Electrical Units in the New SI: Saying Goodbye to the 1990 Values

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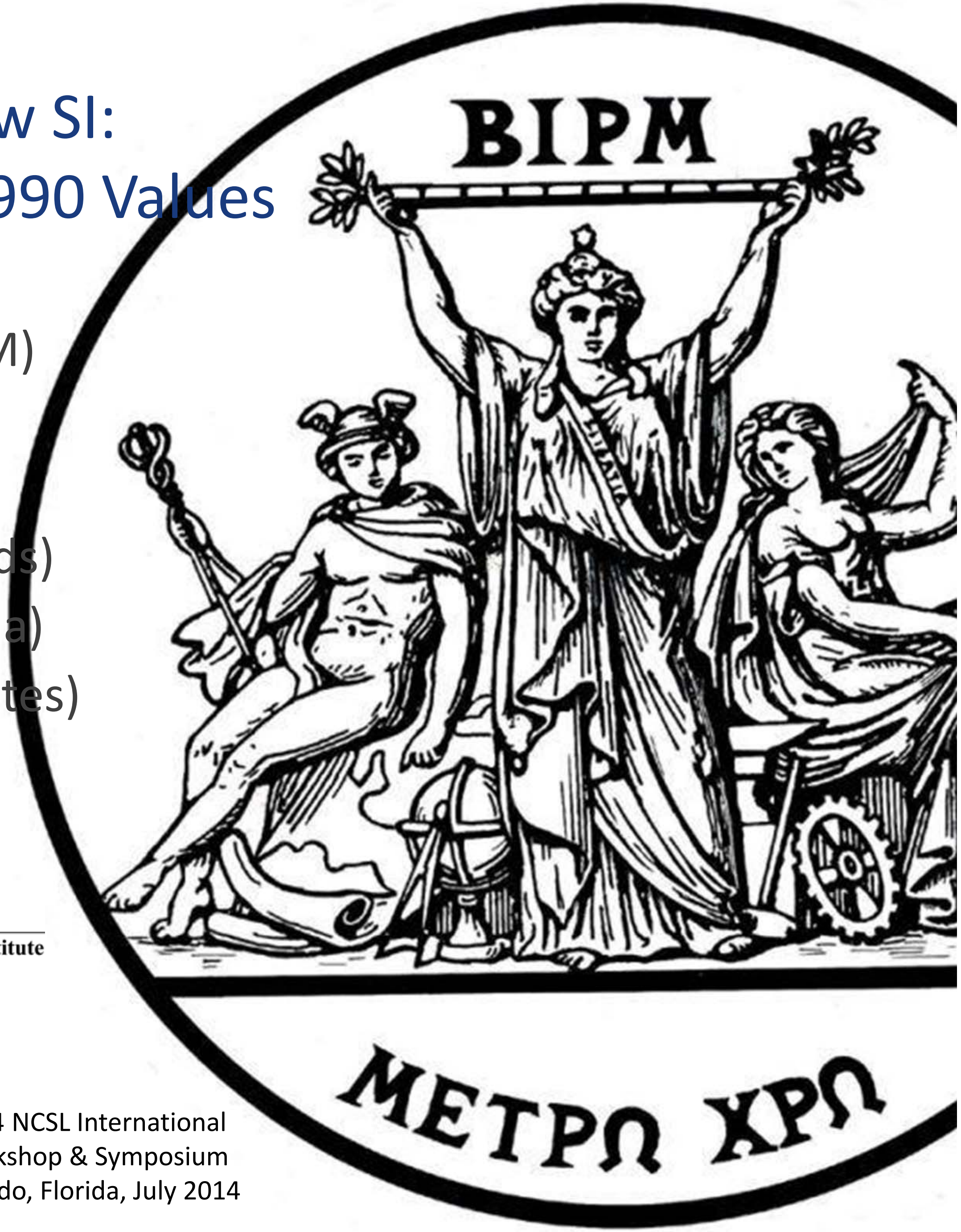

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Australian Government
National Measurement Institute

Bureau International des Poids et Mesures

VSL

2014 NCSL International Workshop & Symposium
Orlando, Florida, July 2014

Outline

- Planned changes to the SI base units
- Updated numerical values for R_K and K_J – replacements for 1990 values
- Impact on electrical traceability
- Implementation details and timing

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The project for a revised SI

- Removing the last arte
  the SI (the prototype k
- 4 updated base unit de
  defined numerical valu
  fundamental constant
    - Planck consta
    - Elementary ch
    - Boltzmann co
    - con

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Search 'new SI'

