Ohm's Law, how hard can it Be???

R = E/I, E = IR, I=E/R ??

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Ohm's Law, How hard Can it Be???

Topics Covered

1. *Resistance Metrology – A Review of*
    1. *The Physical Effects Related to Resistance*
        - Resistance is just V/I so what are the Physical Effects related to Voltage, Current and Resistance?
    2. Resistance Bridges
2. *MIL Resistance Bridges*
    1. A review of the CCC principle and the Measurements International 6010D DC Current Comparator up to 3000A (Current Ratio and traceability for resistance)
3. DC Current Measurements to 3000A
    1. Calibrating DC Current Transducers (Absolute Current and Traceability)
4. DC Voltage Measurements to 1200V
    1. Calibrating the calibrator (Voltage Ratio, Absolute voltage and traceability)
5. Summary and Conclusions
    1. The MI 17025 Scope

Resistance Metrology

Physical Effects Related to Resistance – A Review

Resistance is just V/I so what are the Physical Effects related to Voltage, Current and Resistance?

1. **Seebeck** effect – in a conducting loop with a temperature gradient different parts of a loop with dissimilar metals causes a thermoelectric voltage or thermal emf. This is the reason why you reverse the current through a resistor to cancel the net thermal emf.

2. **Peltier effect** – the reverse of the **Seebeck** effect, a voltage across (or current through) dissimilar metals causes a temperature difference.

   This is the reason why, especially on low value resistors, the resistor and its potential and current arms are made of the same resistive material and transitions to copper terminals are well separated from the resistor body.

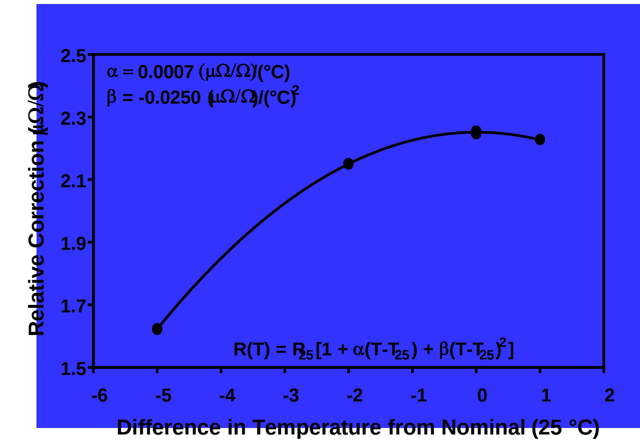
Resistance Metrology

3. **Thompson effect** – current flowing in a conductor with a temperature gradient will evolve or absorb heat depending on the material, temperature difference and current direction. This is why some resistors are designed to be thermally symmetric and with a large thermal mass to equally distribute any heat flow.

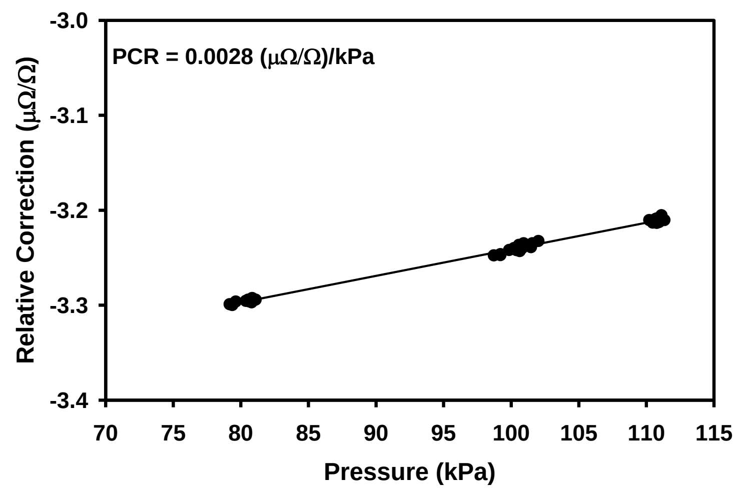
The **Seebeck**, **Peltier** and **Thompson** effect are also magnetically sensitive. Current flow is usually designed to flow through twisted and shielded pairs of leads to minimize generating magnetic fields and operation in magnetic fields is cautioned.

Resistance Metrology

4. **Temperature Coefficient (TC)** – the change in resistance due to a change in temperature. Typically analyzed as a second order polynomial relationship $\Delta R/R = \alpha\ \Delta T + \beta\Delta T$. In resistance measurements the Temperature Coefficient Uncertainty = $TC_{RESISTOR}$/Bath Stability



5. **Pressure Coefficient** - the change in resistance due to a change in pressure. Typically analyzed as a linear relationship $\Delta R/R = \rho\ \Delta P$. For example L&N Thomas type 1 ohm resistors typically have ρ=+0.003 ppm/kPa



Resistance Metrology

6. **Dielectric Absorption** – the change in resistance due to time delays in the redistribution of charge inside insulating parts of the resistor or its case. This is why some resistors have a variation of resistance with respect to rapid current reversal rates. Dielectric absorption can be seen in resistors as low as 1kΩ resistors and higher caused by aging and/or the breakdown of the element.

7. **Voltage Coefficient** - the change in resistance due the change in measuring voltage (but not due to the power being dissipated).

   This is generally associated with higher value resistors and is related to dielectric absorption and higher order interactions of other thermoelectric and physical effects.

Resistance Metrology

8. **Power Coefficient** - the change in resistance due to change in power dissipated in the resistor that is not accounted for by the temperature coefficient. This effect is most evident in low value resistors and is critically dependent on how heat is flowing from the resistor to the environment. It is further complicated by interaction of thermoelectric effects and non-uniform physical effects, such as different temperature coefficients along the resistive element interacting with current flow direction and the Thompson effect.

For example the power coefficient specification on an SR104 is < 1ppm/W.

Resistance Metrology

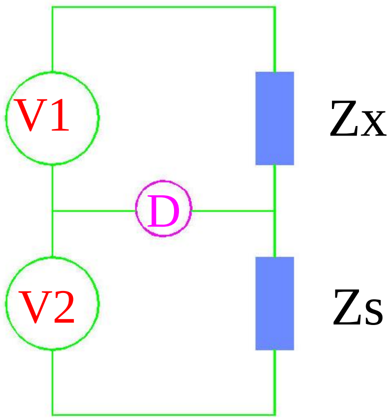
9. **Strain** - the change in resistance due to mechanical dimensional changes in the resistive element. Mechanical dimensional changes can be caused by vibration, impact or even orientation of the resistor.

10. **Hysteresis** – the non-reversible change in resistance caused by reversible change in an influence parameter. This is a difficult effect to clearly identify. An example of a hysteric mechanism is the non-repeatable slipping along two different materials during expansion/contraction of the resistive element against its support structure.

Resistance Metrology

11. Bridge Review

Zx/Zs= V1/V2



Usually, we use a bridge to scale from a known impedance to an unknown impedance.

Bridges convert the accurate measurement of the voltage (or the current) to the ratio of two voltages, two currents or two impedances.

The bridge method has the advantagess:

- A null detector (D), as opposed to a calibrated linear detector
- Low source output impedance thus lower noise…

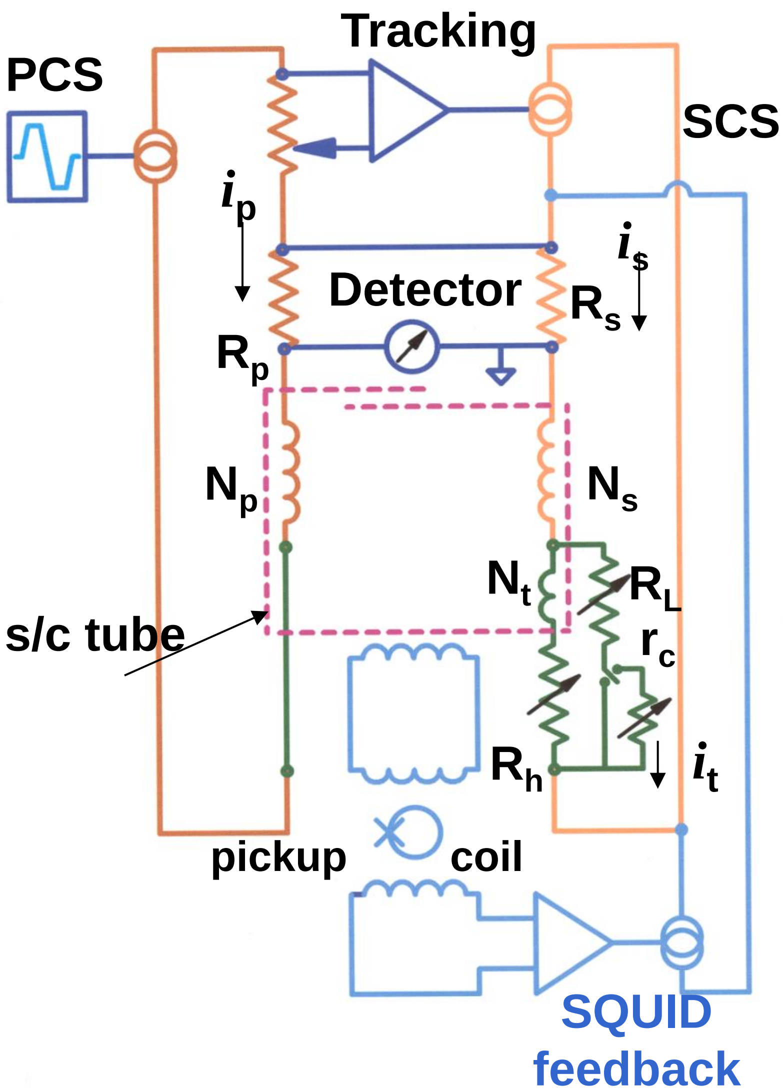
6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

1. The cryogenic current comparator Resistance Bridge

The cryogenic current comparator (CCC) resistance bridge is the most complicated of systems to be discussed especially since it operates on a principle that is not commonly understood. Yet it shares many of the design features with the dc current comparator resistance bridge:

Real Turns, Partial Turns and Ramping Current Sources.

