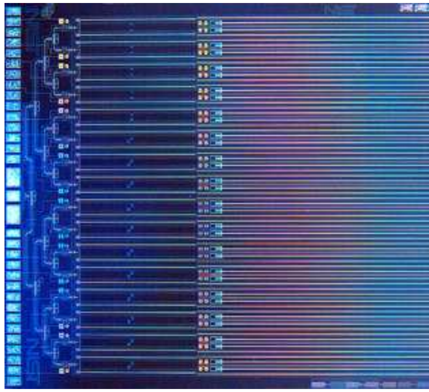
- DC Volt
  - Programmable Josephson Volt Standard
  - Quantized voltages: ±10 V
- AC Volt
  - Programmable Josephson Arbitrary Waveform Synthesizer
  - Quantum accuracy up to 1 MHz



Josephson Voltage Systems

rrently build 10 V programmable Josephson Voltage Chips

32 microwave channels, 300,000 JJ's

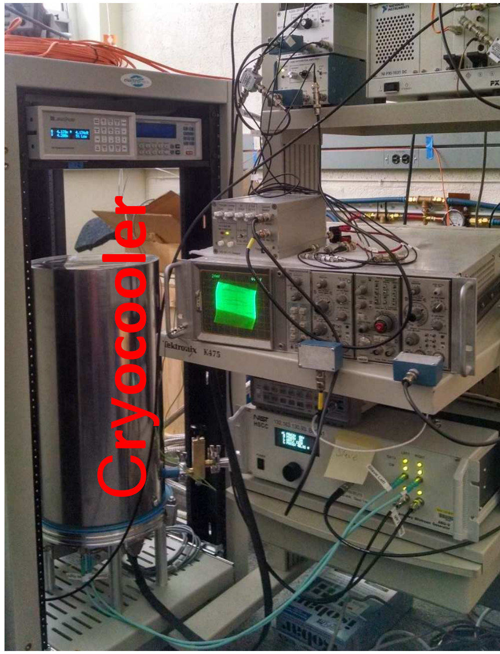


NIST 10 V PJVS chip

Sam Benz holding a 10 V PJVS probe

Next Generation JVS:

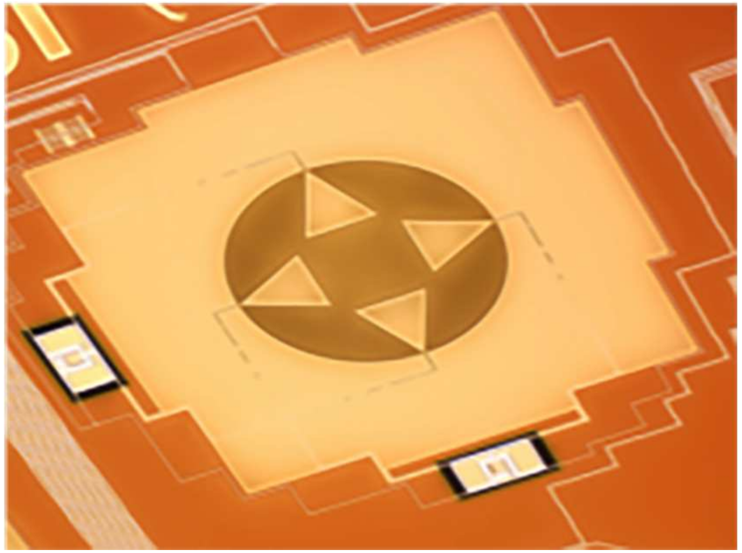
- "Off-the-shelf" instrumentation
- Electronic cyrocooler
  - No liquid He
  - More user friendly
  - Fully automated
- Identical performance



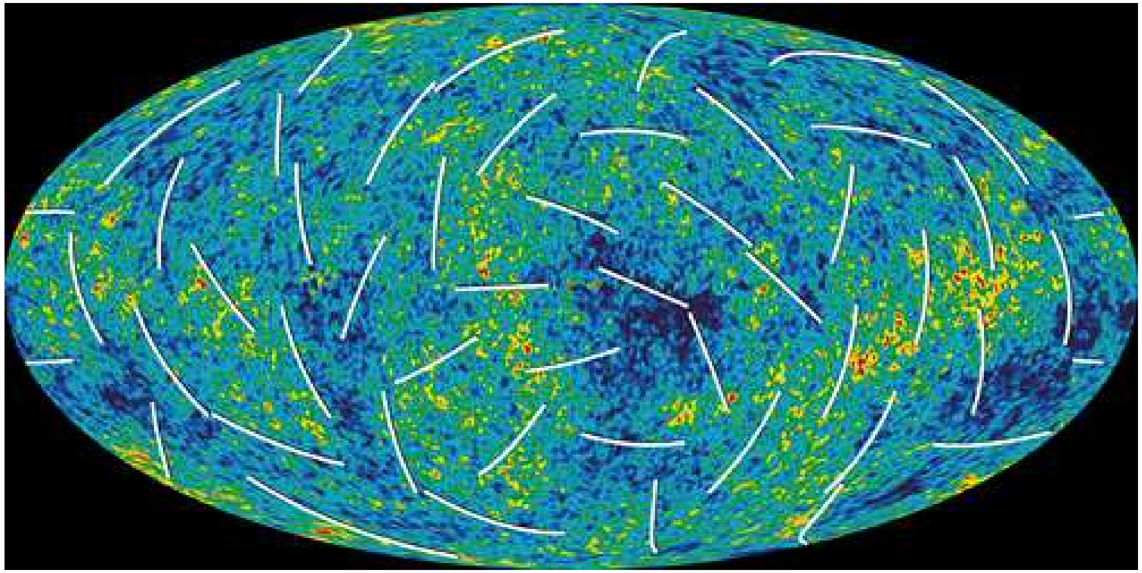
http://www.nist.gov/pml/div686/devices/automated-voltage-standard-ready.cfm

Josephson Voltage Systems

- **Related technology used for NIST Transition Edge Sensors (single photon detectors) and the Atacama Cosmology Telescope**



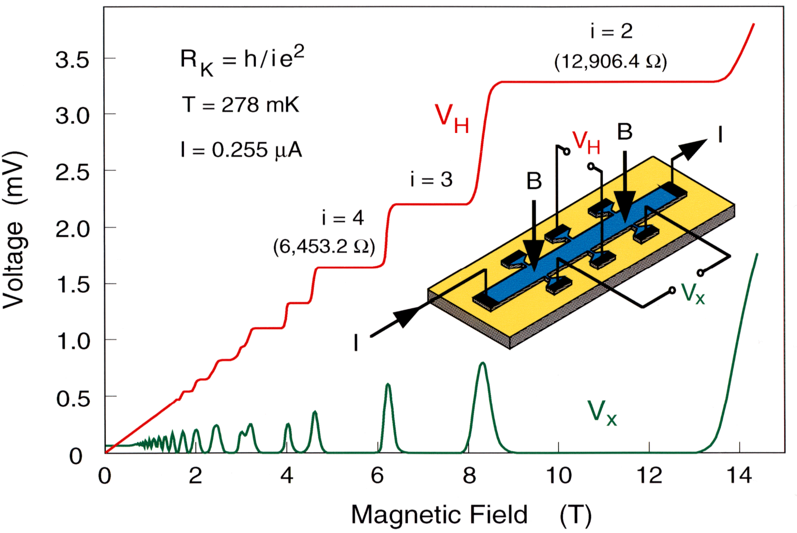
Part of a NIST detector array for the ACT