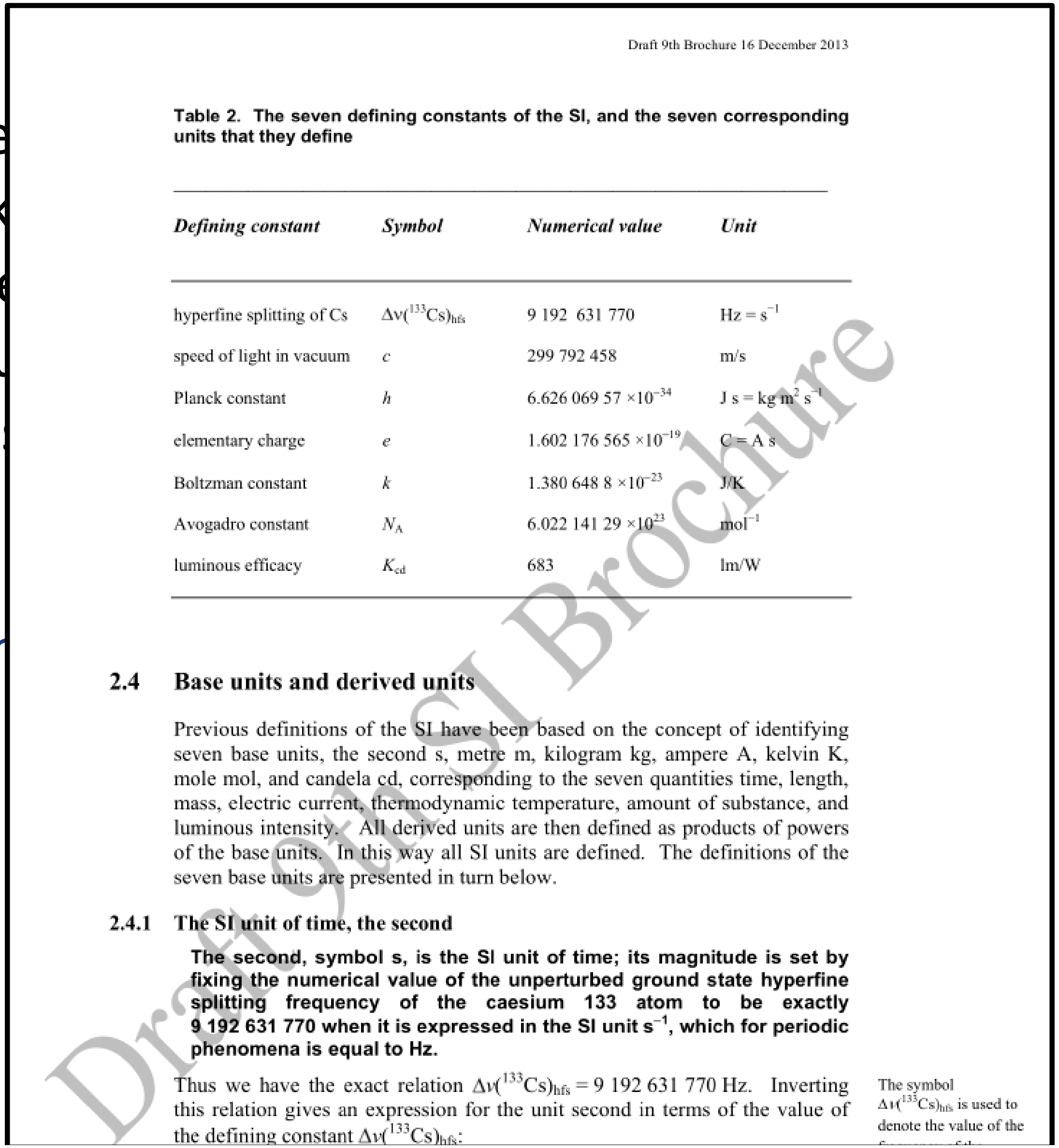

Table 2. The seven defining constants of the SI, and the seven corresponding units that they define

Defining constant	*Symbol*	*Numerical value*	*Unit*
hyperfine splitting of Cs	$\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$	9 192 631 770	$\mathrm{Hz} = \mathrm{s}^{-1}$
speed of light in vacuum	c	299 792 458	m/s
Planck constant	h	$6.626\,069\,57 \times 10^{-34}$	$\mathrm{J\,s} = \mathrm{kg\,m^2\,s^{-1}}$
elementary charge	e	$1.602\,176\,565 \times 10^{-19}$	$\mathrm{C} = \mathrm{A\,s}$
Boltzman constant	k	$1.380\,648\,8 \times 10^{-23}$	J/K
Avogadro constant	N_A	$6.022\,141\,29 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	lm/W

2.4 Base units and derived units

Previous definitions of the SI have been based on the concept of identifying seven base units, the second s, metre m, kilogram kg, ampere A, kelvin K, mole mol, and candela cd, corresponding to the seven quantities time, length, mass, electric current, thermodynamic temperature, amount of substance, and luminous intensity. All derived units are then defined as products of powers of the base units. In this way all SI units are defined. The definitions of the seven base units are presented in turn below.

2.4.1 The SI unit of time, the second

The second, symbol s, is the SI unit of time; its magnitude is set by fixing the numerical value of the unperturbed ground state hyperfine splitting frequency of the caesium 133 atom to be exactly 9 192 631 770 when it is expressed in the SI unit s^{-1}, which for periodic phenomena is equal to Hz.

Thus we have the exact relation $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}} = 9\,192\,631\,770$ Hz. Inverting this relation gives an expression for the unit second in terms of the value of the defining constant $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$:

The symbol $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$ is used to denote the value of the

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The project for a revised SI

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Review Article

Towards a new SI: a review of progress made since 2011

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Abstract

In 2011, the General Conference on Weights and Measures (CGPM) confirmed its intention to adopt new definitions for four of the base units of the SI based on fixed numerical values of selected constants. These will be the kilogram, the ampere, the kelvin and the mole. The CGPM was not able to adopt the new definitions at that time because certain experimental and coordination work was not complete. This paper reviews criteria proposed by the Consultative Committees of the CIPM for such a 'new SI' to be adopted and reports on recent progress with work to address them. We also report on work being undertaken to demonstrate that the most important technical aspects of realizing such a new system are practicable. The progress reported here confirms the consensus developing amongst the Consultative Committees and the National Metrology Institutes that it will be possible for the CGPM to adopt these new definitions in 2018.

Keywords: SI units, metrology, kilogram

S Online supplementary data available from stacks.iop.org/Met/51/R21/mmedia

(Some figures may appear in colour only in the online journal)

1. Introduction

There has been much debate about the benefits of revising the definitions of four of the base units of the SI [1] so that they are articulated in terms of fixed numerical values of certain constants [2, 3]. The limitations of the present system, in fundamental or atomic constants' [6b]. Subsequently, in 2007, at its 23rd meeting, it recognized the possibility of redefining four base units in terms of fixed values of four fundamental constants and invited the NMIs 'to come to a view on whether it is possible' [6c].

Most recently, in 2011, at its 24th meeting, it noted [6d]

Activities of the Consultative Committee for Electricity and Magnetism (CCEM)

- Since 1992, the working group on 'electrical methods for monitoring the kilogram' has been a key forum for reviewing experimental progress – preparing the way for redefinition
- Passed a resolution at 2007 meeting expressing support for the redefinition once there is adequate experimental agreement
- *'Mise en pratique'* for the electrical units derived from the new definitions has been available since 2009
- At 2013 meeting, created a task group for communication and implementation of changes
  –> this presentation

Conventional ‘representations’ for the volt and ohm

1990

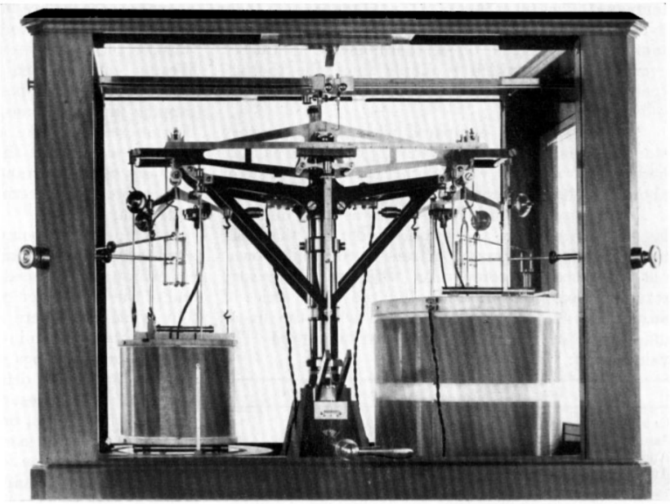
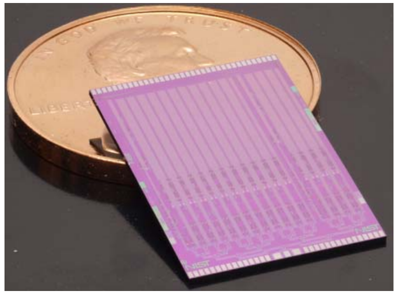