First one needs to understand how a transformer can be made that operates at dc, has almost perfect ratio accuracy and zero leakage effects.



Cryogenic Current Comparator Bridge

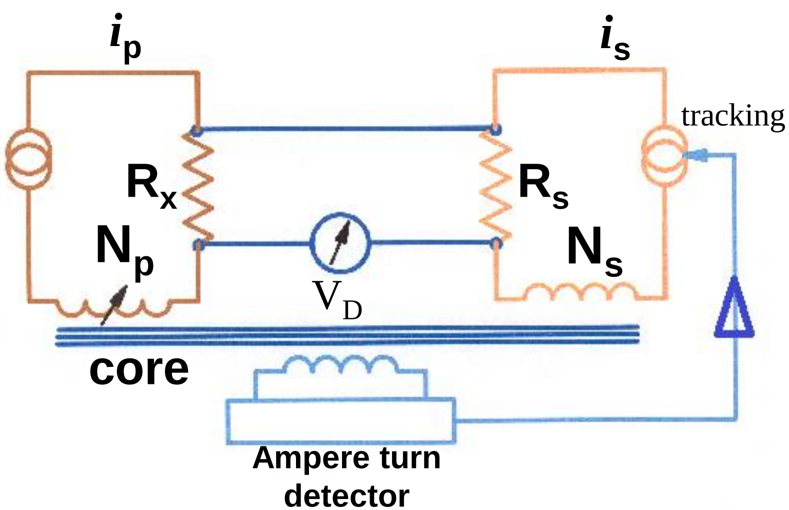
Ampere Turn Device & at balance

$$i_p \times N_p = (i_s \times N_s) + (i_t \times N_t)$$

$$R_p \times i_p = R_s \times (i_s + i_t)$$

(current x turns) imbalance produces current in s/c tube; sensed by pickup coil and SQUID; drives feedback to remove imbalance.

6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE



Master Slave Relationship

- The tracking circuit and N_P are used to create and ampere turns balance in the comparator
- N_p is then varied to zero the difference in voltage drops across resistors (voltage detector VD)
- And hence $i_P R_X = i_S R_S = R_x/R_s = N_P/N_S$
- Excellent linearity < 0.005 ppm
- 0.001 Ω →100 kΩ (Typical Range)
- Various Range Extenders extend the range and improve the accuracy down to 1 μΩ at higher Currents
- The 6010D is a current ratio device Ix:Is. As a result there is no need for current accuracy because of the master slave relationship and automatic ampere-turn balance.

6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

Ratio = $N_x/N_s = R_x/R_s = I_S/I_X$

Where N_s = fixed winding, N_P = Variable turns

$N_p = N_{real\text{-}turns} + N_{partial\text{-}turns}$

For a 10:1 ratio N_{real} = Ns x ratio

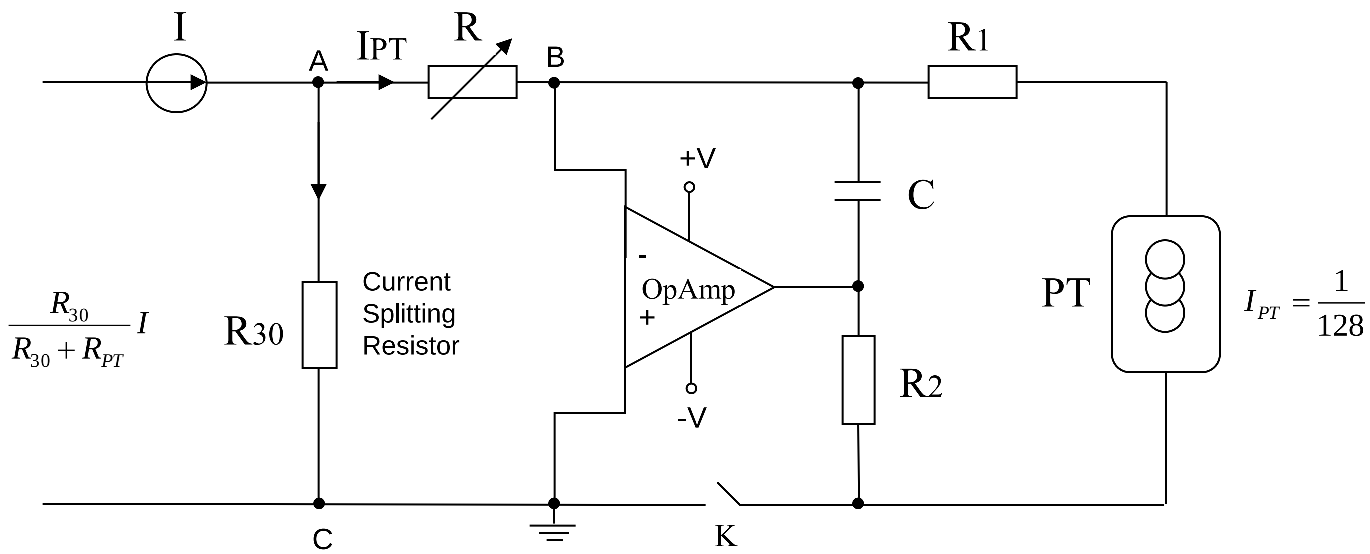
$N_{partial\text{-}turns}$ binary weight = 1/128

1 $Real_{turn}$ – 128 partial $_{turns}$

$V_D = ((Ratio * N_s) – N_{real}) *128 = 1$ ppm

The ratio of power dissipation in the compared resistors is the inverse of the ratio of resistance (the largest power is dissipated in the smaller resistor) < 10 mW

6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

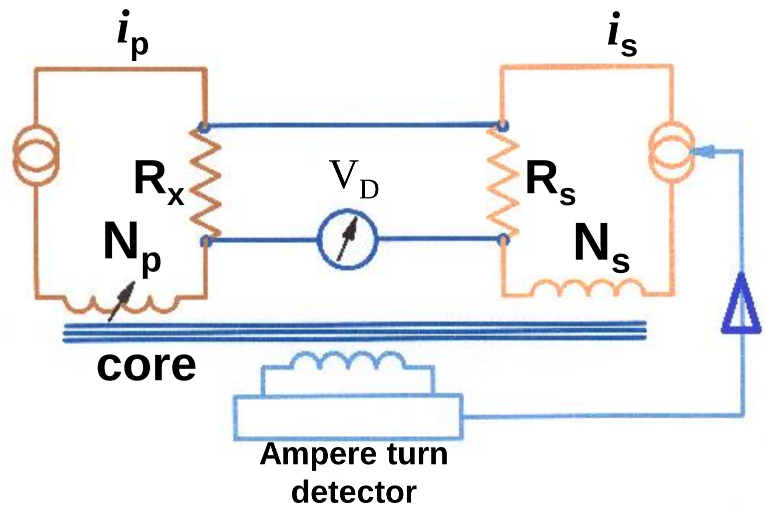


1) Winding resistance of the turns and the relay contact resistance from the current splitting resistor

2) The wire gauge of the Partial turns was increased to improve the TC of the wire and to decrease the resistance in the partial turns.

