Predicted impact of latest *h* and *e* values on resistance and voltage traceability in the new SI

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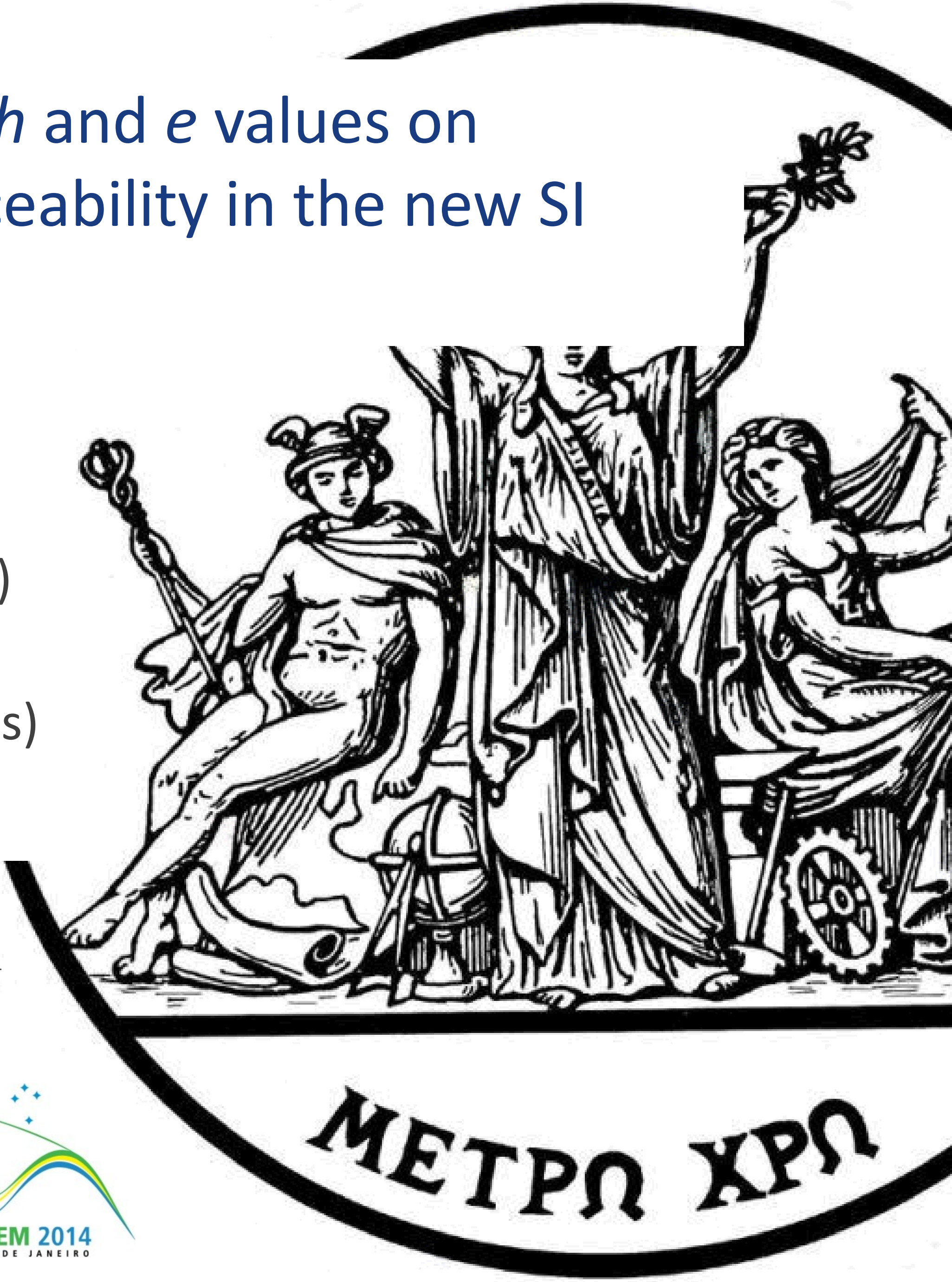


NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Australian Government
National Measurement Institute

Bureau International des Poids et Mesures

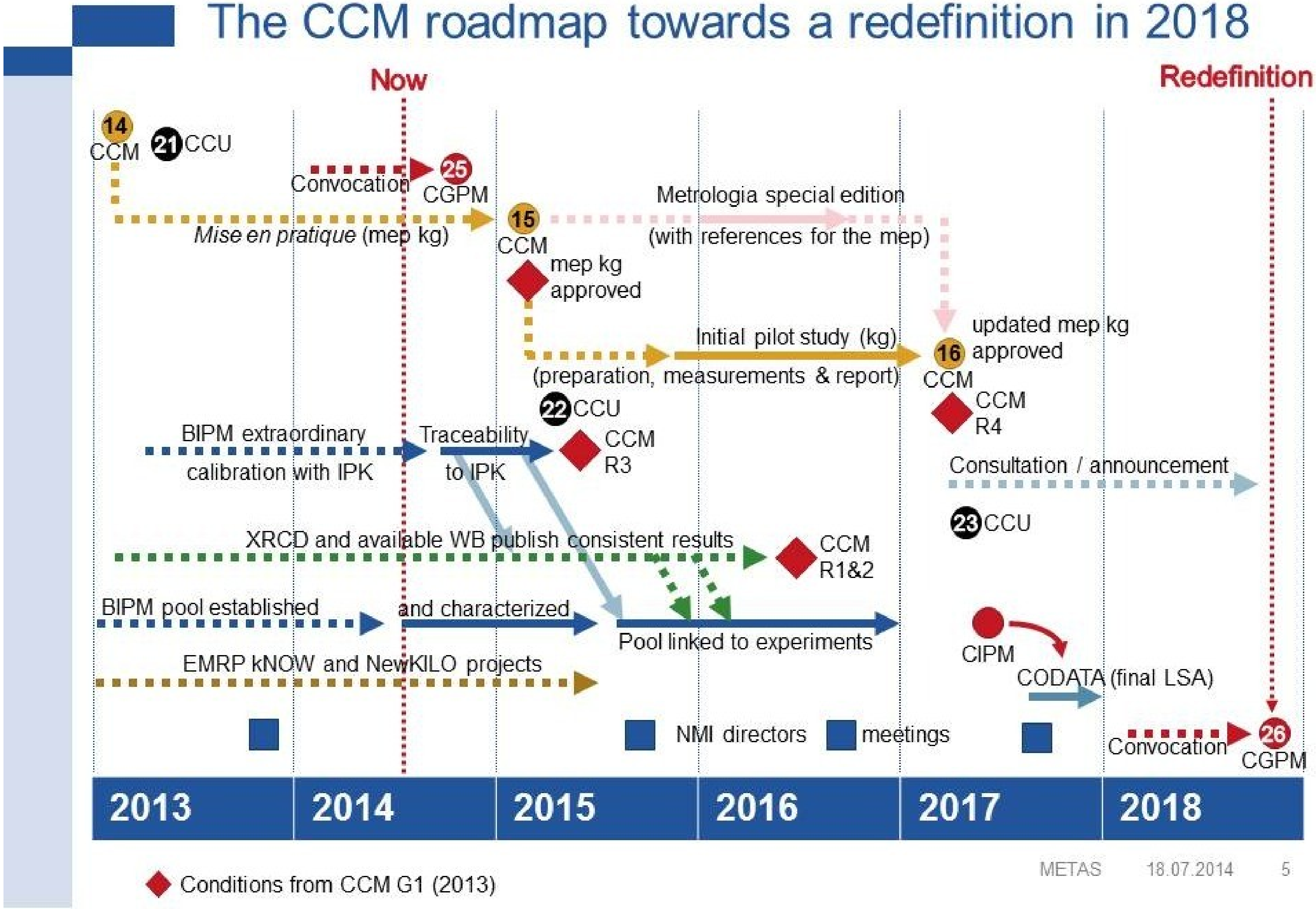
VSL

CPEM 2014
RIO DE JANEIRO

Outline

- CCEM role in redefinition
- Review of 1990 values
- The new value for R_K
- The new value for K_J
- Impact on resistance and voltage traceability