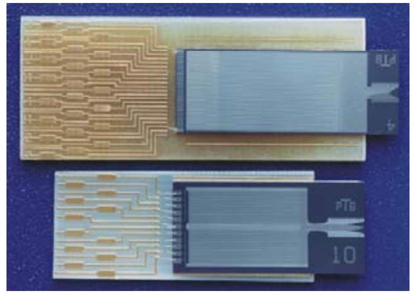
Fig. 1. Current balance of the National Physical Laboratory. One large coil has been lowered so that the suspended coil can be seen

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 metre apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per metre of length.

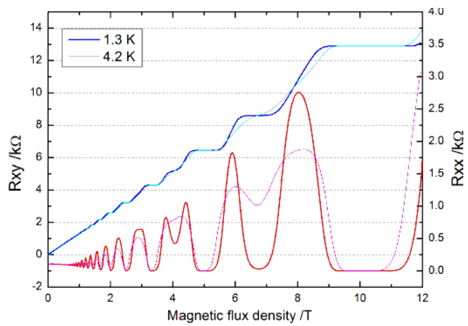
Credit: NIST

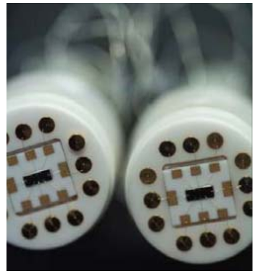


Credit: PTB



$$U_J = n\frac{f}{K_J}, \qquad K_J = \frac{2e}{h}$$





$$R_H(i) = \frac{R_K}{i}, \qquad R_K = \frac{h}{e^2}$$

$\approx 10^{-6}$ Classical | $\approx 10^{-9}$ Quantum

Macroscopic quantum effects: stable, reproducible, universally available

Origins and use of the 1990 values

Guiding principle for the choice of values in 1990:

'The values should be so chosen that they are unlikely to require significant change for the foreseeable future. This means that …. the uncertainties should be conservatively assigned.'

- The recommended relative one-standard-deviation uncertainty for a voltage realised using the Josephson effect and the value $K_{J\text{-}90}$, with respect to the volt, is 4×10^{-7} (CIPM 1988, Resolution 1, PV, 56, 44).
- The recommended relative one-standard-deviation uncertainty for a resistance realised using the quantum Hall effect and the value $R_{K\text{-}90}$, with respect to the ohm, was originally 2×10^{-7} (CIPM 1988, Resolution 2, PV, 56, 45).
- It was reduced to 1×10^{-7} after review of the CODATA 1998 adjustment (CIPM 2001, PV, 68, 101, following CCEM, 22, 90).

What changes in the new SI?

Definition:

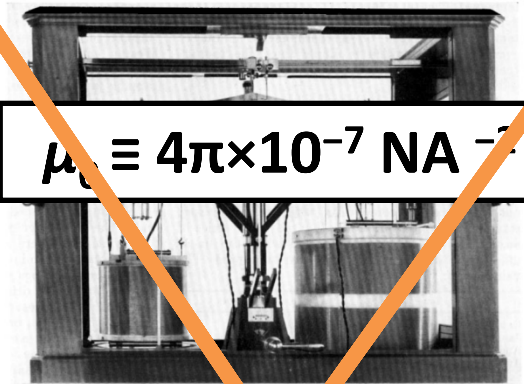


Fig. 1. Current balance of the National Physical Laboratory. One large coil has been lowered so that the suspended coil can be seen

$\mu_0 \equiv 4\pi\times10^{-7}$ **NA^{-2}**

Incompatible

Practical units:

$R_{K\text{-}90} \equiv 25\ 812.807\ \Omega$

$K_{J\text{-}90} \equiv 483\ 597.9$ GHz/V

Definition:

$h \equiv 6.626\ 069\ XX$ Js

$e \equiv 1.602\ 176\ XX$ C

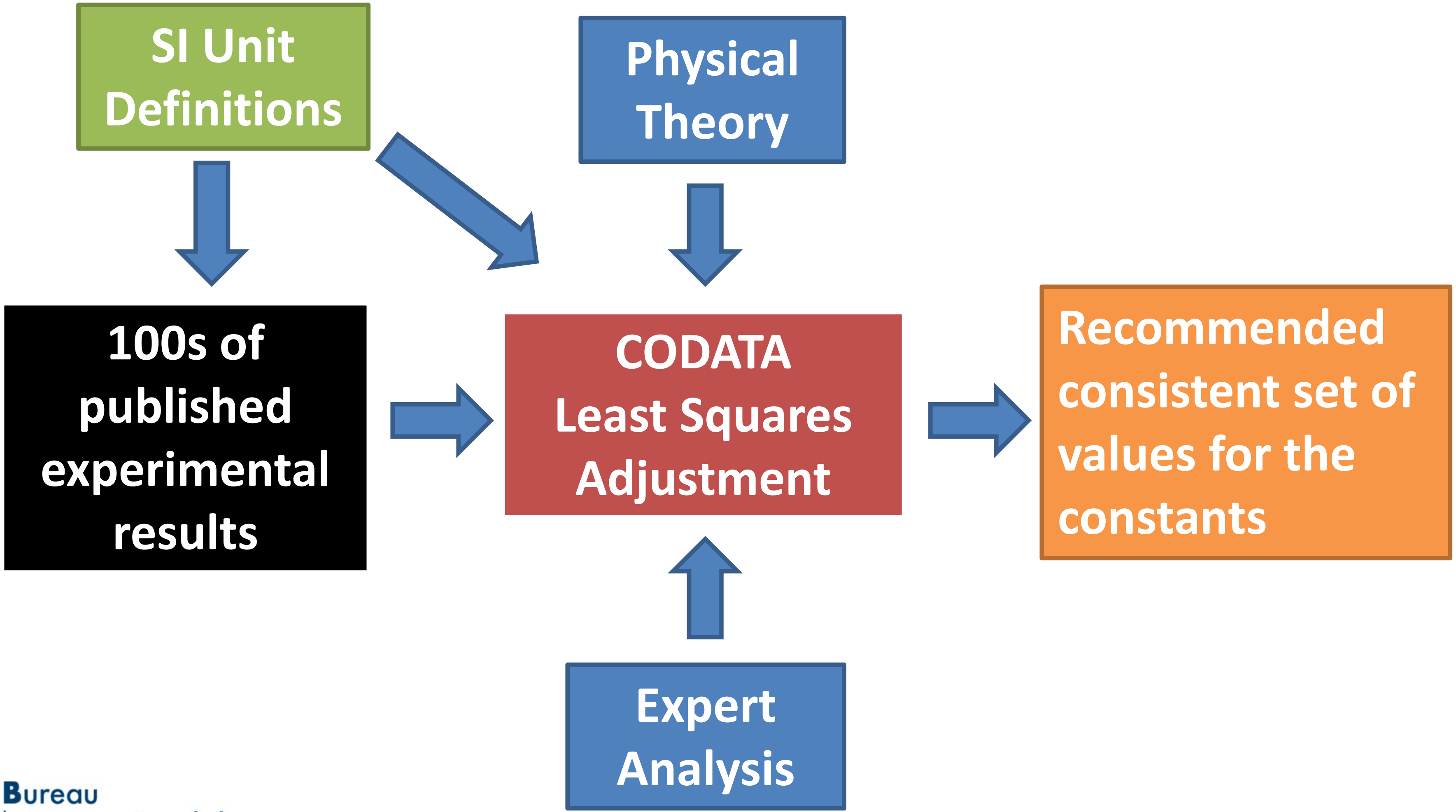
Direct link

Practical units:

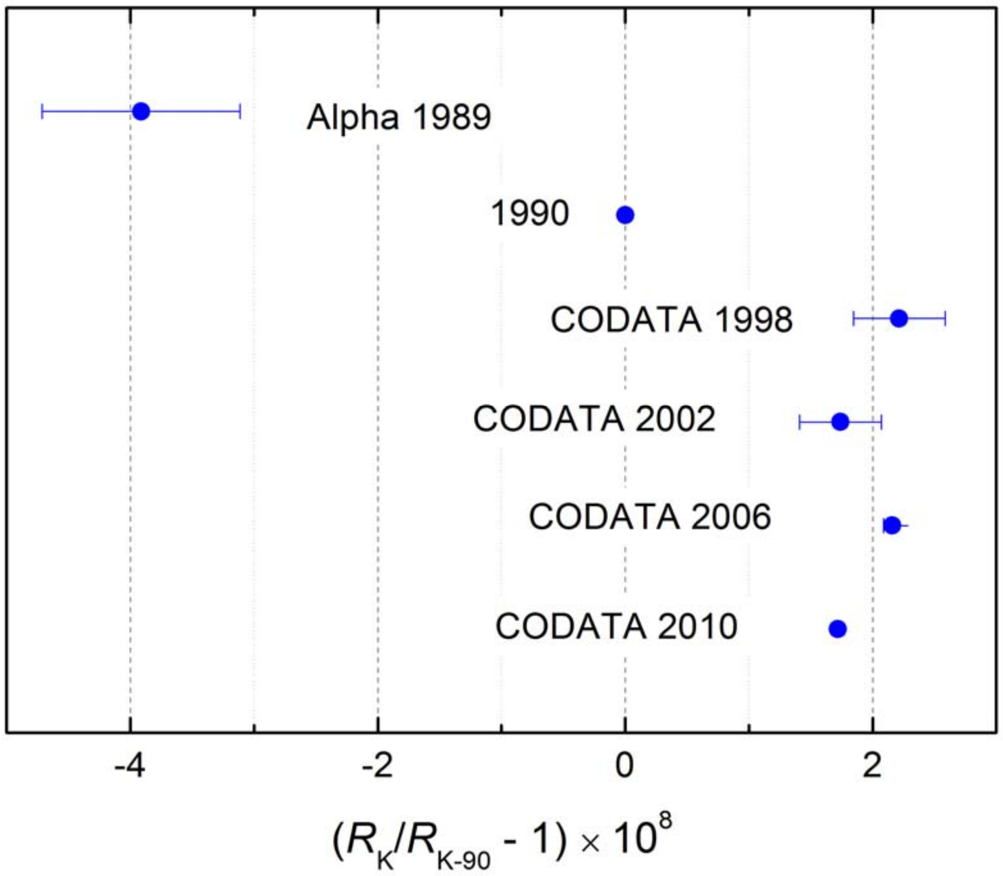
$R_K = h/e^2 \equiv 25\ 812.807\ XX\ \Omega$

$K_J = 2e/h \equiv 483\ 597.9\ XX$ GHz/V

Where do the values of the constants come from?



