The Journey from 12 906.403 5 Ω
Through 19 Orders of Magnitude

Presented at:
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Nashville, Tennessee

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National Research Council Canada
Resistance Metrology Before 1990

![Graph showing changes in resistance measurements from 1962 to 1986](Image)

*From Klaus von Klitzing*

12 May 2008

Dave Inglis, NRC Canada
Representation of the SI Ohm

GaAs/AlGaAs sample on an H4 header
Some Different Quantum Hall Devices
Hall devices from different wafers

Rk-90 = 25 812.807 $\Omega$

V0052
(1x$10^{18}$ cm$^{-3}$)

V0054
(1.65x$10^{18}$ cm$^{-3}$)

Magnetic induction (T)

Resistance ($\Omega$)

0 2 4 6 8 10 12 14

0 5000 10000 15000 20000 25000 30000
**Figure 4:** Results for the step ratio measurements $R_H(i \neq 2) : R_H(i = 2)$.
Resistance and the SI

Since 1990 Resistance has been represented in the SI by the quantum Hall effect (QHE).

\[ R_h = \frac{R_{k-90}}{i}, \]
where \( i \) is an integer coinciding with a plateau.

\[ R_{k-90} = 25 \, 812.807 \, \Omega \]

- Conventional value of Von Klitzing Constant

\[ R_k = \frac{h}{e^2} \]

Redefinition of SI important to resistance metrology!
The Cryogenic Current Comparator
From the QHR to an Artifact

QHR

CCC

Resistance Standard
- Bridge balanced when VR1 = VR2
- CCC is self checking, can be used without resistors.
- Super conducting coils exhibit no leakage

Basic design of all bridges is similar.

\[ N_1 I_1 - N_2 I_2 = 0 \]
CCC, pick-up coil and SQUID assembly.
BIPM.EM-K13.a and SIM.EM-K1  Resistance: 1 Ω

Degrees of equivalence $[D_i$ and its expanded uncertainty ($k = 2$), $U_i]$
NRC Uncertainties

The CIPM MRA has now been signed by the representatives of 92 institutes – from 52 Member States, 36 Associates of the CGPM, and 4 international organizations – and covers a further 147 institutes designated by the signatory bodies.

CMC Calibration and Measurement Capabilities

Peer review (NRC every 5 years) where a measurement expert examines:
- Measurement theory and measurement system operation
- Quality system
- Competency and training
- Thorough examination of uncertainties
- Report Regional Metrology Organizations (SIM, EURAMET, APMP etc.) various NMI’s and lastly CIPM participation in international key comparisons
NRC Uncertainties

As a National Metrology Institute involved in measurement science at the highest level it is MSS policy to always and only report the experimentally determined uncertainty on the calibration certificate issued for any measurements.

The values given for the measurement uncertainties shown in the Calibration and Measurement Capabilities – CMCs (Appendix C) listing on the BIPM website are indicative of the results we would expect to achieve when calibrating a typical good quality client artifact under normal circumstances. It is possible that the uncertainty observed and reported may vary from the CMC value, in either sense.
From QHE to transfer standards
This sample slide shows how you can use imagery. If you are looking for interesting images specific to your presentation, contact: Harry Turner 613-993-4507
Correct for temperature coefficient mathematically

\[ R_t = R_{\text{ref}} \left[ 1 + \alpha(t-t_{\text{ref}}) + \beta(t-t_{\text{ref}})^2 \right] \]
Power Coefficient

This is the value at 0 mA

<table>
<thead>
<tr>
<th>fitted for</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>05-May-12</td>
<td>-11.174</td>
</tr>
<tr>
<td>a0</td>
<td>-13.552</td>
</tr>
<tr>
<td>a1</td>
<td>5.80E-05</td>
</tr>
</tbody>
</table>

The value is mathematically corrected based on the current at which it is being used:  \[ R_{5mA} = R_{0mA} - (0.000598 \times 5mA^2) \]
$1 \Omega$ Pressure Coefficients

- Maganin Resistor
- EvenOhm
- Linear (Maganin Resistor)
- Linear (EvenOhm)

Pressure (kPa) vs. Dev. from std. Pressure ($u\Omega/\Omega$)

Locations:
- NIST
- NRC
- El Paso TX
- Mexico City
0.1 \( \Omega \) to 10 \( k\Omega \)
NRC Working Standards
In-house Inter-Comparisons

NRC 1 Ohm DCC Bridge vs CCC fitted Value

- 64152
- Fit Value
- Linear (Fit Value)
Bridge Calibration

DCC Bridge calibrated using CCC & transfer standards

Power Coefficients  NRC 10 Ω Resistor

- Deviation vs Current
- Linear (Deviation vs Current)

vs. 1 Ω

vs. 100 Ω
The Importance of Bridge Calibration
$0.1 \ \Omega \ \text{to} \ \ 0.00001 \ \Omega$
DCC Bridge and 2 1000:1 Range Extenders

- 5 A source
- 100 A source
- 400 A source
- 10:1, 100:1, 1000:1 Range Extender
- 1000:1 Range Extender
- DCC Bridge
- Scanner
- Standard Resistors in Oil Bath
- Rx
Calibration of Range Extenders

Calibrated Value vs 3 Separate 1 Ω Standards

- Deviation (μΩ/Ω)

