THERMODYNAMIC MINIATURIZED SENSORS AND STANDARDS AND THE QUANTUM SI

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Future of Metrology?

“It’s hard to make predictions, especially about the future”

Yogi Berra
Outline

• Few words on the Système international d’unités (the SI)

• Trend towards a “Quantum SI”

• Trend towards “Embedded Standards”

• Implications for measurement of thermodynamic quantities

• Final thoughts
SI is the Modern, Harmonized Metric System

PML is responsible for 6 of 7 units

NIST seeks to ensure that SI is...

• Scientifically based
• Defined by consensus
• Realized in practice
• Disseminated for routine uses
• Disseminated for new and novel uses
• Maintained and improved

SI underpins all measurements, whether expressed in metric units or otherwise
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Classical to Quantum SI
Meeting the Metrology Challenges of the 21st Century

• Quantum SI
  – Quantum phenomena
  – Fundamental and atomic constants

• Tying metrology back to fundamental atomic quantities
  – Removing artifacts as defining the SI

• kelvin
  – Boltzmann constant

• kilogram
  – Planck constant

• ampere
  – Elementary electric charge

• mole
  – Avogadro constant
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)
Quantum SI Metrology Areas

- Acceleration
- Electrical
- Fluid flow
- Humidity
- Length
- Magnetic field
- Mass and force
- Pressure
- Optical power
- Radiation
- Temperature
- Time and frequency
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PML Priority
Advanced Measurement Dissemination

• Improving dissemination of national standards
  *Using the “21st century toolkit” to reinvent best devices and modes for calibration services, e.g., greater stability, wider dynamic range*

• Embedded sensors: “NIST on a Chip”
  *Miniaturized devices that minimize the need for traditional calibration services by using quantum effects*

• Open metrology: Sharing what we know
  *We commit to providing many, varied training opportunities to our customers to facilitate adoption of best practices*
SI Dissemination Methodologies in Practice

- **Send us an artifact; We’ll measure it and return it**
  - Commercially available ITS-90 fixed-point cells

- **Send us an instrument; We’ll calibrate it and return it**
  - Standard Platinum Resistance Thermometer

- **Don’t send us anything; We’ll calibrate it and return it**
  - SRM 1968, Gallium Melting-Point Standard

- **Don’t send us anything; We’ll observe something together**
  - GPS satellite constellation (atomic clocks in orbit)
Classical Calibration Dissemination Method

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

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

He’s got less work to do
Emerging Technologies Enable Disruptive Change

- Solid state lasers (e.g., VCSELs)
- Microelectromechanical systems (MEMS)

Example: These technologies enabled the Chip Scale Atomic Clock (CSAC)

Optical microresonators on a silicon wafer. (Premier issue of Optica)
Embedded Metrology ("Chip Scale")

- Flexible
  - Integrated, multi-function standard and sensor platform
- Manufactural
  - Commercialization of designs / recipes to foundry
- Deployable
  - Quantum SI realization and zero-chain traceability
- Usable
  - Rugged and easy to use

NIST Quantum SI Standards and Sensors
-Dual mode infra-technology
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Photonic Sensors

• Light based sensor
  – Change in physical property (e.g., index of refraction) creates a resonate frequency shift
  – Frequency notch-filter

• Frequency measurement advantages
  – More accurate than electrical
  – Low noise
  – Telecom industry components
Photonic Temperature Sensor

**Classical technology: Electrical temperature sensors**
- $U \leq 10 \text{ mK} \ (–196 \ ^\circ\text{C} \text{ to } 500 \ ^\circ\text{C})$
- Hysteresis
- Mechanical or thermal shock

![Standard platinum resistance thermometer](image)

**Quantum technology: Photonic crystal cavity sensors**
- Micro/nano-scale size
- Can be embedded
- Low cost and weight
- Immune to electromagnetic interference
- Negligible hysteresis
- Fast response time
- Can tolerate harsh conditions and treatment

![Industrial Pt PRT](image)
Photonic Temperature Sensors

- **Si Bragg Waveguide**
  - $U < 1.25 \, ^\circ\text{C}$

- **Si Crystal Cavity**
  - $U < 0.05 \, ^\circ\text{C}$

- **Si Ring Resonator**
  - $U < 0.01 \, ^\circ\text{C}$

- **Si Nanobeam**
  - $U < 0.001 \, ^\circ\text{C}$
Integrated Photonics Currently

Sensor measurement “platform”:
- Temperature
- Pressure
- Vacuum
- Humidity
- Strain
- Chemicals
- Radiation

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Integrated Photonics
The Future for Mobile Sensing

Sensor measurement platform:
• Temperature
• Pressure
• Vacuum
• Humidity
• Strain
• Chemicals
• Radiation
Possible Route to a Practical “Quantum Kelvin”

- Standard built into the sensor design
  - Nanoscale opto-mechanical silicon beam

**Mechanical mode (standard)**
- Phonon Boltzmann distributions of thermodynamic temperature states created to calibrate sensor temperature response

**Optical mode (sensor)**
- Temperature-dependent shift in sensor resonance is utilized to make temperature measurements

- $Q \approx 1,000,000$
- Resolution: $\delta \lambda_{\text{MIN}} \approx 0.1 \text{ pm}$
- $\delta T_{\text{MIN}} < 1 \text{ mK}$