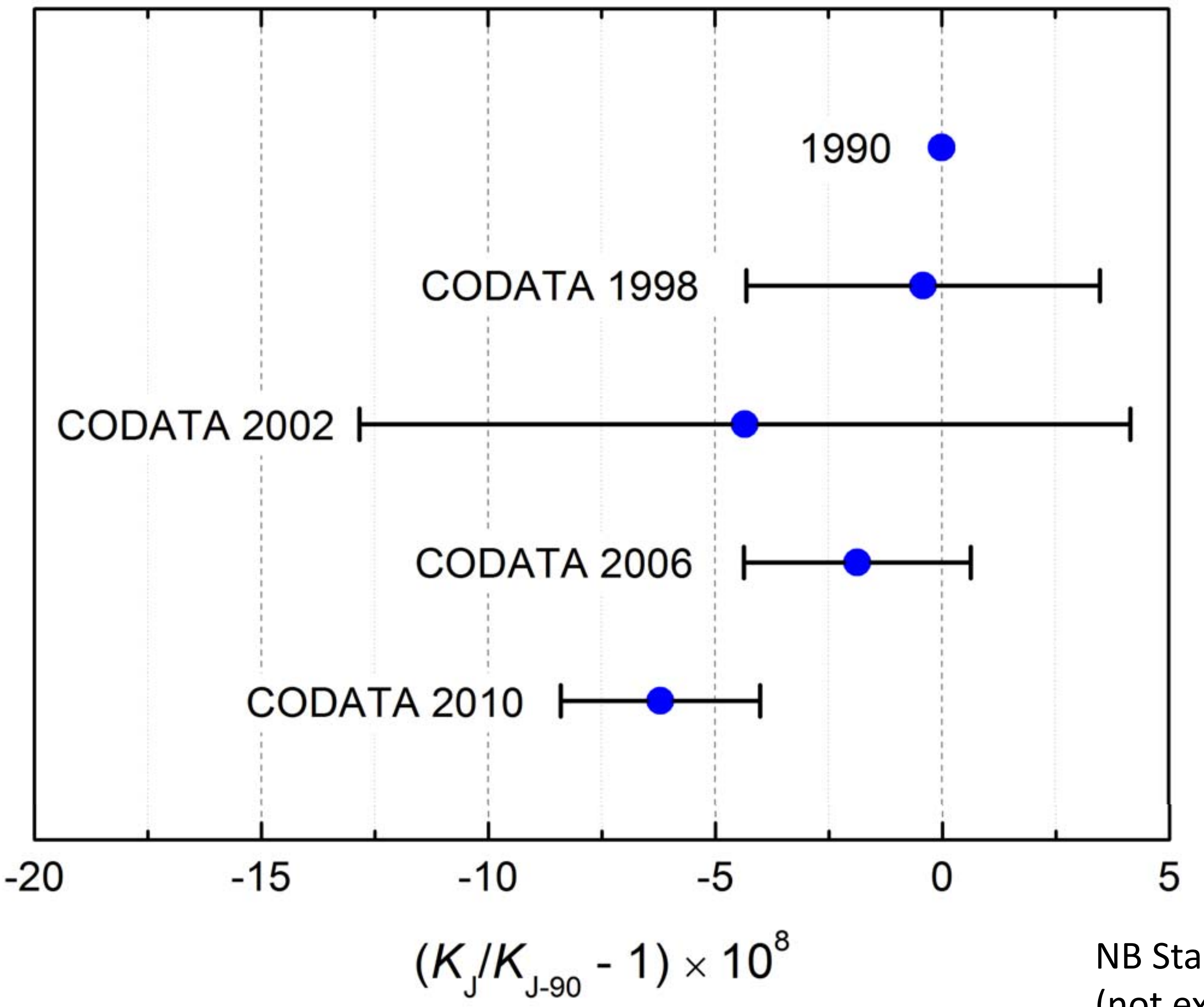
Evolution of values of R_K



$$h/e^2 = \mu_0 c/2\alpha$$

NB Standard uncertainties
(not expanded k=2)

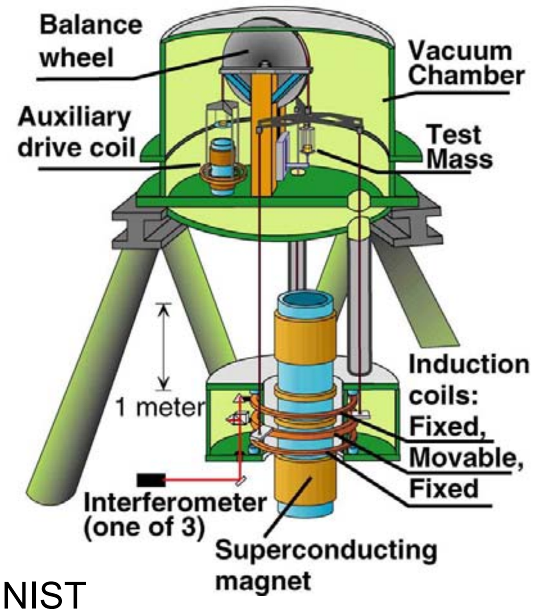
Evolution of values of K_J



$$K_\mathrm{J} = \frac{2}{\sqrt{h \cdot R_\mathrm{K}}}$$

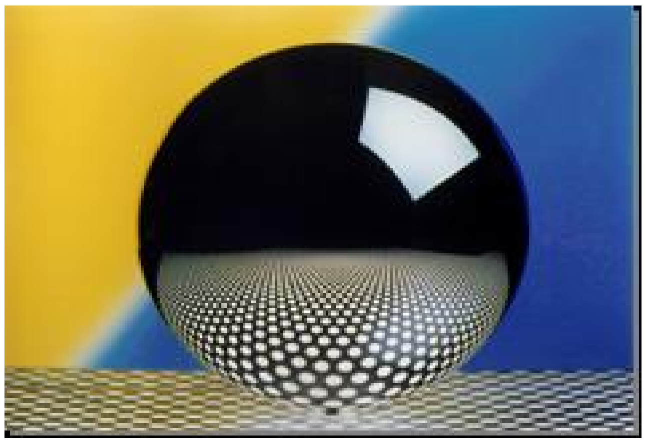
NB Standard uncertainties
(not expanded k=2)

