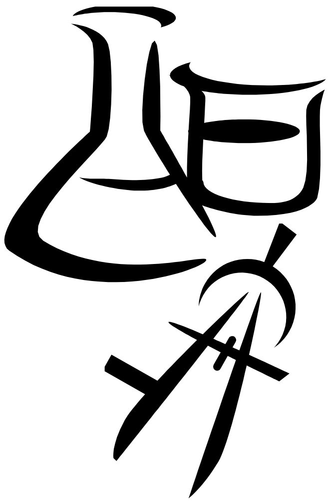
Metrology 101



Robert L. Watters, Jr.
Associate Director for Measurement Services
Material Measurement Laboratory
National Institute of Standards and Technology

Metrology 101

Potential audience:

- NIST technical staff
- NIST administrative staff
- Congressional staff
- Fifth graders
- Congressional members
- NIST Day Care children

Some Definitions

- **Metrology** – science of measurement and its application
- **Accuracy** – closeness of agreement between a measured value and the true value (a concept, not a number)
- **Measurement error** – the difference between a measured value and a reference value
- **Precision** – closeness of agreement among replicate measured values
- **Measurement uncertainty** – an indication of the range about a measured value that we believe contains the true value*

* non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used

Relationship of Metrology Concepts

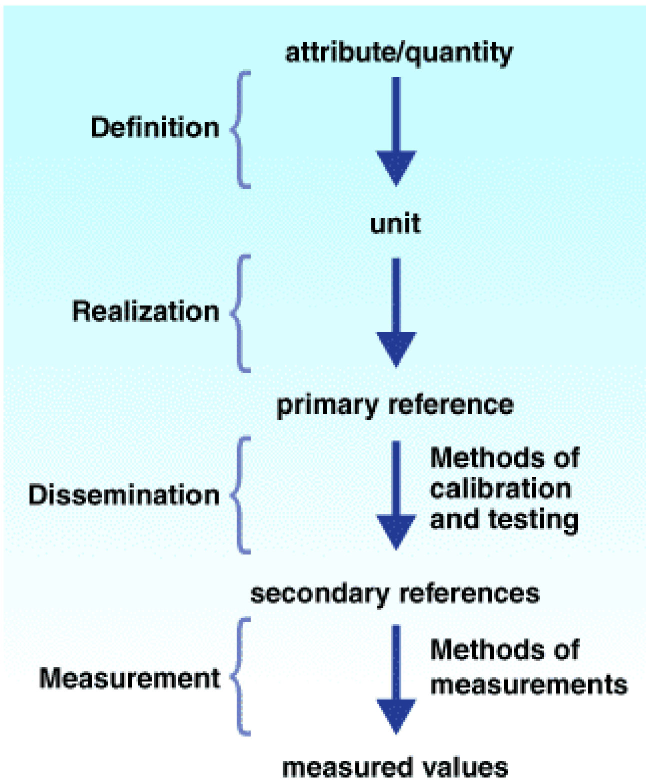


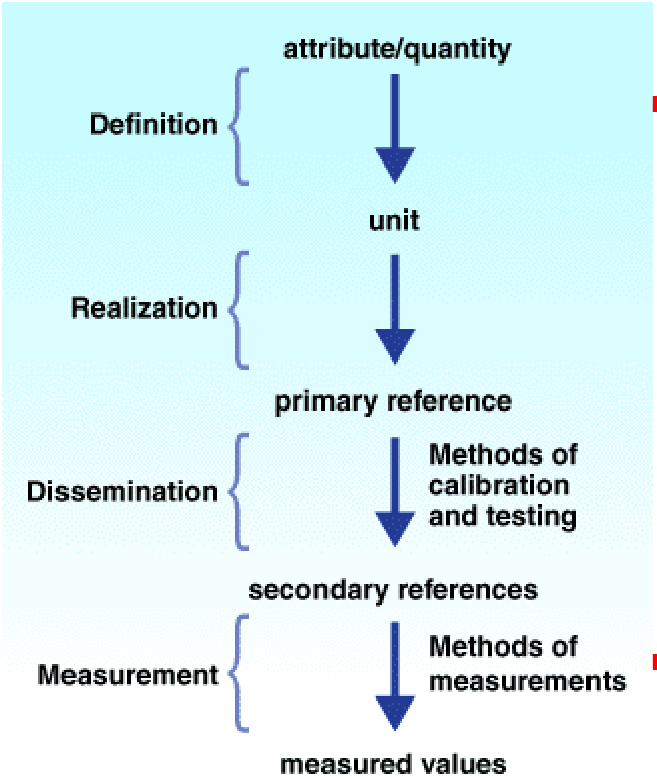
Figure 1 Logical relationship among metrology concepts for use in standardization in measurements.

