The Redefinition of the SI and Mass Metrology

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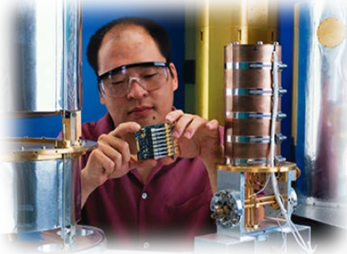
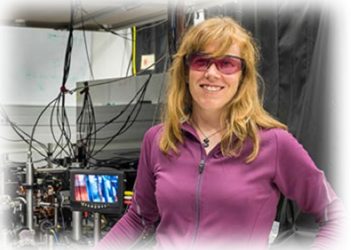


NIST
National Institute of Standards and Technology
U.S. Department of Commerce



PML
PHYSICAL MEASUREMENT LABORATORY

Outline

- NIST and the Physical Measurement Laboratory (PML)
- The Metric System and the Origin of the SI
- Quantum Standards and Movement Toward Redefining the SI
- Quantum Standards and Quantum Metrology Today
- Mass and Force Metrology and the SI Tomorrow
- Towards Democratization of the SI: Embedded Measurements

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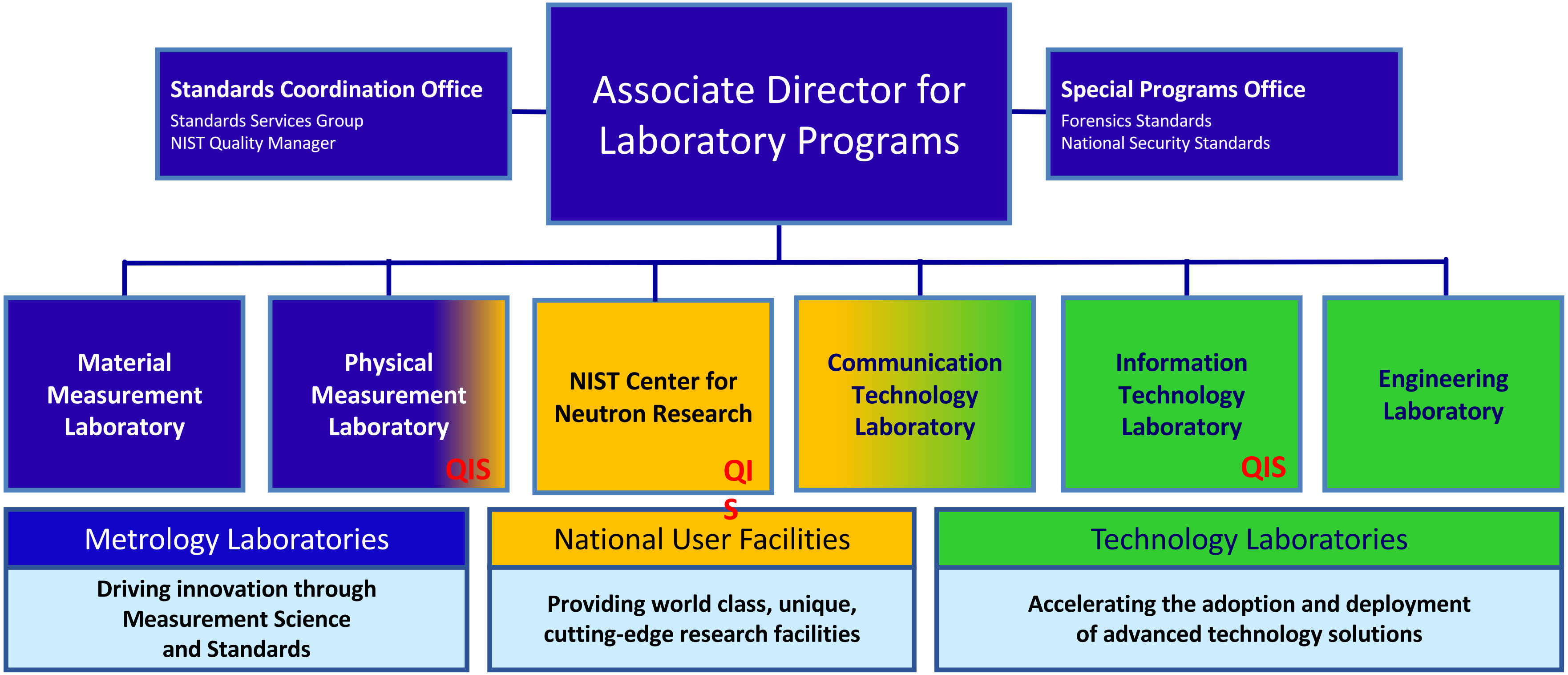
NIST Laboratories and User Facilities



Standards Coordination Office
Standards Services Group
NIST Quality Manager

Associate Director for Laboratory Programs

Special Programs Office
Forensics Standards
National Security Standards

Material Measurement Laboratory

Physical Measurement Laboratory
QIS

NIST Center for Neutron Research
QIS

Communication Technology Laboratory

Information Technology Laboratory
QIS

Engineering Laboratory

Metrology Laboratories

Driving innovation through Measurement Science and Standards

National User Facilities

Providing world class, unique, cutting-edge research facilities

Technology Laboratories

Accelerating the adoption and deployment of advanced technology solutions

PML’s Core Mission

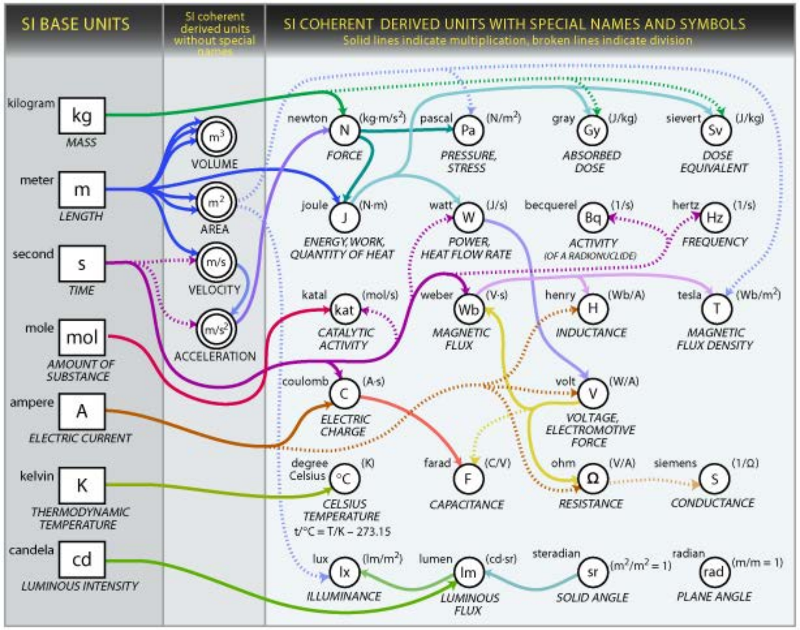
To realize, disseminate, and advance the International System of Units (SI) in the United States

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



METROLOGY MAKES IT HAPPEN

High-tech industries create jobs and economic growth

Many of these same sectors require the tightest manufacturing tolerances

- Petroleum and coal
- Chemicals
- Aerospace
- Pharmaceuticals
- Navigation/Control Instruments
- Semiconductors
- Communications
- Smart Grid

Scientific discovery is built on measurement science

If you can’t measure it you can’t make it reliably or improve it

Industry depends on constantly improving measurement tools to stay innovative and competitive

Metrology and the federal role is established in the United States Constitution. Is is essential to commerce, trade, and innovation.

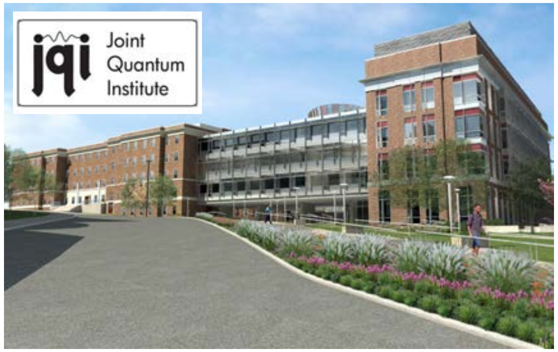
PML: Basic Stats and Facts

Major assets

- ~ $225 million budget [all funding sources]
- ~ 600 employees
- ~ 750 associates
- Principal activities in
  - Gaithersburg, MD
  - Boulder, CO
  - College Park, MD
  - Fort Collins, CO & Kauai, HI

Two collaborative institutes provide opportunities to:

- Attract world class scientists
- Train students and postdocs
- Transfer technology



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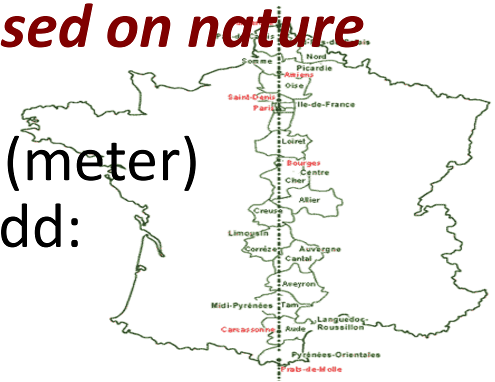
Origin of the Metric System

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 Meridian, Dunkirk to Barcelona 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” (SI)

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?

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

Both while artifacts were remarkably good!