Experiments contributing to *h*



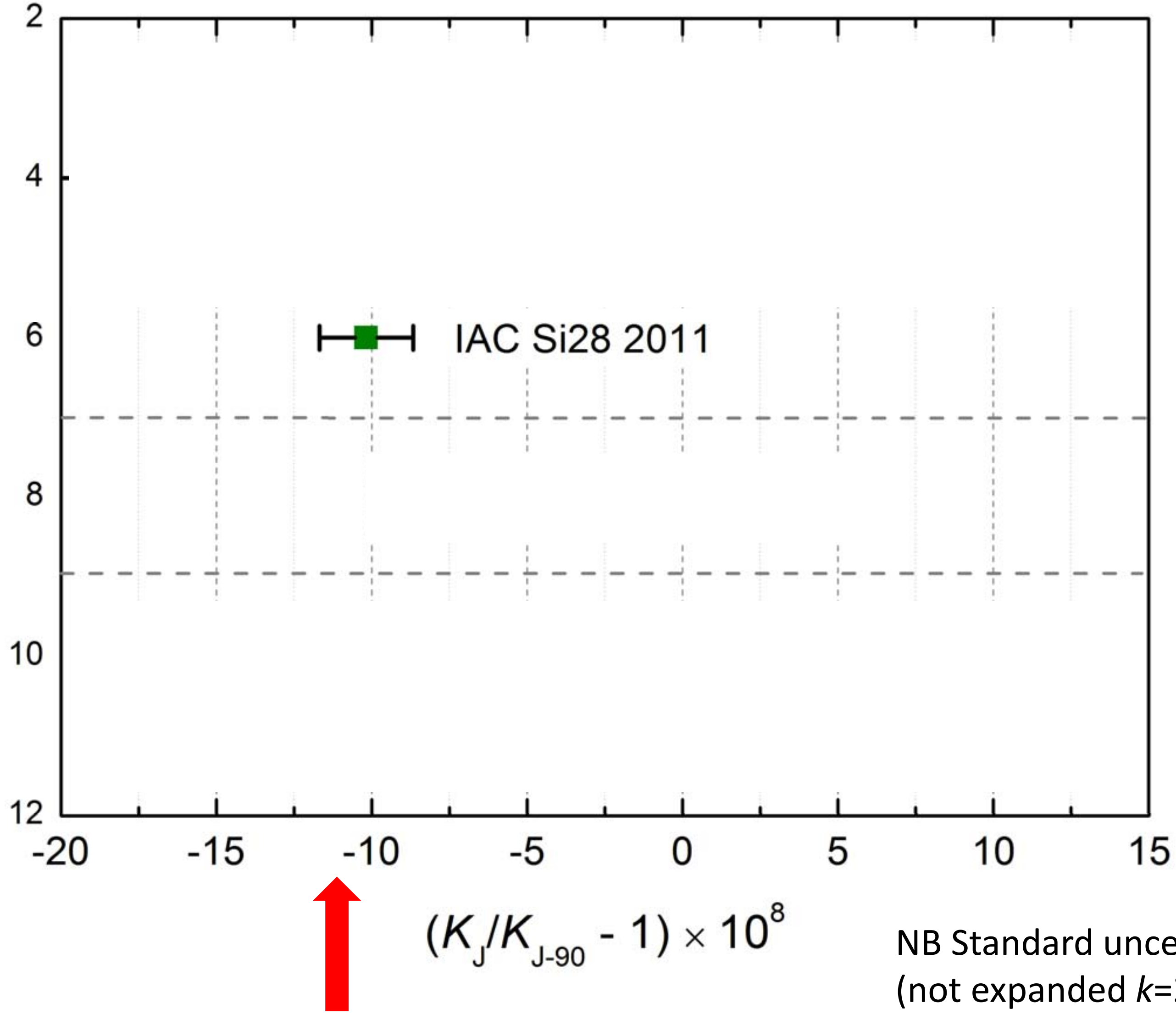
Credit: NIST

Watt balances: linking electrical power (derived from quantum standards) and mechanical power (derived from the kilogram)



Silicon spheres: linking microscopic and macroscopic mass – gives *h* via the Rydberg constant, R_∞

Results published this year



NB Standard uncertainties
(not expanded k=2)

CCM conditions for redefinition

CCM Recommendation G1 (2013, confirming resolution G1 of 2010)

That the following conditions be met before the CIPM asks CODATA to adjust the values of the fundamental physical constants from which a fixed numerical value of the Planck constant will be adopted:

1. at least three independent experiments, including work from watt balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties not larger than 5 parts in 10^8,
2. at least one of these results should have a relative standard uncertainty not larger than 2 parts in 10^8,
3. the BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the watt balance and XRCD (x-ray crystal density) experiments have been compared as directly as possible with the international prototype of the kilogram,
4. the procedures for the future realization and dissemination of the kilogram, as described in the *mise en pratique*, have been validated in accordance with the principles of the CIPM-MRA.'

Implementing the new SI

- When the 1990 values are replaced, small step changes are inevitable

- The relative change from $R_{K\text{-}90}$ to R_K will be of the order 2×10^{-8}
- The relative change from $K_{J\text{-}90}$ to K_J will be of the order 1×10^{-7}

- What will be the impact of these changes?

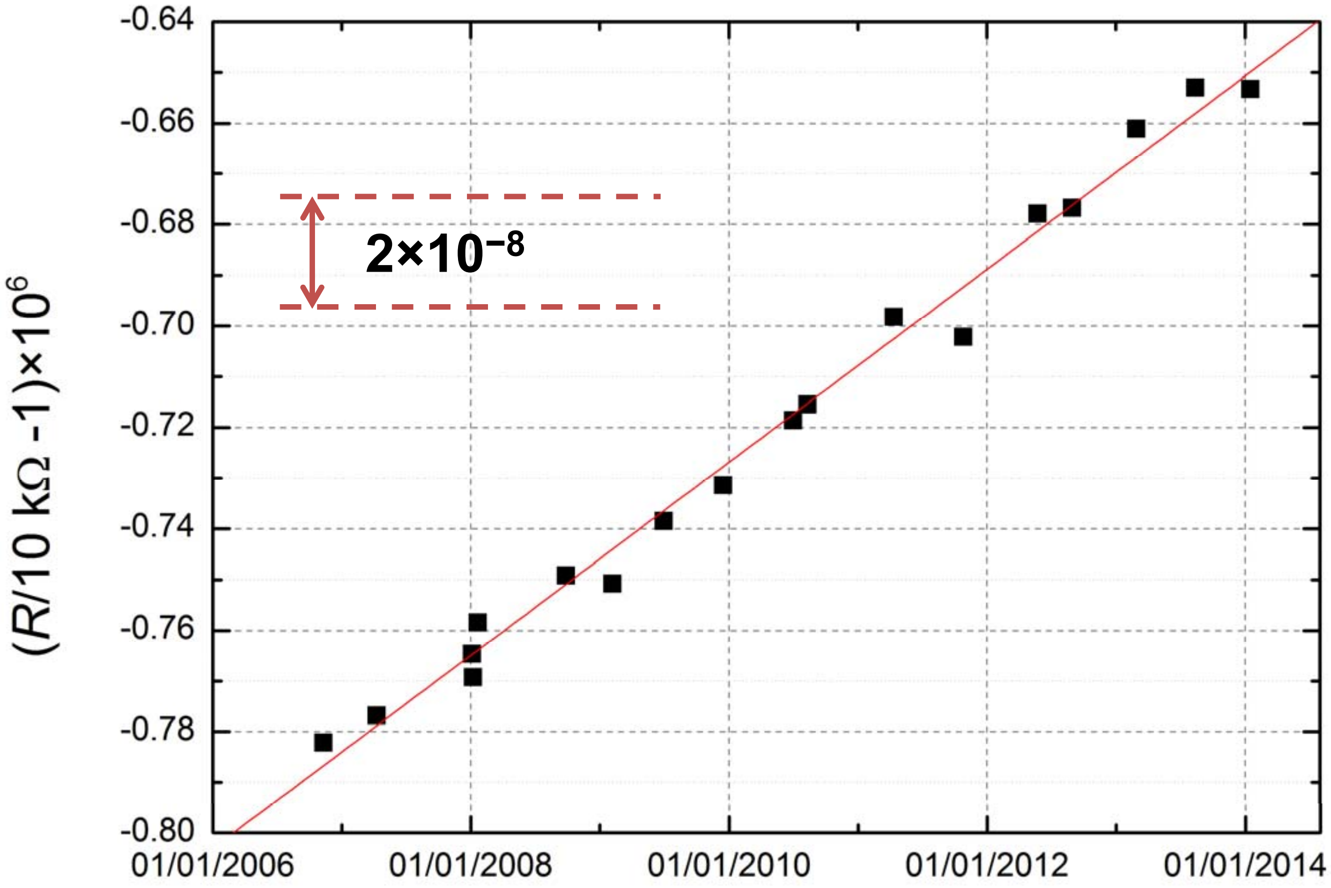
State of the art and routine
Part 1: Resistance