NIST work:

- **Metrology research**
- **Metrology training**
- **Delivery of measurement services**

NISTIR 6025 Metrology for Information Technology (IT), MEL/ITL Task Group on Metrology for Information Technology (IT)May 1997

Relationship of Metrology Concepts



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Metrology Research

- New and/or better ways to measure things
  - More selective, more accurate or more precise

Volume 106, Number 1, January–February 2001
Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. **106**, 47–63 (2001)]

Primary Atomic Frequency Standards at NIST

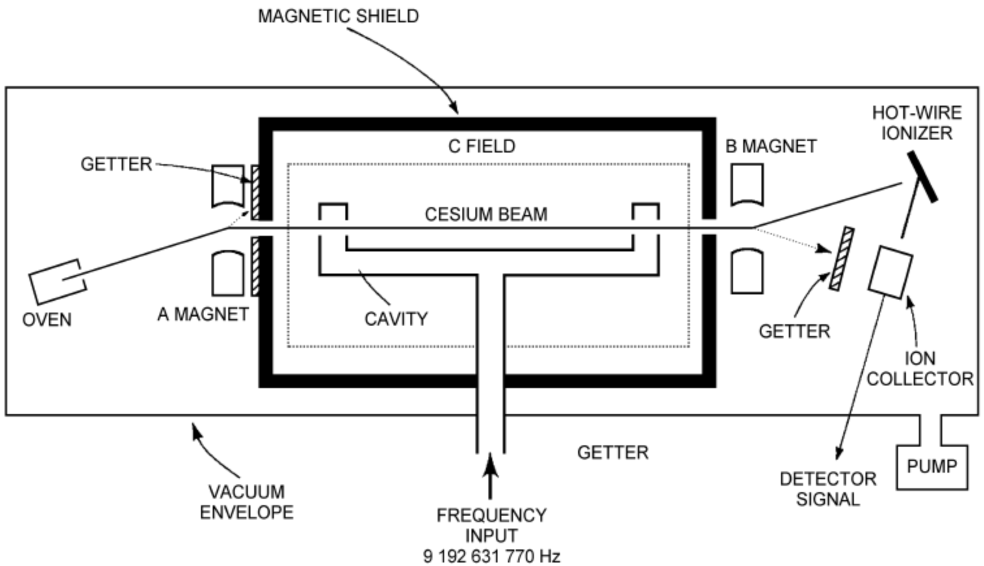


Fig. 1. Diagram of a cesium-beam frequency standard using magnetic state selection and detection. The form of Ramsey interrogation involves a U-shaped microwave cavity, called a Ramsey cavity, where the oscillatory fields are spatially separated.

Metrology Research

- New and/or better ways to measure things
  - More selective, more accurate or more precise
- Better characterizations of the sources of measurement uncertainty

Volume 102, Number 6, November–December 1997
Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. 102, 647 (1997)]

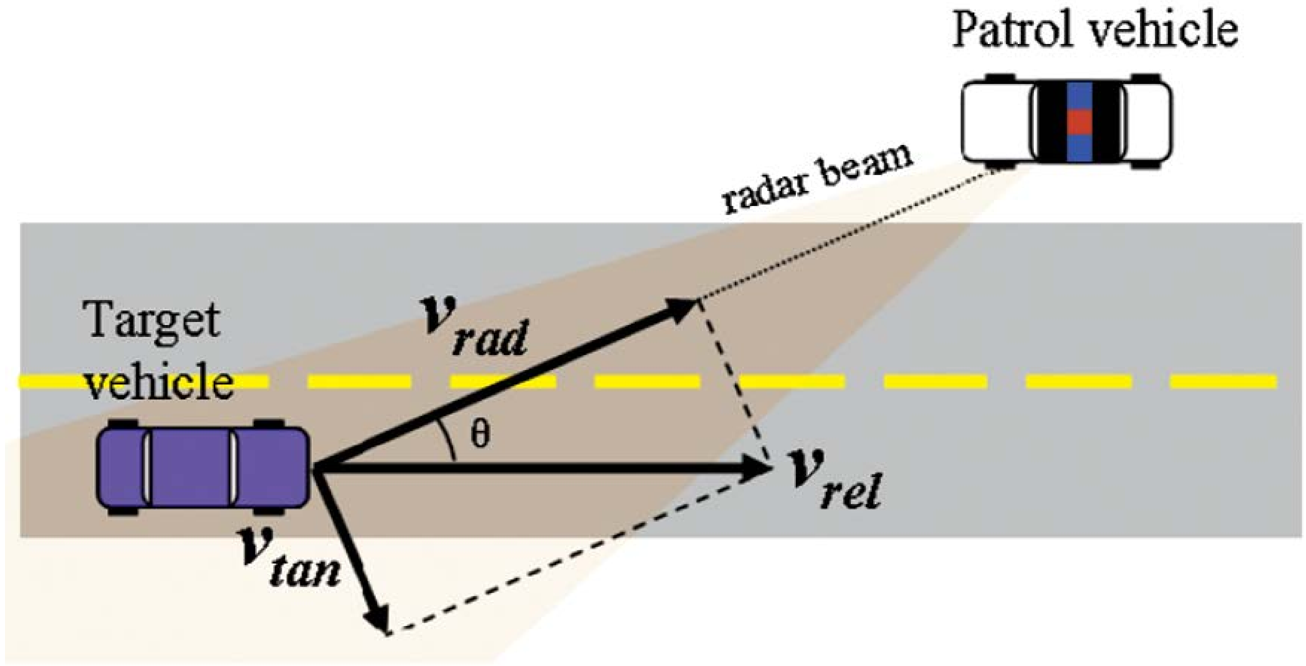
Uncertainty and Dimensional Calibrations

