INTERNATIONAL METROLOGY AND THE REDEFINITION OF THE KILOGRAM

Dr. James Olthoff

Acting Director

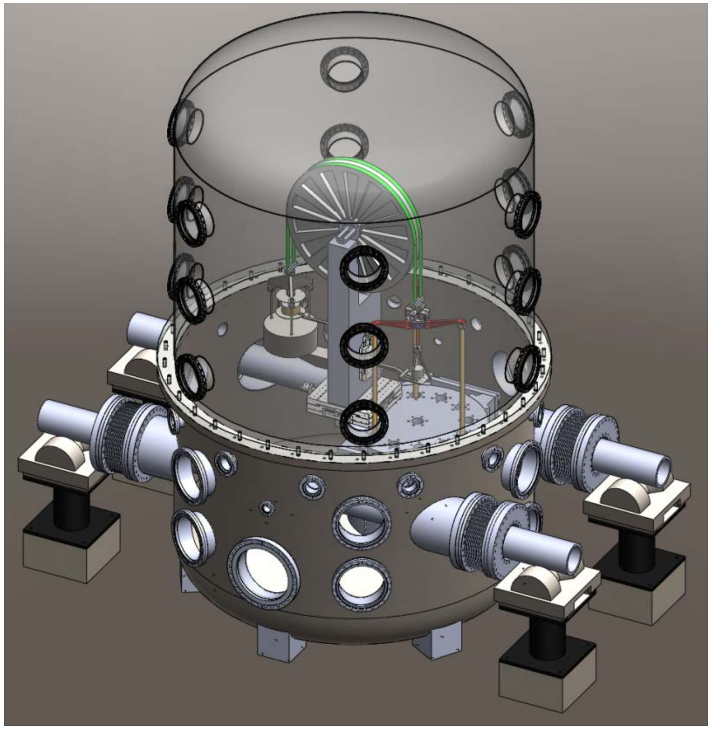
NIST Physical Measurement Laboratory

February 6, 2013

Bottom Line Up Front:
Replacing the Prototype Kilogram

Standard Kilogram prototypes

Shown: International Prototype of the Kilogram, kept at BIPM

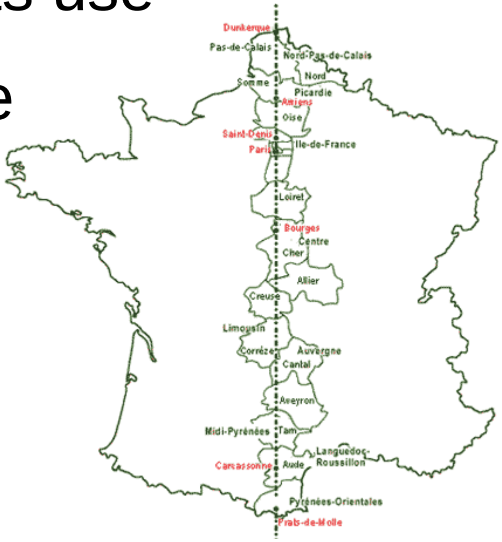


Electronic Kilogram realization

Shown: Computer rendering of NIST-4 watt balance, under construction

The Metric System
Version 1.0

- Adopted by international committee in 1799
- Came into common use in 19th century
  - In U.S., Metric Act of 1866 permitted its use, preempting state laws that forbade its use
- Standards kept in the Archives of France
- Basic principles:
  - Decimalization
  - Based on nature (not monarchs)
  - Open access



Survey of the Meridian, Dunkirk to Barcelona 1792–1799

Version 2.0: Improving the Standards and Governance

1870: Paris conference to consider constructing new primary metric system standards

- Originals from 1799 were aging and worn

1872: Second conference decided that new meters and new kilograms should be constructed to conform with the standards in the French Archives, as they were

- Committee appointed to carry out this decision

1873: Committee agrees upon improved materials and designs for standards

1875: French Government calls diplomatic conference to consider how to validate the new meters and kilograms

- Framework for permanent maintenance

Member States of the Meter Convention

General Conference on Weights and Measures
Conférence générale des poids et Measures
[CGPM]

Consists of delegates from Member States and meets every four years

Intl. Committee for Weights and Measures
Comité international des poids et mesures
[CIPM]

Consists of 18 individuals elected by the CGPM, charged with the supervision of the BIPM and of its activities, meets annually

National Metrology Laboratories

International Bureau of Weights and Measures
Bureau international des poids et mesures
[BIPM]

Intergovernmental organization with headquarters located in Sèvres, France
Direction, Laboratories, and permanent staff

NIST
Technical Staff

State of the Metric System
Late 19th Century

- The "Metric System" was *only* weights (kilogram) and measures (meter)
  - Also areas and volumes, derived from length

Standard Meter prototypes

Standard Kilogram prototypes

The Columbian Exhibition (1893)
Birthplace of International Electrical Standards

Court of Honor and Grand Basin of the
1893 World's Columbian Exposition (Chicago, Illinois)

Here, in 1893, the International Electrical Congress established the first international standards for the measurement of electrical quantities (ampere, ohm, volt, …)

Treaty of the Meter
1921 Amendments

- Added coordinating the measures of electrical units
- Added establishing and keeping standards of electrical units, and their “test copies”
- Added duty to determine the physical constants
- Ratified by the U.S. Senate in 1923

The Beginning of the System of Units

1954: 10th CGPM, Resolution 6: practical system of units

In accordance with the wish expressed by the 9th Conférence Générale des Poids et Mesures (CGPM) in its Resolution 6 concerning the establishment of a practical system of units of measurement for international use, the 10th CGPM

decides to adopt as base units of the system, the following units:

length	meter
mass	kilogram
time	second
electric current	ampere
thermodynamic temperature	degree Kelvin (renamed "kelvin" in 1967)
luminous intensity	candela

A comprehensive system of measurement units was now complete.

