A Poor Man's Resistance Bridge

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1. Abstract

Using only a single DMM, scanner and software, a lab can have their own automated resistance bridge capable of accuracies from sub ppm to a few ppm over its entire range. This paper describes how we created a simple resistance bridge using off the shelf test equipment. Software was created to take dual four-terminal DMM resistance ratio readings and control a scanner to automate the process. Multiple forward and reverse measurements are taken to reduce the effects of thermal EMFs and to provide statistical information.

This "bridge" can be set up to automatically scale up or down over a wide range of resistance values. Results from various 1:1 and 10:1 measurements between 1 ohm and 10 kilohm will be presented.

2. Introduction

Bridges have been widely used for precision resistance measurements for many years. Automated Current Comparator Bridges are commercially available today with the capability of providing very low uncertainties. However, their high cost prevents many smaller laboratories from owning these new bridges. Our objective was to create a simple lower cost system for making standard resistor comparisons for buildups of various resistor sets between 1 ohm and 1 Megohm that would fit in a smaller laboratories budget. Our parameters were that the system would be fully automated and would require a minimum number of pieces. Each piece of equipment should be off the shelf and multipurpose with other standard functions. Our goal for this system was that it would be capable of making 10 to 1 measurements with about 1 part per million or better accuracies for each step. While Current Comparators are certainly capable of better accuracies, 1 ppm may be suitable for a majority of standards laboratories.

In this paper we will present the results of a system developed with the combined efforts of researchers at Fluke Corporation in Everett Washington and Data Proof in Santa Clara California. All of the equipment used in this system is available off-the-shelf and may already be available in many standards laboratories. The measurement software was developed in California and the testing and evaluation was performed in Washington State in the Fluke Primary

Standards Laboratory. A description of this measurement system and the results from our testing of the system are presented

3. Measurement Setup and Procedure

This system requires only two pieces of test equipment, a DMM capable of making precision resistance ratio measurements and a Low Thermal Scanner. The DMM is set up to make four-terminal resistance comparisons. The four Front terminals are connected to the A-Line output of a Quad Scanner and the Rear terminals are connected to the scanner B-Line. In this experiment two 320A Low Thermal Scanners were used instead of a Quad Scanner since these were available in the Fluke Laboratory. Either arrangement can be used. All resistors to be compared are then connected to the scanner inputs.

The software [1,2 and 3] used enables the comparison of from 1:1 up to 10:1 values. For this experiment we first compared a known 1 Ohm to an unknown 10 Ohm. In the next run we compared the 10 Ohm to an unknown 100 Ohm carrying each value up to 10K ohms. Whether making a run with two resistors or more than two resistors in a run, all readings are made with two resistors at a time until all the resistors in the run are included in the measurement. The resistors are measured first in the forward direction with one resistor connected to the front DMM terminals, then the measurement is reversed so the other resistor is connected to the front terminals.

The DMM is set to read the ratio between the two resistors and the average of the forward and reverse reading is recorded. With two resistors in the run this is repeated four times, half with the first resistor in the second position. If more then two resistors are to be compared the software sets up the resistors in pairs in a statistically balanced design. Any number of resistors can be compared with this software, between two and eight. The readings are recorded as the ppm ratio to the nominal value of the highest value resistor in the run. This was necessary because various resistance values may be included in the run. When all the intercomparisons are complete the program computes a least-squares-fit of the data. Values for each of the resistors are assigned based on the least-squares-fit results and the value(s) of the reference resistor(s) in the test. If multiple reference values are included the resistor values will be based on the average of these references.

Since only the average of the difference readings from both forward and reverse measurements is recorded, the DMM needs to be stable only for the duration of a pair measurement rather than for the entire measurement.
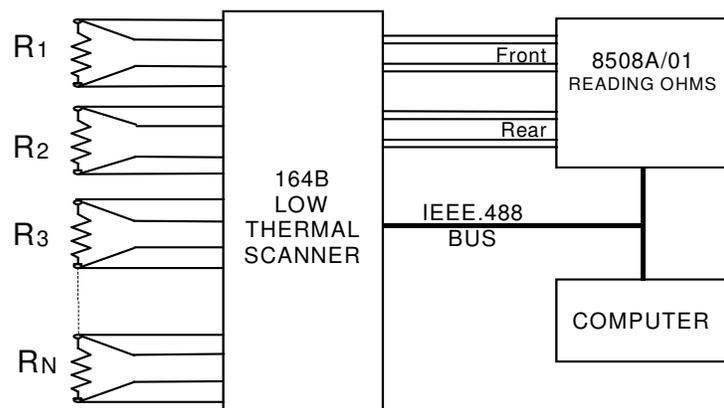
METHOD 1B: DUAL FOUR-TERMINAL CONNECTION TO DMM
Figure 1