1. Master Gage Calibration
2. Long Term Reproducibility
3. Thermal Expansion
   a. Thermometer calibration
   b. Coefficient of thermal expansion
   c. Thermal gradients (internal, gage-gage, gage-scale)
4. Elastic Deformation - Probe contact deformation, compression of artifacts under their own weight
5. Scale Calibration
   a. Uncertainty of artifact standards, linearity, fit routine
   b. Scale thermal expansion, index of refraction correction
6. Instrument Geometry
   a. Abbe offset and instrument geometry errors
   b. Scale and gage alignment (cosine errors, obliquity, …)
   c. Gage support geometry (anvil flatness, block flatness, …)
7. Artifact Effects
   a. Flatness, parallelism, roundness, phase corrections on reflection

Volume 114, Number 3, May-June 2009
Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. **114**, 137-148 (2008)]

Calibration of Speed Enforcement Down-The-Road Radars



Metrology Research

- New and/or better ways to measure things
  - More selective, more accurate or more precise
- Better characterizations of the sources of measurement uncertainty
- Better ways to estimate uncertainties

Volume 116, Number 1, January-February 2011
Journal of Research of the National Institute of Standards and Technology

Maxim… stricted … n … es

$$\min_{\sigma^2,\sigma_1^2,\dots,\sigma_p^2} RL = \min_{\lambda,\sigma^2,\sigma_1^2,\dots,\sigma_p^2}\Bigg[\sum_i \frac{(x_i-\bar{\mu})^2}{\lambda(\sigma^2+\sigma_i^2)} + \sum_i \frac{\nu_i s_i^2}{\lambda\sigma_i^2}$$

$$+\log\Big(\sum_i \frac{1}{\lambda(\sigma^2+\sigma_i^2)}\Big) + \sum_i \log(\lambda(\sigma^2+\sigma_i^2))$$

$$+\sum_i \nu_i \log(\lambda\sigma_i^2)\Bigg]$$

$$= \min_{\sigma^2,\sigma_1^2,\dots,\sigma_p^2}\Bigg[\min_\lambda\Big[\frac{1}{\lambda}\Big(\sum_i \frac{(x_i-\bar{\mu})^2}{\sigma^2+\sigma_i^2} + \sum_i \frac{\nu_i s_i^2}{\sigma_i^2}\Big)$$

$$+(n-1)\log\lambda\Big] + \log\left(\sum_i \frac{1}{\sigma^2+\sigma_i^2}\right) + \sum_i \log\left(\sigma^2+\sigma_i^2\right)$$

$$+\sum_i \nu_i \log\sigma_i^2\Bigg]$$

$$= \min_{y_0,y_1,\dots,y_p}\Bigg[(n-1)\log\left(\sum_i \frac{(x_i-\bar{\mu})^2}{y_0+y_i} + \sum_i \frac{\nu_i s_i^2}{y_i}\right)$$

$$+\log\left(\sum_i \frac{1}{y_0+y_i}\right) + \sum_i \log(y_0+y_i) + \sum_i \nu_i \log y_i\Bigg]$$

$$+n-1-(n-1)\log(n-1)\,. \tag{57}$$

Relationship of Metrology Concepts

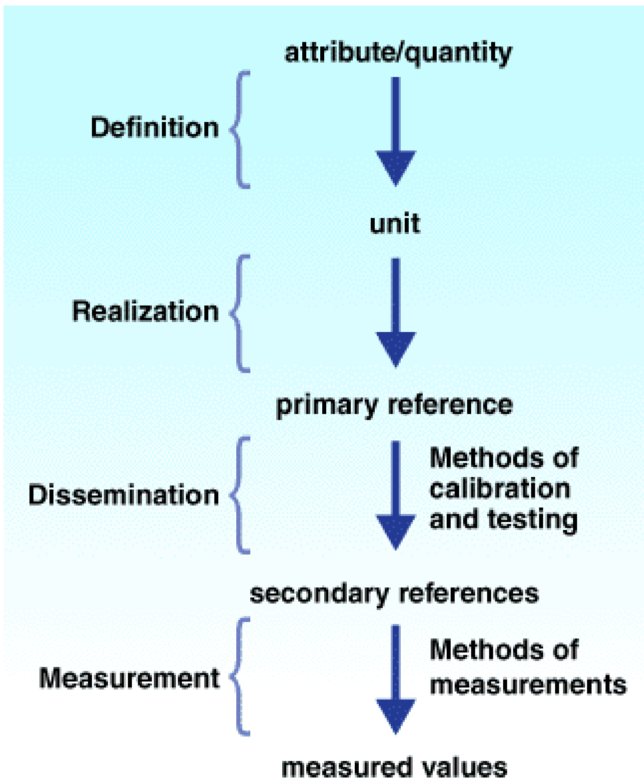


Figure 1 Logical relationship among metrology concepts for use in standardization in measurements.