Version 3.0: The Système International d'Unités (SI)

1960: 11th CGPM adopts the name "Système International d'Unités" for the compilation of its work, the compete, modernized Metric System

- Units of measurement and rules for usage

1971: 14th CGPM adds the "mole" to SI as the seventh base unit, as the amount of substance

- The International Union of Pure and Applied Physics (IUPAP) and the International Union of Pure and Applied Chemistry (IUPAC) did not agree until 1960 to base the mole on ^{12}C, rather than ^{16}O.

The Système International d'Unités (SI)

- Creation of the SI *began* the process to revise and improve the units in a way that benefited the system as a whole
- Since 1960, rapid improvement of unit definitions and realizations
- Examples:
  - Changes to definition of the "second"
  - Changes to definition of the "meter"

Definition of the Second

1967: *The second is 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.*

NIST-F1, today's primary atomic frequency standard

Definition of the Meter

1889: International Prototype Meter

1960: Based on wavelength of ^{86}Kr radiation

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)

Media Attention

CBSNEWS Video | US | World | Politics | Entertainment | Health | MoneyWatc

CNET / *October 29, 2010, 5:50 PM*

Time to Do Away with the Kilogram?

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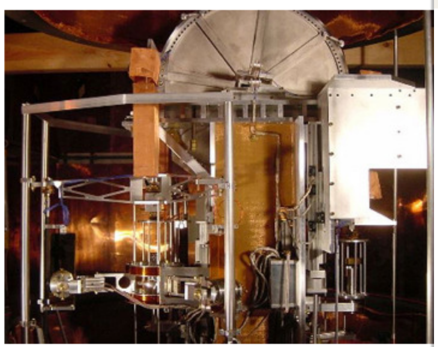
Locked away in a vault at France's Internationa
is a very important platinum-iridium cylinder. I
has served as the base measure for the precise w



The International System of Units; Watt Balance / STEINER, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOG

THE WALL STREET JOURNAL.

U.S. EDITION Friday, January 28, 2011

THE A-HED | January 28, 2011

The Fate of the Kilo Weighs Heavily Minds of Metrologists

Moves Are Afoot to Redefine Measurements; Le Grand K Feels a Wee Bit Lig

By JEANNE WHALEN

In a vault beneath a 17th-century pavilion on the outskirts of Paris
cylinder known as Le Grand K. Since 1889 it has been the internati
the kilogram, the standard against which all other kilos are measur

But over the years, scientists have noticed a problem: Le Grand K h
weight. Weigh-ins at the International Bureau of Weights and Measures show that the bar has shed approximately 50 micrograms—roughly equal to a grain of sand.

National Institute of Standards and Technology

Scientists are using a watt balance (pictured) to calculate Planck's constant, which will be used to define the kilo.

The problem has vexed scientists who monitor the kilo the way tabloids track the waistlines of Valerie Bertinelli and Kirstie Alley. The stakes, however, are weightier.

"It's a scandal that we've got this kilogram hanging around changing its mass and therefore changing the mass of everything else in the universe!" Bill Phillips, a Nobel Prize winning physicist, exclaimed at a scientific summit in London this week. No one knows for sure what went wrong with Le Grand K, but some theorize it lost weight from being cleaned.

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Scientists ask: Is the kilo losing weight?

By Elizabeth Weise, USA TODAY Updated 4/19/2011 10:07 AM | Share

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SÈVRES, France — Ensuring a pound of butter is indeed a pound, or a gallon of milk a full gallon, has long been the province of government agencies that deal with weights and measures. But now it seems scientists are having a little trouble with the golfball size piece of metal that is used to set the standard weight for a kilogram, or kilo.