The project for a revised SI



The CCM roadmap towards a redefinition in 2018

Now

Redefinition

14 CCM

21 CCU

Convocation

25 CGPM

Mise en pratique (mep kg)

15 CCM

Metrologia special edition

(with references for the mep)

mep kg approved

Initial pilot study (kg)

(preparation, measurements & report)

16 CCM

updated mep kg approved

22 CCU

CCM R4

BIPM extraordinary calibration with IPK

Traceability to IPK

CCM R3

Consultation / announcement

23 CCU

XRCD and available WB publish consistent results

CCM R1&2

BIPM pool established

and characterized

Pool linked to experiments

CIPM

CODATA (final LSA)

EMRP kNOW and NewKILO projects

NMI directors meetings

Convocation

26 CGPM

2013	2014	2015	2016	2017	2018

METAS 18.07.2014 5

◆ Conditions from CCM G1 (2013)

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
  –> paper at NCSLi July 2014, to be published in September issue of ‘Measure’
  –> this presentation CPEM 2014

Reminder of the 1990 practical solution

1990

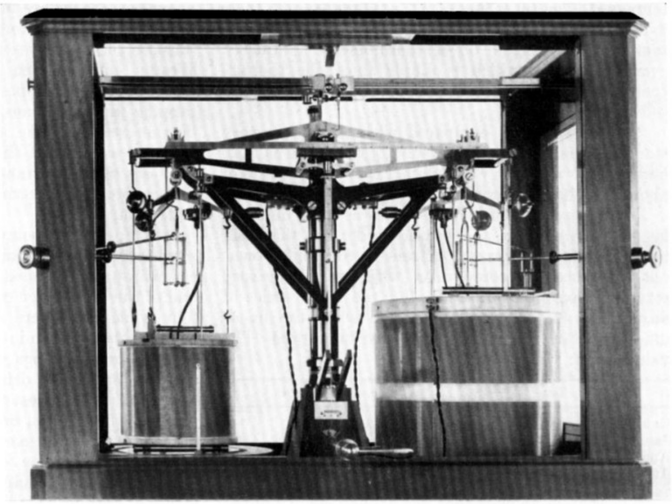


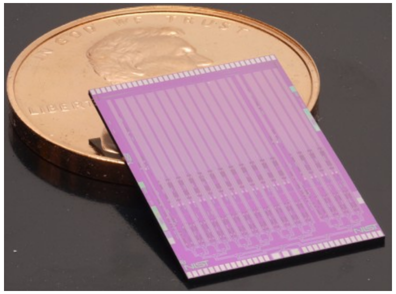
Fig. 1. Current balance of the National Physical Laboratory. One large coil has been lowered so that the suspended coil can be seen

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.

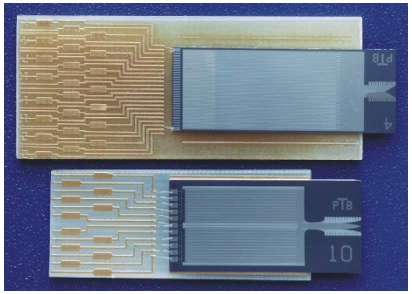
≈ 10^{-6}

Classical

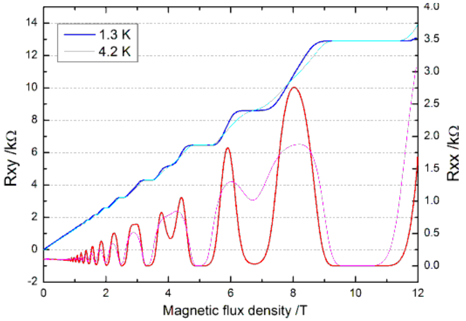
Credit: NIST

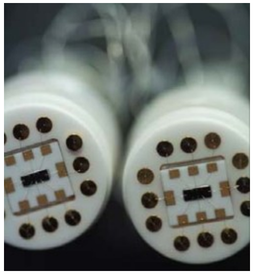


Credit: PTB



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





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

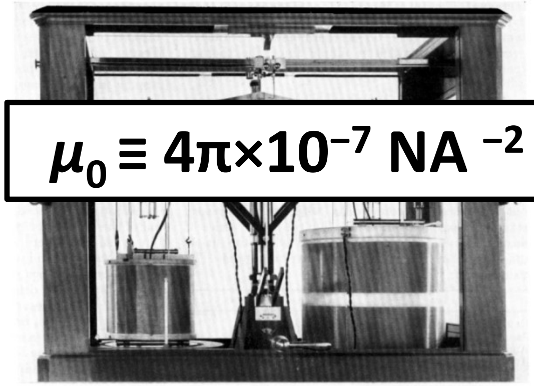
≈ 10^{-9}

Quantum

Macroscopic quantum effects: stable, reproducible, universally available

An end to the 1990 compromise

Definition:



$$\mu_0 \equiv 4\pi \times 10^{-7}\ \mathrm{NA}^{-2}$$

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

Incompatible

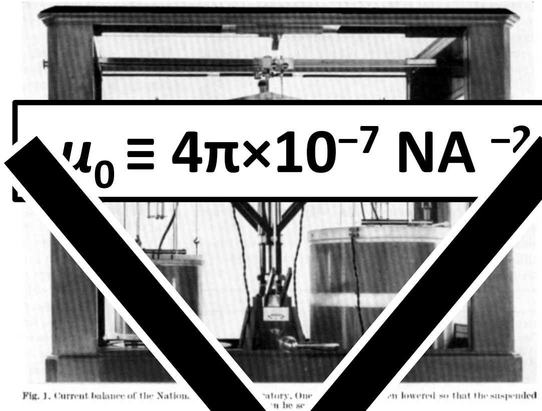
Practical units:

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

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

An end to the 1990 compromise

~~**Definition:**~~



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

~~**Incompatible**~~

~~**Practical units:**~~

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

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

Definition:

$h \equiv 6.626\ 069\ XX\ \mathrm{Js}$

$e \equiv 1.602\ 176\ XX\ \mathrm{C}$

Direct link

Practical units:

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

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

$\mu_0 = 4\pi\times(1+\delta)\times10^{-7}\ \mathrm{NA}^{-2}$

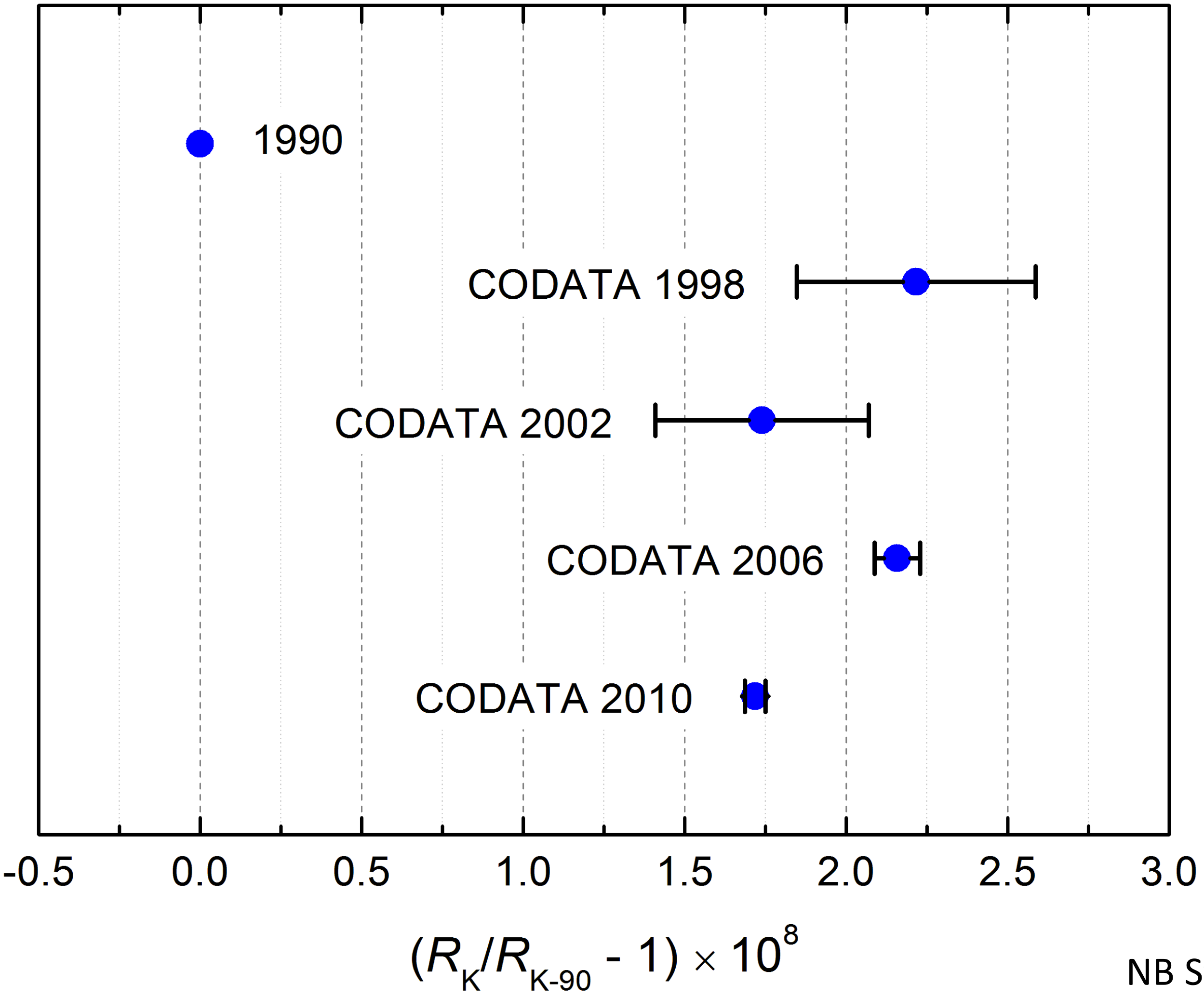
Origins and use of the 1990 values

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).

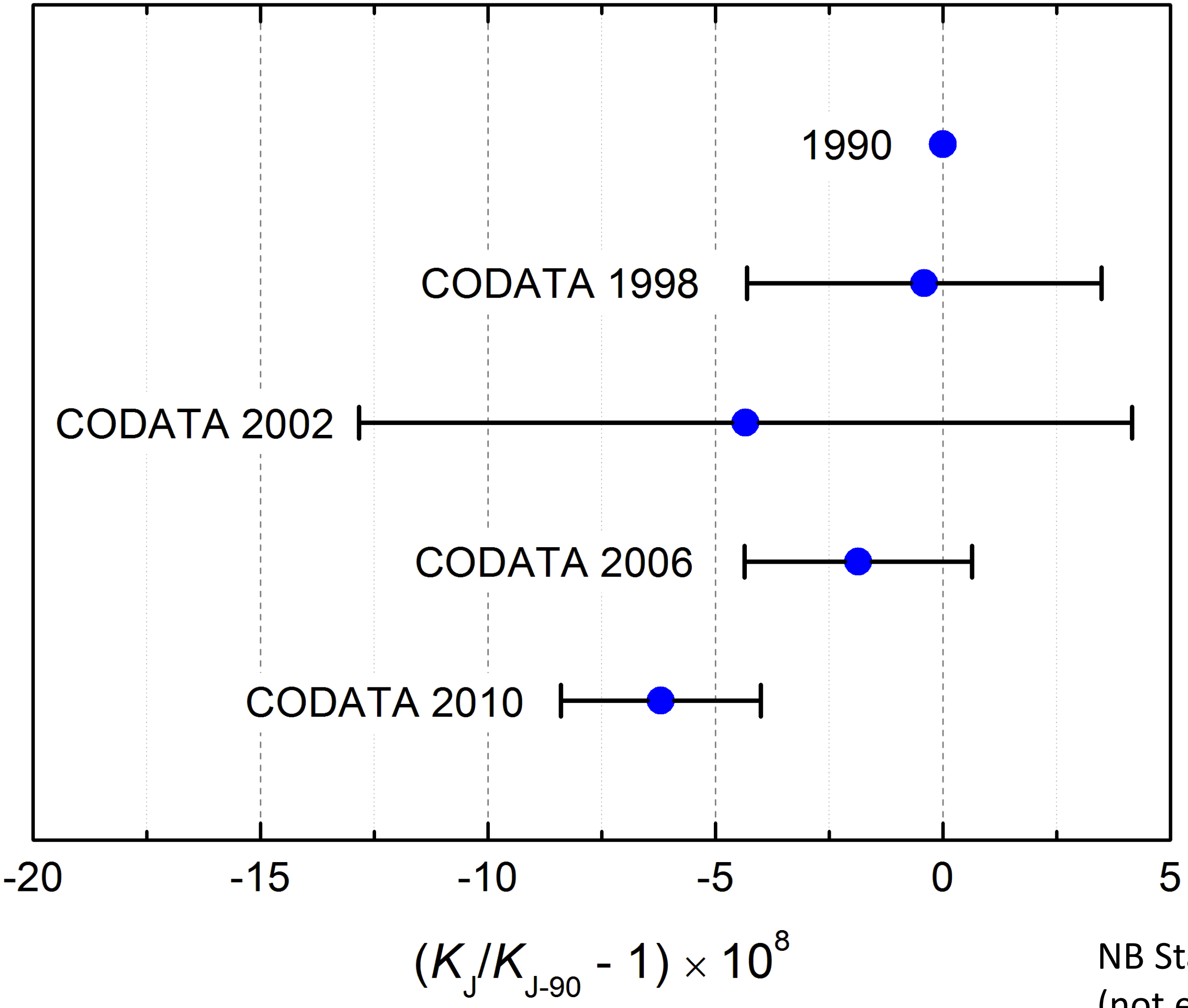
Evolution of values of R_K



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

NB Standard uncertainties (not expanded *k*=2)