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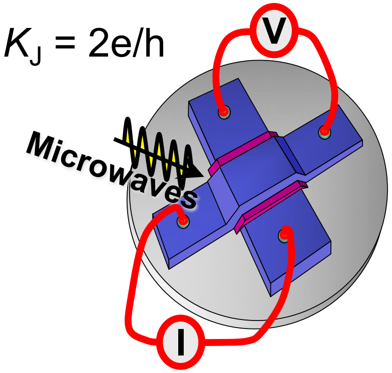
Toward Redefining the SI

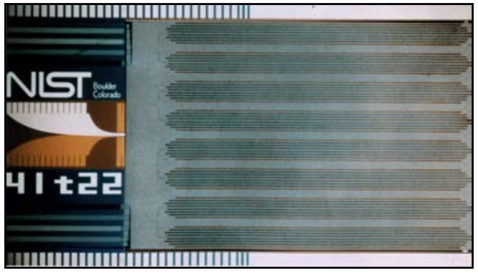
- With the creation of the *SI* in 1960, the process to revise and improve the units in a way that benefits the system as a whole and makes them ***based on nature*** truly begins
- In 1967 the second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition 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?
- *And are our "current" electrical units part of the SI?*

Standards for Electrical Units Since 1990

Josephson Voltage Standard

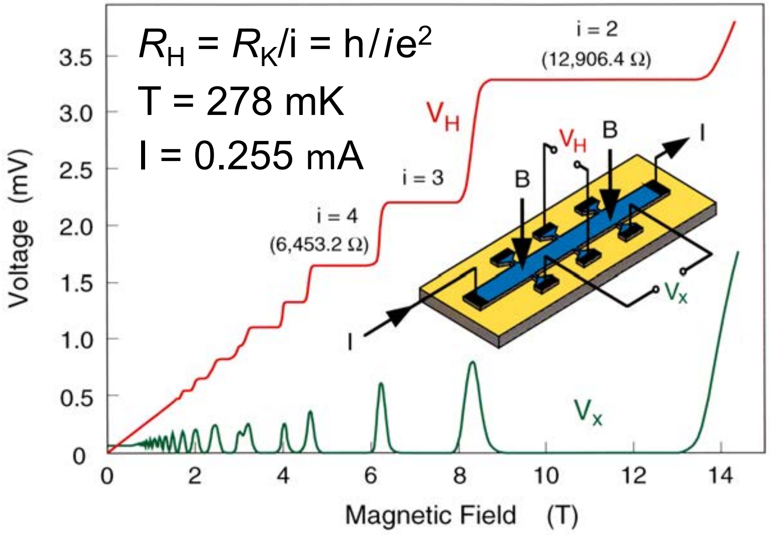
$K_J = 2e/h$





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

GaAs Quantum Hall Resistance



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

These **quantum standards**, the Josephson effect (1962, Nobel Prize 1973) and the quantum Hall effect (von Klitzing 1980, Nobel Prize 1985) are so robust that in 1987 the CGPM (Resolution 6) established *conventional electrical units!*

What do We Mean by “Quantum SI?”

Consider the History of the Meter:

1889: International Prototype Meter (Artifact)

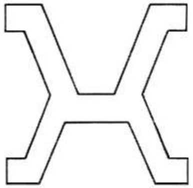
1960: *The meter is the length equal to* 1,650,763.73 *wavelengths in vacuum of the radiation corresponding to the transition between the levels* $2p_{10}$ *and* $5d_5$ *of the krypton* 86 *atom.* **(11th CGPM, Resolution 6)**

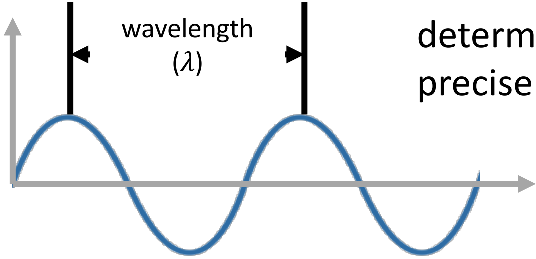
1983: *The meter is the length of the path travelled by light in vacuum during a time interval of* 1/299,792,458 *of a second.* **(17th CGPM, Resolution 1)**

The Meter

Definition of the Meter	Date	Absolute uncertainty	Relative uncertainty
$^{1}/_{10,000,000}$ part of one half of a meridian, measurement by Delambre and Méchain	1795	0.5–0.1 mm	10^{-4}
First prototype *Mètre des Archives* platinum bar standard	1799	0.05–0.01 mm	10^{-5}
Platinum-iridium bar at melting point of ice (1st CGPM)	1889	0.2–0.1 µm	10^{-7}
Platinum-iridium bar at melting point of ice, atmospheric pressure, supported by two rollers (7th CGPM)	1927	n.a.	n.a.
1,650,763.73 wavelengths of light from a specified transition in krypton-86 (11th CGPM)	1960	0.01– 0.005 µm	10^{-8}
Length of the path travelled by light in a vacuum in $^{1}/_{299,792,458}$ of a second (17th CGPM)	1983	0.1 nm	10^{-10}

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

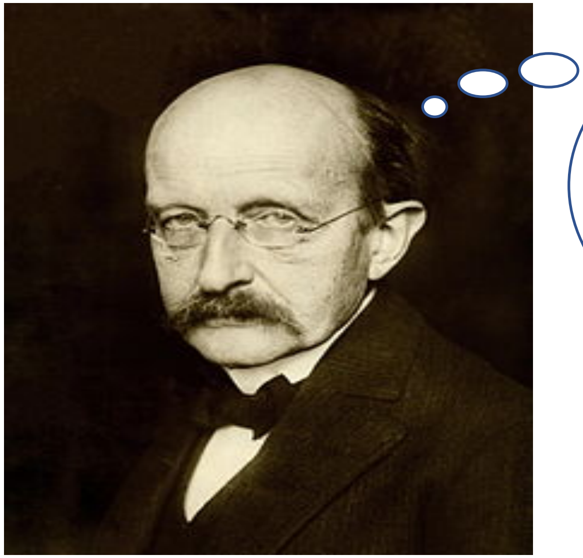




NIST Dimensional Metrology Group realizes the meter to a part in 10^{12}

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

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

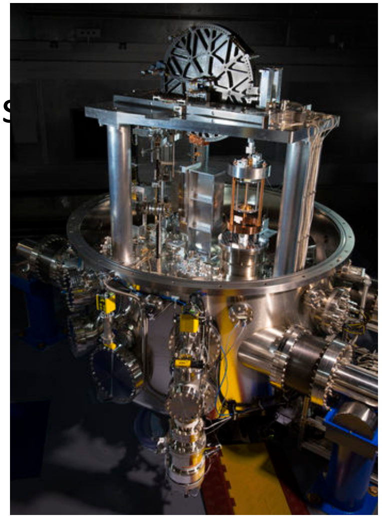
[*] Planck uses language similar to that used by the Marquis de Condorcet when he transferred the original French length and mass standards to the Archives de la Republique in 1799. More on the new SI can be found in Dave Newell's Physics Today article, July, 2014.

From the SI to the Quantum SI

20 May 2019 – World Metrology Day

- **Quantum SI**
  - Quantum phenomena
  - Fundamental constants
- Tying metrology back to fundamental physics (nature)
  - Removing artifacts as defining the SI

NIST Kibble Balance



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

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

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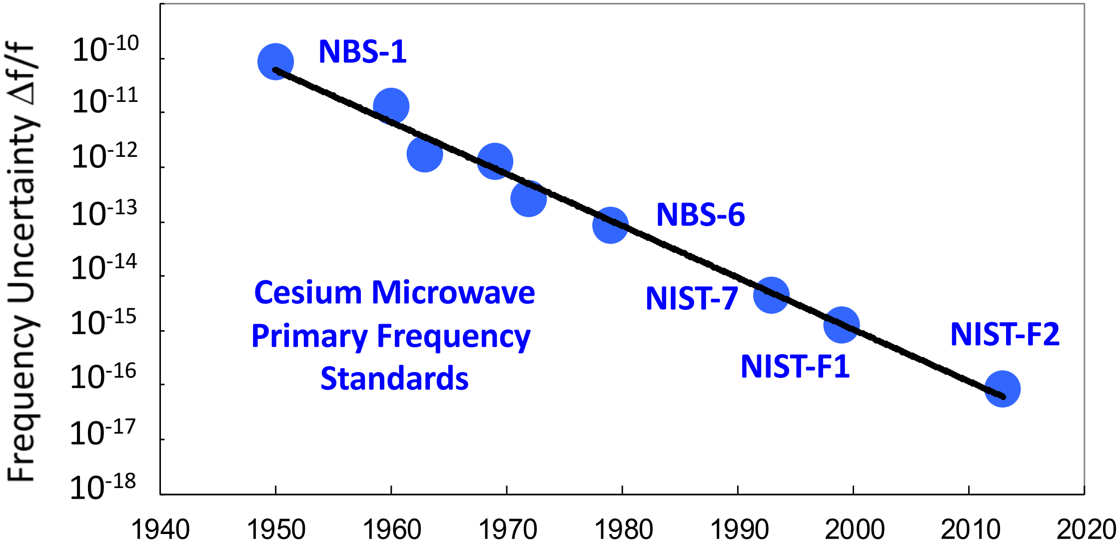
The Power of One Quantum Bit: NIST-F2