International Bureau of Weights and Measures, AFP/Getty Images

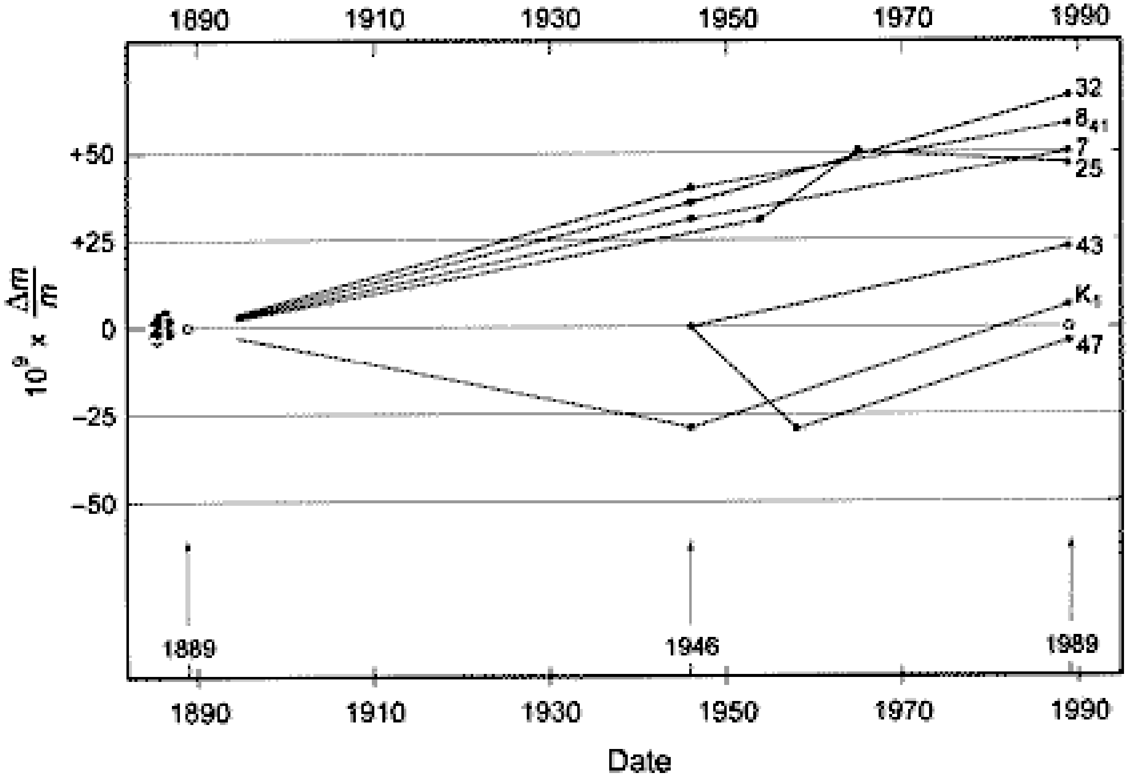
An undated picture from the International Bureau of Weights and Measures shows the international prototype of a kilogram.

A bunch of these prototypes have been made over the years, seven of which are kept in a triple-locked vault at the International Bureau of Weights and Measures in Sèvres, with one known as the International Prototype.

The problem is that as these prototypes have been taken out and weighed, which last happened in 1990, something odd has turned up — their weights began diverging. The international prototype, for example, weighed 50 micrograms less than the others, meaning it had lost weight or the others were getting heavier, or they were all moving a bit — no one knows for certain. And no one knows what caused the changing weights either.

The Two Biggest Headaches in SI Today

1) The artifact kilogram



Compared to the International Prototype Kilogram, the measured masses of prototype kilograms around the world are diverging.

2) The electrical units

NIST Leadership

INSTITUTE OF PHYSICS PUBLISHING METROLOGIA

Metrologia **42** (2005) 71–80 doi:10.1088/0026-1394/42/2/001

Redefinition of the kilogram: a decision whose time has come

Ian M Mills[1], Peter J Mohr[2], Terry J Quinn[3], Barry N Taylor[2] and Edwin R Williams[2]

[1] Department of Chemistry, University of Reading, Reading, RG6 6AD, UK
[2] National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA
[3] Emeritus Director, Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92312 Sèvres, Cedex, France

E-mail: i.m.mills@reading.ac.uk, mohr@nist.gov, terry.quinn@physics.org, barry.taylor@nist.gov and edwin.williams@nist.gov

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Online at stacks.iop.org/Met/42/71

Proposed Solution to Both Problems: Metric System Version 4.0

- Redefine the:
  - kilogram
  - ampere
  - kelvin
  - mole
- By determined through best experiment, then fixing, the values of:
  - Planck constant
  - Elementary electric charge (of electron)
  - Boltzmann constant
  - Avogadro constant

Converging on Consensus

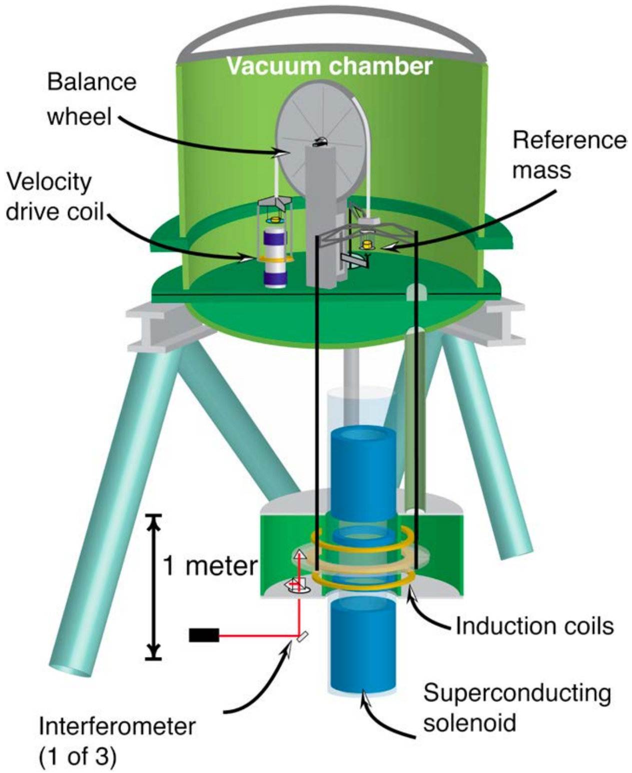
The CGPM, at its 24th meeting (2011), took note of the intention of the CIPM to propose a revision of the SI where:

- the **kilogram** will continue to be the unit of mass, but its magnitude will be set by fixing the numerical value of the **Planck constant** to be equal to exactly 6.626 06X $\times 10^{-34}$ when it is expressed in the SI unit m^2 kg s^{-1}, which is equal to J s
- the **ampere** will continue to be the unit of electric current, but its magnitude will be set by fixing the numerical value of the **elementary charge** to be equal to exactly 1.602 17X $\times 10^{-19}$ when it is expressed in the SI unit s A, which is equal to C
- the **kelvin** will continue to be the unit of thermodynamic temperature, but its magnitude will be set by fixing the numerical value of the **Boltzmann constant** to be equal to exactly 1.380 6X $\times 10^{-23}$ when it is expressed in the SI unit m^2 kg s^{-2} K^{-1}, which is equal to J K^{-1}
- the **mole** will continue to be the unit of amount of substance of a specified elementary entity, which may be an atom, molecule, ion, electron, any other particle or a specified group of such particles, but its magnitude will be set by fixing the numerical value of the **Avogadro constant** to be equal to exactly 6.022 14X $\times 10^{23}$ when it is expressed in the SI unit mol^{-1}

Ref: http://www.bipm.org/en/CGPM/db/24/1/

What remains is to determine the missing digits "X" in each case

Two Approaches to the Kilogram



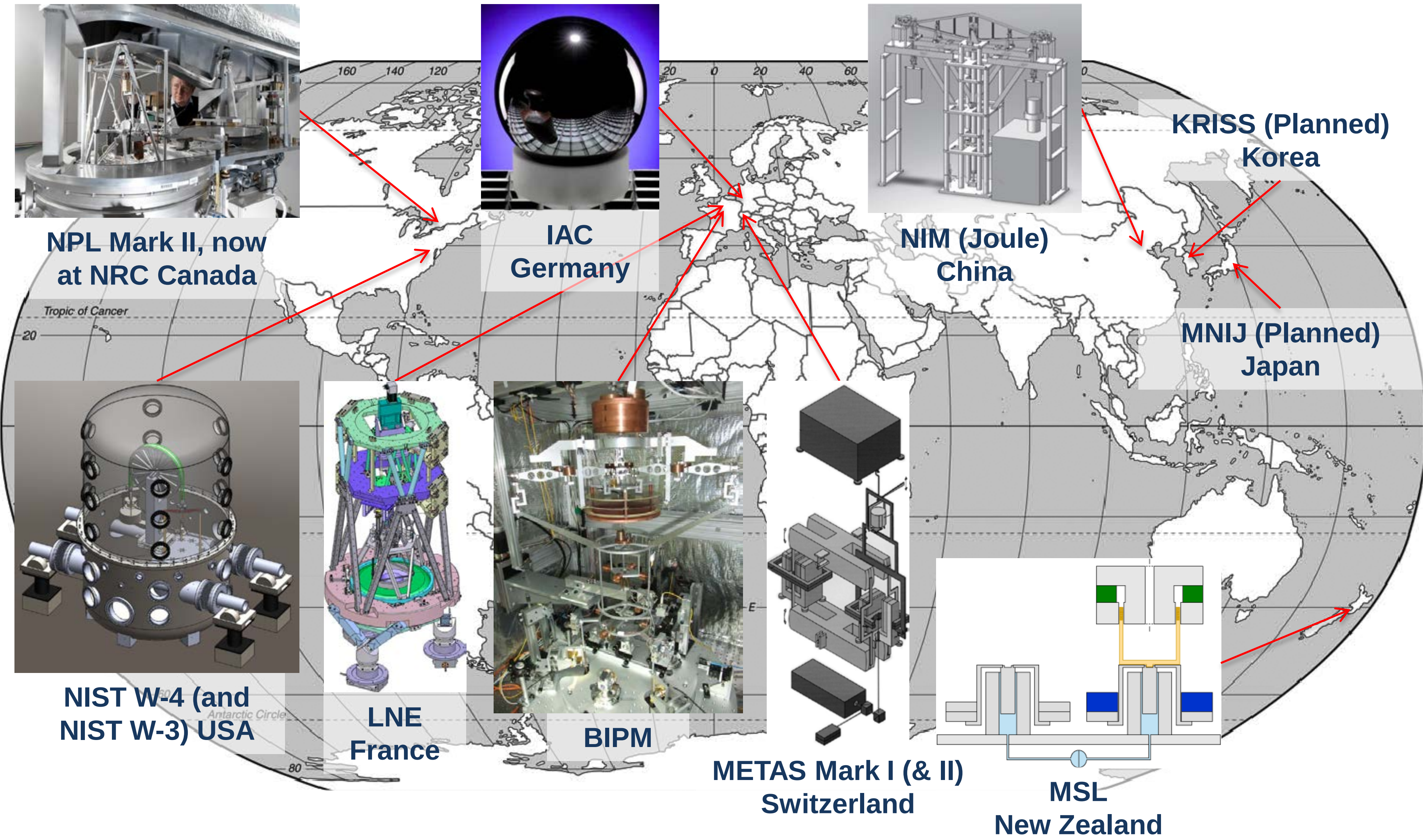
The Watt Balance Approach

Electrical force and power equated to mechanical force and power. Electrical measurements made with quantum standards, derived from *e* and *h*. Local gravitational field must also be measured.

The Avogadro Number Approach

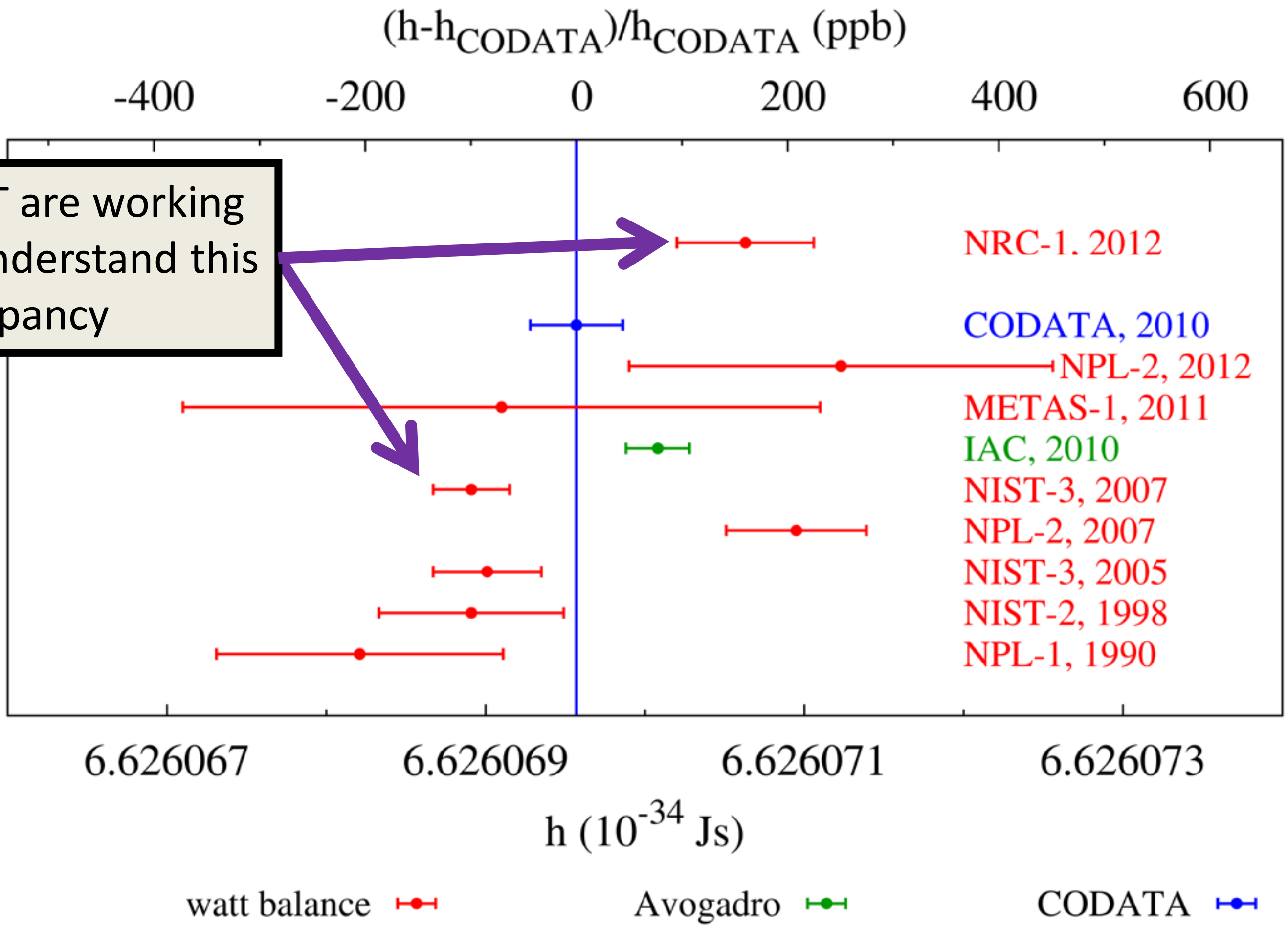
Near-perfect sphere of near-perfect crystal of nearly isotopically pure Silicon-28. Interatomic spacing, determined by x-ray diffraction, gives you the number of atoms in the sphere, which is also the mass standard.