6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

- The ampere turn flux detector is a flux to voltage converter which works at dc by driving the core into saturation using ac pulse and determining the dc ampere turns imbalance as the core comes out of saturation.
- The LSB ampere turn sensitivity of the flux detector is equivalent to 0.01 ppm



6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

Using the Flux Detector the DC Current Comparator can be calibrated as follows:

Real Turn Comparison:

T 1 Error:	-0.0019	+/-	0.00130 ppm
T 2 Error:	0.0013	+/-	0.00105 ppm
T 4 Error:	-0.0018	+/-	0.00181 ppm
T 8 Error:	0.0004	+/-	0.00124 ppm
T 16 Error:	0.0042	+/-	0.00170 ppm
T 32 Error:	-0.0001	+/-	0.00108 ppm
T 64 Error:	0.0036	+/-	0.00119 ppm
T 128 Error:	0.0015	+/-	0.00130 ppm
T 256 Error:	-0.0018	+/-	0.00157 ppm
T 512 Error:	0.0019	+/-	0.00105 ppm
T 1024 Error:	-0.0005	+/-	0.00216 ppm
T 2048 Error:	0.0025	+/-	0.00102 ppm
T 1024 Error:	0.0048	+/-	0.00160 ppm
T 2048 Error:	0	+/-	0.00112 ppm

Partial Turn Comparison:

PT 1/128 Error:	0.0060	+/-	0.00130 ppm
PT 2/128 Error:	0.0004	+/-	0.00125 ppm
PT 4/128 Error:	0.0047	+/-	0.00128 ppm
PT 8/128 Error:	-0.0004	+/-	0.00128 ppm
PT 16/128 Error:	-0.0024	+/-	0.00164 ppm
PT 32/128 Error:	-0.0006	+/-	0.00146 ppm
PT 64/128 Error:	0.0007	+/-	0.00102 ppm

Normally performed once a year

No standards are required

Sensitivity 1uAT = 1 mV = 0.01 ppm

6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

Verification - Intercomparison with a CCC (METAS) over 3 years

Ratio	2010 Ratio Error (10^{-9})	2013 Ratio Error (10^{-9})	Diff 10^{-9}
10:1	18	9	-9
100:10	23	15	-8
1k:100	21	20	-1
10K:1K	17	16	-1
13K:1k	17	9	-8

To maintain a ratio accuracy of 0.04 ppm requires that the difference is < 0.03 ppm

Traceability

Prior to 1990 traceability was defined as Traceable to an NMI

Since 1990 the Quantum Hall is the International Representation of the SI Ohm

Traceable through an NMI to the SI Unit

In the 6010D traceability is provided through the standard resistor (R_S)

Resistance Metrology

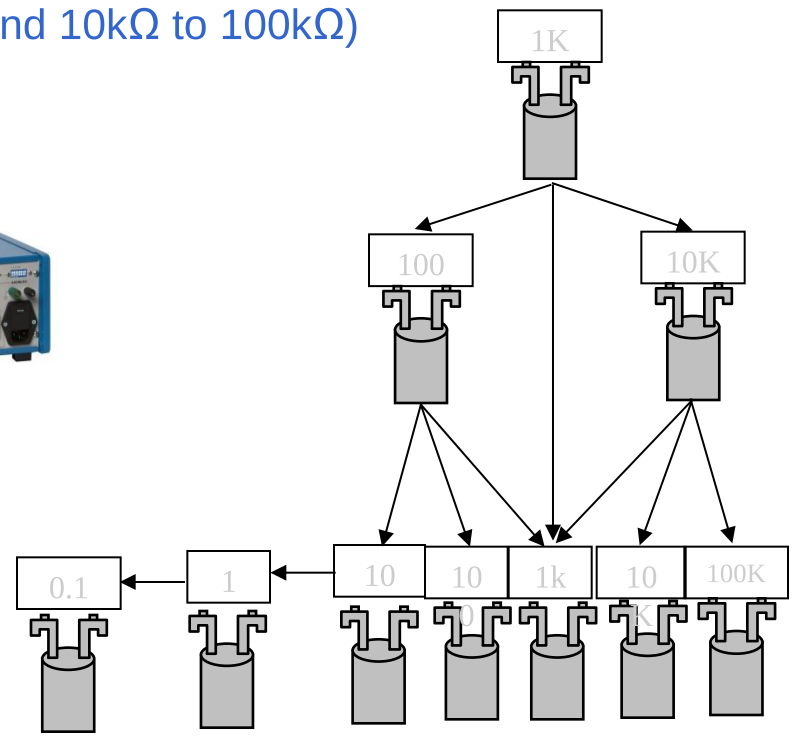
Automation using Matrix Scanners

10 and 20 inputs Four Terminal

Automates the measurements

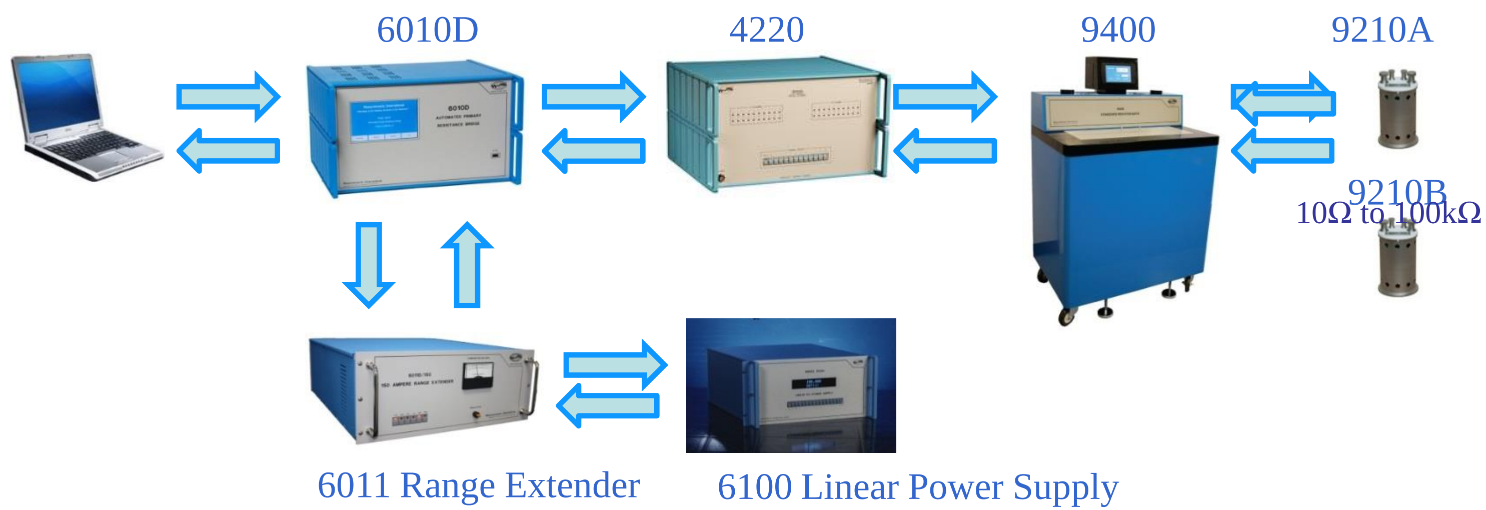
Build up (1Ω to 10Ω to 100 Ω and 10kΩ to 100kΩ)

and Build Down (10kΩ to 1kΩ)



6010D DC CURRENT COMPARATOR RESISTANCE BRIDGE

Range Extenders and Accessories to 1050A



The 6010D bridge is extensively used in NMIs and industry for resistor maintenance and to calibrate customers resistors in the range of 1Ω to 100kΩ

NMIs: NRCC, NIST, CENAM, METAS, PTB, CMI, Singapore, NIMT, NMIJ, New Zealand, NMIA NIM, INMETRO, INTI, INTA, All the major NMI's worldwide.

Government Labs: DOE (USA) NASA, Lockheed, JEMIC, ALPHA,

R=E/I

6010D/3000A System Calibration of Resistors and Shunts

6010D DC Current Comparator

4220A Matrix Scanner

6011D Range Extender
Ratio:10, 100, 1000

3000A Power Supply

Shunt Connection

6014M Range Extender
Ratio: 1000:1

Ratio: 1,000,000:1
For the calibration of shunts
6010D/3000A Software

6010D/3000A System

DC Current Range Extenders Ratio and Uncertainties

Resistance Ratio	Uncertainty	Ratio
1 Ω to 0.1 Ω	0.2 ppm	10
10 Ω to 0.1 Ω	0.2 ppm	100
10 Ω to 0.01 Ω	0.2 ppm	1,000
10 Ω to 0.001 Ω	0.3 ppm	10,000
10 Ω to 0.0001 Ω	2 ppm	100,000
100 Ω to 0.0001 Ω	10 ppm	1,000,000

$I = E/R$

A Bi Polar DC Current Generation and Measurement System
Calibration of DC Current Transducers