Statistical monitoring of the meter readings reduces measurement time by avoiding taking more samples than are necessary. Readings are taken rapidly until five successive readings fall within a preset deviation.

4. Equipment

The meter we used is the Fluke 8508A Reference Multimeter [4] with option 01 which has the rear input terminals in addition to the front input terminals. The reason this meter was selected is because four terminal resistance measurements can be taken with both the front and rear panel input terminals at the same time. This ratio mode has the current from the meter passing through both resistors simultaneously, reducing errors caused by current fluctuations and environmental effects since both resistors are affected the same way at the same time. For resistors below 20 kΩ a stimulus current (of alternating polarity) is applied through both resistors simultaneously, and the potential difference measured across the resistors is scanned between the Front and Rear Terminals. The alternating polarity greatly reduces the affect of thermal EMFs on the   measurements.

Since the ratio mode uses both the front and rear terminals of the 8508A it is critical that a good range zero be performed to cancel any zero offsets in the meter.

A Low Thermal Scanner [5] is used to fully automate the system and to reduce offsets in the metering circuit. Besides switching between resistors, the scanner connects each resistor alternately to both inputs of the DMM. The 164A Quad Scanner is ideally suited for this purpose because it is specifically designed for making direct four-terminal comparisons between two sets of four output connectors. Two conventional Low Thermal Scanners can also be used in this system. The simplest way to set up two scanners is to connect one scanner to the potential terminals of the DMM and resistor and the other to the current terminals and then set them both to the same address. This will function the same as a 164B Quad Scanner. The Low Thermal Scanners we used contributed minimal thermal emf errors (less than 20 nanovolts typical) with minimal leakage (better then 10^{12} ohms).

A driver and procedure was written into the OhmRef Automated Resistance Maintenance Program [6] to take advantages of the features of the 8508A/01Reference Multimeter. With the OhmRef software, the operator can now select from several test methods including this new test method. For those of you familiar with OhmRef you'll recognize this method as similar to Method 1 but because we are using the ratio mode the new method is called Method 1B. This software allows the operator to store information for each of their resistors. Any resistor on the list can then be selected to be include in the test run, up to eight at a time within a 1:10 ratio. The software will set up the test pattern; control the scanner and meter to take the readings, then compute and display the results in a report. The computed value of a resistor from the previous run is stored so it can be used as the known value in the next test run. This makes it easy to do build-ups beginning with known values for only the first run. A new feature was also added to store a run or sequence of runs so with a few clicks of the mouse a series of test runs can be repeated. Test runs can be set up to run repeatedly to make it easier to run multiple tests in a day or during the night, to accumulate sufficient data over a shorter period of time.

The resistors used in this experiment were Fluke 742A standard resistors. Values from 1 Ω to 10 kΩ were used in an environment that was kept at 23°C ±0.6.

5. Results

We began with a 1 Ω resistor with a known traceable value. All of the other resistors were treated as unknown values resistors with just the nominal value entered in the appropriate screen of the software. While the value of the 10 kΩ resistor was also known, it was entered as an unknown so we could compare the results of the sequence of runs from 1 to 10K ohms with our target value. For the values between 10 Ω through 10 kΩ the results show the measurements within 1 μΩ/Ω of the certified values. The 1 to 10 Ω measurement shows results just over 1 μΩ/Ω. More work is continuing on getting better readings from 1 to 10 Ω. 10 Ω measurements should be able to be improved by changing some parameters in the measurement process. We will continue to investigate this and make improvements to the measurement process.

Figures 1 through 5 show the results of a series of build ups from 1 Ω to 10 kΩ. These figures are taken from the reports available in the OhmRef, Automated Resistance Maintenance Program software. Information included in the reports show the measurement results along with the statistics of the measurements.