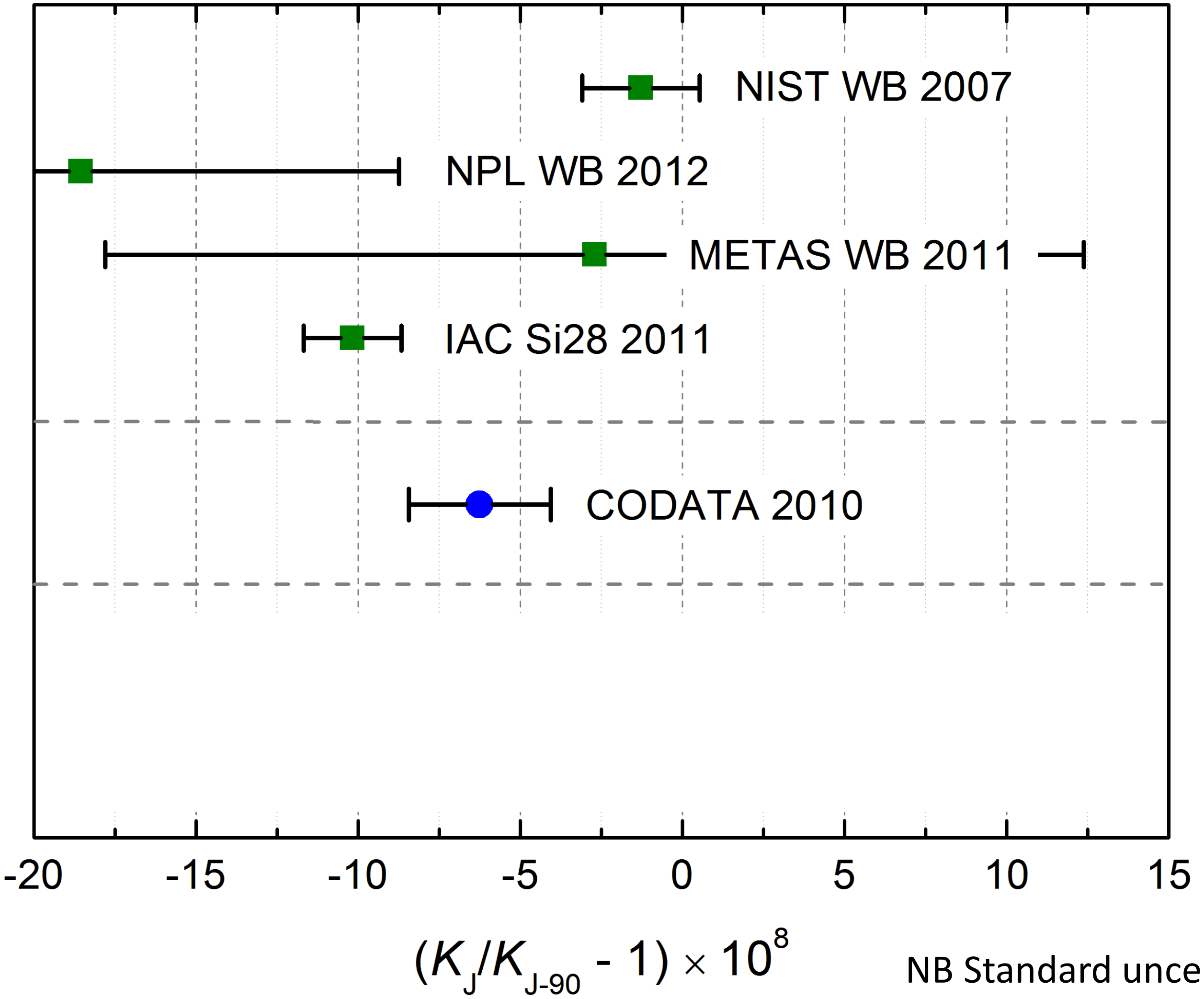
Evolution of values of K_J



$$K_J = \frac{2}{\sqrt{h \cdot R_K}}$$

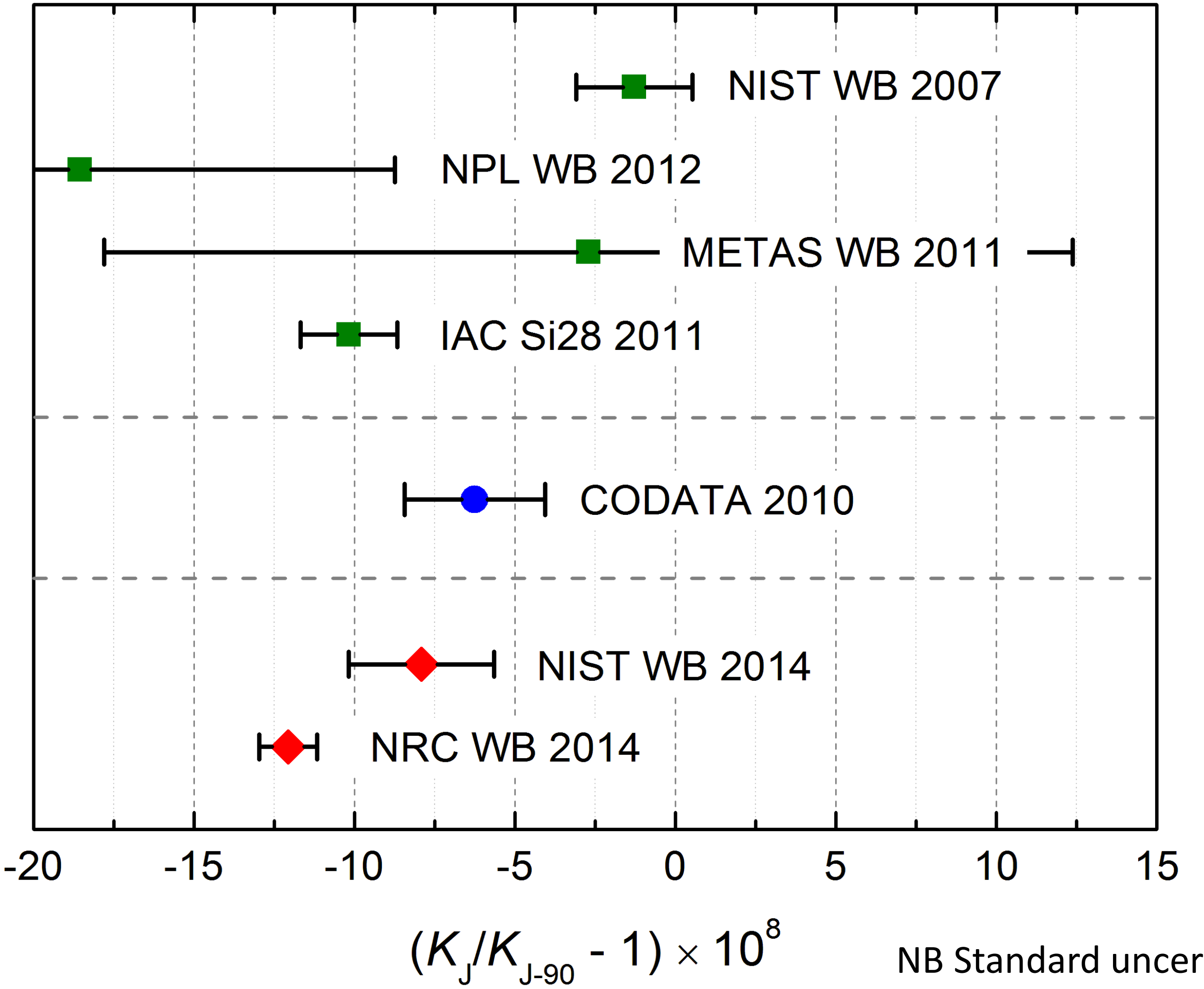
NB Standard uncertainties
(not expanded *k*=2)