6010D was replaced with two DMMs

4220 scanner 10 or 20 channels

6011D Extender Ratio 10, 100, 1000

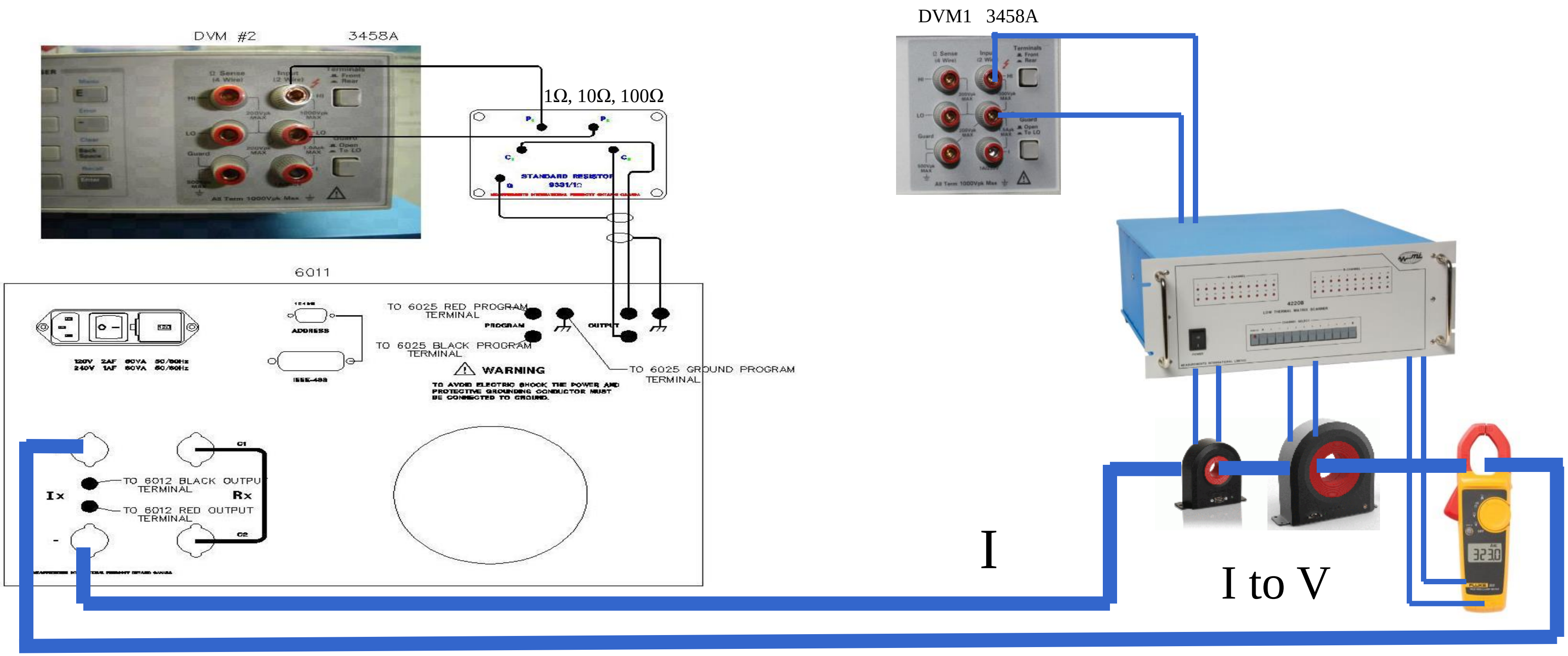
±3000A

Current Output
I

$I_{ABS} = V_{ABS}/R_{ABS}$ x Range

6014M Extender Ratio 1000

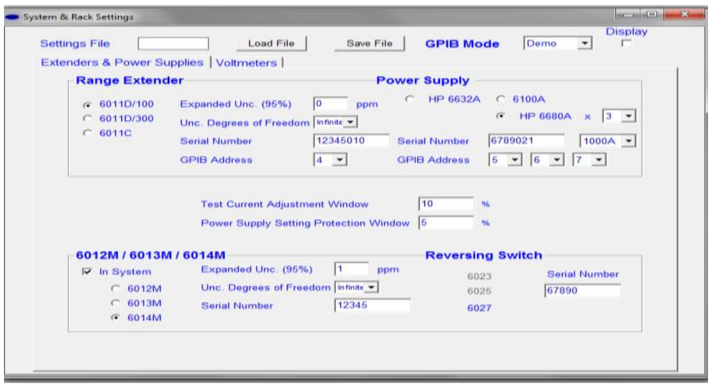
DC Current Calibration for 100A, 300A, 400A, 1000A and 3000A Systems.

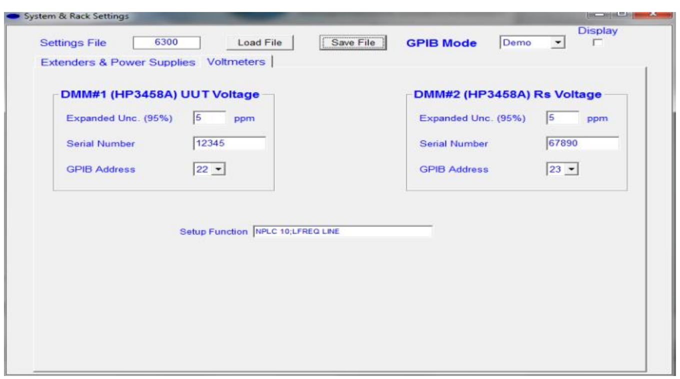


$$I = \frac{\frac{V}{R} + \frac{-V}{R}}{2} * Ratio\ (where\ ratio = 10\ to\ 1{,}000{,}000)$$

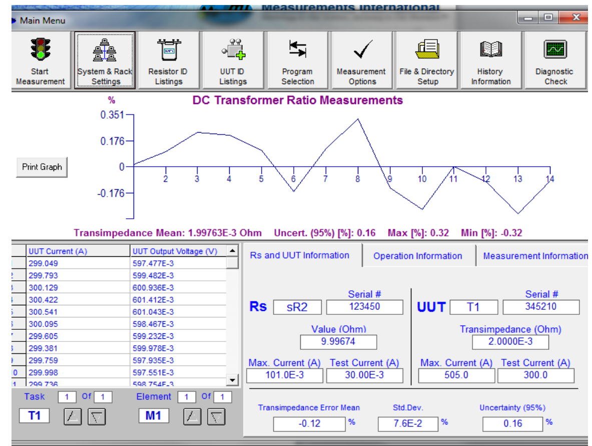
$$U = (DMM1_{UNC}^2 + DMM2_{UNC}^2 + R_{UNC}^2 + EXT1_{UNC}^2 + EXT2_{UNC}^2 + STD_{DEC}^2)^{1/2}$$

Operating Software

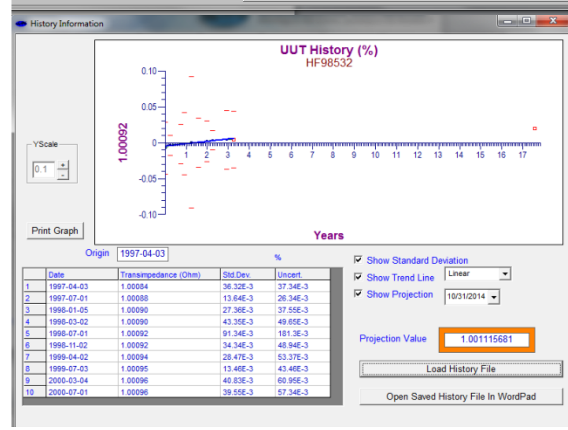




System Setup files and UUT Files



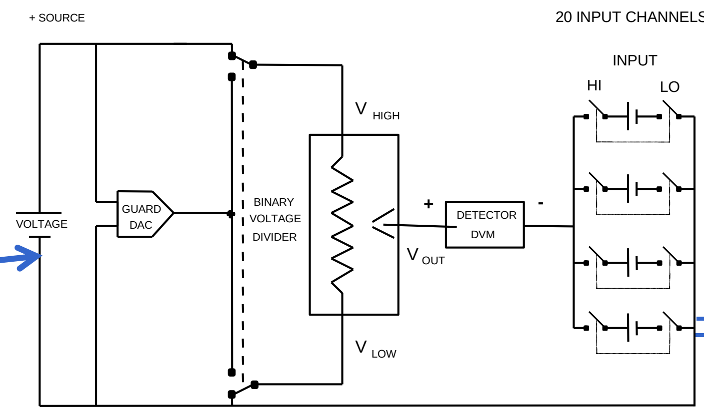
Main Screen



History file

www.mintl.com

DC Voltage Calibration System



BVD Schemtic

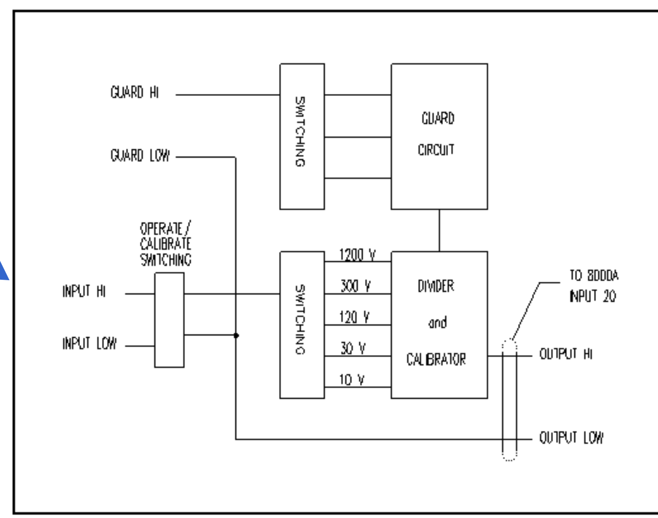
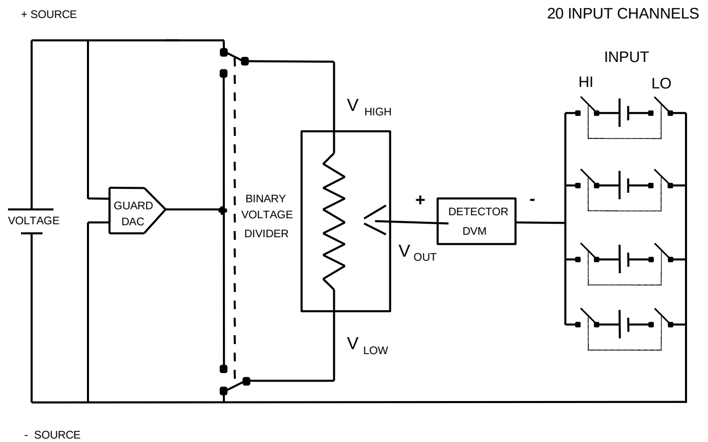