NIST work:

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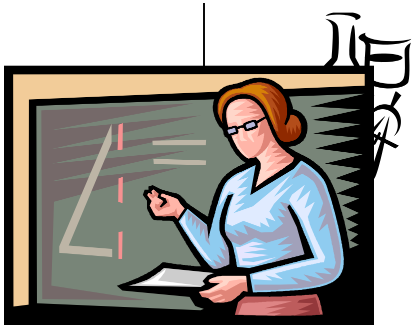
- **Metrology training**
- Delivery of measurement services

NISTIR 6025 Metrology for Information Technology (IT), MEL/ITL Task Group on Metrology for Information Technology (IT)May 1997

Metrology Training

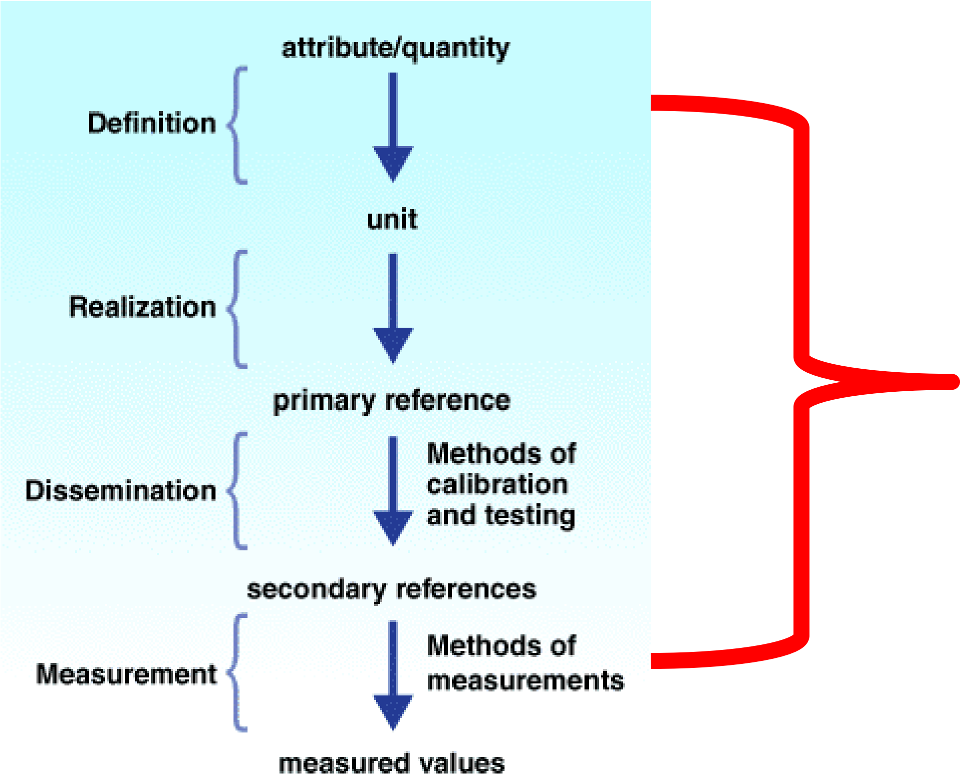


- Weights and Measures Enforcement
  - Specifications and Tolerances for Commercial Devices (Handbook 44)
  - Checking the Net Contents of Packaged Goods (Handbook 133)
  - Price Verification
- Laboratory/Metrology Seminars
  - Balance and scale metrology
  - Measurement Assurance Programs
  - Accreditation (NVLAP), Practical Measurement Assurance
- Specific metrology workshops
  - Microwave, antennas, and electrical
  - Pressure, flow, thermometry
  - Time and frequency
  - Dimensional
- Summer Programs for Students and Teachers
- User Facilities and Associated Instrumentation

60 classes

1000 students

Relationship of Metrology Concepts



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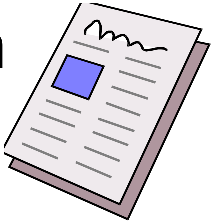
NIST Measurement Services

- NIST does it:
  - Publications on measurement science research
  - Fee-supported services
    - Standard Reference Data
    - Calibration services
    - Standard Reference Materials
    - Laboratory accreditation services (NVLAP)
- DIY – *You can do it; we can help.*
  - Services for legal metrology labs
  - Metrology training
  - Measurement practice guides
  - User facilities (CNST and NCNR)