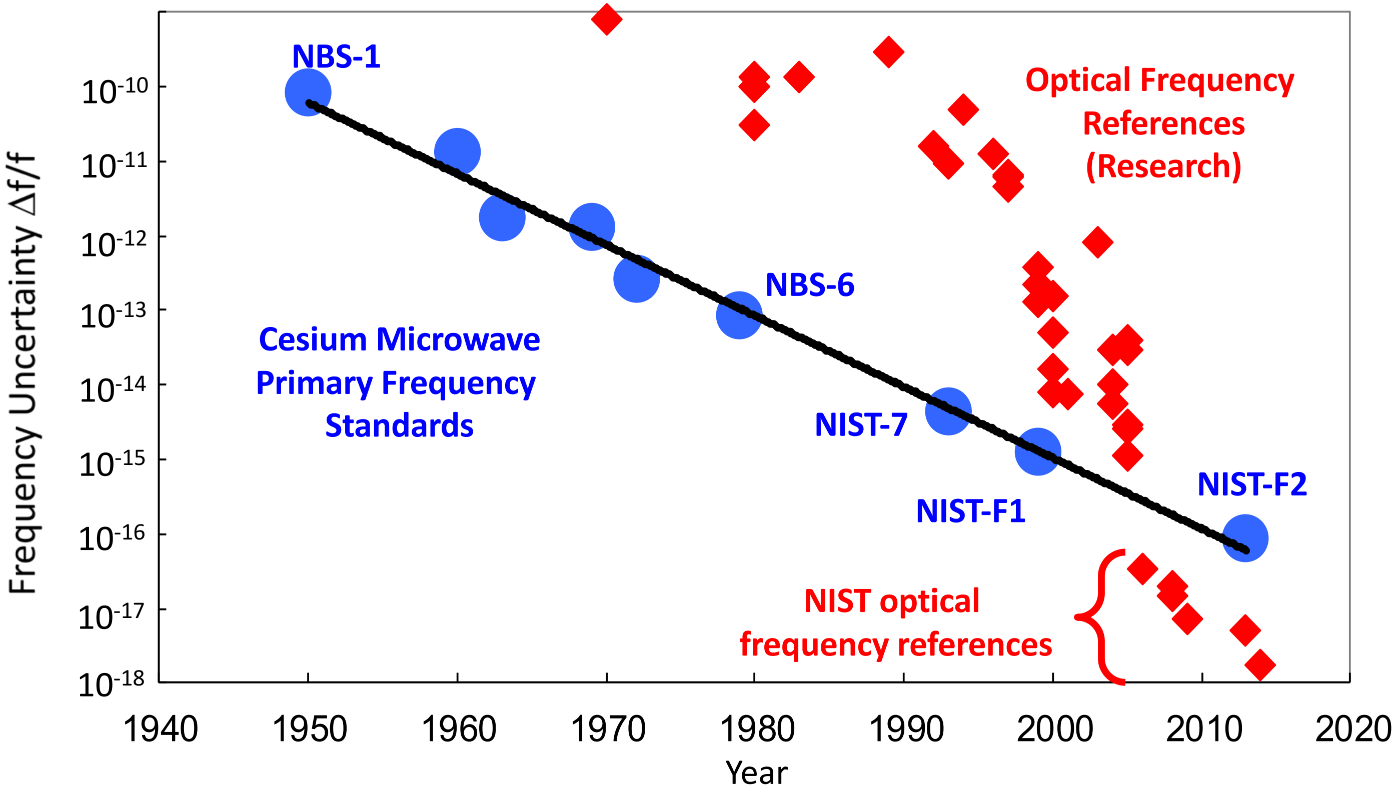
1 second is defined as the duration of 9,192,631,770 cycles of the cesium hyperfine transition.

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

NIST-F2 laser-cooled fountain standard atomic clock



Optical Frequency Standards

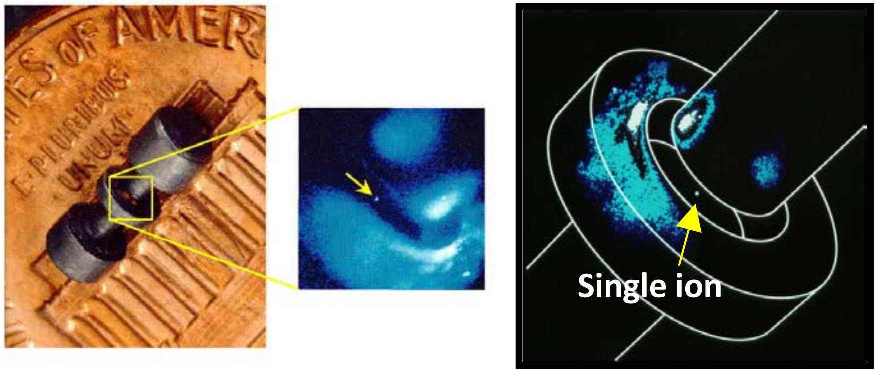


Since 2005 optical frequency standards have shown better fractional uncertainty and estimated systematic uncertainty then primary standard

Possible redefinition of time now being discussed for 2026

Optical Frequency Standards

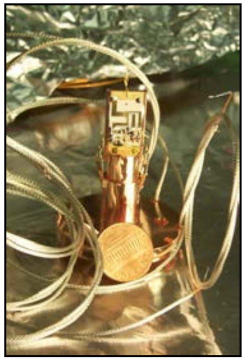
$\Delta f/f \sim 10 \times 10^{-18}$



Single mercury ion trap

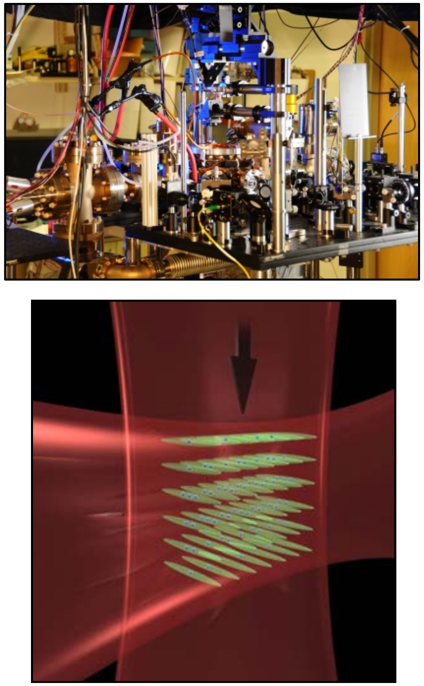
- High-frequency optical clocks outperform microwave (cesium) clocks.
- Potential to perform ~100 times better than best cesium clocks
- Many years before SI second redefined to optical standard(s) *(est. now 2026)*

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



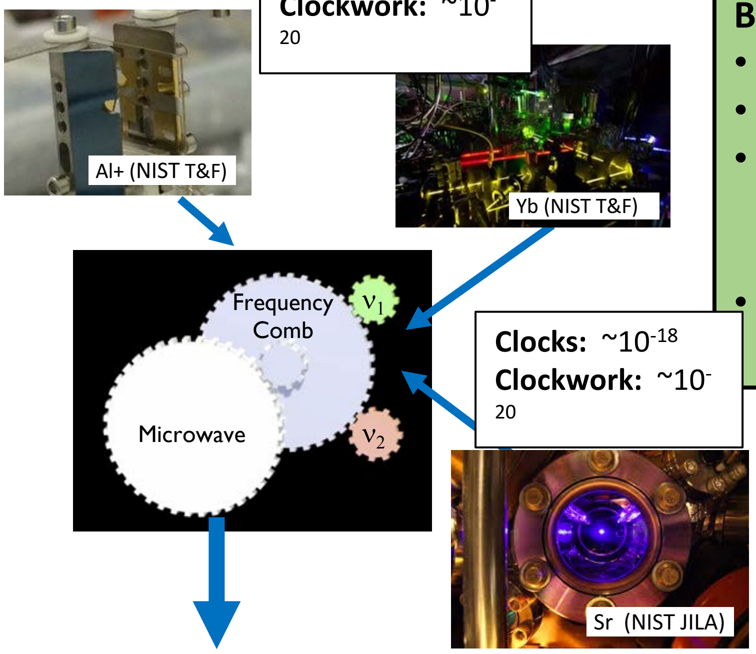
Aluminum ion logic clock

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



Strontium or Ytterbium optical lattice clocks

Quantum Metrology in an Optical Clock Network



Clocks: ~10^{-18}
Clockwork: ~10^{-20}

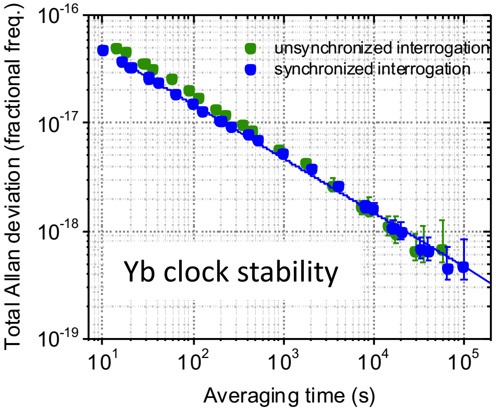
Clocks: ~10^{-18}
Clockwork: ~10^{-20}

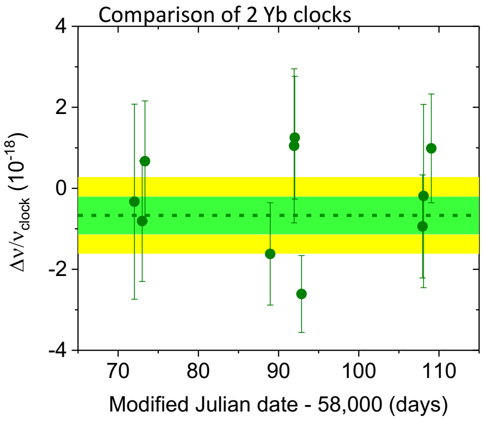
H-masers, NIST Timescale, UTC and the SI second

Boulder Optical Clock Network

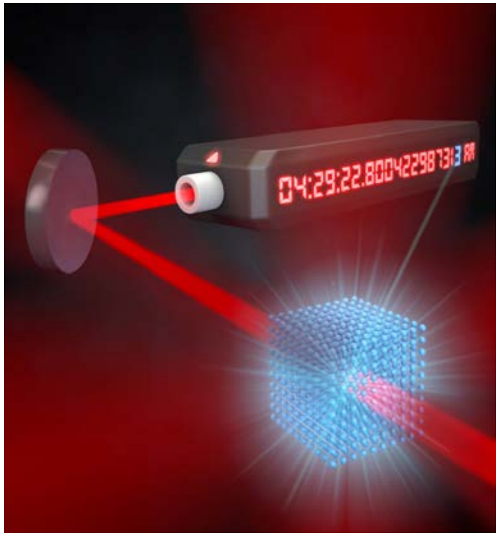
- Re-definition of the SI second & optical atomic timescales
- Relativistic geodesy, VLBI telescopy, navigation
- Fundamental science (tests of relativity, search for dark matter and gravitational waves, time variation of fundamental constants, …)
- Correlation and entanglement to reduce classical & quantum noise

Stability and Accuracy at 1×10^{-18} level





Quantum Degenerate Fermi Gas 3D Optical Lattice Clock

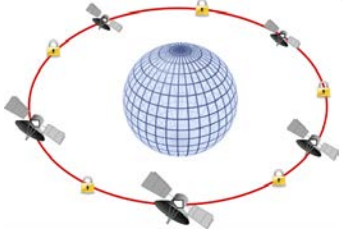


- First application of a quantum degenerate gas to improve a "practical" measurement.
- On path to precision 3 x 10^{-20} in one second in near future, 10^{-22} in a few years.