Results published this year



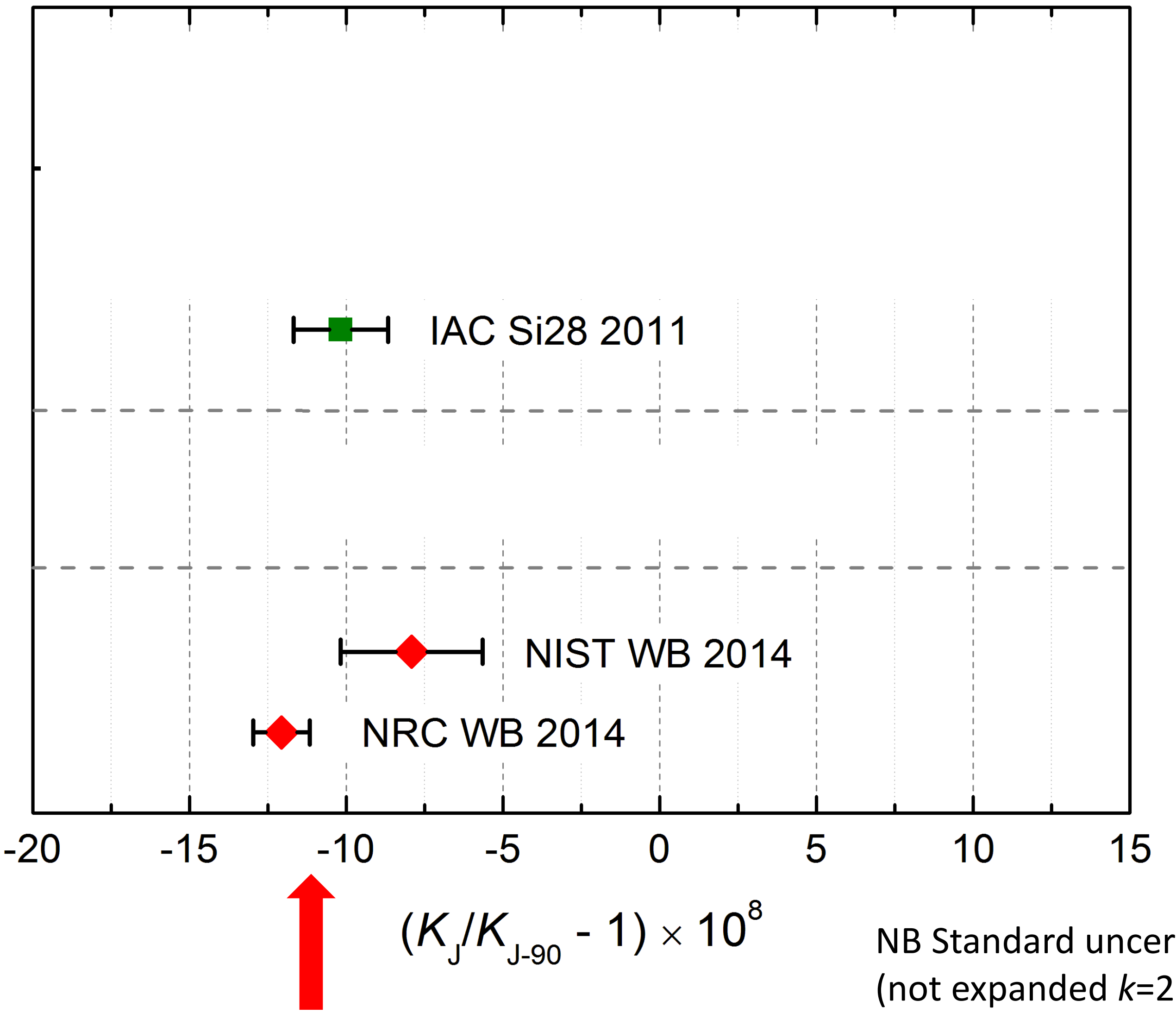
NB Standard uncertainties
(not expanded k=2)

Results published this year



NB Standard uncertainties
(not expanded *k*=2)

Results published this year



NB Standard uncertainties
(not expanded *k*=2)

Implementing the new SI

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

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

- What will be the impact of these changes?

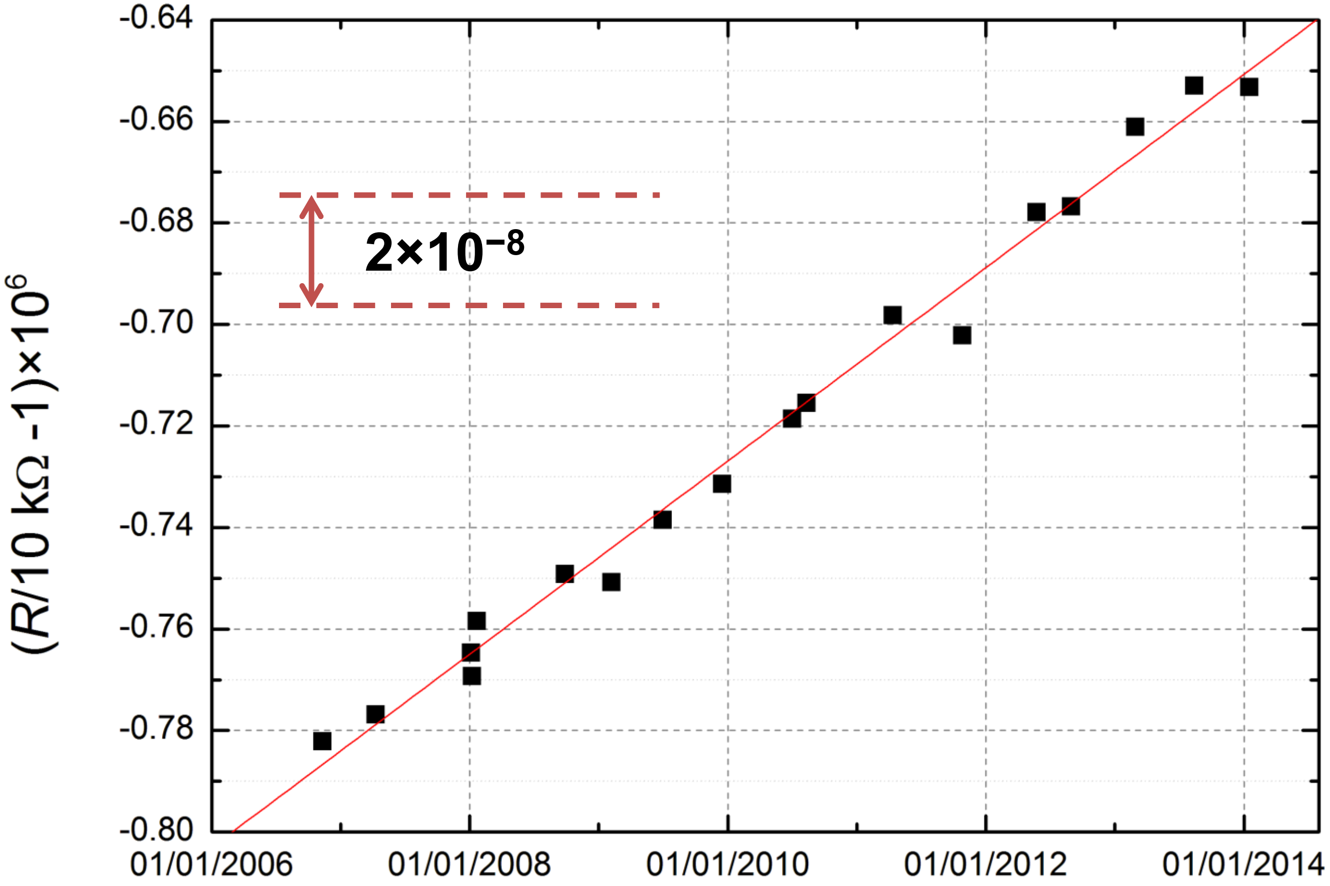
State of the art and routine
Part 1: Resistance

- **QHR-QHR consistency tests: $<1\times10^{-10}$**
- **On site QHR comparisons: to $\approx1\times10^{-9}$**
- **Travelling standards, routine calibrations, CMCs: $>1\times10^{-8}$**

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)