FIGURE 1...8001A SYSTEM SCHEMATIC

BVD or Binary Voltage Resistive Divider
Input Impedance of 40k
10V
1.018V
Self Calibration
Standardization
Measurement
With verification features

Resistive Divider
With Ranges of
10V
30V
120V
300V
1200V
Self calibration using the BV

An Accurate Self Calibrating Binary Voltage Resistive Divider System

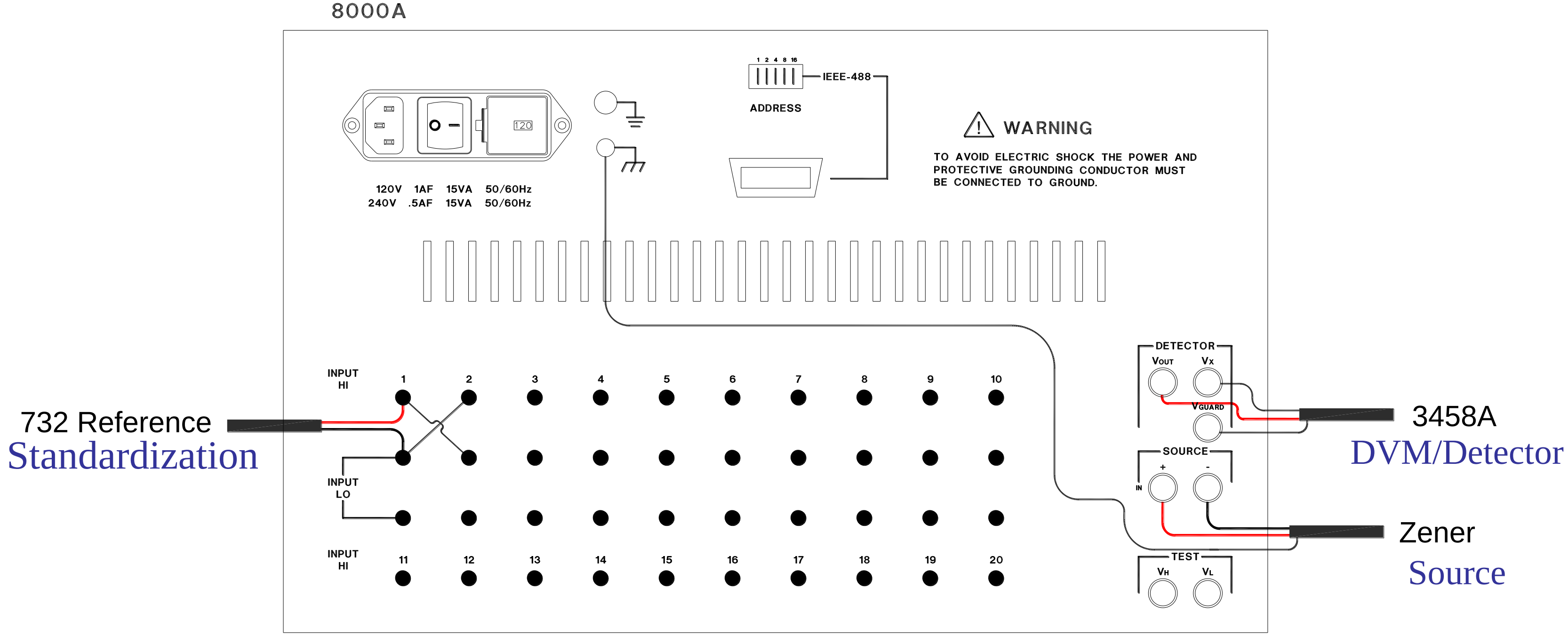


13 Bit Binary Voltage Divider
$10V/2^{13} = 1.2\ mV$
DMM only sees voltages below 1.2mV

System consists of the BVD, A 3458A Detector, a stable 10V Voltage Source Voltage and a stable 10V Zener Reference

The sources of error have been critically examined, carefully controlled and accounted for. The system features various methods to verify the ratios from 1mV to 1200V with traceability to the 10V Zener Reference. This makes the system ideal for calibrating both DC References and DC Voltage Calibrators.

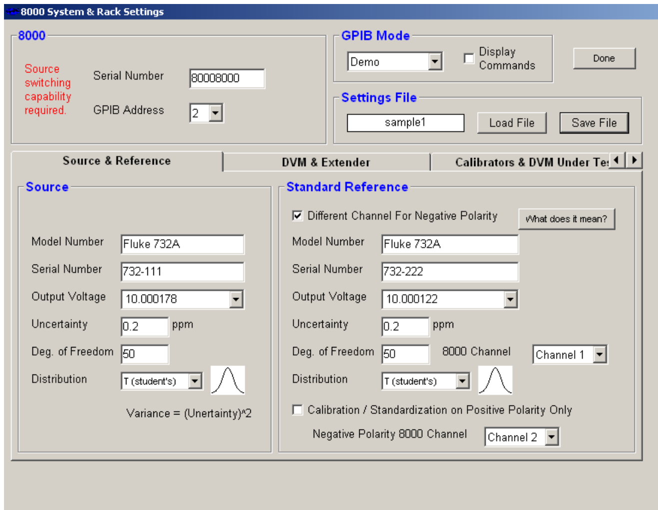
BVD Connection Diagram



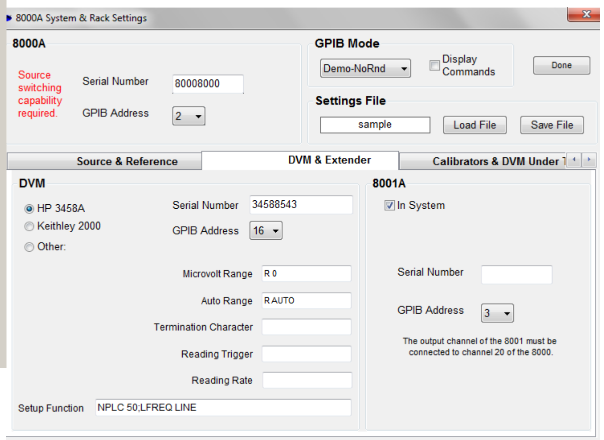
Source, DVM/Detector & Reference
Reference: Known 10V (JJ)
Source: Stable 10V Zener

System Configuration

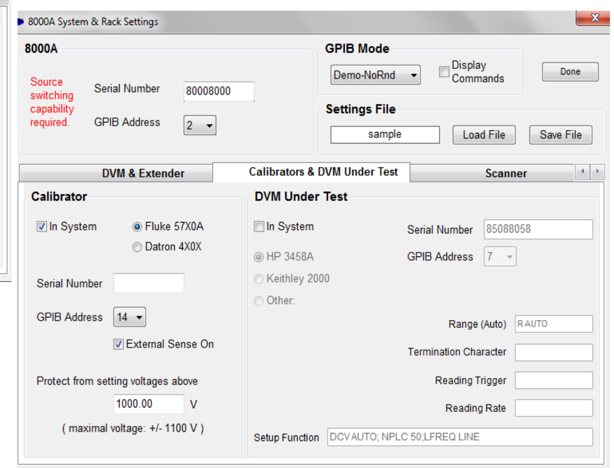
Source & Reference



DVM/Detector & Extender



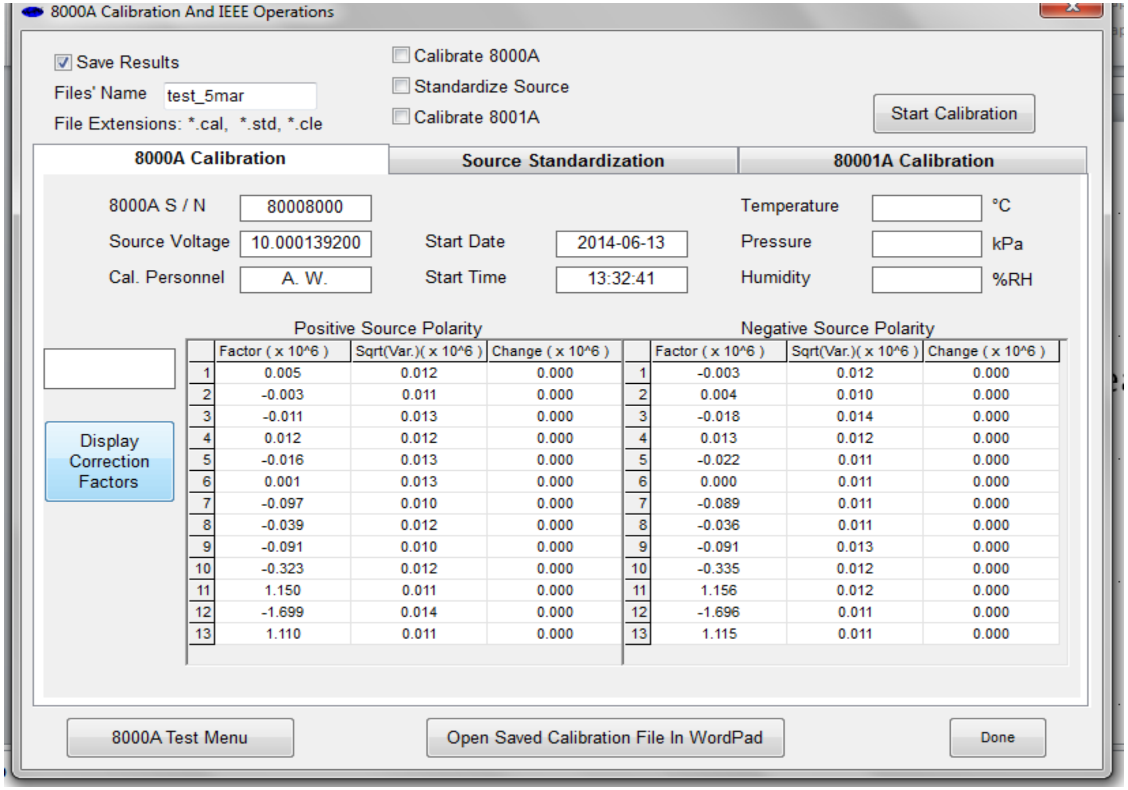
Calibrator & DVM (UUT)



Measurement Process

1. Calibrate the 13 bits of the BVD
2. System Standardization – remove the DC thermals and offsets in the BVD and Detector to make it direct reading.
3. Verification – re-measure the source that you just standardized against.