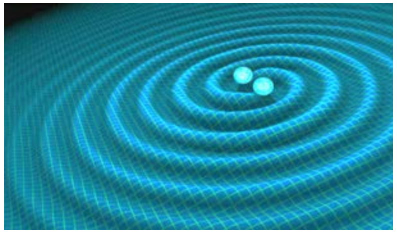
- Quantum-enhanced precision measurements.
- Dramatically improve "traditional" timing applications: navigation/location, telecom, etc.
- Improve measurements of gravity, EM fields, force, etc.

- Tabletop fundamental physics complementing or exceeding multibillion dollar "big physics" experiments:

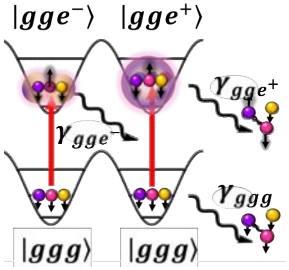
Dark matter detection/measurement



Global network of precision clocks (10^{-21}) for secure quantum communications networks, long-baseline astronomical observation, etc.



Gravity wave measurement at frequencies inaccessible to LIGO/VIRGO



Study of multi-body SU(N) interactions in atomic systems: Probe details of Standard Model on tabletop. (June 2018)

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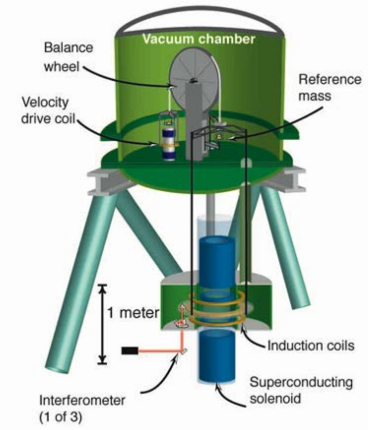
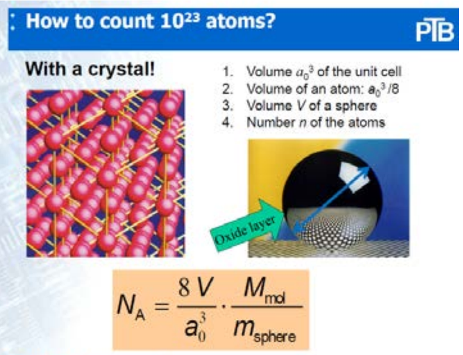
Primary Realization of the Kilogram

- **Watt Balance:** Equates mechanical quantity of power to the corresponding electrical quantity when the latter is measured in terms of quantum electrical effects.
- **Avogadro Project:** Compares a macroscopic mass to the mass of a single atom of a specified isotope.

- Approaches are complementary - Either can be used to realize the definition of the kilogram.
- SI kilogram realized in vacuum.



$$N_A h = \frac{M(e)}{m(e)} \cdot h = \frac{M(e) c \alpha^2}{2 R_\infty}$$



How to count 10^{23} atoms?

With a crystal!

1. Volume a_0^3 of the unit cell
2. Volume of an atom: $a_0^3/8$
3. Volume V of a sphere
4. Number n of the atoms

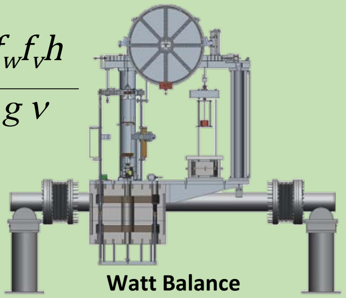
$$N_A = \frac{8V}{a_0^3} \cdot \frac{M_{mol}}{m_{sphere}}$$

The Perfect Artifact!

Mise en Pratique at NIST

Realization

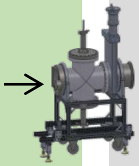
$$m = \frac{n_w n_v f_w f_v h}{4\,\alpha\, g\, v}$$



Watt Balance

Realization of the kilogram in vacuum through a fixed Planck constant

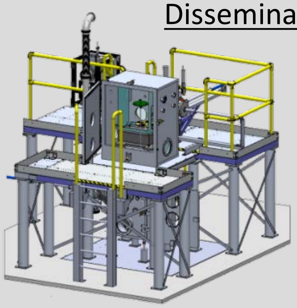
Mass Transport Vehicle (MTV) →

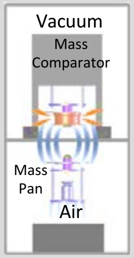


Direct traceability to SI

Vacuum artifacts

Dissemination





Vacuum-to-Air Transfer

Direct comparison of known mass in vacuum to unknown mass in air using magnetic suspension

Air artifacts

Monitor Watt Balance stability

Vacuum artifacts

Check sorption artifact method

Vacuum Balance

Volume Artifacts

Surface Artifacts

Surface and Volume Artifacts

Characterize sorption properties and air density for measurement of mass in vacuum and mass in air

Vacuum, air artifacts

Vacuum and Air Storage

Vacuum

- Vacuum chamber pressure ~10^{-5} Pa
- Monitor pressure and gas composition of storage environment
- Load-lock to insert and remove artifacts with MTV

Air

- Constant flow of filtered room air
- Monitor temperature, pressure and humidity
- Load-lock to insert and remove artifacts with MTV

Artifact Pool

Dissemination from an ensemble of Pt-Ir and SS artifacts

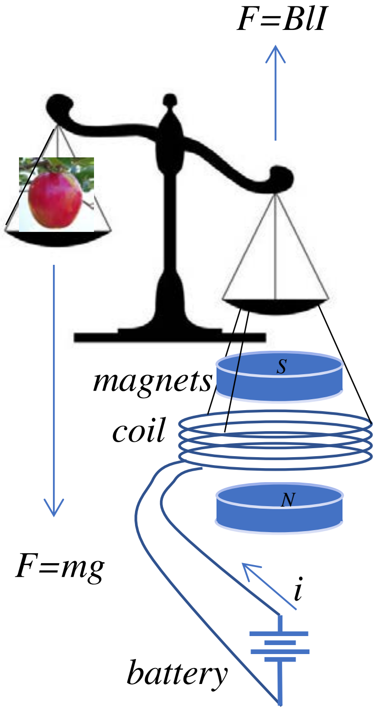
You can Weigh an Apple with a Scale

One usually weighs apples using a scale to compare their gravitational force to that of a known artifact

With a watt balance electromagnetic scale (see magazine cover below) one **compares the apple's gravitational force to that of a *calculable* force that is known in terms of physical invariants, like the figure on the right**

www.physicstoday.org
physics today
July 2014
A publication of the American Institute of Physics
volume 67, number 7

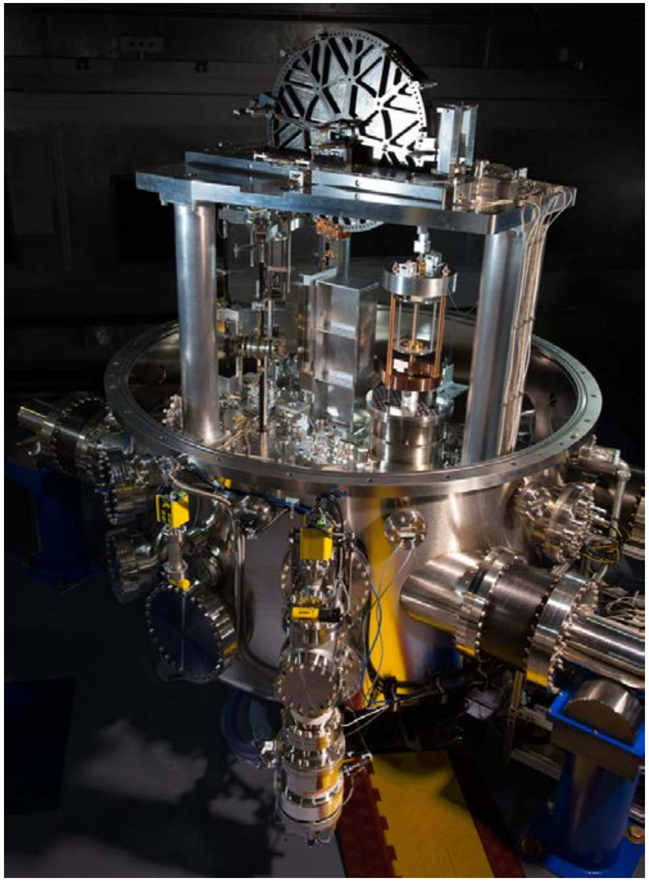
A makeover for the SI
also:
Cold electrons for fast diffraction ◄
The ozone hole turns 30 ◄
Strategizing for high-energy physics ◄



Kibble Balance Basics

- **Weighing or Force mode:** An unknown weight *mg* is balanced by an electromagnetic force on a horizontal coil of wire-length *L* in a radial magnetic field of flux density *B* when a current *I* flows through the coil $mg = BLI$
- **Calibration or Velocity mode:** The magnet's strength *BL* is measured by moving the coil at a velocity *v* while recording the voltage *V* across the coil terminals $BL = \frac{V}{v}$
- The two modes can compare mechanical and electrical power, hence the name, watt balance