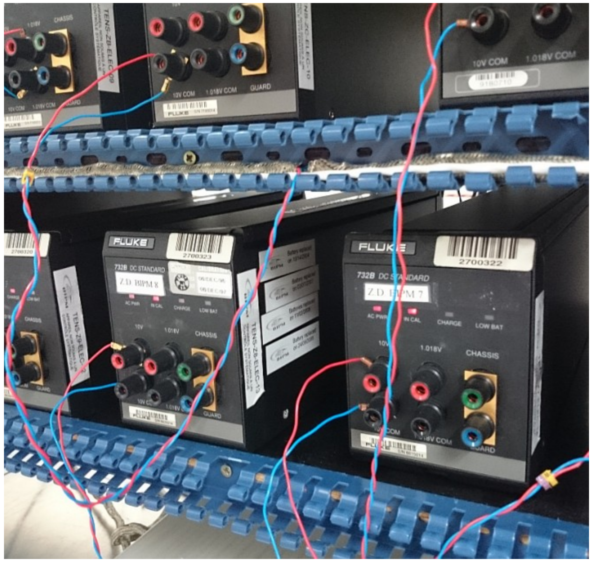
Resistor drift example

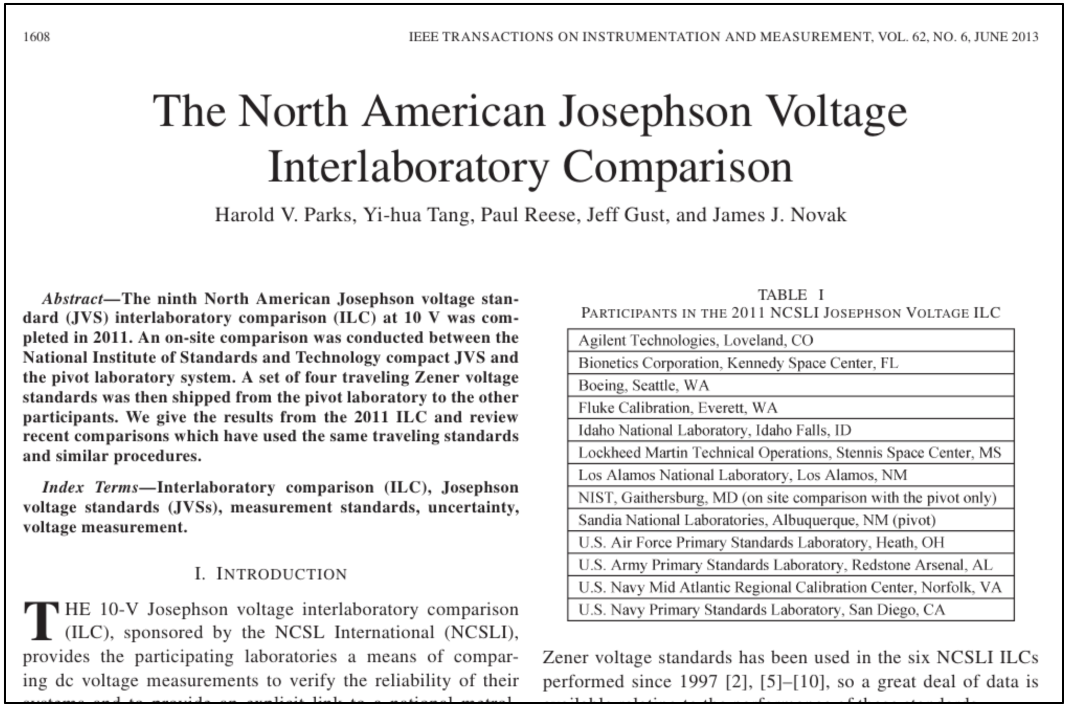


Example of a 10 kΩ working standard maintained at the BIPM – measurements against the QHR over last 10 years

State of the art and routine
Part 2: Voltage

- **Direct consistency tests: 10^{-22} !**
- **On site Josephson comparisons: to $< 1\times10^{-10}$**
- **On site comparisons via Zeners: $\approx 5\times10^{-9}$**
- **Comparisons via travelling Zeners, calibrations, CMCs: $\approx 2\times10^{-8}$**