Overcoming difficulties with the 1 Ω to 10 Ω measurements caused delays in our work that did not allow us to make the planned measurements from 10 kΩ to 1 MΩ. These measurements will take place and we hope to report on them in the future.
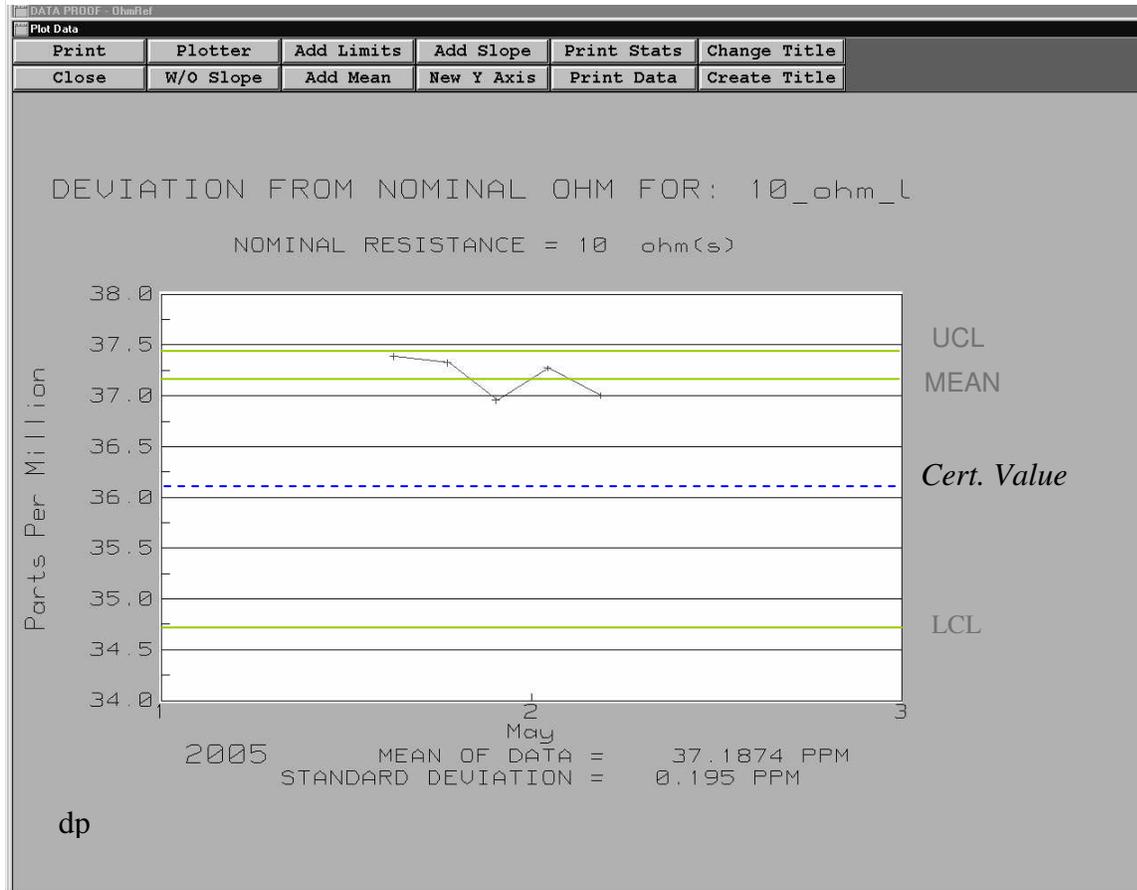
RESISTOR DATA:

                    NOMINAL RESISTANCE = 10 ohm(s)
             ACTUAL CERTIFIED VALUE = 36.1 PPM (10.000361)
                  EXPANDED UNCERTAINTY = 1.37 PPM

DATA STATISTICS:

               DEVIATION FROM NOMINAL OHM FOR: 10_ohm_U

                    MEAN OF DATA: 37.187 PPM
                  STANDARD DEVIATION: 0.195 PPM

                 HIGHEST VALUE IN DATA: 37.384 PPM
                  LOWEST VALUE IN DATA: 36.954 PPM
            UPPER CONTROL LIMIT (+ 2 Sigma): 37.47 PPM
            LOWER CONTROL LIMIT (– 2 Sigma): 34.73 PPM

Comparison average verses certified value: 1.087 PPM

Figure 2. 10 Ω Build Up From 1 Ω.