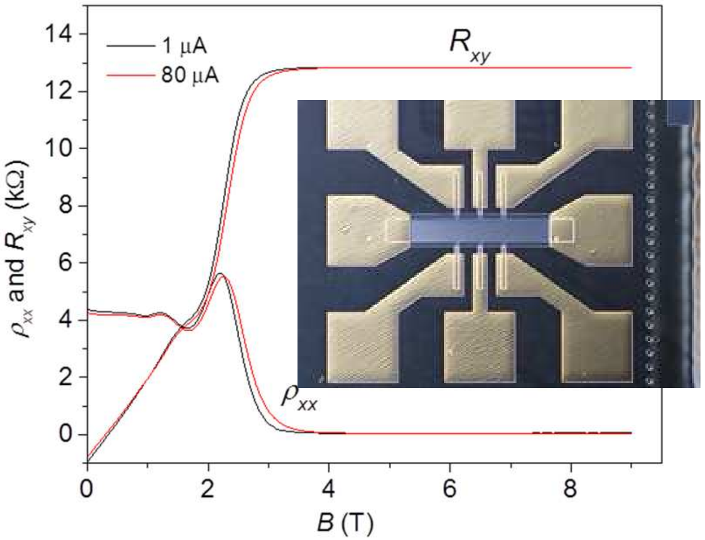


Polarization of the Cosmic Microwave Background: WMAP/NASA

e: http://www.nist.gov/pml/div686/devices/cmb-polarization-detector.cfm

Quantum Hall Standards





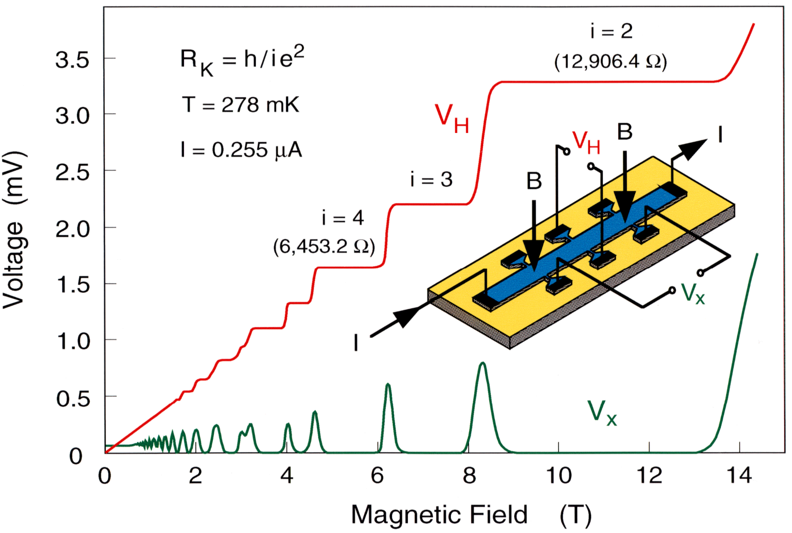
GaAs Quantum Hall Resistance

- Basis for the Ohm
- Runs at 12.9 kΩ
- Difficult to scale
    - Specialized equipment and training

Graphene Quantum Hall Resistance

- Runs at 12.9 kΩ
- Runs at higher temperatures
- More easily scalable
- Possible future basis for the Ohm

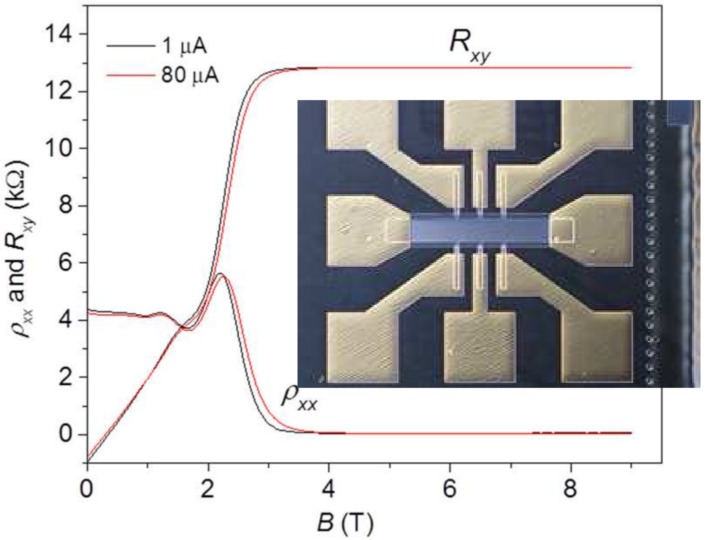
Quantum Hall Standards



$$R_H = \frac{V_H}{I} = \frac{B}{eN_s}$$

$$N_s = \left(\frac{eB}{h}\right) i$$

$$\boxed{R_H = \left(\frac{h}{ie^2}\right)}$$



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Graphene Quantum Hall Resistance

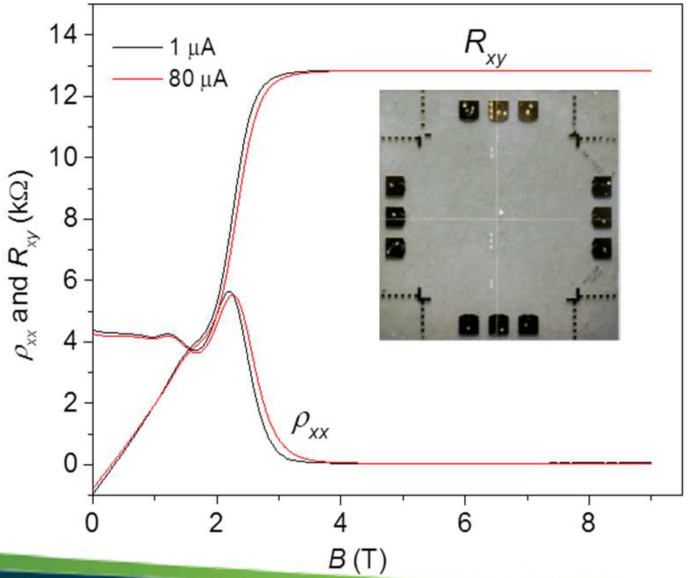
antum Hall Resistance (QHR) Standards

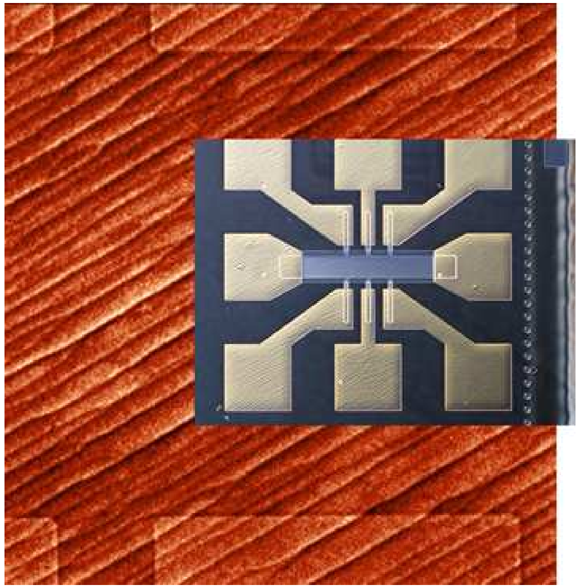
xisting GaAs semiconductor QHR standards are:

- Difficult to manufacture
- Costly and complex to use

raphene QHR standards can be made at NIST:

- Work at lower magnetic field strength
- Work at higher temperature
- Work at higher current levels
- Greatly reducing the cost of operation.

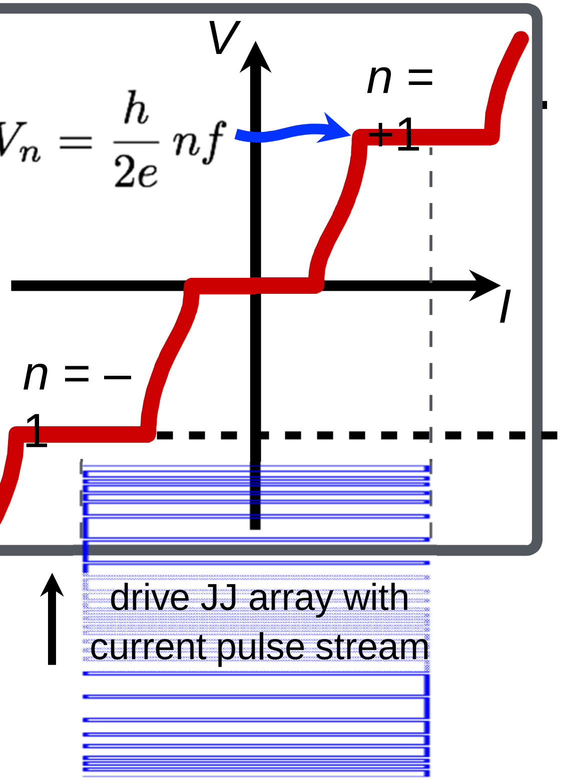




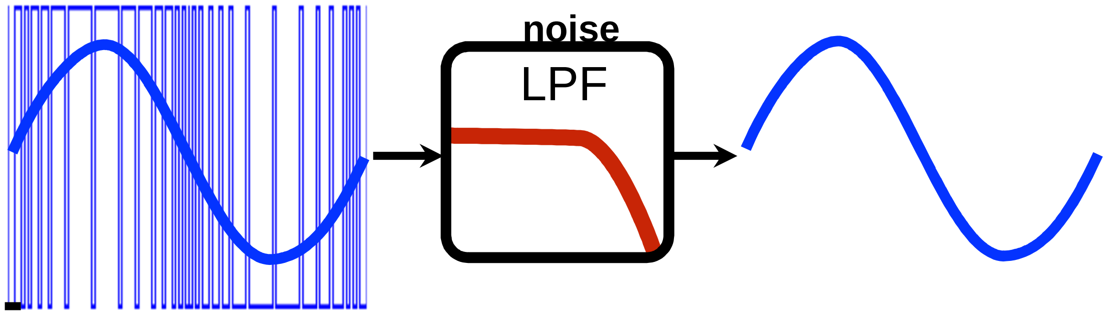
Recent Success

- NIST has developed novel techniques to grow graphene on Si C and to process the material into **high current QHR devices.**
- Devices are compatible with our existing highly customized measurement infrastructure
- Device can be used directly with commercially available room temperature bridge systems

AC Josephson Voltage Standard (ACJVS)



drive JJ array with current pulse stream



output voltage stream is perfectly quantized

remove high-*f* quantization noise

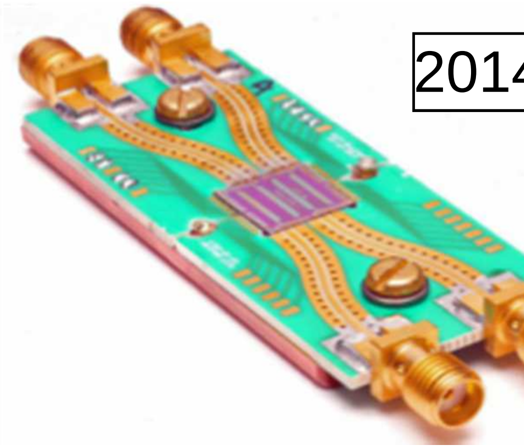
waveform with calculable voltage

- intrinsically accurate, *quantum* voltage standard
- JJs act as perfect quantizers, converting arbitrary input pulses to output *voltage* pulses with quantum-accurate *V*-*t* area:

$$\int_{\text{pulse}} V(t)dt = \frac{h}{2e} \approx 2.07\ \text{mV-ps}$$

- 30 Gb/s data rate ⇒ picosecond pulse timing

precision control over amplitude and phase of arbitrary waveforms via pulse pattern and timing



201

photograph of 4-arra
ACJVS cryopackage

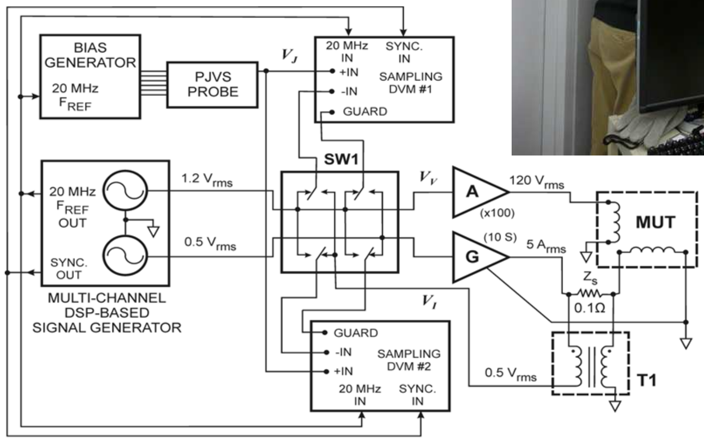
12,800 Josephson junctions p
array

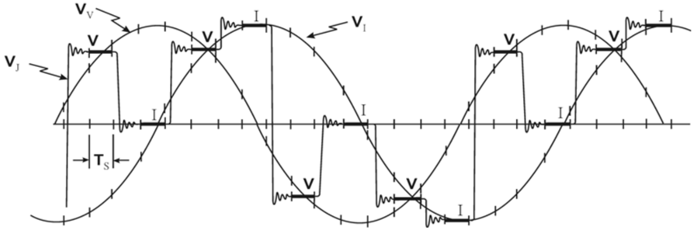
- rms output up to 1 V for n=1
- requires 4 separate bias cha
- 2 V, 4-array chip under development
- Extends previous 2-array ch
6,400 JJs: 0.5 V