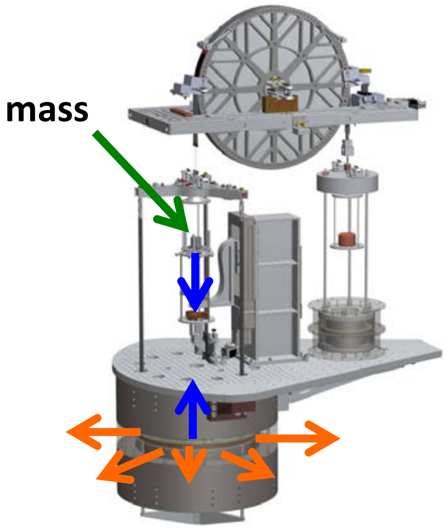
$$mgv = VI$$



NIST-4 Kibble Balance

Watt Balance Principles

Force mode



Velocity mode

$$mg = BLI \qquad V = vBL$$

$$BL = \frac{mg}{I} \qquad BL = \frac{V}{v}$$

$$\frac{mg}{I} = \frac{V}{v}$$

$$mgv = VI$$

$$mgv = \frac{V_1 V_2}{R}$$

$$mgv = \frac{n_1 f_1 \frac{h}{2e} n_2 f_2 \frac{h}{2e}}{\alpha \frac{h}{e^2}} = \frac{n_1 n_2}{4\alpha} f_1 f_2 h$$

$$h = \frac{4\alpha}{n_1 n_2} \frac{gv}{f_1 f_2} m$$

before redefinition

after redefinition

$$m = \frac{n_1 n_2}{4\alpha} \frac{f_1 f_2}{gv} h$$

Small Mass Metrology

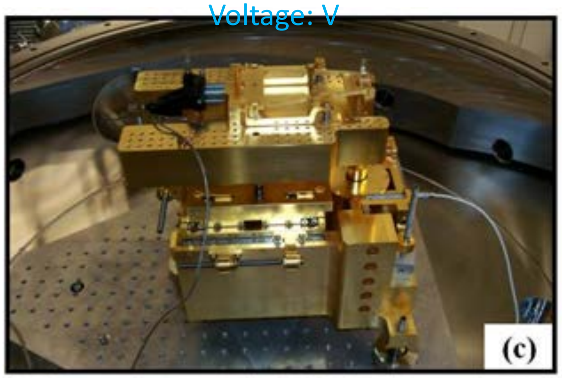
G. Shaw, J. Melcher, J. Sterling,
J. Pratt, J. Kramar, A. Koffman,
R. Steiner, P. Abbott, Z. Kubarych

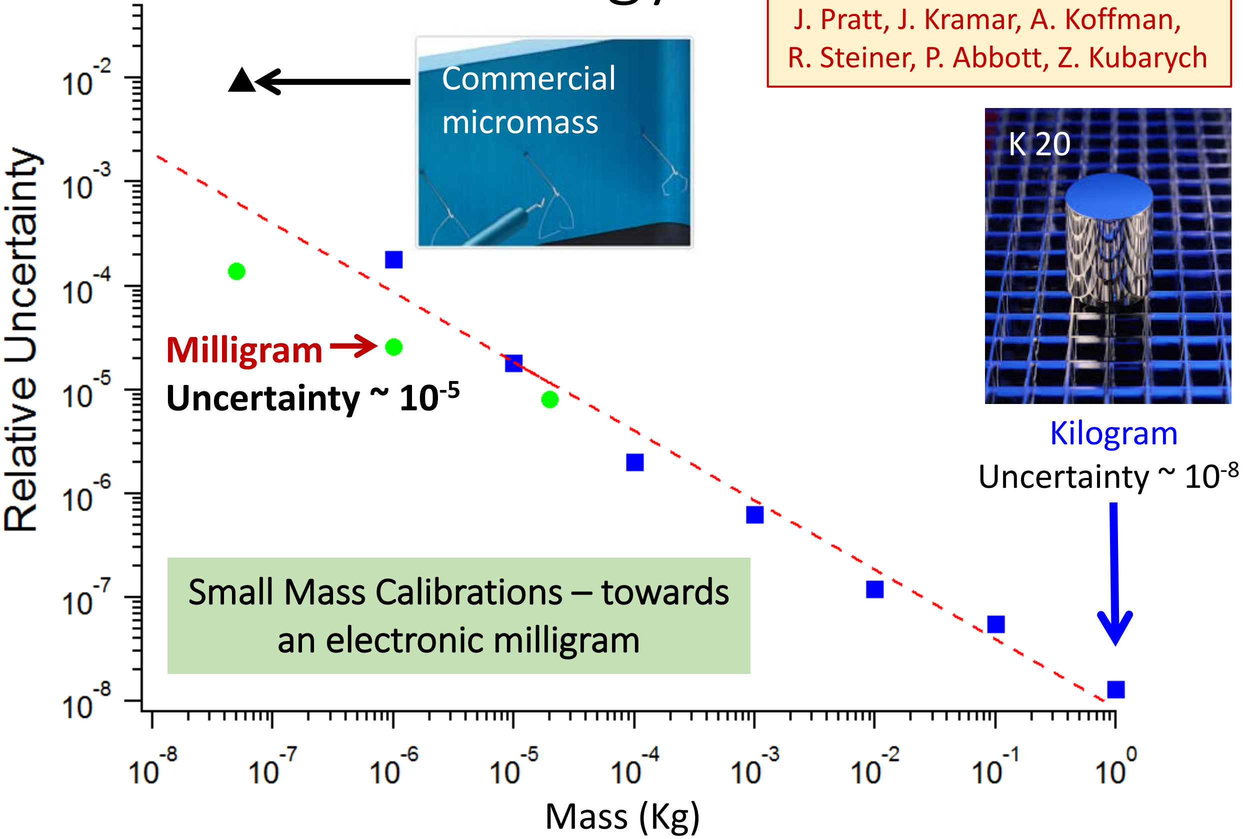
Electrostatic Force

NIST Electrostatic Force Balance (EFB) provides a reduction in uncertainty of 1-2 orders of magnitude at milligrams

$$F = mg = 1/2(dC/dz)V^2$$

Capacitance: C Position: z Voltage: V





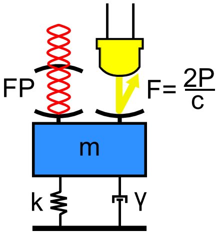
Milligram → Uncertainty ~ 10^{-5}

Small Mass Calibrations – towards an electronic milligram

Kilogram
Uncertainty ~ 10^{-8}

Linking SI Mass, Force, and Laser Power

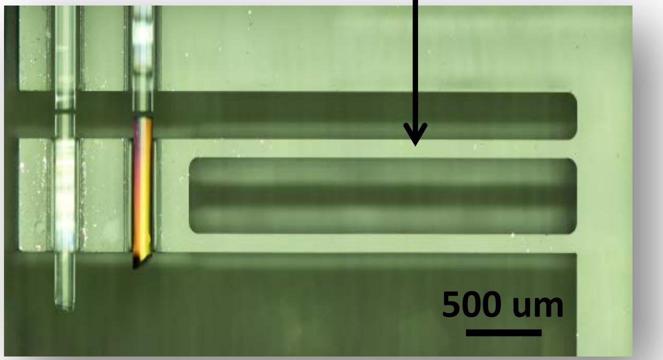
- Self-calibrating optomechanical system can balance mechanical force with photon pressure force
- Integrated interferometer and calibrated light source
- Optical power standards provide low uncertainty for small force measurements
  - Scales down to the single photon level
  - Femtonewton resolution
- Calibration of atomic force microscopy

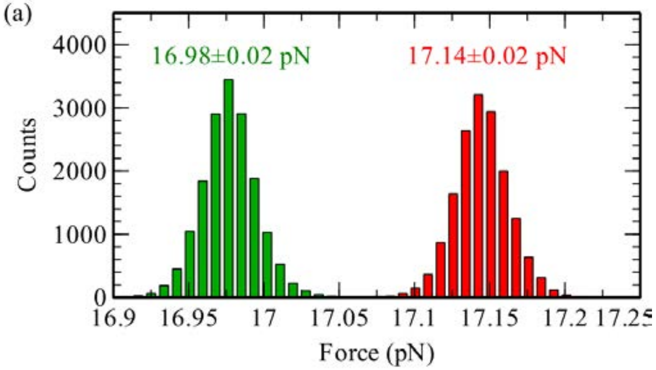


Fabry-Perot Interferometer (for displacement)

Superluminescent diode (for photon momentum force)

Flexure Stage (for mass and restoring force)





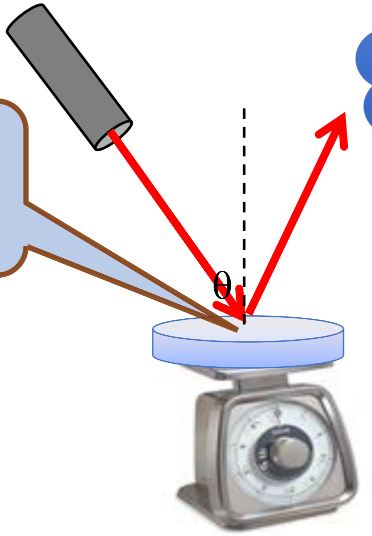
Measured RMS force for two different amplitudes of modulated laser power with a resolution of 14 fN

See: J. Melcher, et al., "*A self-calibrating optomechanical force sensor with femtonewton resolution*," Appl. Phys. Lett. **105**, 233109 (2014).

Measuring Radiation Force: Concept

A precision scale with a mirror can measure the radiation force of light.

Minimal absorption, power-scalable, no thermal recovery time.



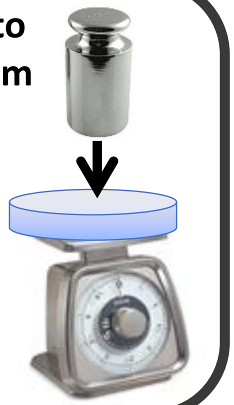
laser light still available for use

$$F = (2P/c)r\cos\theta$$

F = Force (Newtons)
P = optical power (Watts)
c = speed of light (m/s)
$r = R+(1-R)\alpha/2$ → reflectivity
θ = angle of incidence

$$P = F\cdot(c/2r\cos\theta)$$

Traceable to the kilogram



Calibration done with a standard mass.