DEVIATION FROM NOMINAL OHM FOR: 100_ohml

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RESISTOR DATA:
                NOMINAL RESISTANCE = 100 ohm(s)
           ACTUAL CERTIFIED VALUE = 3.3 PPM (100.00033)
              EXPANDED UNCERTAINTY = 0.62 PPM

DATA STATISTICS:

            DEVIATION FROM NOMINAL OHM FOR: 100_ohmU

                    MEAN OF DATA: 3.254 PPM
                 STANDARD DEVIATION: 0.133 PPM

              HIGHEST VALUE IN DATA: 3.400 PPM
               LOWEST VALUE IN DATA: 3.015 PPM
     UPPER CONTROL LIMIT (+ 2 Sigma): 3.920 PPM
     LOWER CONTROL LIMIT (− 2 Sigma): 2.680 PPM
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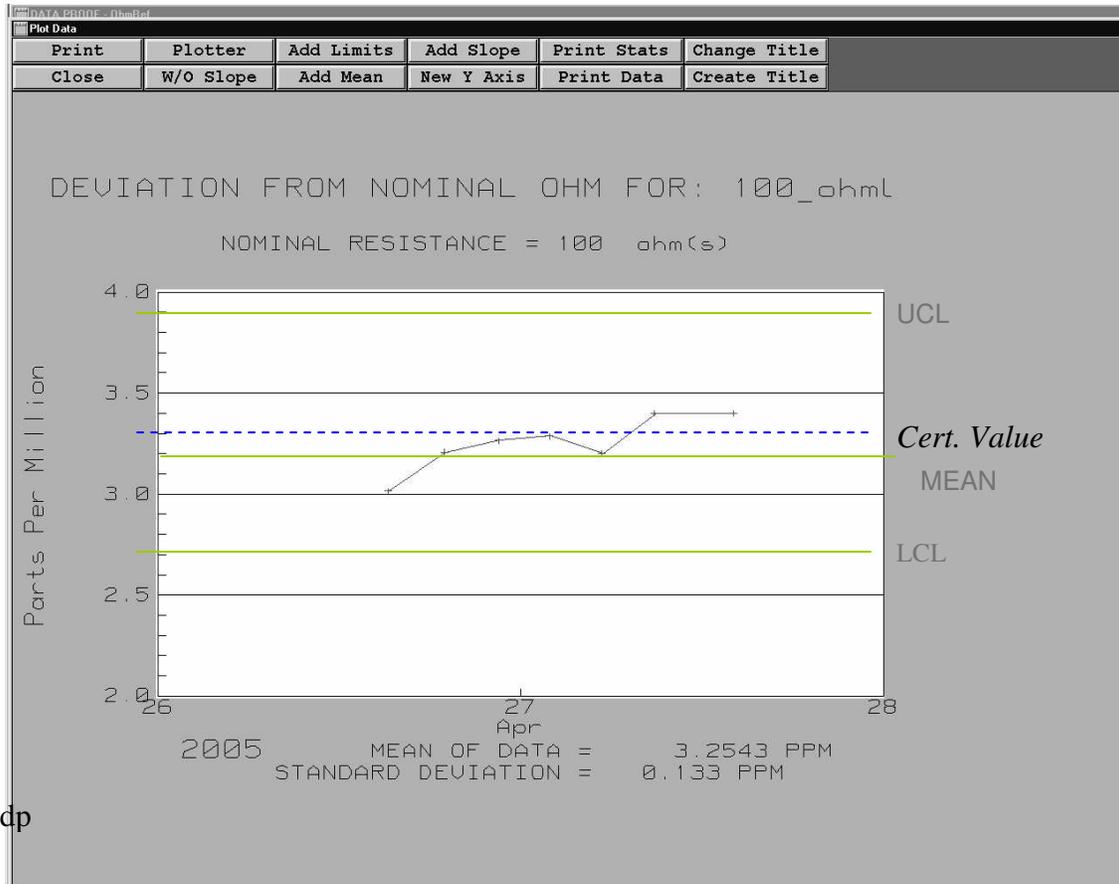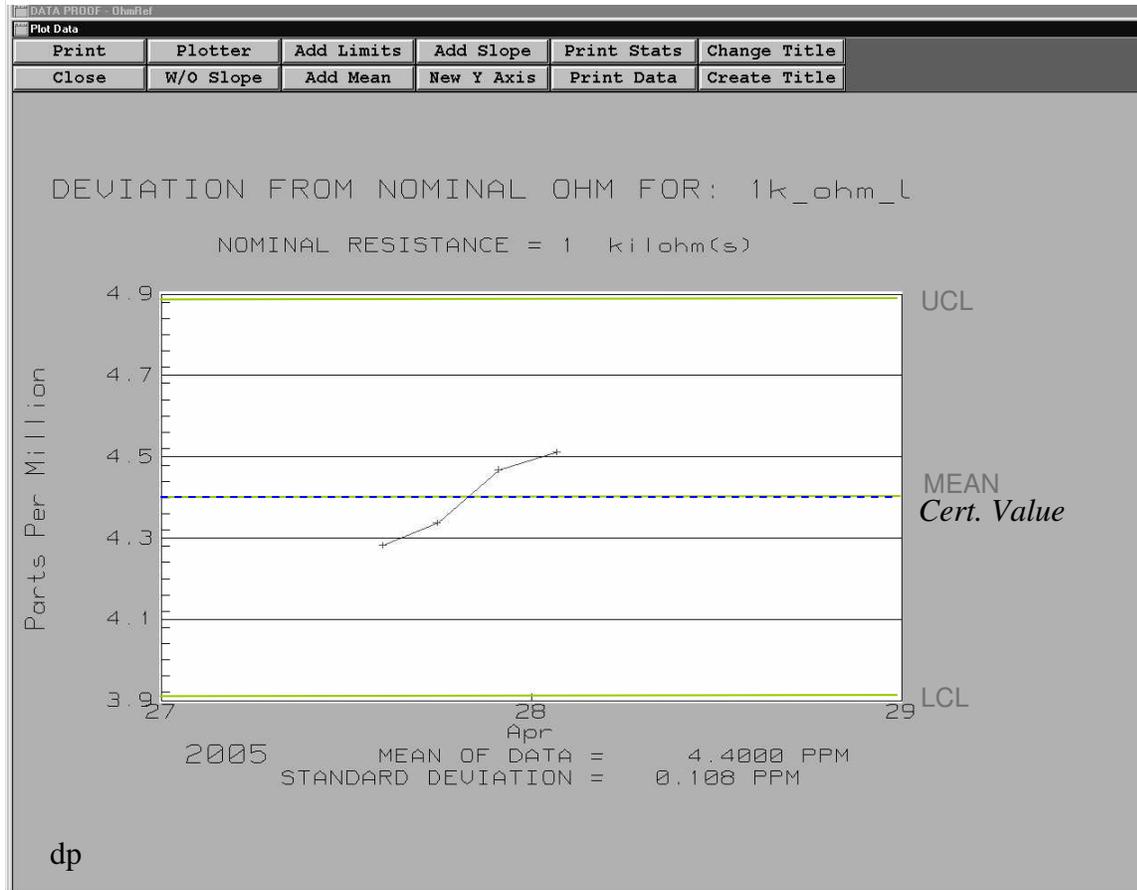
Comparison average verses certified value: - 0.046 PPM