Additional Quantum Electrical Standards

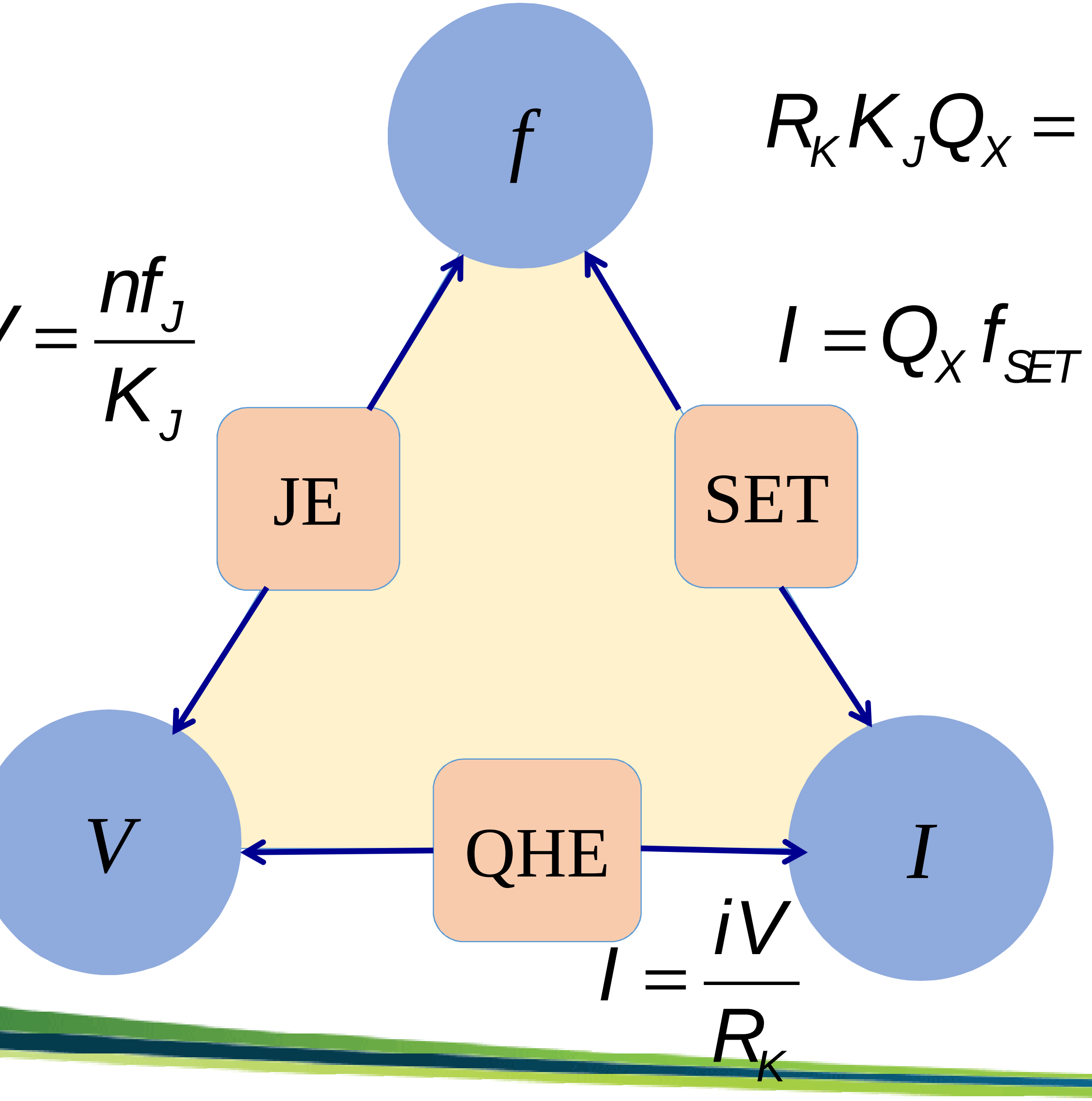
- Quantum Watt: Voltage reference from a PJVS applied to a power meter (5A, 120V). Voltage and current are adjusted to minimize difference between sampled and reference voltage.
- Arbitrary waveform synthesis up to 300 GHz is underway at NIST using Josephson effect
- Efforts to create Single Electron Transistors (SETs) have gone on for more than 2 decades for the Ampere
  - Many efforts in GaAs, also Al, more recently Si
  - Quantum Ampere project in Europe at the moment
  - NIST is working on Si SETs (1 → 100 pA, 100 in parallel → 10 nA
- Apply Ohm's Law (V=IR) and between JE, QHR, and SETs can in principal generate all Electrical quantities from quantum standards