Williams, *et al.*, Optics Letters **38**, 4248-4251 (2013)

Measuring Radiation Force: Sensitivity

Laser power	Application	Equivalent mass	Comparable mass
10 W	marking	6.7 microgram	eyelash 
1 kW	welding/cutting	670 microgram	grain of sand 
100 kW	Research / Defense	67 milligrams	two staples 

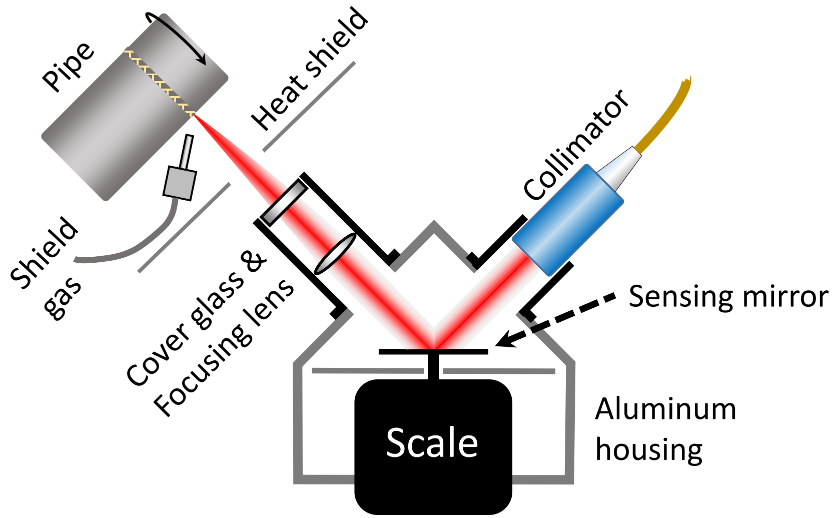
Conversion factor (for normal incidence and perfectly reflecting mirror):

$$k = 6.67\times10^{-9}\ \mathrm{N/W} \longrightarrow 670\ \mu\mathrm{g}/\mathrm{kW}$$

> *“The photonic mole:” One mole of photons at wavelength of 1 µm is approximately 120 kW*

Towards a Calibrated Laser Weld

- First real-time, calibrated laser power measurement during a laser weld
- New radiation pressure technique measures the very small force of light as it reflects from a mirror
  - Force is proportional to laser power
  - Laser beam not absorbed, also used for the weld
  - Force measured with sensitive, commercial scale



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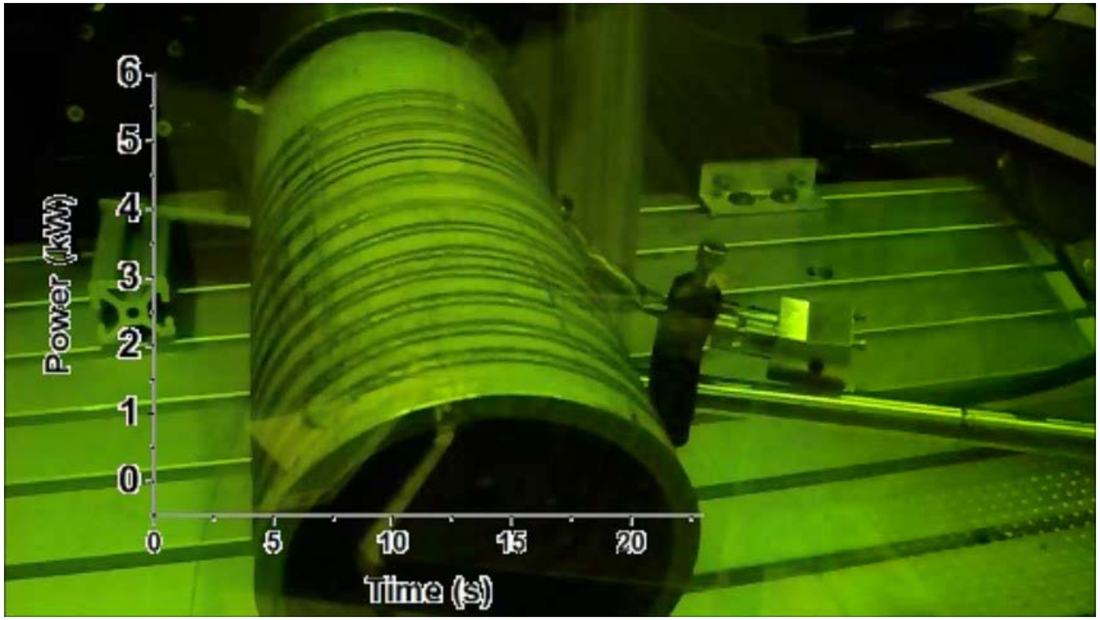


B. Simonds, P. Williams, J. Sowards, J. Hadler

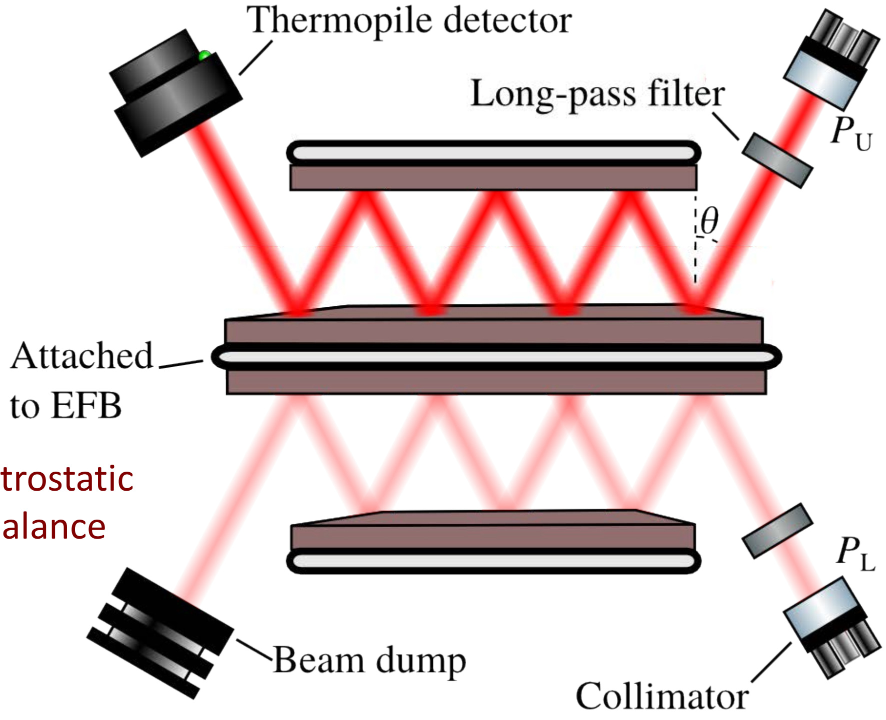
Laser Power from Electrostatics

Comparison of 3W laser power used measuring electrostatic forces and a conventional thermopile detector

- Laser power from force and reflectivity

$$P = \frac{cF}{2R}$$

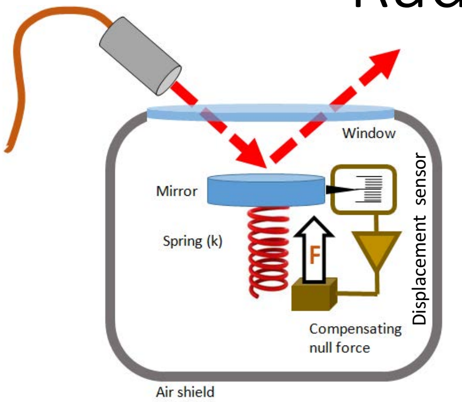
- Optical switch to switch between upper and lower collimators
- Two 4-bounce etalon cavities between central mirror on balance and two fixed mirrors – multiplies force



EFB: Electrostatic Force Balance

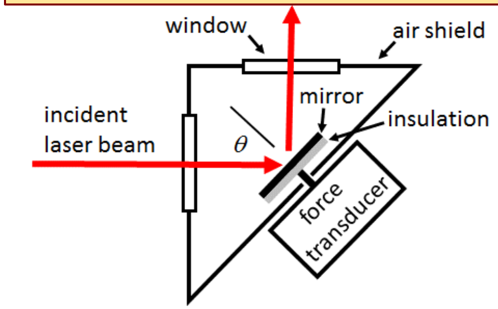
G. Shaw, J. Stirling, J. Lehman, P. Williams, R. Mirin

Radiation Pressure Power Meter



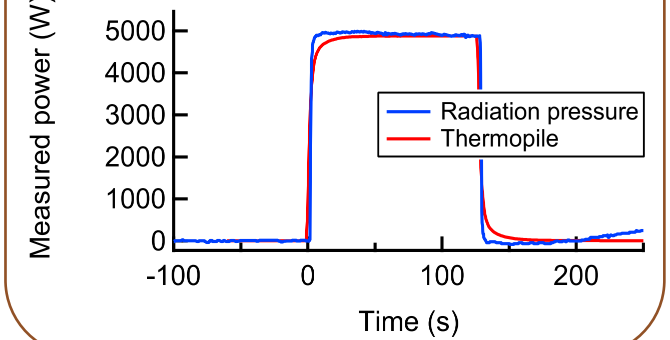
2017 R&D 100 WINNER

With Scientech, Inc., Boulder, Colorado



Comparison with traditional-thermopile power measurement at 5 kW (equivalent mass ~ 2.4 mg)