Worldwide Realizations



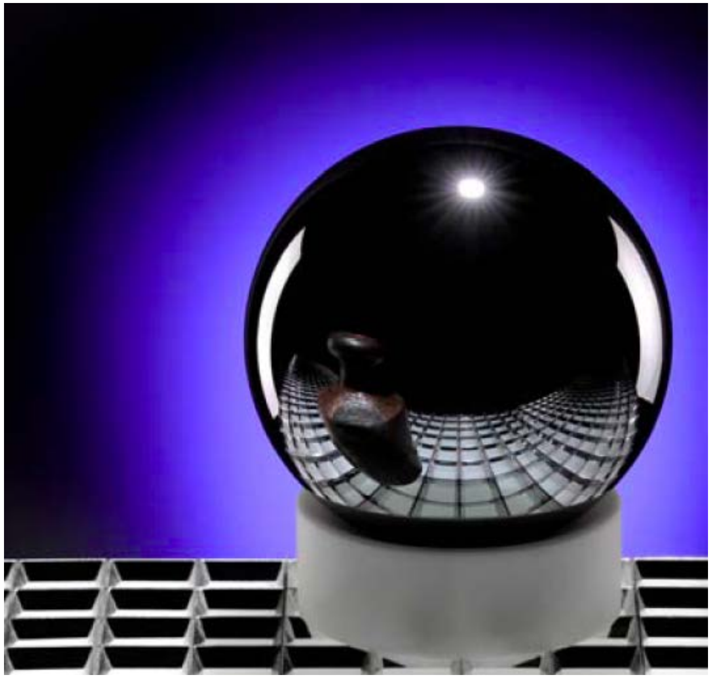
Status of the Planck Constant

NRC and NIST are working together to understand this discrepancy



NIST Contribution to the Avogadro Project

- NIST provided independent measurement of the molar mass of the crystal
  - Mass spectrometry / Isotope ratio measurement
  - Results to be published
  - NIST result tends to agree with PTB measurement



Improvements to Watt Balance W-3

Central knife edge reinvented and replaced

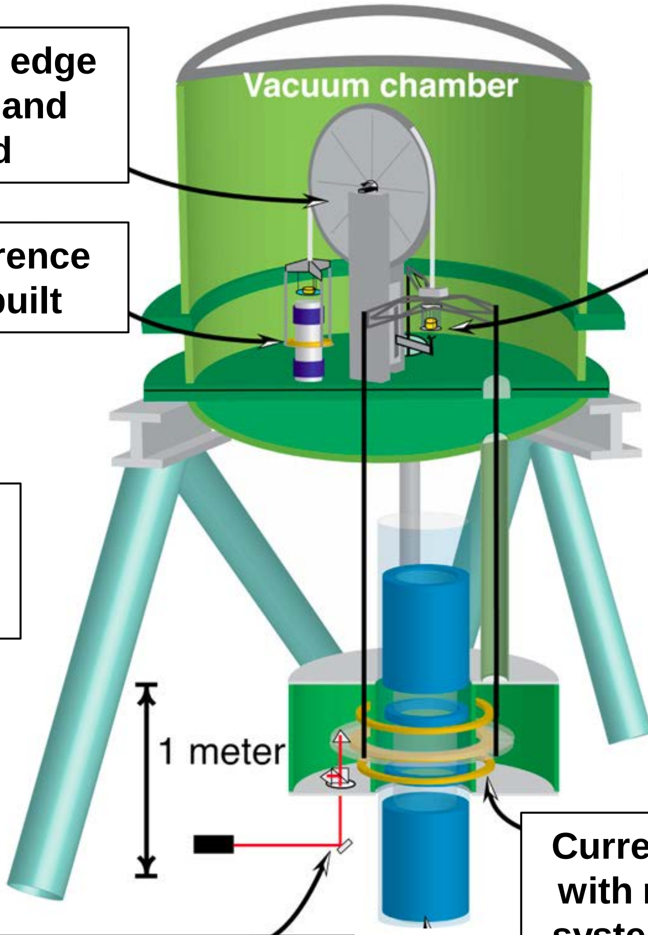
Voltage reference system rebuilt

Our mass, K85, went back to BIPM for calibration and vacuum characterization

Temperature control in room improved

Electric power system revamped to lower noise and improve grounding

Gravity measurement system compared to NRC and NOAA. Agreement better than 10 ppb



Current sources replaced with new, ultra-low noise systems invented at NIST

Velocity measurement system revamped, for lower noise

Watt Balance W-3 Cross Checks

- FY 2012: All primary standards used by NIST watt balance upgraded, being cross-checked with NRC
  - Voltage (compared to NRC in 2006)
  - Resistance (compared to NRC in 2008)
  - Time
  - Length
- Test masses
  - Check transport, handling, procedural differences
- Contribution of gravity measurements to discrepancies is now constrained to be < 1 part in 10^8