Quantum Watt





Quantum Metrological Triangle



$$V = \frac{nf_J}{K_J}$$

$$I = Q_X f_{SET}$$

$$I = \frac{iV}{R_K}$$

$$R_K K_J Q_X = n \frac{i}{G} \frac{f_J}{f_{SET}}$$

or

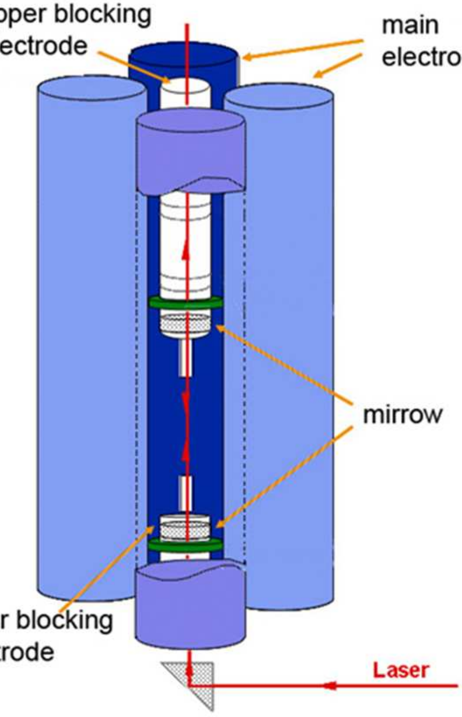
$$V = R_H G I_{SET}$$

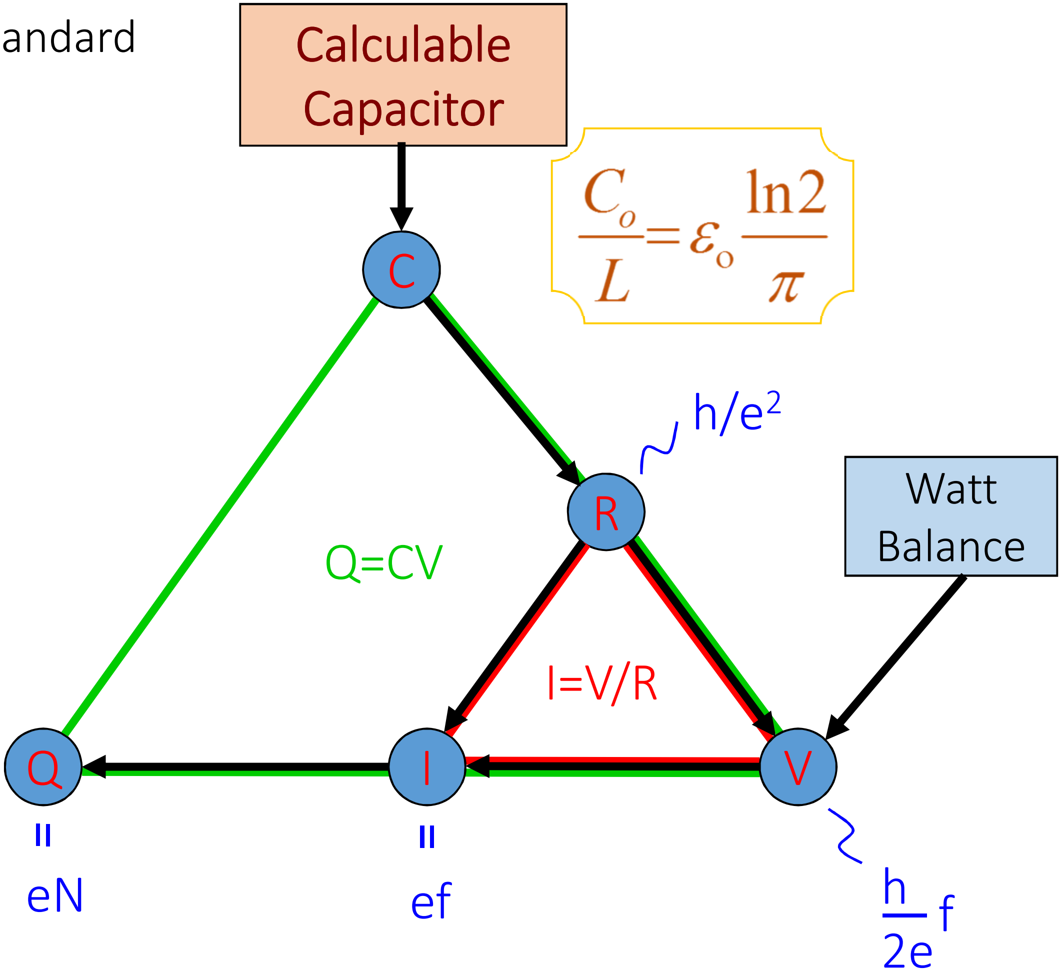
Where *G* is the gain from a Cryo
Current Comparator (CCC)

- <u>Single Electron Transistors:</u>
  - Many efforts in GaAs, also Al, more recently Si
  - NIST demonstrated an Al SET at 1 pA at an uncertainty o 1.5 x 10^{-8} in 1996 (*Applied Physics Letter*, **69**, 1804 (1996
  - PTB, as part of the Qu Ampere project, has demonstrate a GaAs SET at 100 pA at an uncertainty of 2 x 10^{-8} in 201
  - Australians using Si SETs out of there Q. Computing project have new results (unpublished)
- QMT – which is an application of Ohm's Law (V=IR) has been realized
  - NIST demonstrated this at an uncertainty of 1 x 10^{-6} in 1999 (*Science* **285**, 1706 (1999))
  - Underway again in Qu. Ampere

Not all Electrical Standards are Quantum

- e simplest link to a mechanical unit
- ost accurate capacitance standard
- etermine QHR value





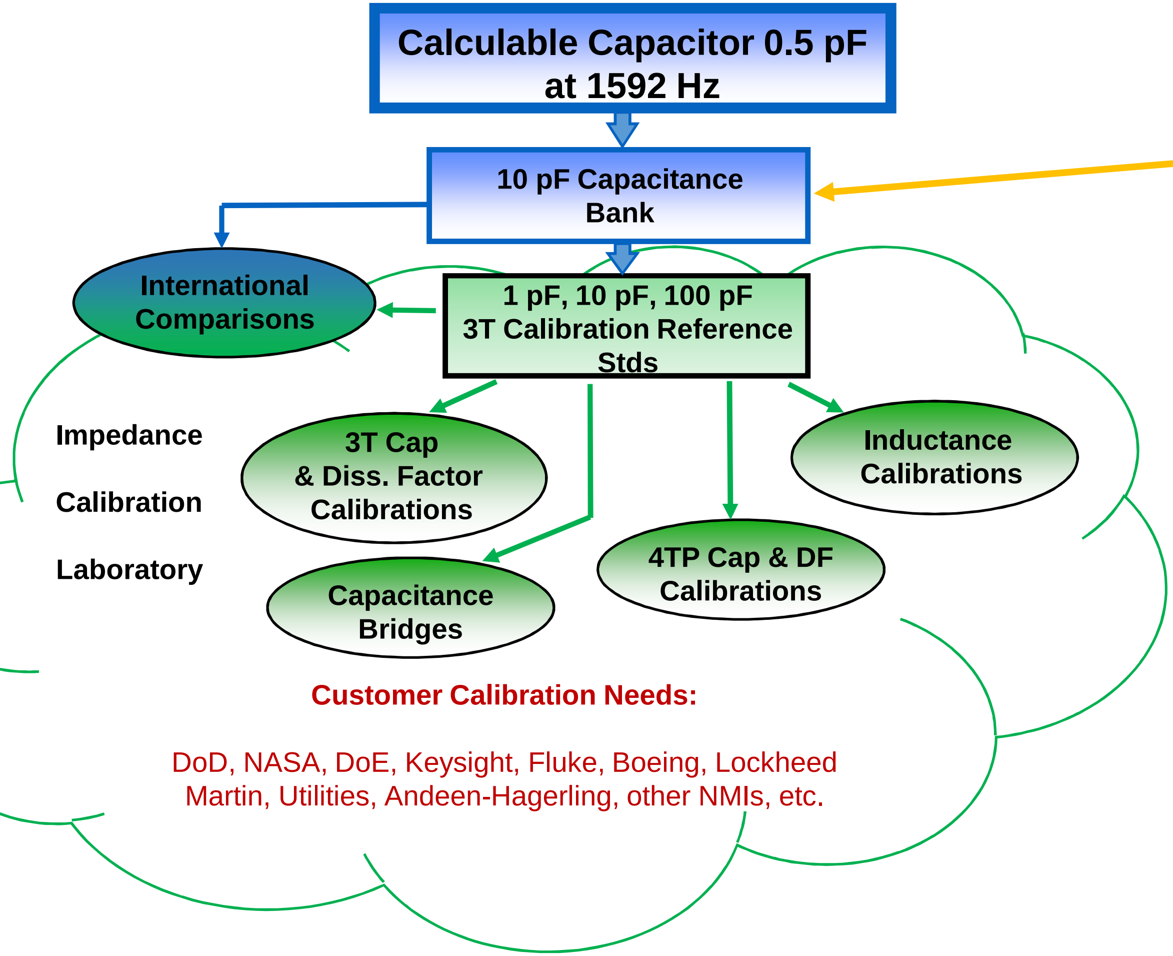
Calculable Capacitor

$$\frac{C_o}{L} = \varepsilon_o \frac{\ln 2}{\pi}$$

Watt Balance

- NIST is building a new Calcul
  Capacitor
  - Replace or have a backup for
    old one
  - Continuously tunable
  - Most linear capacitance stan
  - Possible tool for measuring t
    non-linearity of capacitance
    bridges
  - Could lead to a calibration
    method to correct the bridge
    nonlinearity
- But what about AC-QHR?
  - This would be a quantum
    standard and more easily
    integrated with other quantu
    standards