Constant power (5 kW): **1%** discrepancy



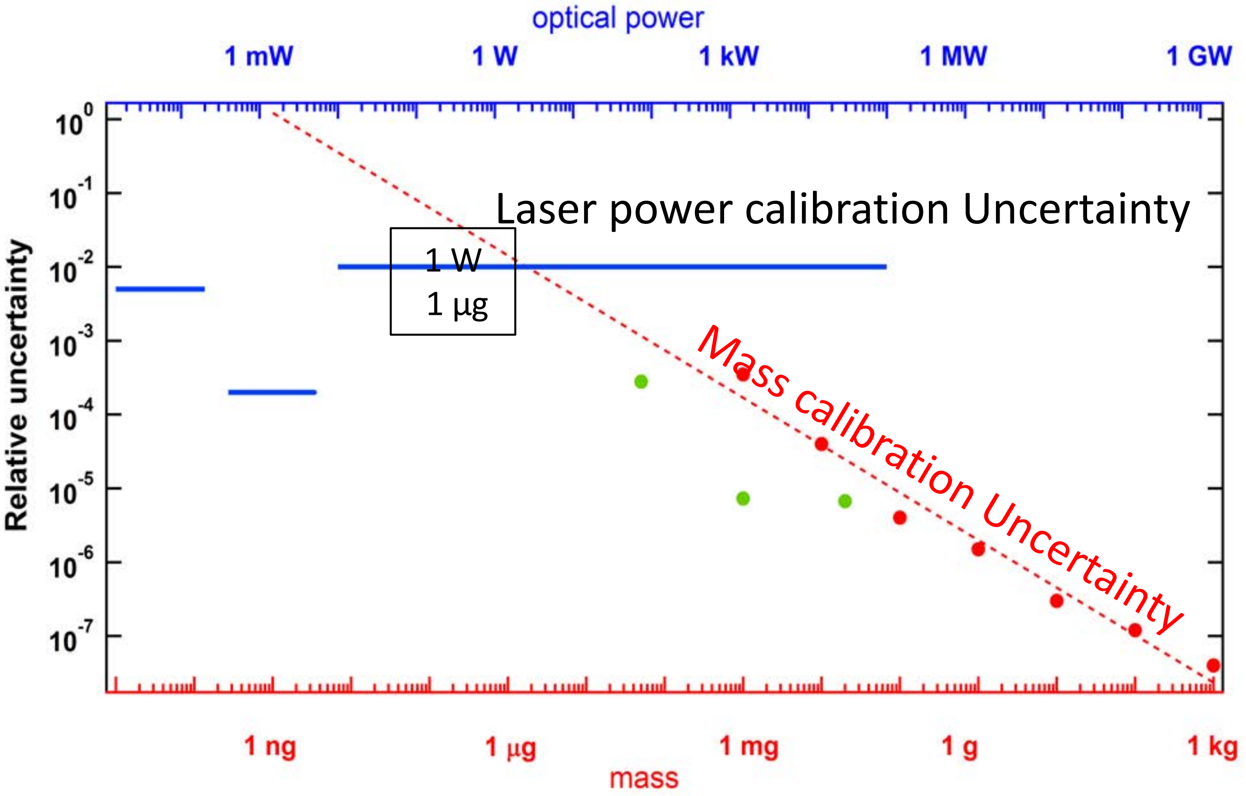
Specifications

Dimensions:	30x30x30 cm^3
Power:	
Noise-equivalent power	100 W/√Hz
Calibrated and validated (1.6 %, 2U)	1 – 10 kW
Early prototype measurement	92 kW
Non-NIST intracavity measurement	500 kW
Response time:	
Settling time	5 s

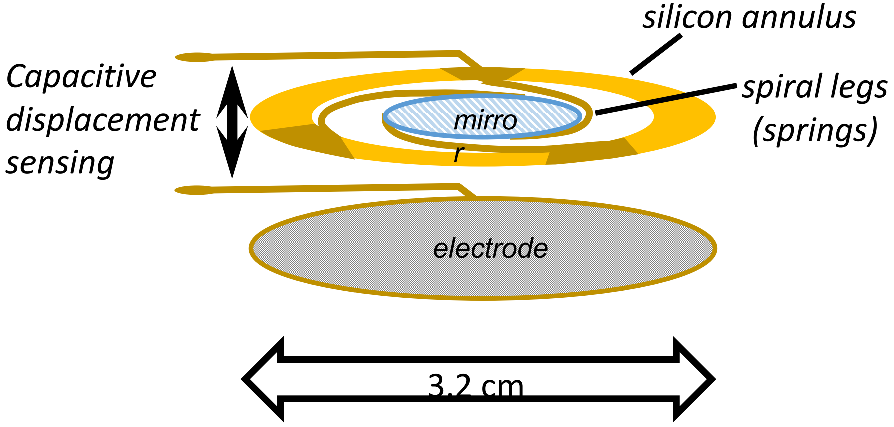
P. Williams, et al., *Optics Express*, **25**, 4382 (2017)

Tying Together Mass, Force, and Power

Low-power with Commercial Mass Scale at 15 GHz



Smart Mirror: Laser Power Metrology



silicon annulus

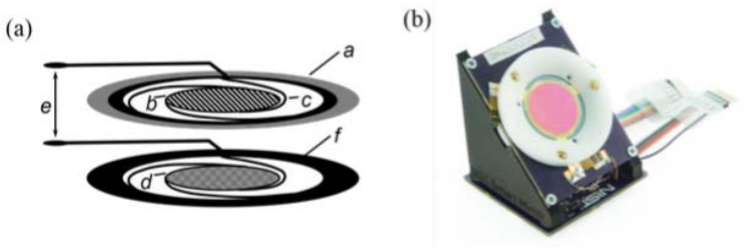
Capacitive displacement sensing

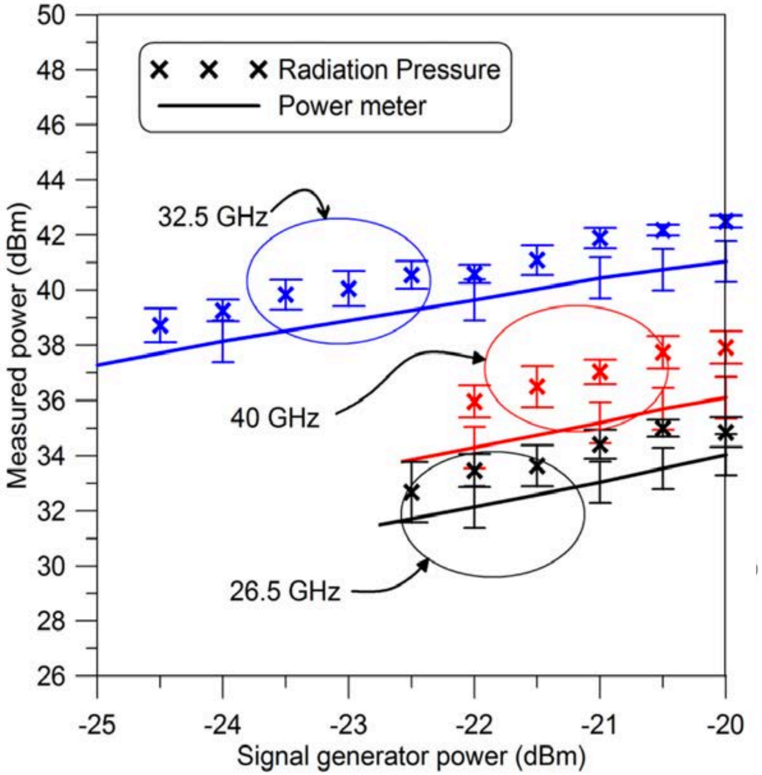
spiral legs (springs)

mirror

electrode

3.2 cm

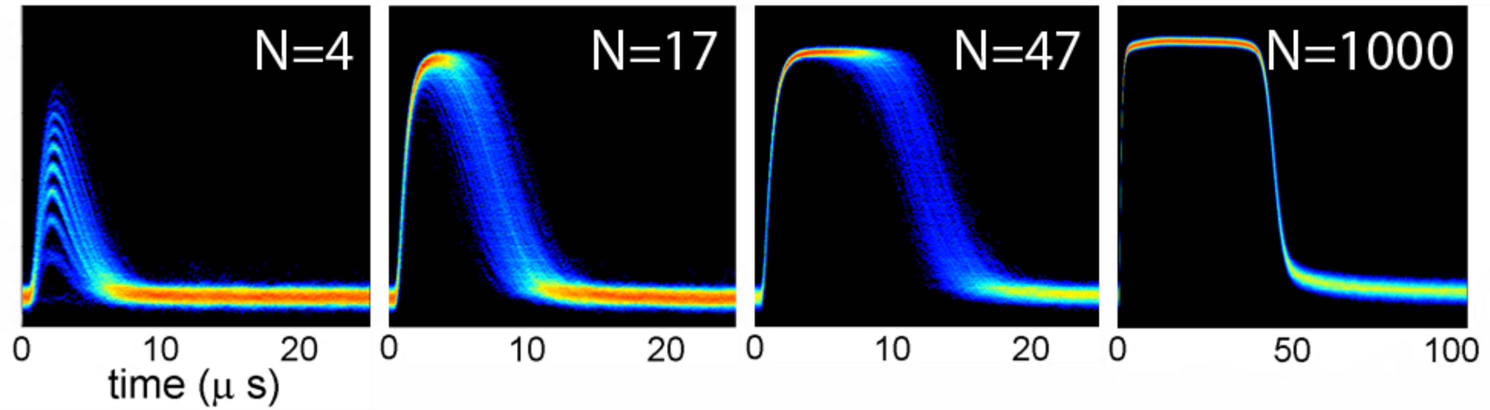




C. Holloway, et al., *App. Phys. Lett.*, **113**, (*to appear*, 2018)

Determining Photon Number in a Weak Pulse

Transition edge sensor (TES) is capable of counting the number of as many as 1,000 photons in a single pulse of light with an accuracy limited mainly by the quantum noise of the laser source.