Measurement Comparability

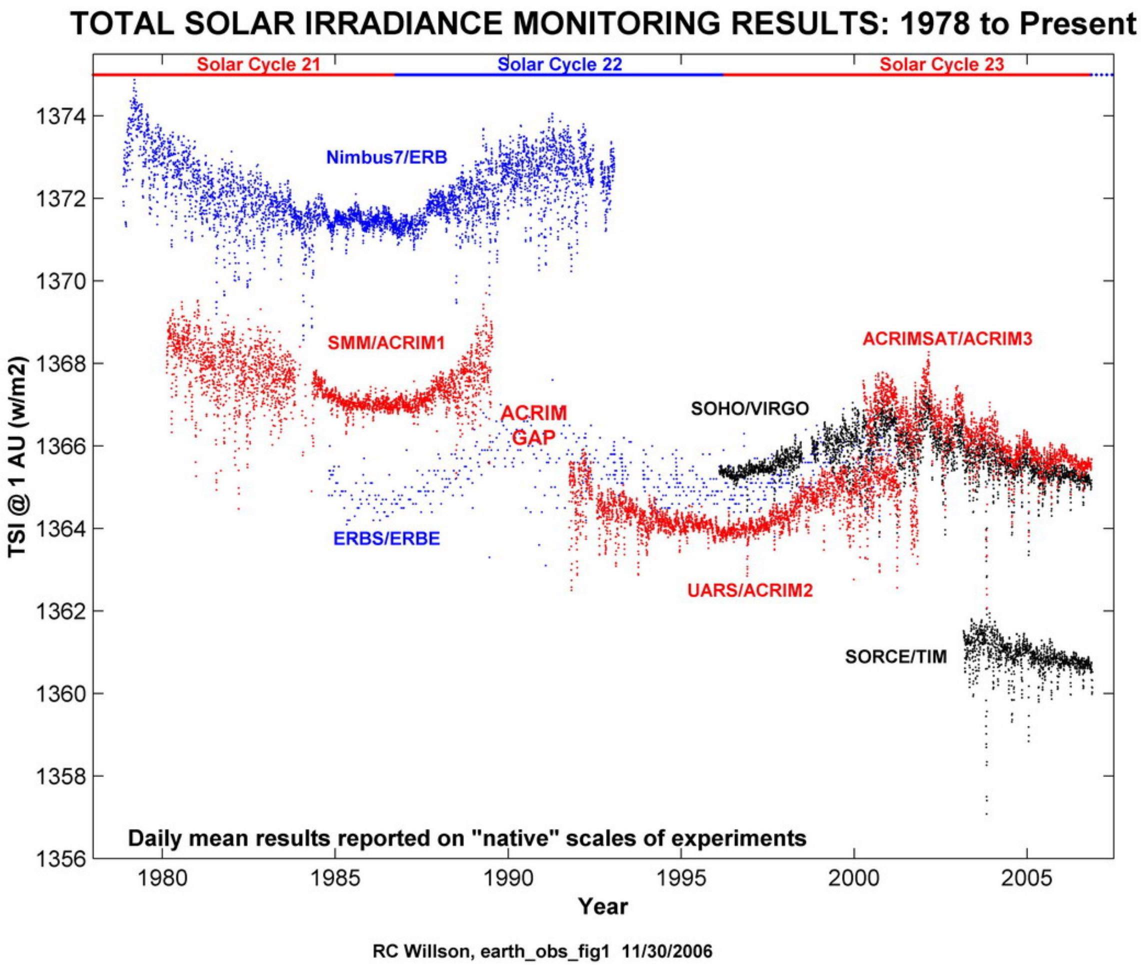
… when measurements agree to within a level of uncertainty that is small enough to be useful.

- User community depends on comparability of measurements
  - Buyers – sellers
  - Contributors to characterization of complex or time-dependent systems
  - Regulatory conformance

However, the state of measurement practice is challenged

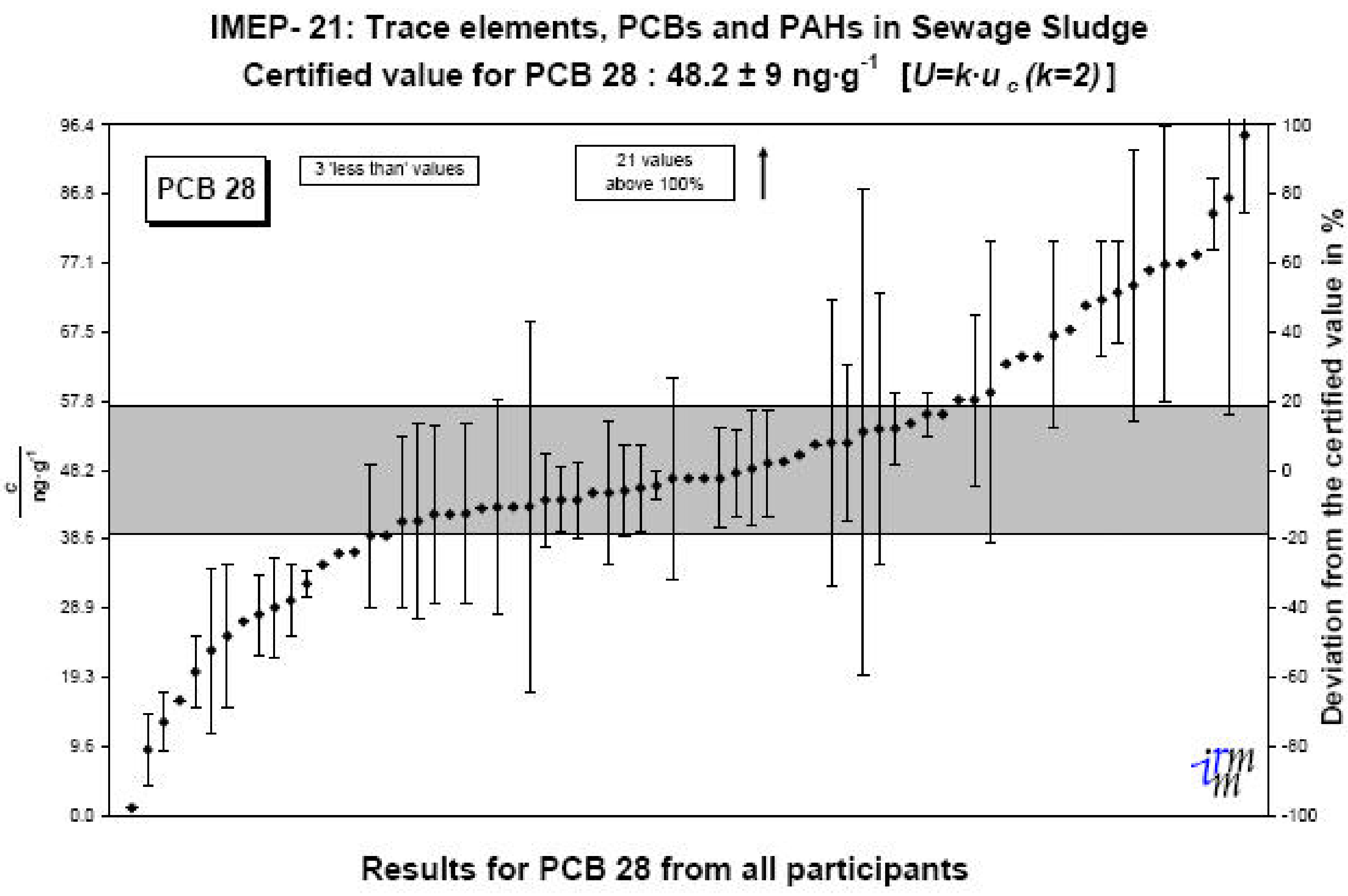
- By current or future accuracy requirements
  - Primary calibrations and currently available voltmeters
- When comparability of measurement results is required among *all* stakeholders, and the stakeholder group is too large or diffuse