Impedance Scaling and Calibration Support



Calculable Capacitor 0.5 pF at 1592 Hz

10 pF Capacitance Bank

1 pF, 10 pF, 100 pF 3T Calibration Reference Stds

International Comparisons

Impedance

Calibration

Laboratory

3T Cap & Diss. Factor Calibrations

Inductance Calibrations

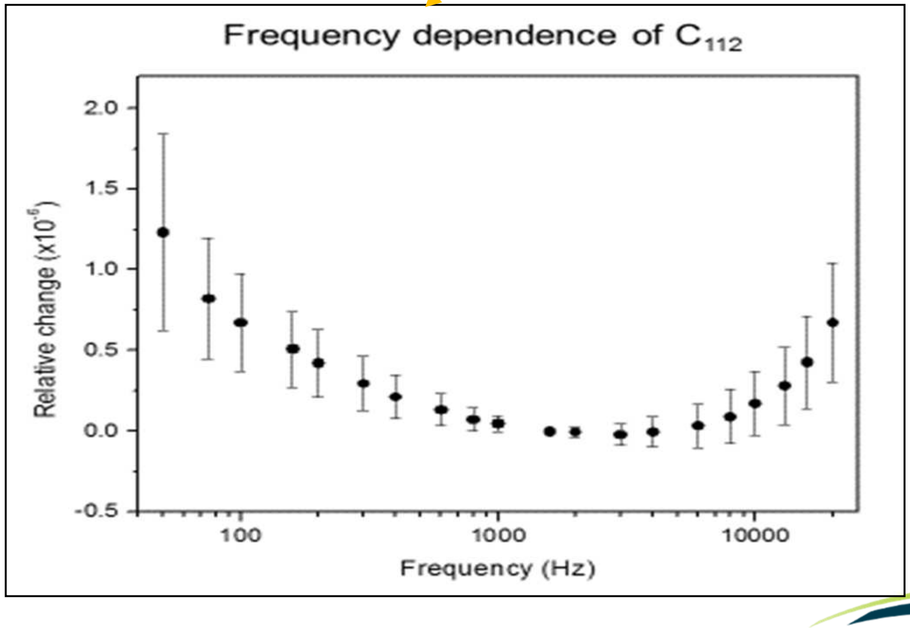
4TP Cap & DF Calibrations

Capacitance Bridges

Customer Calibration Needs:

DoD, NASA, DoE, Keysight, Fluke, Boeing, Lockheed Martin, Utilities, Andeen-Hagerling, other NMIs, etc.

Various scaling techniques have been developed to link capacitance at different magnitudes and frequencies. Loss factor of the capacitance standard is calculated based on the Kronig-Kramers relations.



Electrical Metrology in the Future

- Electrical units will be brought back into the SI and *conventional units will be abrogated*
- Current QHR systems are not robust
- Graphene based QHR has been demonstrated but not yet robust
- Numerous efforts for Single Electron Transistors (SETs) is underway (Si, GaAS, …)
- Integration of two quantum standards (QHR, SETs, JVS) on a single device would revolutionize electrical instrumentation – through on chip application of Ohm's law to create self-calibrating instruments
- Demonstrated ACJVS in collaboration with METAS last fall to directly do impedance
- AC QHR may also be used to do impedance – more easily integrated
- Arbitrary waveform metrology using JVS at high-speed is underway

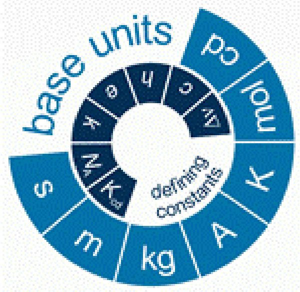
Outline

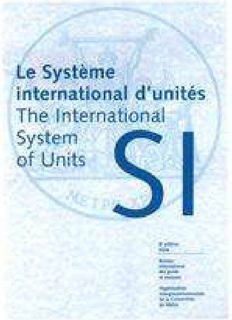
- NIST and the Physical Measurement Laboratory (PML)
- The Metric System and the SI
- Quantum Standards and Movement Toward Redefining the SI
- Quantum standards and Quantum metrology today
- From Instrumenting the SI to Embedded Measurements
- Implications

Disclaimer: This talk is very "NIST-centric"

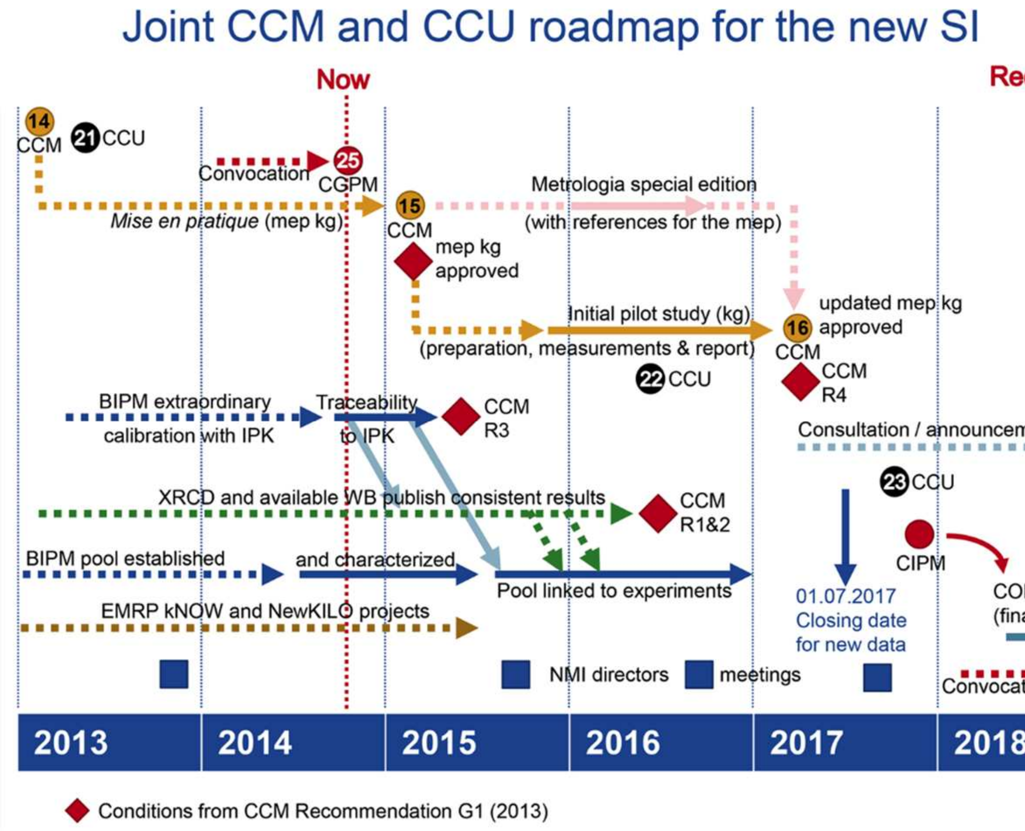
From the SI to the Quantum SI
Meeting the Metrology Challenges of the 21st Century