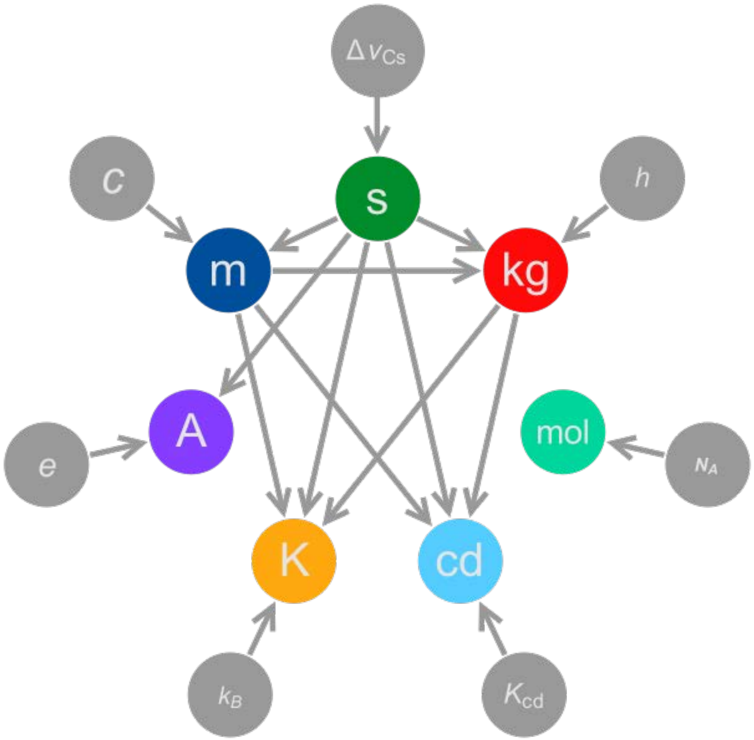
This series of data read-outs shows how the TES relaxation time increases with photon number. For N=4 photons, the TES returns from the elevated-resistance state to the edge of the transition region in less than 10 µs. At N=47 photons, it takes around 15 µs. And when the count is 1000, the relaxation time is approximately 50 µs.

Outline

- NIST and the Physical Measurement Laboratory (PML)
- The Metric System and the Origin of the SI
- Quantum Standards and Movement Toward Redefining the SI
- Quantum Standards and Quantum Metrology Today
- Mass and Force Metrology and the SI Tomorrow
- Towards Democratization of the SI: Embedded Measurements

Quantum SI

New SI

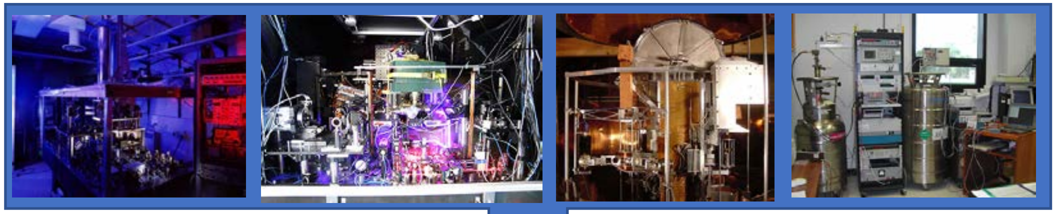


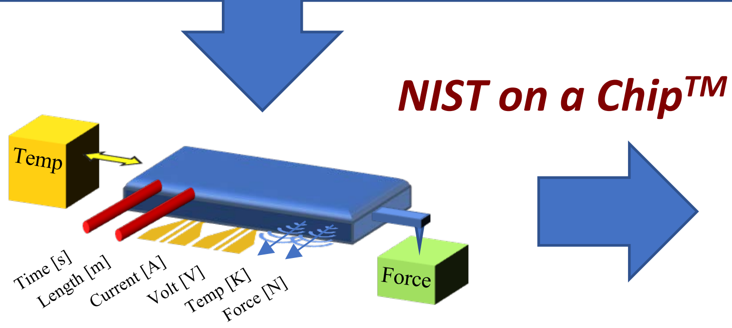

Traceability directly to the SI


Zero-length traceability chain


Democratizing Metrology

Democratization: Toward Embedded Standards





NIST on a Chip™

- Direct SI-traceable measurement capability built into instruments
- Goals: flexible, useful, reliable, manufacturable, deployable
- Get rid of the middle-man (us!)

SI Dissemination Methodologies in Practice

Send us an artifact;
We'll measure it and return it.

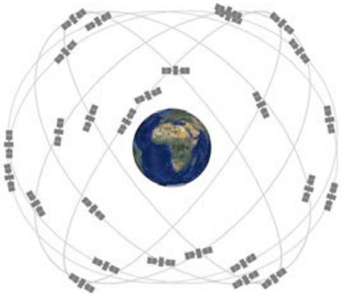
Example shown here: Gauge blocks and other artifacts used as dimensional metrology standards. Other examples: masses, resistors and other electrical devices.

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.

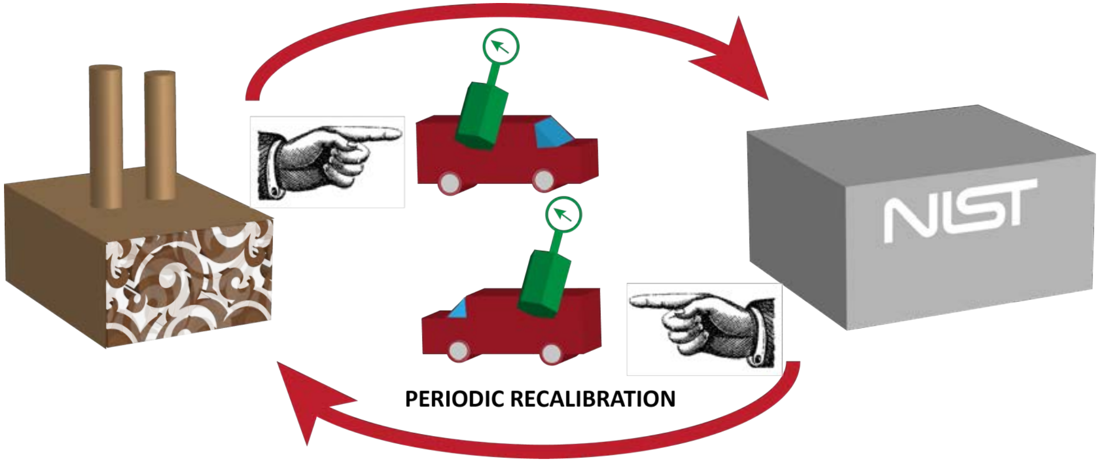
Example shown here: Ocean Shellfish Radionuclide Standard (SRM 4358). Other examples: certain lamps and photodiodes for photometry and radiometry.



Don't send us anything; We'll observe something together.

Example shown here: GPS satellite constellation (atomic clocks on orbit). Satellite common-view used to transfer precision time and frequency standards.

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



Delivery guy:
He 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

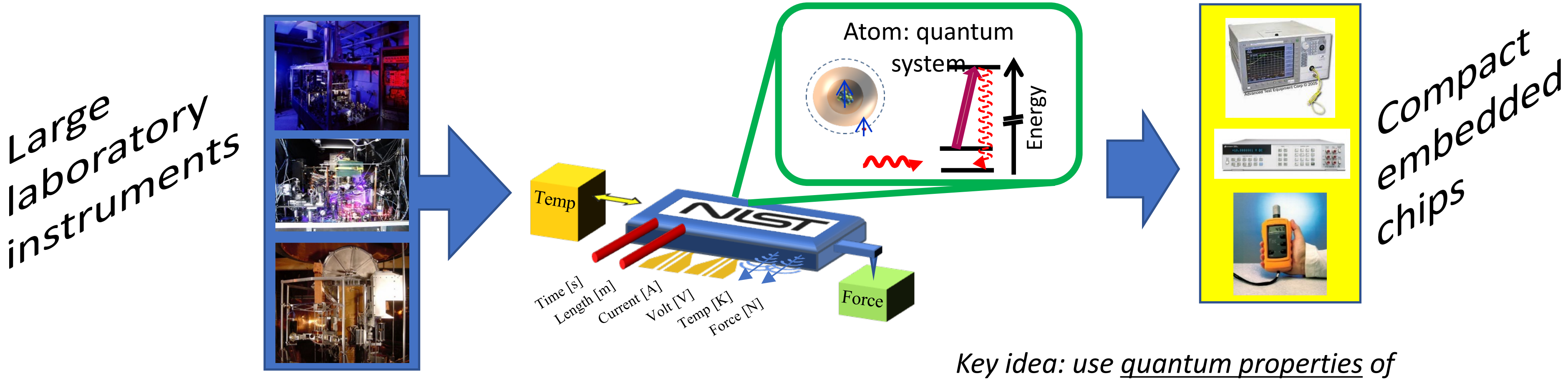
But the measurements are used everywhere . . .

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

Chip-Scale Quantum Technologies

NIST on a Chip^{TM}

- Quantum-based physical standards on a chip would allow accurate realization of SI units with low power and low cost



- Embedded, SI-traceable calibration built into instruments
- Goals: **flexible, useful, manufacturable, deployable**

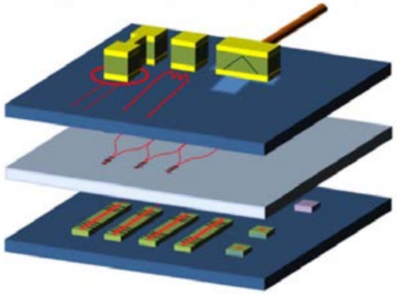
Key idea: use quantum properties of atoms to realize accurate and reliable measurement tools in a manufacturable, chip-scale format

Embedded Standards

Develop SI-traceable measurements and physical standards that are:

- **Deployable** in a factory, lab, device, system, home, anywhere...
- **Usable:**. Small size (usually), low power consumption, rugged, easily integrated and operated
- **Flexible**: Provide a range of SI-traceable measurements and standards (often quantum-based) relevant to the customer's needs / applications
  - One, few, or many measurements from a single small form package
- **Manufacturable:**
  - Potential for production costs commensurate with the applications
  - Low cost for broad deployment; or
  - Acceptable cost for high-value applications

Time, electrical, magnetic, temperature, force, length, etc.



Physical, chemical, material, biological, etc.

Emerging Technologies Enable Disruptive Change

- Solid state lasers (e.g., VCSELs)
- Microelectromechanical systems (MEMS)
- Miniaturized Combs and Microresonators
- 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

A 21st century toolkit can enable the development of a new generation of artifacts and instruments with capabilities that far exceed those traditionally used for traceability

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

Metrology Adapts to Needs and Technology

- Metrology is not “just status quo”
    - Realization, Maintenance, and Dissemination of Units
- Constantly evolving to meet the ever changing needs of industry
- Infra-technology that drives innovatio
the global economy (80 % of all globa

Metrologists represent about 0.0001 % of the world’s population and need to foreshadow where technology should evolve!

Thank you!

Any questions?

carl.williams@nist.gov

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