1608 IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 62, NO. 6, JUNE 2013

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

IOP Publishing — Measurement Science and Technology

Meas. Sci. Technol. 23 (2012) 124001 (10pp) — doi:10.1088/0957-0233/23/12/124001

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

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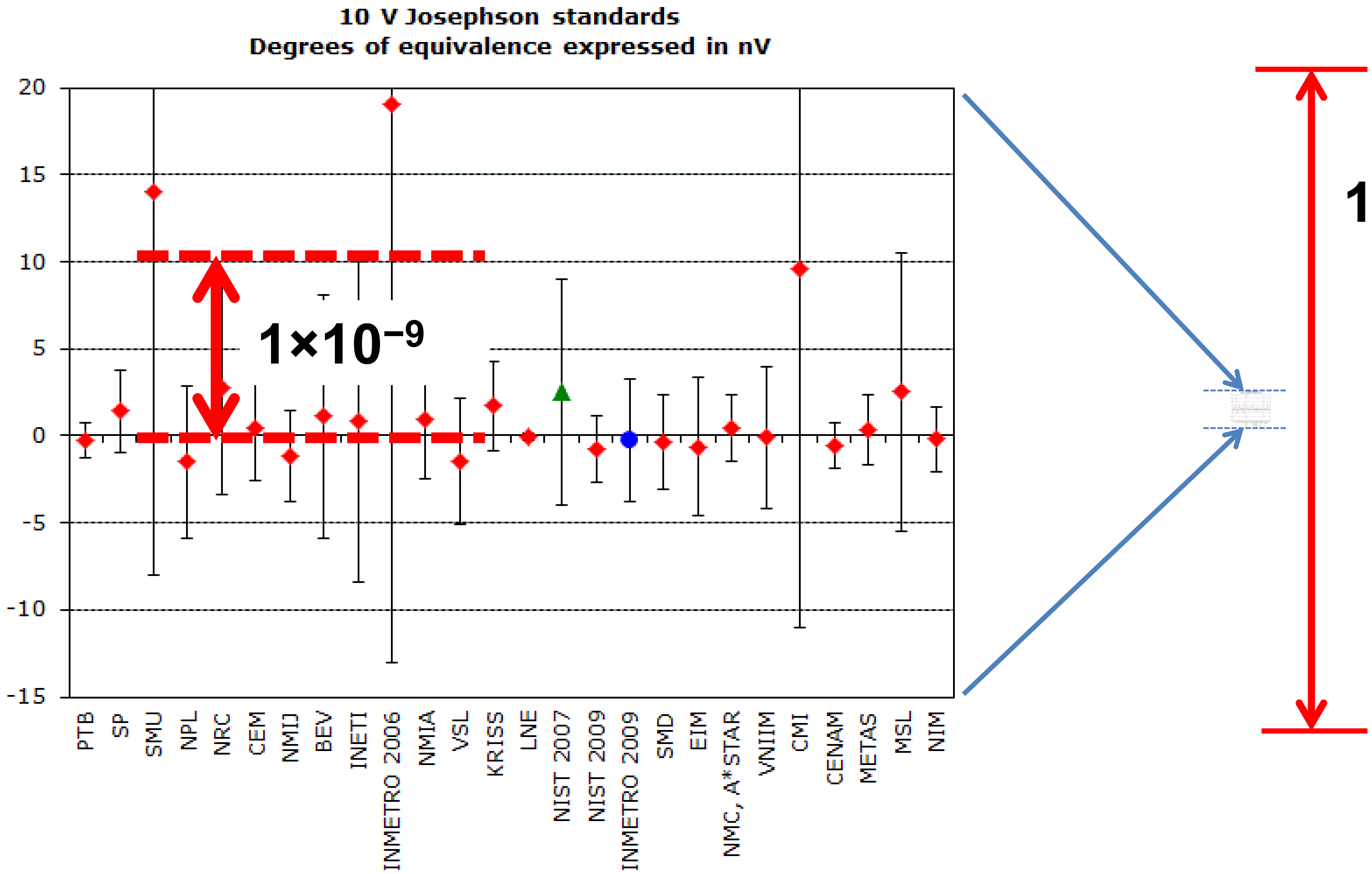
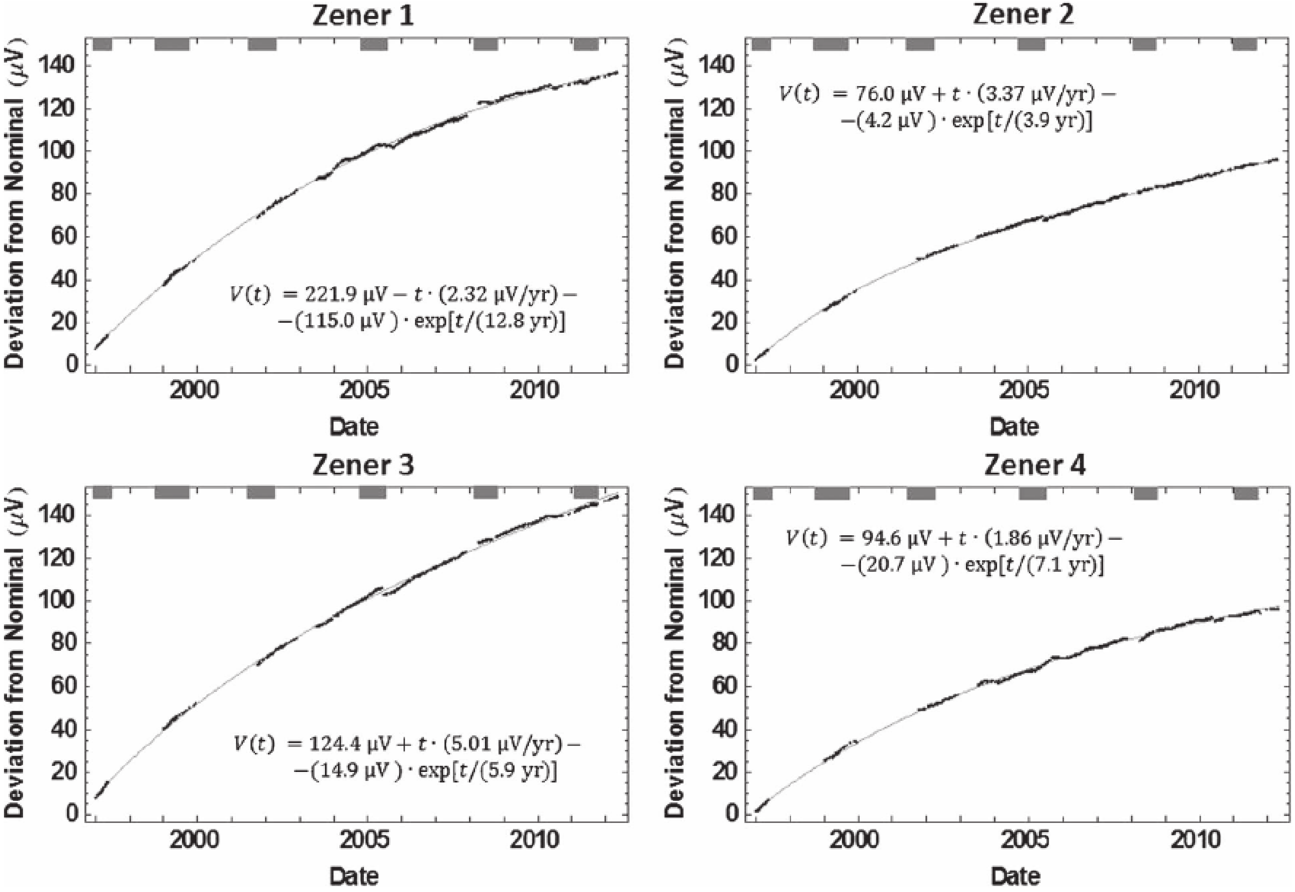
Direct Josephson comparisons