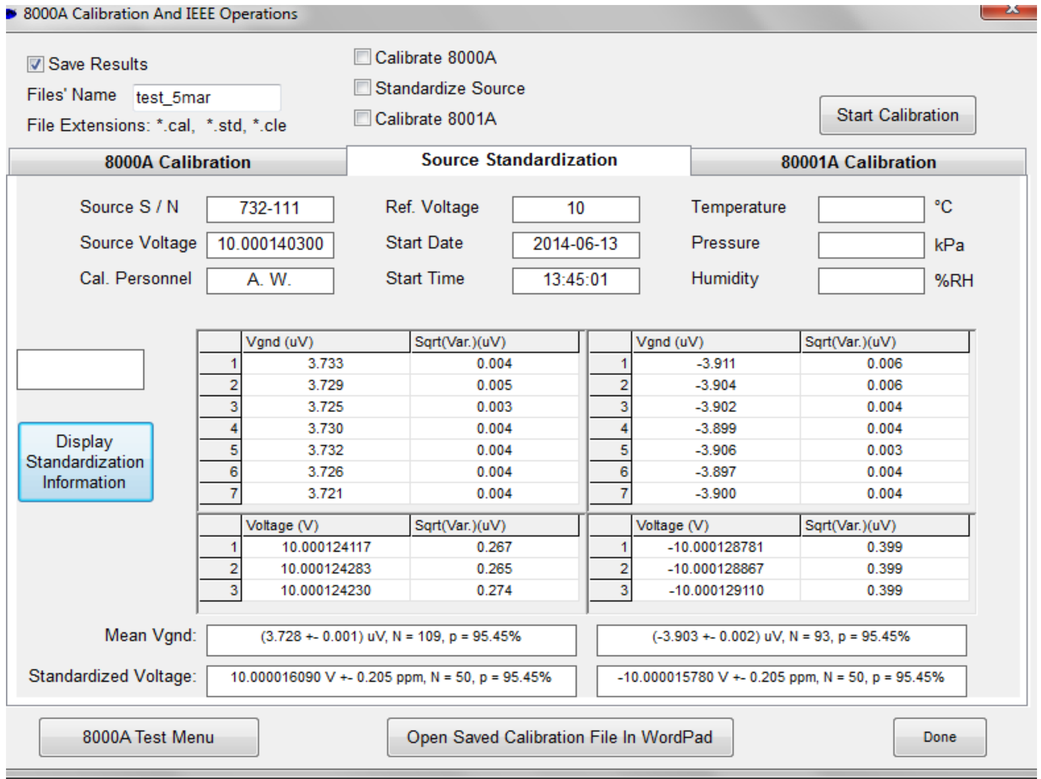
BVD Stage Calibration ± 10V



	Positive Source Polarity			Negative Source Polarity		
	Factor (x 10^6)	Sqrt(Var.)(x 10^6)	Change (x 10^6)	Factor (x 10^6)	Sqrt(Var.)(x 10^6)	Change (x 10^6)
1	0.005	0.012	0.000	-0.003	0.012	0.000
2	-0.003	0.011	0.000	0.004	0.010	0.000
3	-0.011	0.013	0.000	-0.018	0.014	0.000
4	0.012	0.012	0.000	0.013	0.012	0.000
5	-0.016	0.013	0.000	-0.022	0.011	0.000
6	0.001	0.013	0.000	0.000	0.011	0.000
7	-0.097	0.010	0.000	-0.089	0.011	0.000
8	-0.039	0.012	0.000	-0.036	0.011	0.000
9	-0.091	0.010	0.000	-0.091	0.013	0.000
10	-0.323	0.012	0.000	-0.335	0.012	0.000
11	1.150	0.011	0.000	1.156	0.012	0.000
12	-1.699	0.014	0.000	-1.696	0.011	0.000
13	1.110	0.011	0.000	1.115	0.011	0.000

BVD has a reversing switch built in for reversing the source
Self Calibration removes the long term drift of the system

BVD Standardization



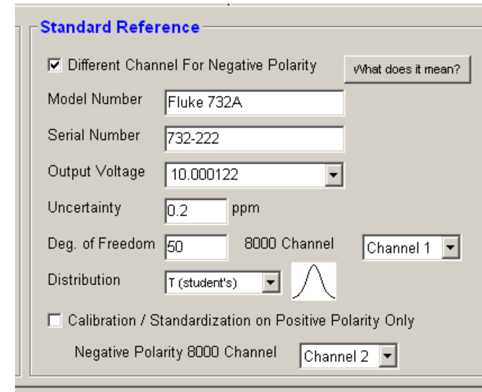
The BVD is a ratio device, it measures the ratio of two voltages. Standardization makes the 8000 direct reading in terms of Absolute

Standardization Verification Process

Reference Voltage = 10.0000122 UNC = 0.02 ppm

732B calibrated using Josephson Array

Connected to Channel 1 and 2



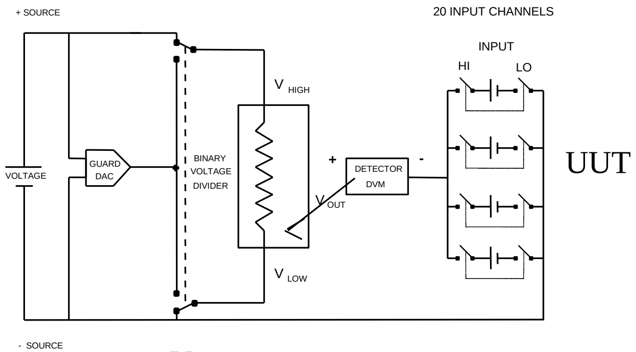
Measure Channel 1

Voltage Measurement = 10.00001220 ± 0.01 ppm

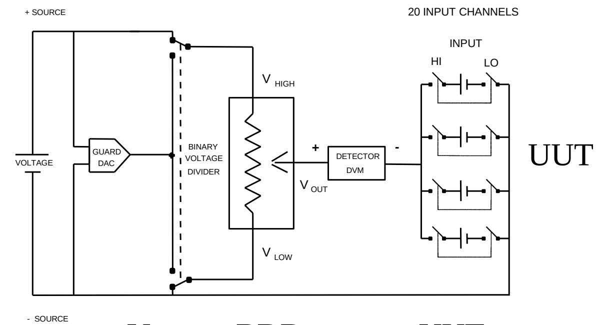
Alternatively you could measure two calibrated 732's and record the difference in the value as the error. The 732's would require calibration on the JJ