- **Quantum SI – 2018 ?**
  - – Quantum Phenomena
  - – Fundamental and Atomic Constants





- o **kilogram**
  - Planck constant
- o **ampere**
  - Elementary electric charge
- o **kelvin**
  - Boltzmann constant
- o **mole**
  - Avogadro constant



SI Dissemination Methodologies in Practice

Send us an artifact;
measure it and return it.

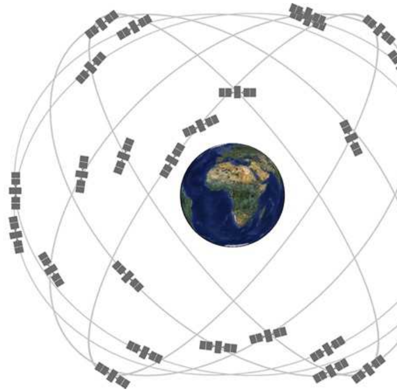
e shown here: Gauge
nd other artifacts used as
onal metrology standards.
xamples: masses, resistors
er electrical devices.

Send us an instrument;
We'll calibrate it and return it.

Example shown here: Proving ring for force metrology. Other examples: thermometers, pressure gauges, photodiodes (e.g., for optical power).

Don't send us anything;
Buy one, and we'll ship it to you.

Example shown here: Ocean Shellfish Radionuclide Standard (SRM 4358). Other examples: certain lamps and photodiodes for photometry and radiometry.



Don't send us anything;
observe something toge

Example shown here: GPS s
constellation (atomic clock
orbit). Satellite common-vi
used to transfer precision t
and frequency standards.

NIST Calibration Services Today

591 measurement services in eight metrology areas

Dimensional

- Length (Q)
- Angular
- Diameter and Roundness
- Complex Dimensional (Q)
- Surface Texture

Electromagnetic

- Voltage (Q)
- Resistance (Q)
- Power and Energy (Q)
- EM Field Strength
- Precision Ratios

Environmental

- Ozone Measurements
- Mercury Measurements

Ionizing Radiation

- Radioactivity
- Sources & Dosimetry (Neutron, x ray, gamma ray, and electron)
- High Dose Applications

Mechanical

- Mass
- Force (Q*)
- Volume and Density
- Fluid Flow
- Acoustics and Vibration

Optical Radiation

- Photometry
- Optical Properties of Mtls
- Color and Appearance
- Spectroradiometry
- Laser Power and Energy

Thermodynamic

- Thermometry
- Pressure and Vacuum
- Humidity
- Radiance Temperature
- Thermal Resistance

Time and Frequency

- Time Dissemination (Q)
- Frequency Measurement (
- Oscillator Characterization
- Noise Measurement (Q)
- GPS Receiver Analysis

Representative selection

Catalog online at: **http://www.nist.gov/calibrations/**

NIST Calibration Services Tomorrow

591 measurement services in eight metrology areas

Dimensional

- Length (Q)
- Angular
- Diameter and Roundness
- Complex Dimensional (Q)
- Surface Texture

Electromagnetic

- Voltage (Q)
- Resistance (Q)
- Power and Energy (Q)
- EM Field Strength (→ Q)
- Precision Ratios

Environmental

- Ozone Measurements
- Mercury Measurements

Ionizing Radiation

- Radioactivity (→ Q)
- Sources & Dosimetry (Neutron, x ray, gamma ray, and electron)
- High Dose Applications

Mechanical

- Mass (→ Q*)
- Force (Q)
- Volume and Density
- Fluid Flow
- Acoustics & Vibration (→Q)
- *Acceleration* (→ Q)

Optical Radiation

- Photometry
- Optical Properties of Mtls
- Color and Appearance
- Spectroradiometry
- Laser Power & Energy (→Q)

Thermodynamic

- Thermometry (→ Q)
- Pressure & Vacuum (→ Q)
- Humidity
- Radiance Temperature
- Thermal Resistance

Time and Frequency

- Time Dissemination (Q)
- Frequency Measurement (Q
- Oscillator Characterization (
- Noise Measurement (Q)
- GPS Receiver Analysis

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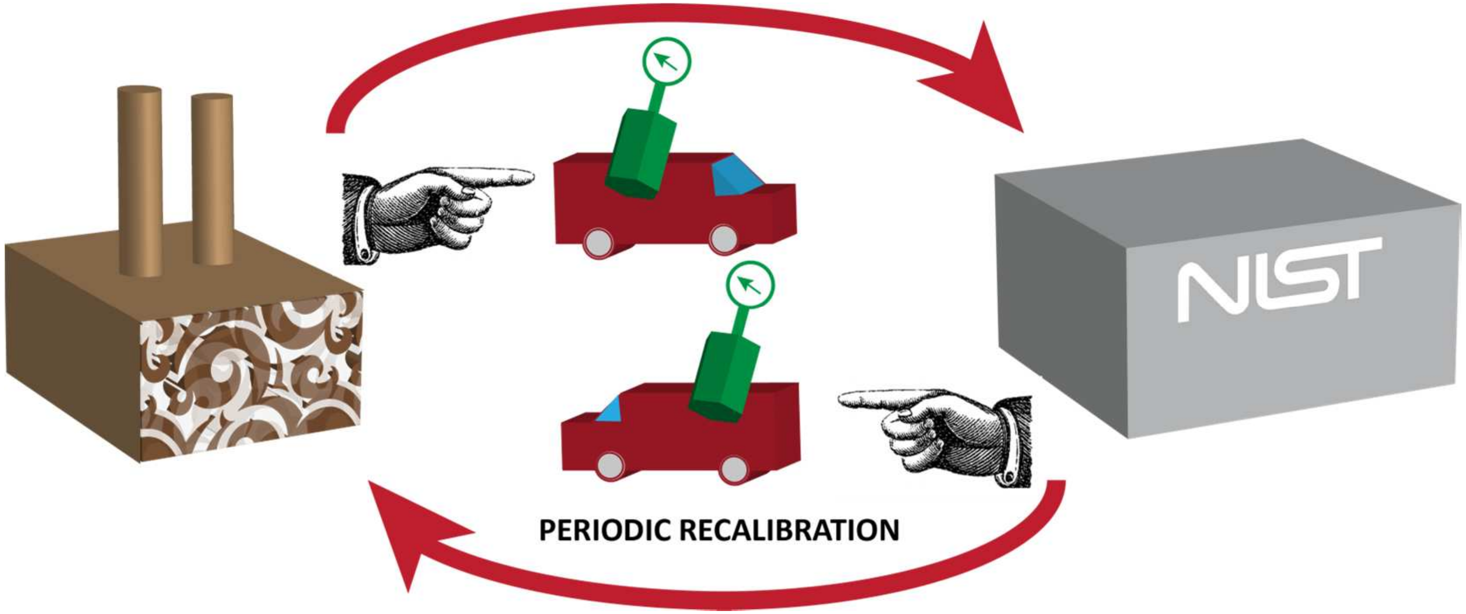
Classical Calibration Dissemination Method: How NMI's Work Now …