- **QHR-QHR consistency tests: <1×10^{-10}**
- **On site QHR comparisons: to ≈1×10^{-9}**
- **Travelling standards, routine calibrations, CMCs: >1×10^{-8}**

Commercial QHR systems exist, but not widely used outside national metrology institutes

(New graphene based references should become more widely available in the next few years)

Resistor drift example



Example of a 10 kΩ working standard maintained at the BIPM – measurements against the QHR over last 10 years

State of the art and routine
Part 2: Voltage

- **Direct consistency tests: 10^{-22} !**
- **On site Josephson comparisons: to < 1×10^{-10}**
- **On site comparisons via Zeners: ≈ 5×10^{-9}**
- **Comparisons via travelling Zeners, calibrations, CMCs: ≈ 2×10^{-8}**

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The North American Josephson Voltage Interlaboratory Comparison

Harold V. Parks, Yi-hua Tang, Paul Reese, Jeff Gust, and James J. Novak

***Abstract*—The ninth North American Josephson voltage standard (JVS) interlaboratory comparison (ILC) at 10 V was completed in 2011. An on-site comparison was conducted between the National Institute of Standards and Technology compact JVS and the pivot laboratory system. A set of four traveling Zener voltage standards was then shipped from the pivot laboratory to the other participants. We give the results from the 2011 ILC and review recent comparisons which have used the same traveling standards and similar procedures.**

***Index Terms*—Interlaboratory comparison (ILC), Josephson voltage standards (JVSs), measurement standards, uncertainty, voltage measurement.**

I. Introduction

THE 10-V Josephson voltage interlaboratory comparison (ILC), sponsored by the NCSL International (NCSLI), provides the participating laboratories a means of comparing dc voltage measurements to verify the reliability of their

TABLE I
PARTICIPANTS IN THE 2011 NCSLI JOSEPHSON VOLTAGE ILC

Agilent Technologies, Loveland, CO
Bionetics Corporation, Kennedy Space Center, FL
Boeing, Seattle, WA
Fluke Calibration, Everett, WA
Idaho National Laboratory, Idaho Falls, ID
Lockheed Martin Technical Operations, Stennis Space Center, MS
Los Alamos National Laboratory, Los Alamos, NM
NIST, Gaithersburg, MD (on site comparison with the pivot only)
Sandia National Laboratories, Albuquerque, NM (pivot)
U.S. Air Force Primary Standards Laboratory, Heath, OH
U.S. Army Primary Standards Laboratory, Redstone Arsenal, AL
U.S. Navy Mid Atlantic Regional Calibration Center, Norfolk, VA
U.S. Navy Primary Standards Laboratory, San Diego, CA

Zener voltage standards has been used in the six NCSLI ILCs performed since 1997 [2], [5]–[10], so a great deal of data is

Direct Josephson comparisons

- Measurements made on-site using a specially developed travelling Josephson standard
- On-going comparisons BIPM.EM-K10.a and K10.b
- Results at kcdb.bipm.org

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BIPM direct on-site Josephson voltage standard comparisons: 20 years of results