-43.16
-43.18
-43.20
-43.22
-43.24
-43.26
-43.28

- Rx
- Cal Value
- 6011 spec ± 0.05 (k=1)
- Avg value
Calibration of Range Extenders

0.1 Ω @ 150 mA    All 3 Ranges

Deviation (μΩ/Ω)

-43.30
-43.40
-43.50
-43.60
-43.70
-43.80
-43.90
-44.00
-44.10
-44.20

△ vs 1 ohms  ∆ vs 10 ohm  × vs 100
Calibration of Range Extenders

0.1 Ω Shunt Resistor @ 1A
All 3 Ranges

Deviation (μΩ/Ω)

-125.5  -125.6  -125.7  -125.8  -125.9  -126.0  -126.1  -126.2  -126.3  -126.4  -126.5

2.09  2.24  2.38  2.62  3.07  3.21  3.36  3.50

vs 1 ohms  vs 10 ohm  vs 100
Calibration of Second Range Extenders (1000:1 Fixed)

0.001 ohm shunt measured in Oil at 100 A

- Multi Range Ext Opening Values
- 1000:1 Fixed Extender
- Closing Values
New Oil Bath for Shunts
Mid Range 100 kΩ to 1 GΩ
NRC High Resistance Scale

Dual Source Bridge

Wheatstone Bridge

TeraOhmMeter
This sample slide shows how you can use imagery. If you are looking for interesting images specific to your presentation, contact: Harry Turner 613-993-4507
Use of Check Standards

10 M Calibration

Fitted Value vs Measured Value \((k=2)\)

- 53836 fitted value @ 10V
- 53836 measured @ 1V
Improvement over time

Historical Data for Client 1 MΩ Oil Resistor

Deviation ($\mu \Omega/\Omega$)

Date

- 24-Jul-98
- 19-Apr-01
- 14-Jan-04
- 10-Oct-06
- 6-Jul-09
- 1-Apr-12
- 27-Dec-14
1 G to 100 T
Dual Source Bridge

\[ \frac{R_1}{R_2} = \frac{V_1}{V_2} \]

\[ \frac{V_1}{R_1} - \frac{V_2}{R_2} = I \]

\[ \frac{R_1}{R_2} = \frac{V_1}{V_2} \left( 1 - \frac{R_1 \cdot I}{V_1} \right) \]
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Dual Source Bridge Noise

Current (fA)

Time (s)
Small changes in current have a large influence

<table>
<thead>
<tr>
<th>I</th>
<th>V</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000 000 000 010 000</td>
<td>1000</td>
<td>100 000 000 000 000 000</td>
</tr>
<tr>
<td>0.000 000 000 009 999</td>
<td>1000</td>
<td>100 010 001 000 100</td>
</tr>
</tbody>
</table>

1 fA results in a change in value of slightly more than 100 ppm
High Resistance Uncertainties

<table>
<thead>
<tr>
<th>Resistance</th>
<th>CMC Uc (µΩ/Ω)</th>
<th>ILC</th>
<th>Uc (µΩ/Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 G</td>
<td>40</td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td>10 G</td>
<td>250</td>
<td></td>
<td>4.2</td>
</tr>
<tr>
<td>100 G</td>
<td>300</td>
<td></td>
<td>13</td>
</tr>
</tbody>
</table>
The Journey is over

Thanks to:  
Dave Inglis  
Carlos Sanchez  
Francois Lemay

Questions yes,  

But first a couple of important announcements!
Resistance Metrology Tutorial
NCSLI 2014

A course targeted for the folks in the lab

Kai Wendler
NRC

&

Marlin Kraft
NIST
HOT OFF THE PRESSES
NCSLI 2014
How to Run a Successful Inter-Laboratory Comparison

Kai Wendler
NRC

&

Georgette Macdonald
NRC

Canada
Adieu Dave Inglis

Dave will be retiring from NRC at the end of July 2013.
Questions?
INTERNATIONAL RESISTANCE COMPARISON
Differences between laboratory and BIPM values, in ppm.

- First international comparison of resistance standards between labs using QHE: 1 Ω & 10 kΩ
- Later attempts employed 100 Ω – with varying success
  - K12: Direct QHR:QHR is very good – but expensive, and time-consuming. BIPM vs. LCIE, METAS, PTB, NPL, NIST: 1 nV ± 3 nV.
  - K10: travelling 100 Ω, PTB
\[ \text{Rh} = \frac{\text{Rk}}{i}, \quad \text{where } i \text{ is an integer coinciding with a plateau.} \]

- Conventional value of Von Klitzing Constant \( \text{R}_{k-90} = 25,812.807 \, \Omega \)
- Plateau #2 used at NRC - well defined - resistance of \( 12 \, 906.403 \, 5 \, \Omega \)
- Independent of exact value of magnetic field or temperature and repeatable to parts in \( 10 \times 10^{-10} \).
Temperature Coefficient

Thermal deviation of NML64150 from nominal

\[\alpha(25) = -0.007 \text{ ppm/C},\]
\[\beta(25) = -0.0026 \text{ ppm/C}^2\]
NIST vs NRC 1G
Expanded Uncertainty
$k=2$
NIST vs NRC 100G

Expanded Uncertainty $k=2$
Leakage Paths

Leakage most likely with high voltage

\[ R_{\text{leak}} \approx 1 \times 10^{14} \text{ to } 1 \times 10^{15} \]

Very low voltage in this path

\[ I_{\text{Imbalance}} \]