Figure 3. 100 Ω Build Up From 10 Ω.

DATA PROOF - OhmRef

Print	Plotter	Add Limits	Add Slope	Print Stats	Change Title
Close	W/O Slope	Add Mean	New Y Axis	Print Data	Create Title

DEVIATION FROM NOMINAL OHM FOR: 1k_ohm_l

NOMINAL RESISTANCE = 1 kilohm(s)

UCL
MEAN
Cert. Value
LCL

2005   MEAN OF DATA =   4.4000 PPM
        STANDARD DEVIATION =   0.108 PPM

dp

RESISTOR DATA:
            NOMINAL RESISTANCE = 1 kilohm(s)
         ACTUAL CERTIFIED VALUE = 4.4 PPM (1,000.0044)
            EXPANDED UNCERTAINTY = 0.49 PPM

DATA STATISTICS:
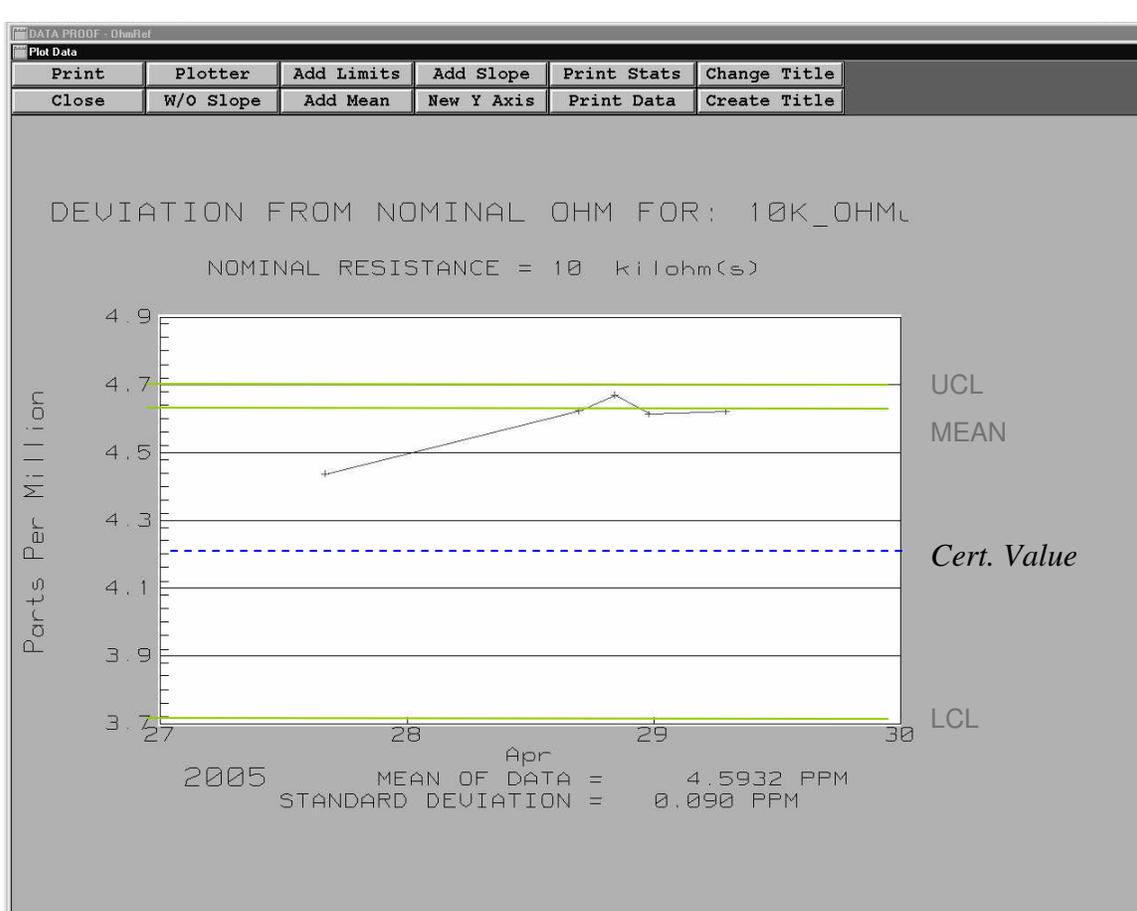   DEVIATION FROM NOMINAL OHM FOR: 1k_ohm_U

                MEAN OF DATA: 4.400 PPM
             STANDARD DEVIATION: 0.108 PPM

               STARTING DATE: 27 Apr 2005
                ENDING DATE: 29 Apr 2005
            HIGHEST VALUE IN DATA: 4.512 PPM
            LOWEST VALUE IN DATA: 4.282 PPM
         UPPER CONTROL LIMIT (+ 2 Sigma): 4.890 PPM
         LOWER CONTROL LIMIT (– 2 Sigma): 3.910 PPM

Comparison average verses certified value: 0.000 PPM

Figure 4. 1 kΩ Build Up from 100 Ω.