The Great Gravity Showdown
NIST, NOAA, NRC (Canada)
February 6–10, 2012

Goal: Converge on *h* value prior to CCU meeting, June 2013

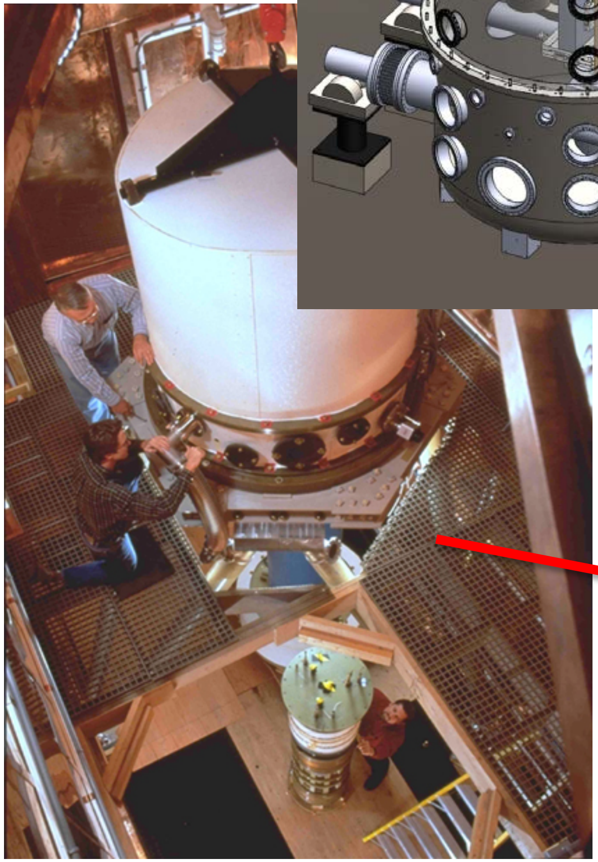
Blinded Experiment

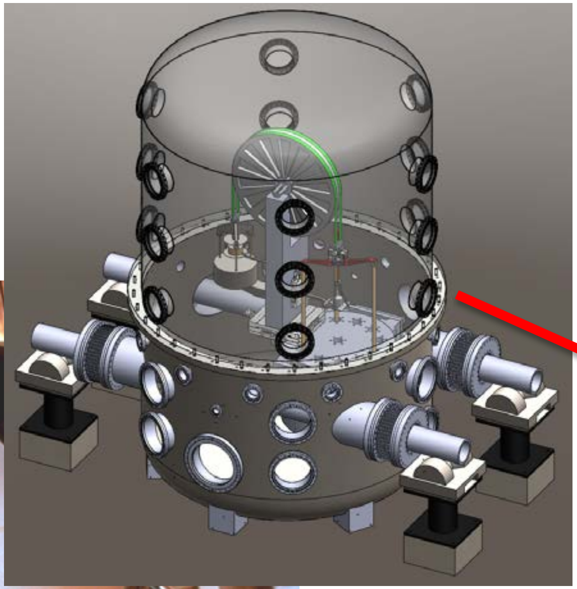
- Watt balance group evaluating instrument using variety of tests to explore systematic deviations
- Watt balance group making new determination of Planck's constant (*h*) using a mass with an unknown (to them) offset
- Mass group knows offset
- When value of *h* has been determined, offset will be added (shifting *h*)
- New NIST-measured value of *h* by March 2013

Timeline

- Nov 2012: Workshop on *mise en pratique*
- Draft *mise en pratique* circulating now
- Jan 2013: BIPM decides to *not* yet use IPK in comparison
  - Precludes final adoption of new system at 25th CGPM
- Feb 2013: Meeting of Consultative Committee on Mass
- March 2013: New NIST value from W-3
- Spring/Summer 2013: NIST will work with NRC, PTB to dry run the *mise en pratique*
- June 2013: Meeting of Consultative Committee on Units
- Fall 2013: Meeting of the CIPM
- Fall 2014: 25th CGPM
  - Decision on next opportunity for adoption

NIST's Watt Balances





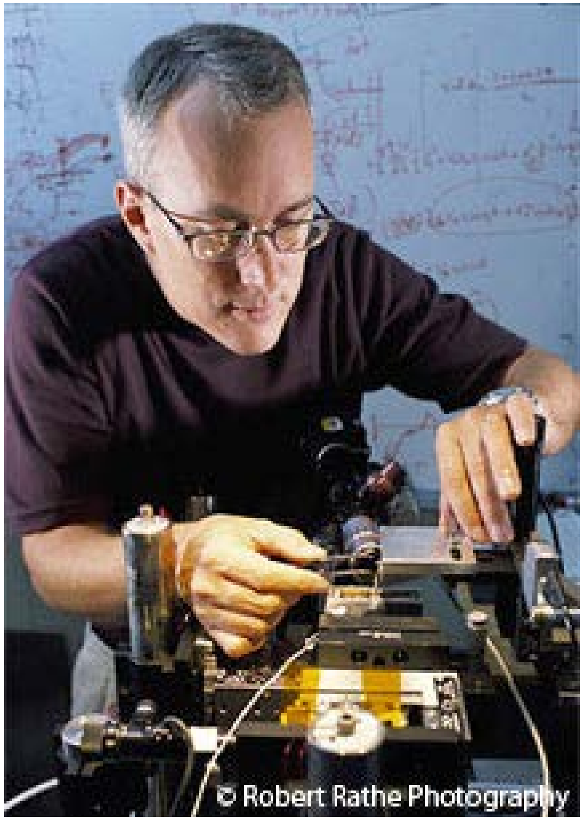
Impact on Practical Dissemination of Mass

- Education and training
- Develop W-4, whose primary purpose is the realization of the kilogram
  - "Ease" of use
- Transfer of standards between air and vacuum
  - New issue
  - Need to study stability of mass artifacts

Patrick Abbot inspects the upper (vacuum) section of the vacuum levitation system.