Total solar irradiance uncertainty requirements not met

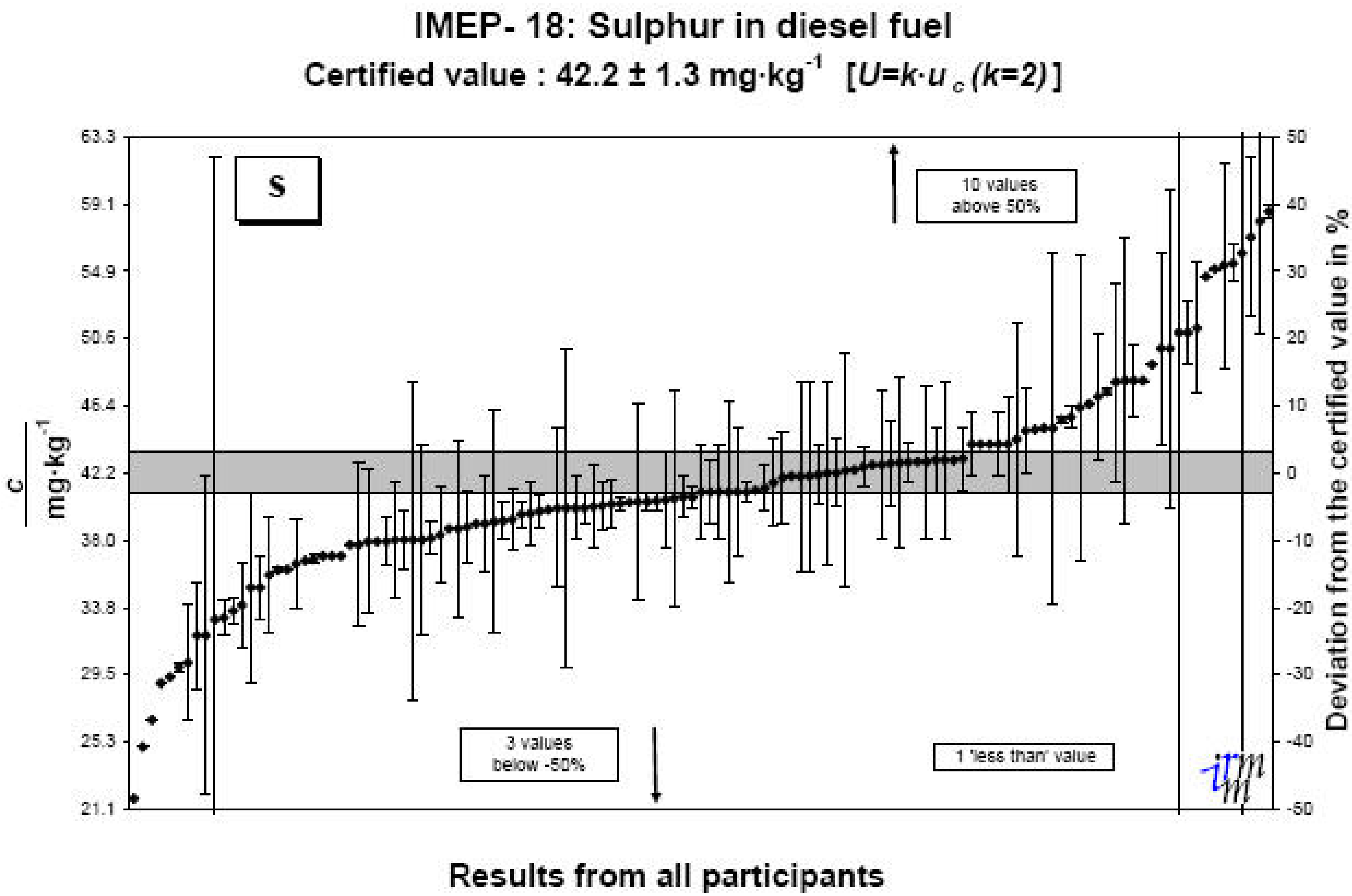


TSI Measurement Uncertainty Requirement ~ 0.2 W m^{-2} decade^{-1}

Comparability for PCB measurements does not exist



Measurement support for commodity pricing is lacking



Comparability *vs.* Traceability

- Comparability through consensus
  - Can be achieved with a quality control standard
  - Cannot be extended beyond consensus base or beyond the life of the QCS
  - Subject to long-term drift
  - No anchor point