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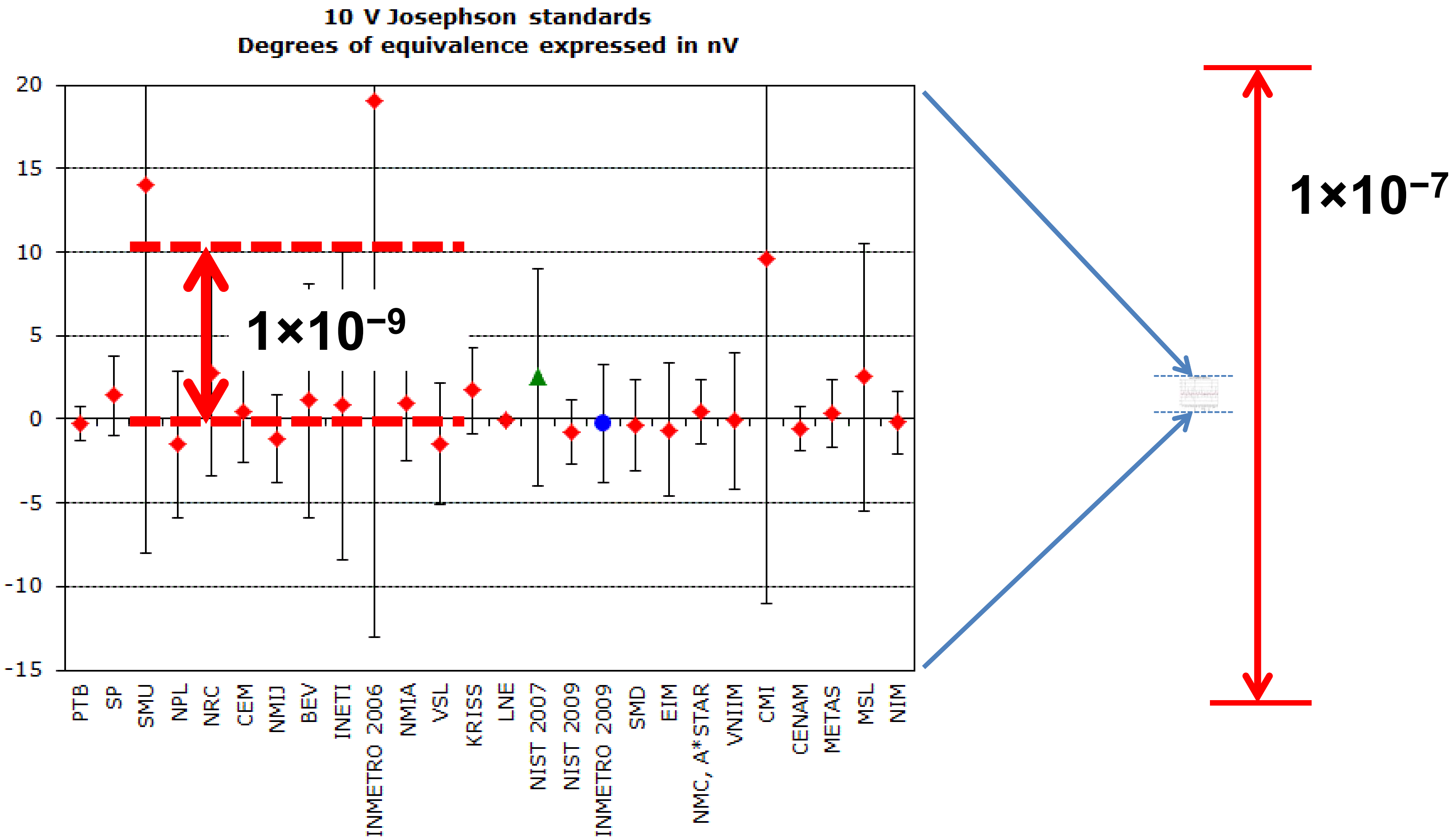
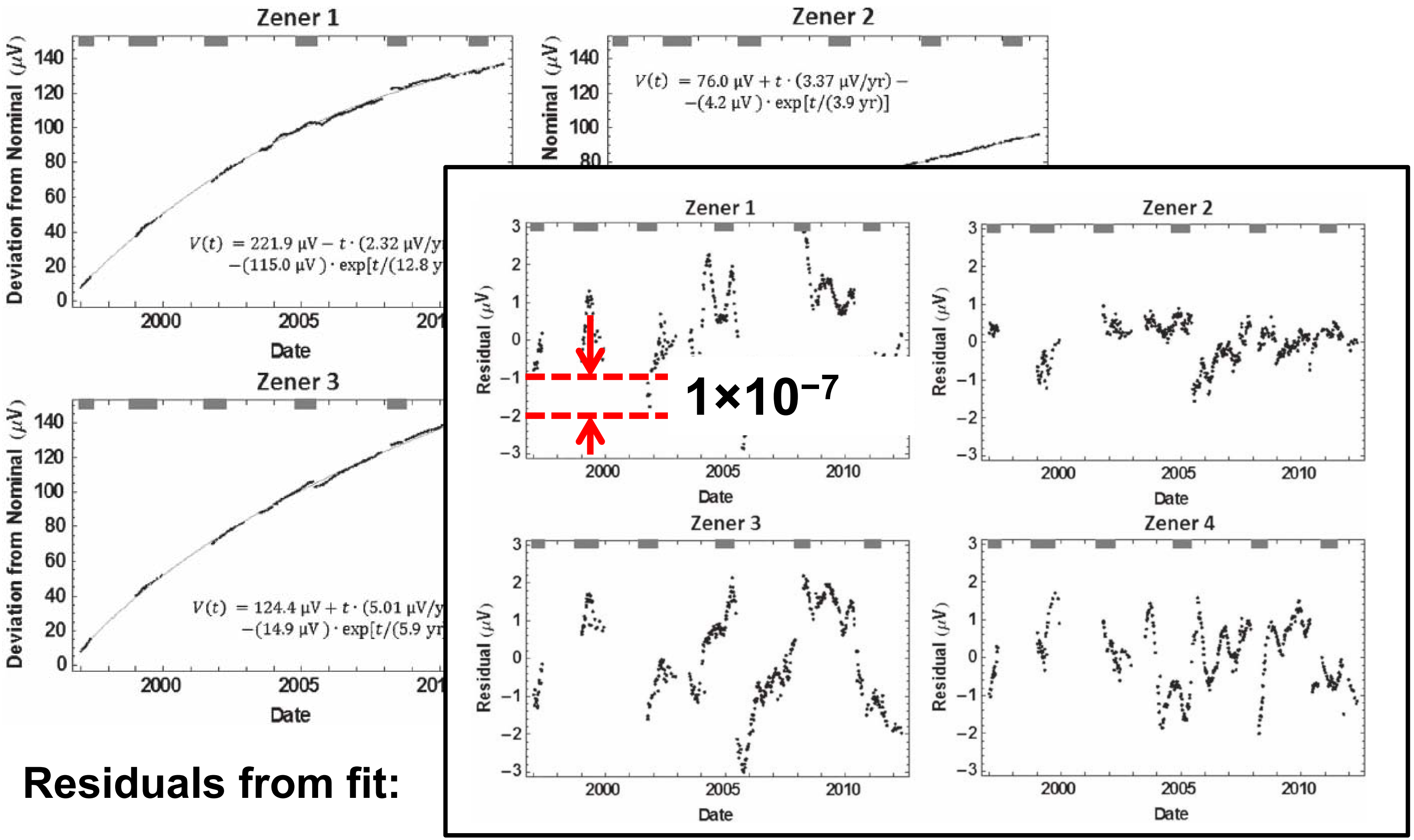
Direct Josephson comparisons



Zener drift example: long term



Residuals from fit:

Wider impact:
Other electrical quantities

- Primary standards in resistance and voltage are the starting point for a whole range of vital measurements
- Capacitance calibrations can be made at the 10^{-8} level – could be affected in the same minor way as resistance
- Power measurements are one of the other most demanding areas – but uncertainties are rarely below 1 ppm and should be unaffected
- **Conclusion: no need for widespread recalibrations or adjustments beyond a few primary standards**

Implementation:
Timing and practical Issues

- On target for 2018 following CCM roadmap
- Detailed timetable for implementation still to be finalised
  – should have new values available 1 year before implementation to allow coordinated update for software and quality systems
- NMIs will provide national guidance and communication

Summary

- When the 1990 values are replaced, small step changes are inevitable
- The relative change from $R_{K\text{-}90}$ to R_K will be of the order 2×10^{-8}
- The relative change from $K_{J\text{-}90}$ to K_J will be of the order 1×10^{-7}

- The changes should only be visible to labs operating primary quantum standards; calibrations of even the most stable standard resistors and Zener references should be largely unaffected

- The long term benefit will be the integration of the quantum electrical standards directly into the SI

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