10 V Josephson standards
Degrees of equivalence expressed in nV

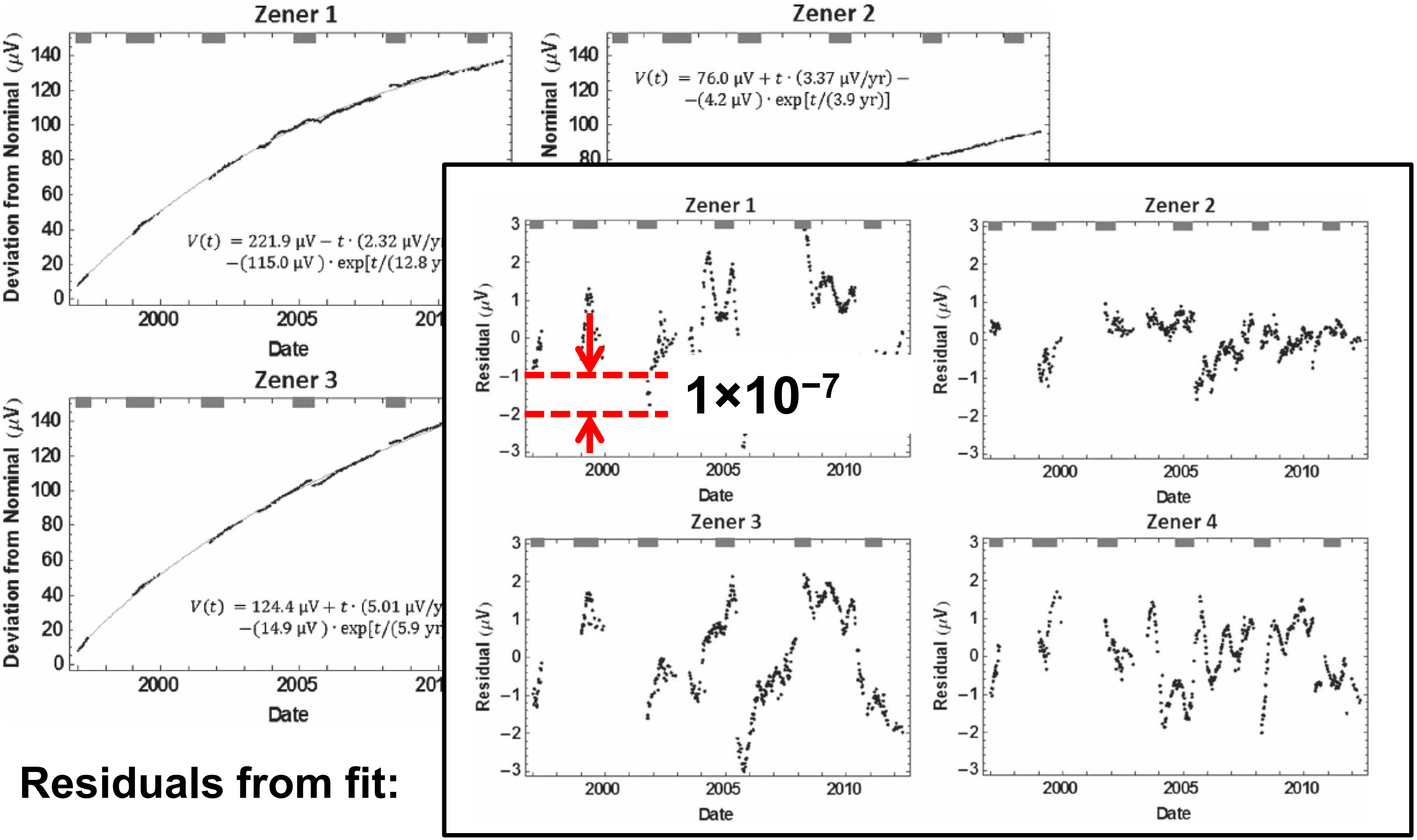
Zener drift example: long term



Set of 4 Zeners used in North American comparison series

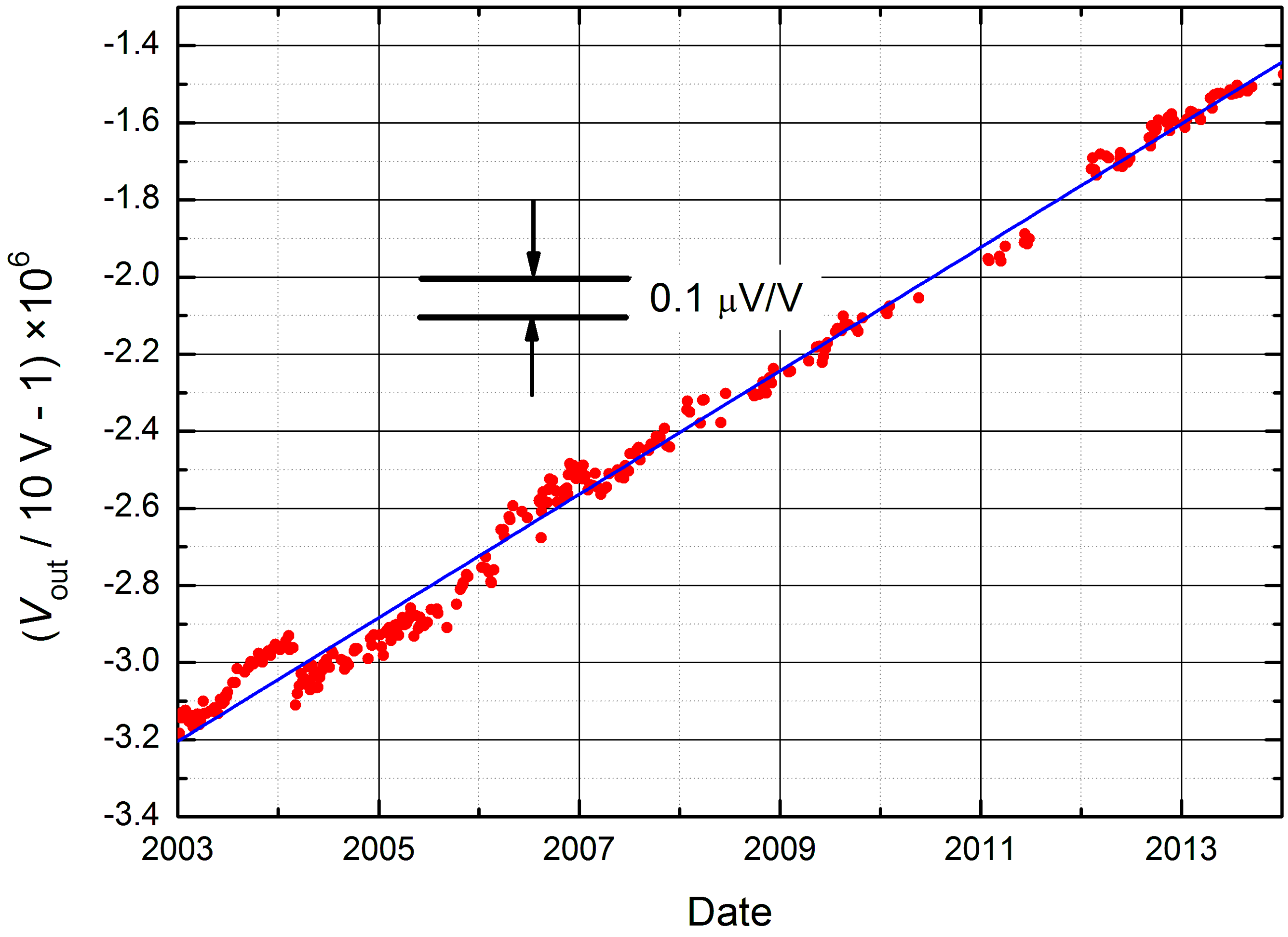
From Parks *et al*, IEEE *Trans. Instrum. Meas.*, June 2013

Zener drift example: long term



Residuals from fit:

Zener drift example 2



Stable Zener left undisturbed in BIPM lab (raw drift, not residuals)

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

Thank you!

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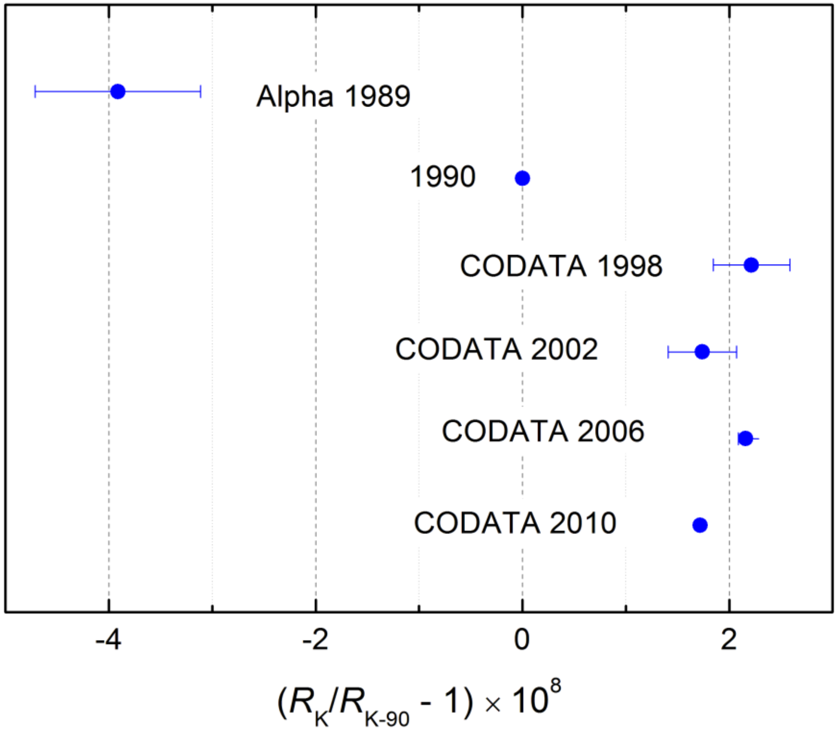
Some history of α determinations



Best published value available to those fixing the 1990 values turned out to be in error.
(QED calculation, combined with measurement of a_e)
Kinoshita, *IEEE Trans. Inst. Meas.*, **38**, no.2, pp 172-174, **1989**

The chosen 1990 value was based on a mean of this one QED value for α and the set of direct electrical determinations of R_K - in retrospect a wise choice!

- α determinations now have more diversity, and the value is robust to $<1\times10^{-8}$
- However, the CODATA value still shifted by 6.5 u from 2006 to 2010 (due to an error in the theory)
- Any error in the value of α at the time of redefinition will be taken up in the numerical value of μ_0

$$\mu_0 = 4\pi \times (1 + \delta) \times 10^{-7}\ \text{NA}^{-2} \quad \text{where} \quad \delta = (\alpha - \alpha_{2018}) / \alpha$$

Extracting K_J from the LSA

The CODATA values come from a complex least squares adjustment of all the available data, but to understand what is going on we can often take a simplified view.

There are no competitive direct measurements of K_J, or of h or e on their own.

Given the relative uncertainty on α ($<1\times10^{-9}$) in recent adjustments we can safely take K_J values from h via:

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

(Note the square root dependence)

Watt balance measurements give h almost directly via $K_J{}^2 R_K = 4/h$
Avogadro experiments give h indirectly via the the Rydberg constant $R_\infty = \alpha^2 m_e c/2h$
- another convenient approximation to the full LSA