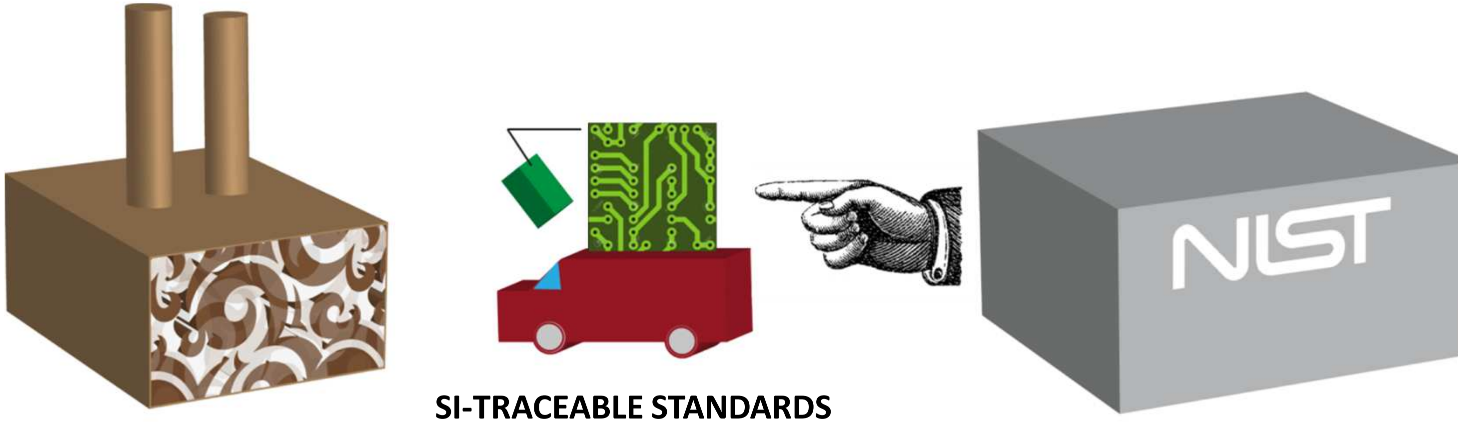
Delivery guy:
le likes things as they are

Routine shipment of artifacts
and instruments for calibration

Over 14,000 artifacts per year – Expensive modality

Advanced Measurement: Quantum SI Dissemination

He’s got less work to do



SI-TRACEABLE STANDARDS AND SENSORS

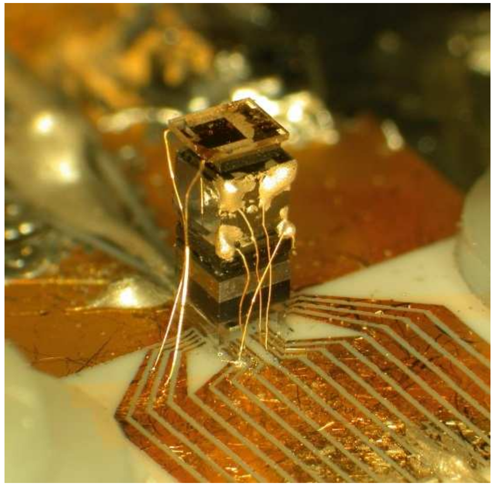
Technology transfer

- Dual platform standards and sensors
- SI realization outside the walls of NIST
- New faster/lower cost calibration services – on factory floor
- Enhance economic impact through elimination of waste in industrial processes
- Number of calibrations approaches zero
- Traceability more complex

Emerging Technologies: Enable Disruptive Change

- Solid state lasers, e.g., Vertical Cavity Surface Emitting Lasers (VCSELs)
- Microelectromechanical systems (MEMS) fabrication
- Other deployable quantum standards are coming
- Will become ubiquitous

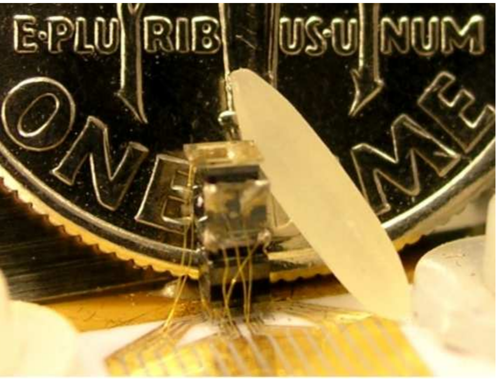
These technologies enable the Chip-Scale Atomic Clock (CSAC)



NIST Prototype (2004)

Commercialized (20

Deployed Metrology Enables Technology Infrastructure



Chip Scale Atomic Clock

(10^{-11} uncertainty)

As commercialized

Telecom networks

>€2 trillion/year globall

Improved small clocks with improved long-tern stability could provide a deployable GPS backu

But the measurements are used everywhere . . .

Goal: NMI-quality measurements and physical standards available directly where the customer/user needs them.

Technologies May Enable Disruptive Change

- Solid state lasers (e.g., VCSELs)
- Microelectromechanical systems (MEMS) fabrication
- Micro- and Nano-fabrication
  - Nanoelectronic
  - Microfluidics
  - Integrated photonics
- Superconducting systems
- Quantum-based standards and phenomena
  - Fundamental atomic and molecular properties
  - New material properties
  - Ultracold systems

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Emerging Technologies
Enable Disruptive Change

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- Quantum-based standards and phenomena
  - Fundamental atomic and molecular properties
  - New material properties
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A 21st century toolkit can enabl the development of a new generation of artifacts and instruments with capabilities that far exceed those traditionally used for traceabilit

In some cases, they might rival the capabilities of NMI!

Implications

- Will modify the character of NMIs → less calibration, more monitoring, more research
- Will require changes in legal metrology on what does it mean to be traceable
- Will have broad social impact from monitoring of major infrastructure like bridges to limiting over exposure of x-rays
- My next talk will talk about the future quantum based measurements and the talk on Friday will suggest possible limits on the “quantum SI”

Thank you!

Any questions?

carl.williams@nist.gov

National Institute of
Standards and Technology
U.S. Department of Commerce