RESISTOR DATA:
                NOMINAL RESISTANCE = 10 kilohm(s)
            ACTUAL CERTIFIED VALUE = 4.2 PPM (10,000.042)
                EXPANDED UNCERTAINTY = 0.50 PPM

DATA STATISTICS:
            DEVIATION FROM NOMINAL OHM FOR: 10K_OHMU

                    MEAN OF DATA: 4.593 PPM
                STANDARD DEVIATION: 0.044 PPM

                    STARTING DATE: 27 Apr 2005
                    ENDING DATE: 30 Apr 2005
                HIGHEST VALUE IN DATA: 4.297 PPM
                LOWEST VALUE IN DATA: 4.210 PPM
        UPPER CONTROL LIMIT (+ 2 Sigma): 4.700 PPM
        LOWER CONTROL LIMIT (− 2 Sigma): 3.700 PPM

Comparison average verses certified value: 0.393 PPM

Figure 5. 10 kΩ Build Up from 1 kΩ.

6. Uncertainty Analysis

While the results show the build ups from 1 Ω to 10 kΩ, this uncertainty analysis will show the uncertainties of measurements starting at 10 kΩ and building down to 1 Ω which gives the best uncertainties over the greatest range. The descriptions of the uncertainty components are divided into three parts. The components associated with the transfer uncertainty of the 8508A. The components associated with OhmRef Method 1B. Finally, the reference resistor and the combination of build up or build down transfers are discussed.

Table 1. Fluke 8508A uncertainty components.

8508A Range	Reference Nominal	UUT Nominal	8508A Transfer Uncertainty (20min)		8508A Measurement Uncertainty		Degrees of Freedom
			µΩ/Ω Reading	µΩ/Ω Range	Reference µΩ/Ω (U_{RM})	UUT µΩ/Ω (U_{UM})	
20	10	1	0.8	0.7	2.2	14.8	200
200	100	10	0.2	0.15	0.5	3.2	200
2,000	1,000	100	0.2	0.15	0.5	3.2	200
20,000	10,000	1,000	0.2	0.15	0.5	3.2	200
				Type	B	B	
				Distribution	Normal	Normal	
	Confidence Limit (C.L.) or Coverage Factor (C.F.)				95%	95%	

Table 1 shows the uncertainty components coming from the Fluke 8508A. The 8508A is set up to use the ratio mode for these measurements so the Transfer Uncertainty was used. The 8508A Transfer Specification uses both µΩ/Ω of reading and µΩ/Ω of range specifications. These were combined and computed separately for both the reference and UUT resistors. For example, the 10 Ω UUT is measured using the 200 Ω Range which has a 0.15 µΩ/Ω of range specification and 0.2 µΩ/Ω of reading specification. The 10 Ω UUT will have an uncertainty of 3.2 µΩ/Ω ([0.15 µΩ/Ω of 200 is 0.00003 Ω + 0.2 µΩ/Ω of 10 is 0.000002 Ω] / 10 * 1E+6 = 3.2). The uncertainty contribution for the 8508A is listed under the columns labeled 8508A Measurement Uncertainty, one column for the Reference resistance measurement and another column for the UUT resistance measurement. The degrees of freedom for these specifications were infinite. In the Fluke Primary Standards Lab we enter 200 for any degrees of freedom that are infinite.

Table 2. OhmRef uncertainty components.

UUT Nominal	Effect of 1E+12 Ω leakage		Degrees of Freedom	OhmRef Method 1B Type A µΩ/Ω (U_A)	Degrees of Freedom	Transfer Combined Uncertainty µΩ/Ω	Effective Degrees of Freedom
	Ref µΩ/Ω (U_{RL})	UUT µΩ/Ω (U_{UL})					
1	0.00	0.00	200	0.20	4	7.5	209
10	0.00	0.00	200	0.13	5	1.6	212
100	0.00	0.00	200	0.11	5	1.6	211
1,000	0.01	0.00	200	0.04	4	1.6	210
Type	B	B		A		B	
Distribution	Normal	Normal		Normal		Normal	
C.L. or C.F.	95%	95%		1		1	