Ref 1 – Ref 2 < uncertainty of the two references

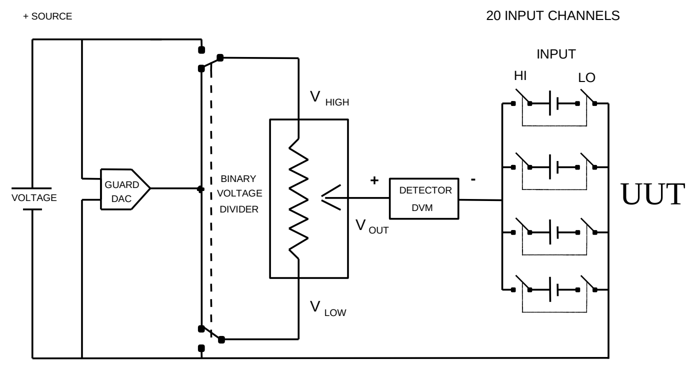
Voltage Measurement



$V_{NOMINAL}$



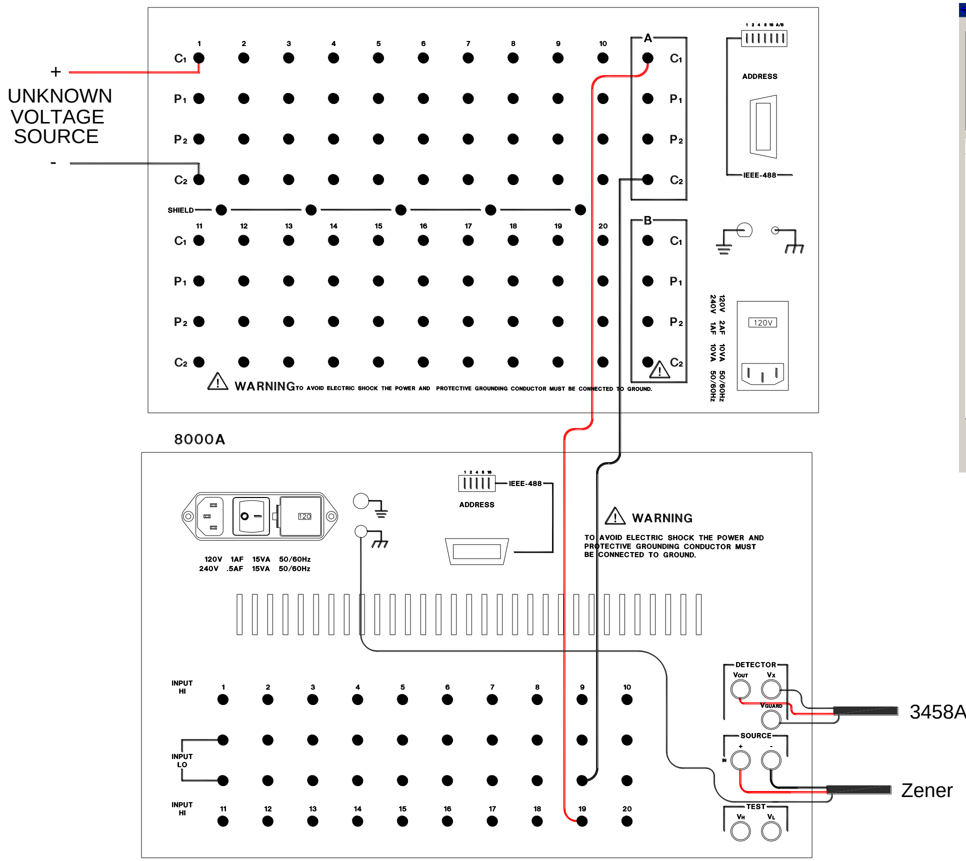
$V_{DIFF} = BDD_{VOLTAG} – UUT_{VOLTAGE}$

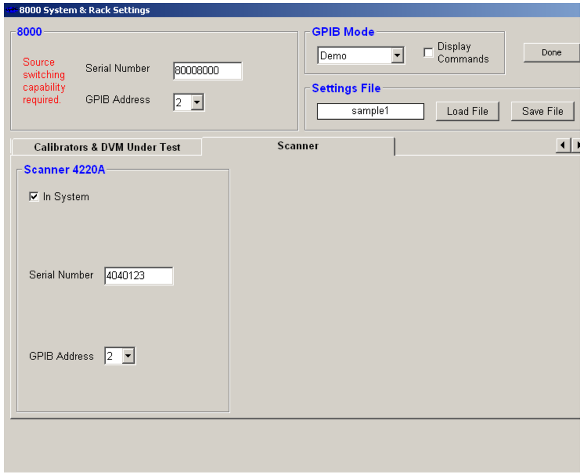


V_{OFFSET} = offset of DMM

$$UUT_{VOLTAGE} = BVD_{VOLTAGE} + (V_{DIFF} - V_{OFFSET})$$

Channel Extension

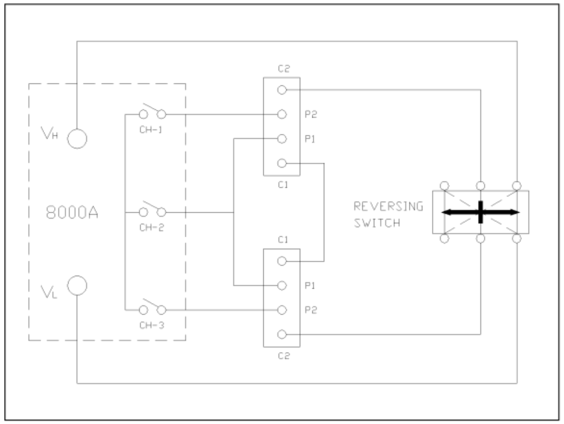




Software Configuration for the Scanner

Connecting a 20 Channel Scanner

8000 Verification Box



RATIO VERIFICATION: Where external resistors are used to verify the ratios of the 8000.
If you don't have a JJ

Included in the box is a pair of standard Resistors.
Good Short Term Stability
eg: for 1:1 ratio, two 10 K standard resistors.
eg: for 10:1 ratio, 1 K and 10 K standard resistors.
A low thermal reversing switch (R).

Either one of these two techniques can verify the BVD Ratio to < 0.02 ppm
Built into the software where input channels are specified

8001B 1200V Divider

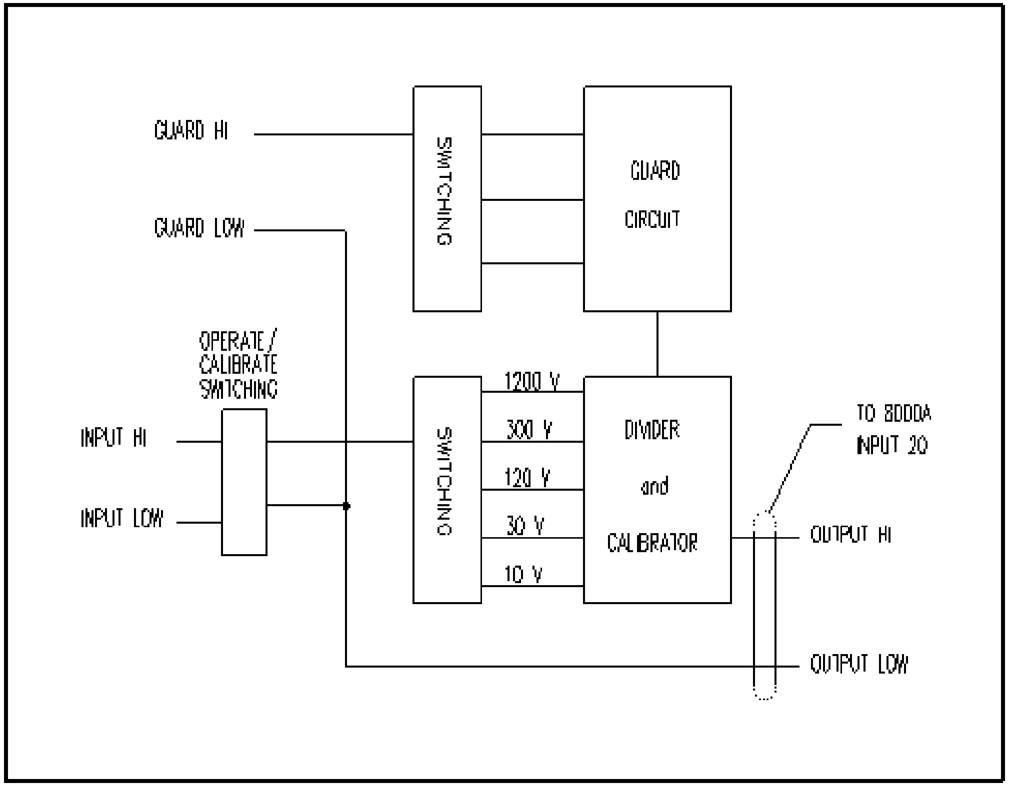
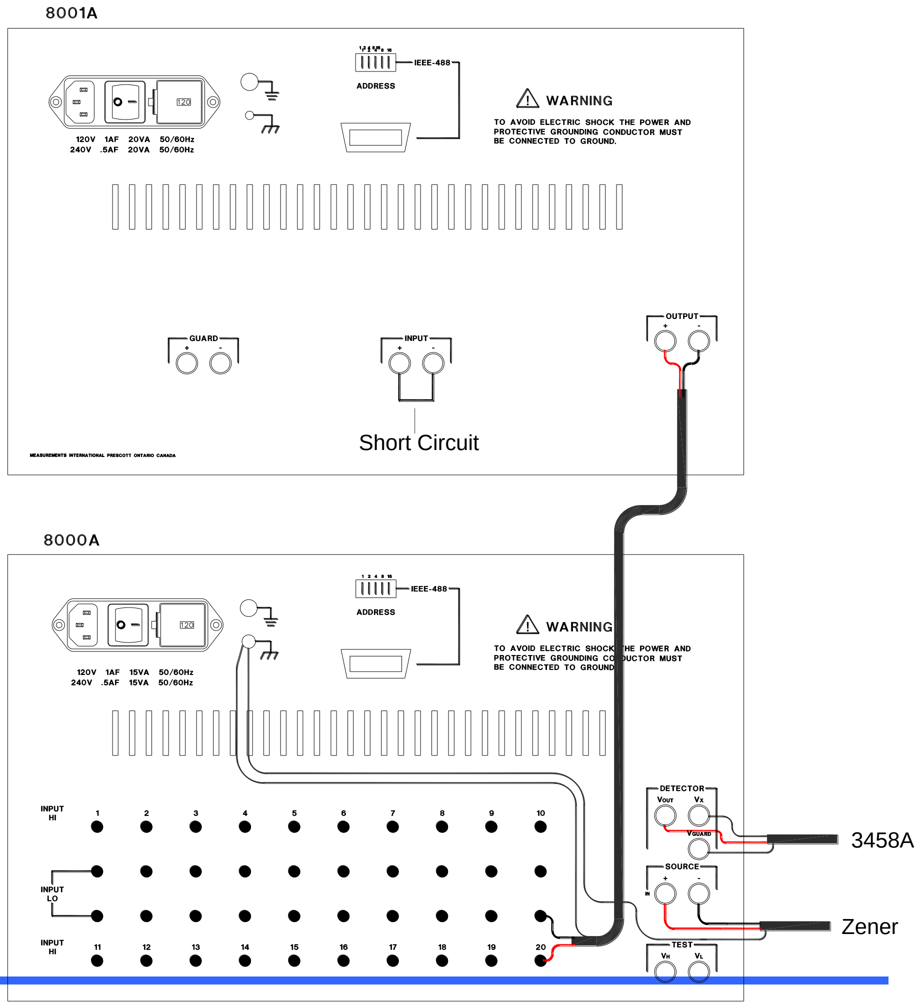


