New Developments in Resistance Measurement Systems

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ABSTRACT

Traditionally, DC resistance measurements to sub-ppm accuracy have been performed by using a number of discrete measurement, reference resistance and temperature bath devices that were manually connected together by the test technician. These devices may have been manually controlled or provided with automated control through data acquisition software. This paper describes developments in incorporating all of the necessary hardware components and data acquisition software into one integrated DC resistance measurement system. Automated methods for verifying the accuracy of the resistance measurement system and calibrating its working standard resistances against resistance standards traceable to National Standards are presented. Automated methods for testing special resistive devices are also presented.

1 INTRODUCTION

There is an increasing demand to provide automated turnkey solutions to the process of calibrating precision resistive devices, such as discrete reference resistors, decade boxes and transfer standards, and resistance measurement test equipment, such as automated resistance calibrators, in order to reduce running operating costs by simplification of the measurement process and by minimising user involvement. Specific applications for such automated systems are manufacturers of precision resistive devices and resistance measurement test equipment, and calibration laboratories that process large volumes of resistive devices, where the capital expenditure for such a system is justified by the resulting improvements in running operating costs. This paper describes the implementation of such an Automated Resistance Measurement System that includes a Computer System, Direct Current Comparator (DCC) Resistance Measurement Bridge, Current Range Extender, Matrix Scanners, Temperature Stabilized Air Bath, Environmental Monitor and Working Resistance Standards. These components can be physically integrated in a rack enclosure, except for the separately mounted Temperature Stabilized Air Bath and Environmental Monitor, while the Computer System is implemented using an off-the-shelf personal computer. The Computer System is provided with a data acquisition software program containing a graphic user's interface for the control and monitor of the other units in the system. The control and monitor communications between the Computer System and the other units is via an IEEE-488 General Purpose Interface Bus (GPIB). The DCC Resistance Measurement Bridge provides the actual measurement instrument. The Current Range Extender provides the capability to measure smaller resistance values and apply higher currents than could be supported by the DCC Resistance Measurement Bridge alone. The Matrix Scanners provide the capability to select a particular reference resistor and unknown resistor (i.e., the resistive device being measured or calibrated) from a series of resistive elements for the DCC

Resistance Measurement Bridge to compare for the resistance measurement. The Temperature Bath provides the means of stabilizing the temperature of the unknown resistor. The Environmental Monitor measures the ambient air temperature, humidity and air pressure in the vicinity of the unknown resistor. The reference resistors required to support the DCC Resistance Measurement Bridge across its full measurement range are provided by a Working Resistance Standards unit, which contains a set of permanently installed, temperature stabilized resistances. The Working Resistance Standards can, in turn, be automatically calibrated against a set of portable Reference Resistance Standards, which are only required for connection to the system for the duration of the calibration process of the Working Resistance Standards. These two sets of resistance standards can also be used to automatically perform a series of resistance ratio comparisons to verify the accuracy and integrity of the system. Thus, with Reference Resistance Standards acting as prime standards, that are traceable to National Standards, a fully traceable calibration of the Working Resistance Standards and system accuracy can be achieved. The data acquisition software is capable of performing a variety of automated tests and analysis, in addition to these calibration and verification tests. The typical system components configuration of the Automated Resistance Measurement System, with the associated resistors, is illustrated in Figure 1.