Impact on Practical Dissemination of Mass

- Realizations at arbitrary scale points
  - Should improve uncertainties of measurement of very small masses



Mechanical engineer Jon Pratt makes an adjustment to the prototype NIST Electrostatic Force Balance designed to measure nanoscale forces.

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

Credits

1) Title Slide: Photograph of David Wineland, © Geoffrey Wheeler, 2003; Dawn Cross, NIST, 2011; Charles Gibson, © Robert Rathe, 2002; Sae Woo Nam, © Geoffrey Wheeler, 2003
2) International Prototype of the Kilogram, http://www.bipm.org/en/scientific/mass/prototype.html, © BIPM; NIST W-4 Watt Balance, NIST
3) Survey of the Meridian, from http://www.planetseed.com/node/16531
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5) Photograph of Dr. Patrick Gallagher from http://www.nist.gov/director/bios/gallagher.cfm, and of Dr. Willie May from http://www.nist.gov/director/bios/willie_may.cfm.
Organizational chart, after http://www.bipm.org/utils/en/pdf/structure.pdf.
The Treaty of the Meter is published in The Statutes at Large of the United States of America, Vol. 20, pp. 709–724 (1879).
6) Meter bar, from the NIST Museum Collection, http://museum.nist.gov/object.asp?ObjID=37; International Prototype of the Kilogram, http://www.bipm.org/en/scientific/mass/prototype.html
7) The Columbian Exhibition, photographer unknown, from http://en.wikipedia.org/wiki/World's_Columbian_Exposition
8) The 1921 Amendments to the Treaty of the Meter are published in
The Statutes at Large of the United States of America, Vol. 43 (Part 2), pp. 1686–1694 (1925)
9) More on SI and its history at: http://physics.nist.gov/cuu/Units/bibliography.html, in particular, NIST Special Publication 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf

Credits (Continued)

12) NIST-F1 frequency standard, photograph © 2005 Geoffrey Wheeler; http://www.nist.gov/pml/div688/grp50/primary-frequency-standards.cfm. See http://physics.nist.gov/cuu/Units/second.html and NIST Publication SP 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf, Sec. 2.1.1.3.
13) International Prototype Meter, photograph from http://www.nist.gov/pml/wmd/metric/length.cfm See http://physics.nist.gov/cuu/Units/meter.html and NIST Publication SP 330 http://physics.nist.gov/Pubs/SP330/sp330.pdf, Sec. 2.1.1.1.
14) International Prototype of the Kilogram, http://www.bipm.org/en/scientific/mass/prototype.html; data plot from http://www.bipm.org/en/scientific/mass/verifications.html; both © BIPM
15) See http://dx.doi.org/10.1088/0026-1394/42/2/001. See also http://dx.doi.org/10.1088/0026-1394/43/3/006.
16) Media clips from: http://www.cbsnews.com/8301-501465_162-20021243-501465.html, http://online.wsj.com/article/SB10001424052748704062604576106094010476886.html, and http://usatoday30.usatoday.com/tech/science/2011-04-18-kilo-weight.htm.
17) See http://www.nist.gov/pml/newsletter/siredef.cfm. See http://www.bipm.org/utils/common/pdf/si_brochure_draft_ch2.pdf.
18) See http://www.bipm.org/en/CGPM/db/24/1/.
19) NIST watt balance, from http://dx.doi.org/10.1109/TIM.2008.2007060, © 2008 IEEE; Silicon sphere, from http://www.scienceimage.csiro.au/mediarelease/mr07-108.html. See also: http://www.csiro.au/en/Outcomes/ICT-and-Services/Data-deluge/ Precision-spheres-in-push-to-re-define-kilogram.aspx, both © CSIRO Industrial Physics.

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NIST W-4 rendering, NIST.

21) See, e.g., http://dx.doi.org/10.1088/0034-4885/76/1/016101.

22) Silicon sphere, from http://www.euramet.org/fileadmin/docs/EMRP/JRP/JRP_Summaries_2011/SI_JRPs/SIB03_Publishable_JRP_Summary.pdf

23) NIST W-3, from http://dx.doi.org/10.1109/TIM.2008.2007060, © 2008 IEEE

24) Photograph of gravity comparison, from http://www.nist.gov/pml/div684/gravity_comparison.cfm

27) Photograph of NIST W-3, rendering of NIST W-4, NIST; Aerial imagery of NIST Gaithersburg, MD site, © 2013 Google and Google Map imagery providers: Commonwealth of Virginia, DigitalGlobe, GeoEye, U.S. Geological Survey, and/or USDA Farm Service Agency

28) Photograph of Patrick Abbot, from http://www.nist.gov/pml/div684/maglevkg.cfm

29) Photograph of Jon Pratt, from http://www.nist.gov/pml/div684/grp07/sfmet.cfm