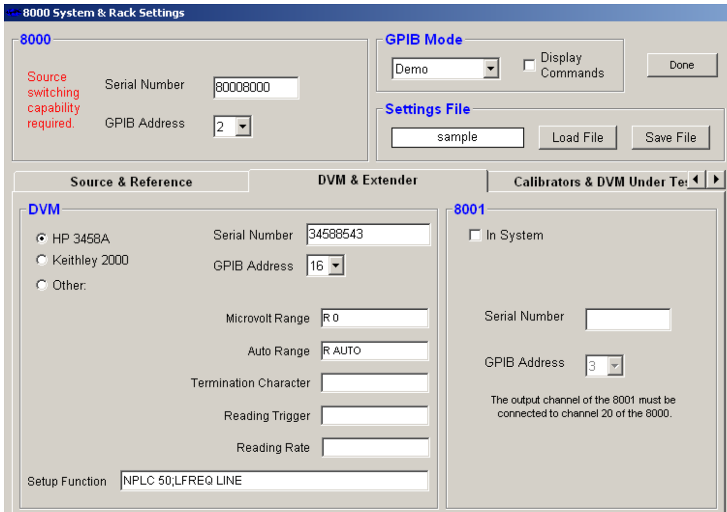
FIGURE 1...8001A SYSTEM SCHEMATIC

The Ext is also a resistive divider and maintains excellent short term drift and is self calibrating using the BVD after standardization is complete. Application for the BVD & Ext include the calibration and verification of the linearity and absolute voltage measurements of both calibrators and DMM's up to 1200V.

BVD/EXT Connection Drawing

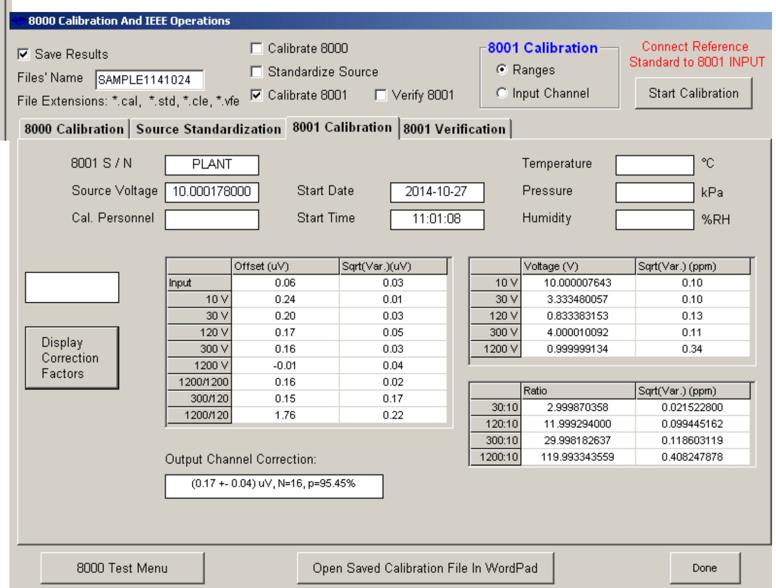


EXT Setup & Calibration

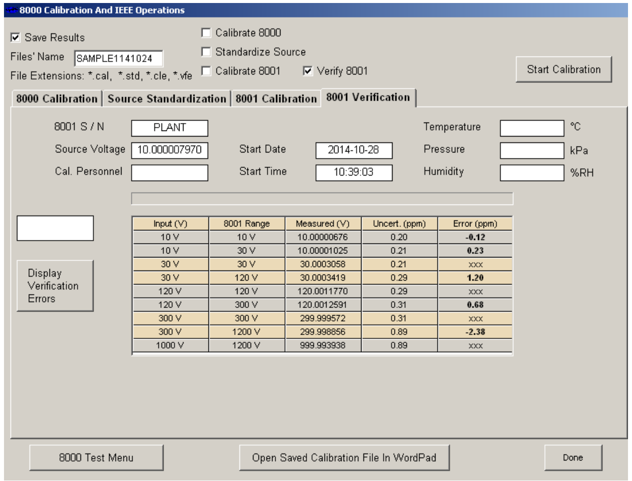


Ext Software Configuration

Extender Calibration using the calibrated BVD



EXT Verification



Input (V)	8001 Range	Mesured (V)	Uncert (ppm)	Error (ppm)	Input
10V	10V	10.00000676	0.2	-0.12	10V Reference
10V	30V	10.00000103	0.21	0.23	10V Reference
30V	30V	30.0003058	0.21	XXX	Calibrator 30V
30V	120V	30.0003419	0.29	1.2	Calibrator 30V
120V	120V	120.001177	0.29	XXX	Calibrator 120V
120V	300V	120.001259	0.31	0.68	Calibrator 120V
300V	300V	299.999572	0.31	XXX	Calibrator 300V
300V	1200V	299.99982	0.89	-0.83	Calibrator 300V
1000V	1200V	999.993938	0.89	XXX	Calibrator 1000V

Summary: Resistance Metrology MIL 17025 Scope

Resistance Range

1 µΩ to 10 µΩ	500 to 20 ppm
10 µΩ to 100 µΩ	20 to 2 ppm
100 µΩ to 1 mΩ	2 to 0.9 ppm
1 mΩ to 10 mΩ	0.9 to 0.22 ppm
10 mΩ to 100 mΩ	0.22 to 0.17 ppm
100 mΩ to 1Ω	0.17 to 0.16 ppm
1Ω to 10 Ω	0.1 to 0.19 ppm
10 Ω to 100 Ω	0.19 to 0.22 ppm
100 Ω to 1kΩ	0.22 to 0.25 ppm
1kΩ to 10 kΩ	0.25 to 0.1 ppm
13 kΩ	0.2 ppm

10:1 Resistance Ratio

0.1 Ω to 1 Ω	0.05 ppm
1 Ω to 10 Ω	0.05 ppm
10 Ω to 100Ω	0.05 ppm
100 Ω to 1kΩ	0.05 ppm
1 kΩ to 10 kΩ	0.05 ppm
1 kΩ to 13 kΩ	0.05 ppm
10 kΩ to 100 kΩ	0.08 ppm
100 kΩ to 1MΩ	0.1 ppm
1 MΩ TO 10MΩ	0.15 ppm
10 MΩ TO 100 MΩ	1.5 ppm

1:1 Resistance Ratios

1 Ω to 1 Ω	0.03 ppm
10 Ω to 10 Ω	0.03 ppm
100 Ω to 100 Ω	0.03 ppm
1 kΩ to 1 kΩ	0.03 ppm
10 kΩ to 10 kΩ	0.03 ppm
100 kΩ to 100 kΩ	0.10 ppm
1 MΩ TO 1 MΩ	0.12 ppm
10 MΩ TO 10 MΩ	0.15 ppm
100 MΩ TO 100MΩ	1.5 ppm

1000V 2 ppm

Full MI Scope NRCC Website

Summary

1) Ohms Law, how hard can it be???

   Understanding the physical effects related to measuring a resistor to improve the measurement uncertainty. A resistor has a personality and it is only through experimentation and data collection that you can begin to understand it.

2) Importance of understanding and removing DC Offsets in all measurements to improve uncertainties

3) DC Voltage measurements

   The importance of verifying the self calibration techniques for making accurate measurements to insure the best uncertainties when calibrating DC voltage calibrators that use (artifact calibration) and DMMS.

4) Why all this work?

   Way to improve the Technologies for the improvement of measurement uncertainties worldwide for improving the quality of Life..

References and Related Documents and Websites

1. R. Cutkowsky,“ A New Switching Technique for Binary Resistive Dividers”, IEEE I&<M Trans, 1978

2. H. Tsao, “A 25-Bit Resistive Voltage Divider”, IEEE I&<M Trans, 1987

3. Measurements from 10µΩ to 1TΩ with Traceability from the QuantΩ, 13:00-17:00 August 6, 2006 Nashville TN, Duane Brown & Barry Wood

4. A. F. Dunn "Measurement of Resistance Ratios in the Range to 100 Megohms" IEE Transactions on Instrumentation and Measurement, Vol 40. NO. 2 April 1991.