Table 2 shows the uncertainty components associated with OhmRef Method 1B. Data Proof Scanners have a thermal EMF specification of 50nV but is typically 20nV. Because the 8508A is in the TruOhm mode for measurements below 20 kΩ, the 8508A reverses the current through the resistors during the measurement process, reducing the thermal EMFs to negligible levels. The first two columns contain the uncertainty caused by the specified leakage resistance of 1E+12 Ω. Again, like the 8508A section, the uncertainty for measurements of reference resistors and UUT resistors are listed separately. The next component is the Type A component. In this case, we have chosen to show the standard deviation of repeated measurements. For example, the 100 Ω UUT Type A was determined by repeating the measurement six times and determining the standard deviation of the six reported values. This shows the excellent repeatability of the entire system. Another approach would be to use the standard deviation listed on the software report. The column labeled Transfer Combined Uncertainty is the combination of all the components we've discussed so far. Essentially, this column has the normalized, relative specification of the resistance measurement system.

Table 3. Final combination of uncertainty components.

UUT Value	Standard Resistor Uncertainty μΩ/Ω (U_{STD})	Degrees of Freedom	Combined Uncertainty μΩ/Ω (U_C)	Effective Degrees of Freedom	Expanded Uncertainty μΩ/Ω (U_E)
1	0.3	200	8.0	271	16
10	0.3	200	2.8	637	5.6
100	0.3	200	2.3	425	4.6
1,000	0.3	200	1.6	214	3.3
Type	B		B		B
Distribution	Normal		Normal		Normal
C.L. or C.F.	95%		1		95%

Table 3 shows the combination of the Transfer Combined Uncertainty with that of the Standard Resistor. This brings the uncertainty from a relative relation to an absolute value. In our example we are using the uncertainty of an ESI SR 104 10 kΩ resistor calibrated by the Fluke Primary Lab as our standard. This resistor is the starting point for all measurements. If measuring a 1 kΩ resistor, the Transfer Combined Uncertainty for the 1 kΩ UUT is combined with the Standard Resistor Uncertainty. However, if you are going to measure a 10 Ω resistor then you must combine the Transfer Combined Uncertainties of the 10 Ω UUT, 100 Ω UUT, 1 kΩ UUT and the Standard Resistor.

Below is the mathematical model for the 1 kΩ measurement. The components listed match those in tables 1 through 3 above. The expanded uncertainty is 2 times the combined uncertainty in this case because the effective degrees of freedom of the combined uncertainty is so high.

U_C = Combined uncertainty

$$Uc = \sqrt{\left(\frac{U_{RM}}{2}\right)^2 + \left(\frac{U_{UM}}{2}\right)^2 + \left(\frac{U_{RL}}{2}\right)^2 + \left(\frac{U_{UL}}{2}\right)^2 + \left(\frac{U_{STD}}{2}\right)^2 + U_A{}^2}$$

U_E = Expanded uncertainty
K = 2

$$U_E = k * U_C$$

7. Evaluation / Conclusion

The results of these measurements were well within the 1 µΩ/Ω goal for 10 Ω through 10 kΩ measurements and just above 1 µΩ/Ω for the 1 Ω to 10 Ω measurements. While the data so far is very encouraging, we should exercise caution before drawing conclusions from such a small number of data points.

The uncertainty of the OhmRef Method 1B is about half the uncertainty of the meter itself with the major contributor of the uncertainty the transfer uncertainty of the Fluke 8508A. With some work to characterize the transfer uncertainty of the 8508A in the OhmRef system the uncertainty could be reduced to improve the overall uncertainty of the system.

While the system's uncertainty could never approach the uncertainty of a current comparator, these initial measurements lead us to believe that achieving uncertainties close to 1 µΩ/Ω between 1 Ω and 10 kΩ are possible with a little additional work.

References
1) Kenneth L. Garcia; "AUTORES: Automated Resistance Maintenance Program",
MSCProceedings, January 1992
2) James A. Marshall and Thomas A Marshall; " Improving Automated Measurements for
Voltage, Resistance and Temperature", NCX *Proceedings,* August 199 I
3) Thomas A. Marshall and James A Marshall, Developing Resistance Measurement Software,
MSC Proceedings, January 1993
4) Fluke 8508A Digital Reference Multimeter Users Manual, July 2002
5) Data Proof Operating Manual & Service Manual For 160B, 164B, 320B Low Thermal
Scanners, 1984-2005
6) Data Proof Automated Resistance Maintenance Program User Manual, 1994-2005