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Steps Toward Si Traceability to Dynamic Temperature

- Dynamic temperature
  - Developing laser temperature traceability (e.g., welding, chip manufacturing, eye surgery)
- First attempt – proof of concept
- YAG laser at 50 mJ
  - $\Delta P = 32 \ \mu W$
  - $\Delta T = 0.74 \ K$
- SI traceable $T$ through a photonic sensor
Quantum Pressure Standard and Sensor: FLOC (Fixed Length Optical Cavity)

• Compact, portable, quantum-based primary barometric pressure standard
• Replaces multiple commercial gauge technologies
• Range of 1 mPa to 1,000 kPa (10 atm)
  – Eight decades of pressure measurement in one instrument
• Based on refractive index of He (calculable to 0.1 ppm)
  \[ n - 1 \propto P / (k_B T) \]
Key Advantages of Photonic Pressure

- Elimination of mercury-based pressure standards
  - 400 year old technology
- 35× more sensitive
  - Resolution of 0.1 mPa
- 100× faster
  - Replaces inherently slow electrical-based measurements
- 1,000× lower pressure range
- Uncertainty smaller than Hg manometer
- Dual standard and sensor

Brings SI to the factory floor:
- Pressure
- Length
  ➢ Reducible to size of cell phone

![Hg manometer](image1)

![Photonic standard](image2)

Physical Measurement Laboratory
Cold Atom Vacuum Standard (CAVS)

- First-principle realization for UHV ($10^{-6}$ to $10^{-9}$ Pa) and XHV ($\leq 10^{-10}$ Pa)
- Quantum-based vacuum standard and sensor
  - When a background molecule collides with a trapped atom, the atom is ejected with near 100% probability
  - Measuring trap lifetime gives pressure

Quantum SI realization – reducible to cell-phone size
- Accelerators
- Semiconductor mfg
- Space sciences
- Surface sciences
- Quantum Information

Condensed alkali atoms

25 mm

Physical Measurement Laboratory
Dynamic Pressure – SI Traceability

- Static vs Dynamic SI Traceability
  - Dynamic is the next frontier

- Standards
  - SI traceable impulse standards and calibration methods are not available

- Sensors
  - Pressure sensors are only as good as their calibrations

- Develop new SI Traceable Standard and NoaC sensors
Next Frontier: Dynamic, Impulse Measurement Standards

Temperature Compensated, Dynamic Pressure Sensor Mach–Zehnder based Design

**Design Specifications**
- Size 2 mm × 1 mm
- High sensitivity
- High speed > GHz
- Dynamic range ≈ 10% of operating pressure

Rapid tuning broad bandwidth laser source

Pressure Test Section

Reference Arm
Long Term Vision

Rapid tuning broad bandwidth laser source

Photonic crystal cavity absorption cell

Sealed Photonic crystal cavity absorption cell with Ref Gas

Pressure
Temperature
Relative Humidity

Stabilized Photonic crystal cavity
Absolute frequency reference

Fully integrated dynamic measurement sensor for pressure, temperature, relative humidity, and chemical species
Other Applications – Studies in Progress

Infrastructure Monitoring

Laser Power Meters

“Smart Bed”

Brain Imaging
Nanotube Black—For Laser Power Meters

• >99 % conversion of light (broadband) to heat
• Enabling technology for high-accuracy optical (e.g., laser) power measurements
  – Terahertz [THz] radiation, currently a hot research topic for wireless communications
  – 300 nm to 500 μm
• Less expensive, more accurate, more portable than sensor technology it replaces
  – Zero-chain traceability
• Collaboration with PTB (Germany)
Deployed Quantum SI Enables Technology Infrastructure

- Chip Scale Atomic Clock
  \((10^{-11} \text{ uncertainty})\)
- Telecom networks
  \(>\$2 \text{ trillion/year globally}\)

As commercialized
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Possible Implications for NMIs

• For NIST
  – Focus shifts from artifact calibration to new deployable dual standards and sensors
  – Disruptive SI dissemination
  – Quantum-based metrology
  – Commercialization

• For international metrology
  – Traceability
  – Mutual recognition
  – Accreditation (think 17025)

• For NMIs in the “distant” future
  – What is the future of calibrations?
  – Will we still be necessary for traceability?

• For NIST
  – New metrology frontiers
  – Quantum-based SI everywhere
  – Expertise is still essential
  – Solve really hard problems
  – Training
Open Metrology – Key NMI Role

With dissemination of advanced measurement technology directly to the end user, training becomes even more critical

SIM Metrology School

Office of Weights and Measures (OWM) conducts training classes for trainers
Enabling the **Next Generation of Metrology**
- Embedded Standards
- Ultrastable Lasers
- Optical Clocks
- Advanced Imaging
- Quantum Information
- Nanoscale Measurement
- Redefining the SI

Custom **Measurement Solutions**
Take advantage of NIST’s unparalleled depth of measurement expertise, world-class facilities, and one-of-a-kind instruments.

Providing **Measurement Services**
- Calibrations
- Standard Reference Materials
- Standard Reference Data
- Standard Reference Instrumentation
- Training