Comparability *vs.* Traceability

- Traceability
  - Achieved by the use of a realization of a base or derived unit of measurement
    - Introduces the concept of *accuracy*
    - Comparability based on a standard: SI Units or well-defined method-dependent unit
  - Extended beyond consensus group through realization of the SI
  - Anchored to ensure stability

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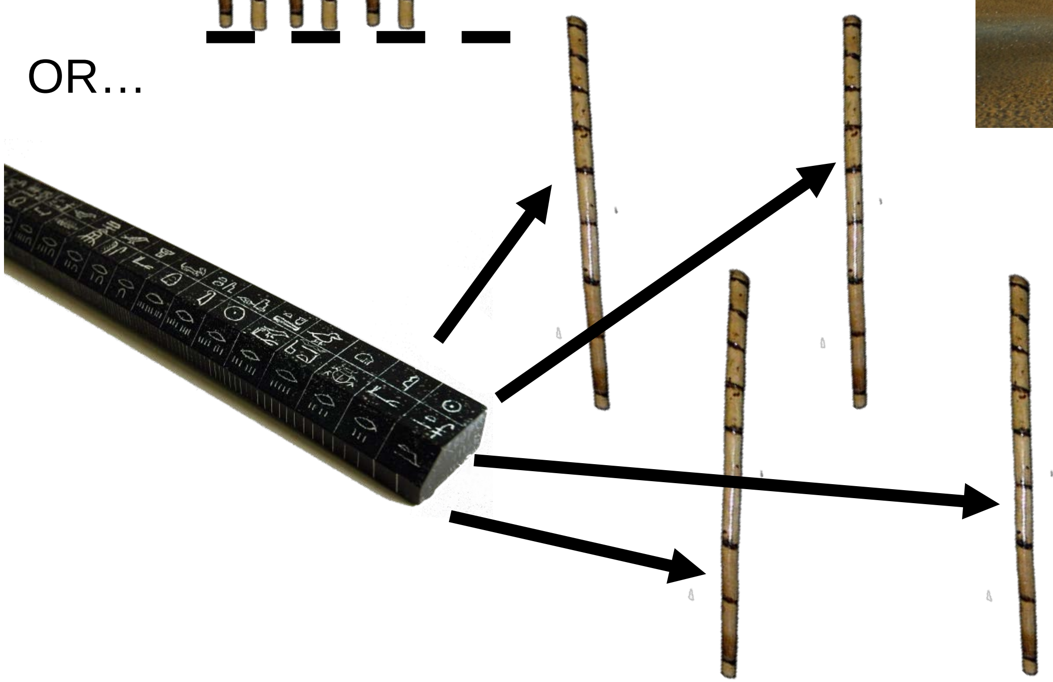
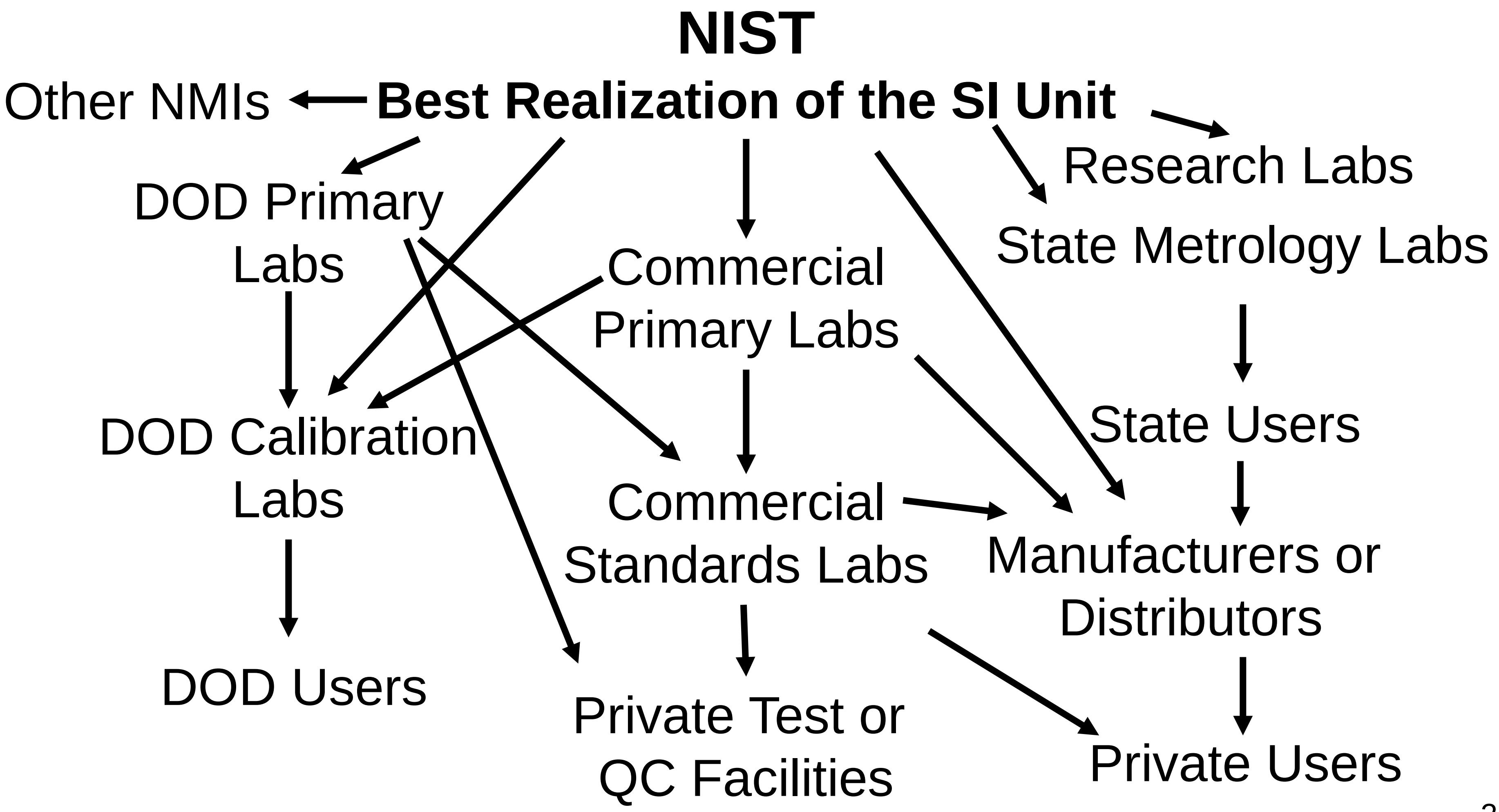
Comparability Achieved through Traceability

OR…



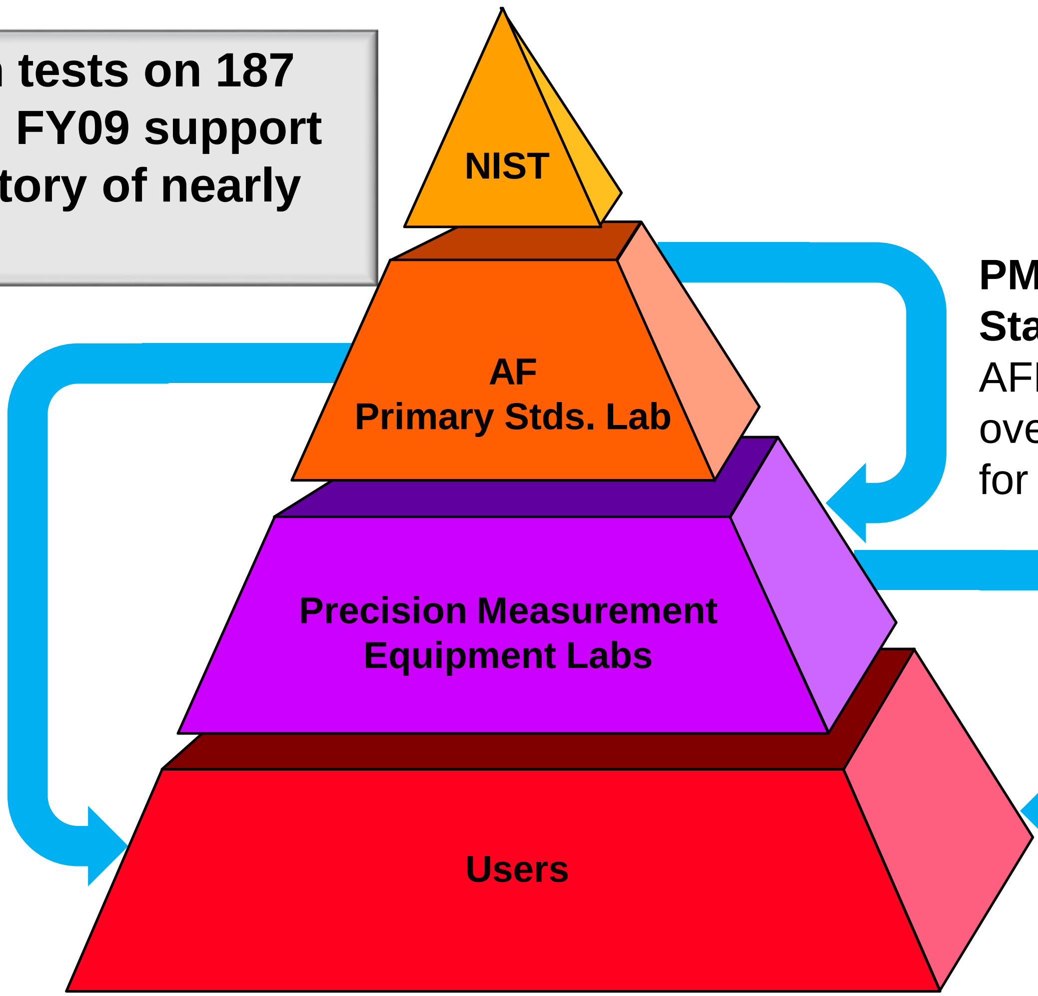
- Requires, wherever possible, an anchor point – a realization of an SI unit

Traceability Pathways in the U.S.



AFMETCAL Calibrations

1238 calibration tests on 187 items at NIST in FY09 support a total AF inventory of nearly 700,000 items



PMEL Measurement Standards: The AFPSL calibrates over 3,000 annually for PMELs

End Items: The AFPSL calibrates over 20,000 end items annually for PMELs and Major Command Customers

End Items: The PMELs in turn calibrate over 400,000 end items annually for Major Command Customers

Metrology to Support Regulations and Trade Worldwide