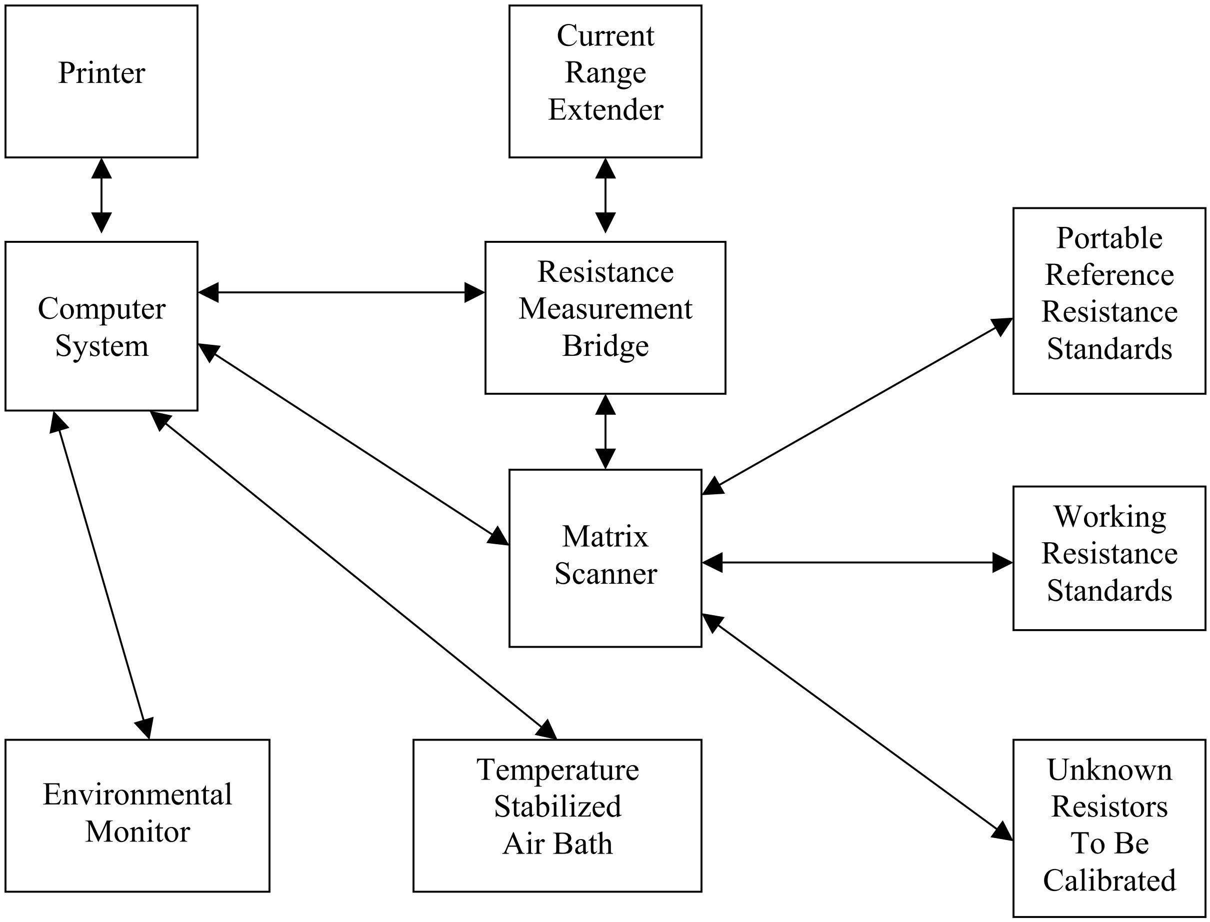

Figure 1. Automated Resistance Measurement System components configuration.

2 DCC RESISTANCE MEASUREMENT BRIDGE

The heart of an automated resistance measurement system is the measurement device itself. An automated Direct Current Comparator (DCC) Resistance Measurement Bridge with a communication link to a computer can be used. Enhancements to the existing model 6675A, as implemented in the model 6622, incorporate necessary features that are required to support automated measurements.

One enhancement has demonstrated that such a bridge can accurately measure Rx:Rs (unknown resistance : reference resistance) ratios from 1:1 to 100:1, with reduced accuracy for ratios less than 1:1, and measure resistance from 1m ohm to 100M ohm. Previously, the maximum achievable ratio was 13.4:1. In the new implementation, there are two ratio measurement ranges, 13.4:1 and 100:1. The range switching is achieved by selecting either 648 turns (13.4:1) or 81 turns (100:1) of servo winding and comparing this to up to 8747 turns of primary winding. Besides the ability to make a wider range of measurements using one reference resistor, 100:1 ratio measurements provide the means of performing verification checks of system accuracy, by allowing the performance of closure measurements, which compare a 100:1 ratio measurement with two equivalent laddered up 10:1 ratio measurements. As described in section 9, through the use of the data acquisition software, it is possible to mathematically invert an Rx:Rs measurement, with Rx:Rs = reference resistance : unknown resistance, to achieve accurate measurements for ratios as low as 0.01:1.

A second enhancement resulting from the use of bipolar power supplies provides independent current for each of the resistances being compared. This change results in manually adjusted lead compensation not being required for high ohms voltage mode measurements. This change also eliminates the need for a separate high voltage connection from the bridge in addition to the usual four wire connections for current and voltage. Thus, unnecessary manual adjustments and connections for the test set-up are avoided in an otherwise automatically performed test, and makes effective use of Matrix Scanners for selecting the resistors to be compared.

A third enhancement provides the capability to store calibration data for the DCC Resistance Measurement Bridge in its non-volatile memory. The data stored is the correction factor and calibration uncertainty for each necessary resistance ratio measurement versus the nominal reference resistance. The correction factor is used by the DCC Resistance Measurement Bridge to correct the resistance ratio of the measurement being performed. The calibration uncertainty is used by the data acquisition software as one of the factors, along with the uncertainty of the reference resistor and the random uncertainty of the measurement itself, to determine the total measurement uncertainty. The correction factor and calibration uncertainty for a ratio that is between two calibrated points are determined by mathematical interpolation.

A typical resistance measurement specification for an Automated Resistance Measurement System, that is capable of performing 100:1 maximum resistance ratio measurements, is as follows in Table 1. It has been demonstrated that only the DCC Resistance Measurement Bridge has a significant contribution to the system's relative uncertainty. All other system components, especially the Matrix Scanners and the interconnecting wiring, make a negligible contribution to the relative uncertainty. However, the composite system relative uncertainty can be determined during the calibration of the bridge in the system and accounted for in the calibration data stored in the bridge.

Table 1. Resistance measurement specification.

Unknown Resistance Range (Ohms)	Working Resistance Standard		Unknown Resistance Measurement	
	Value (Ohms)	Uncertainty (±ppm)	Relative Uncertainty (±ppm)	Total Uncertainty (±ppm)
0.001 to 0.01	1	0.4	99	≤100
0.01 to 0.1	1	0.4	9	≤10
0.1 to 1	1	0.4	0.6	≤1
1 to 10	1	0.4	0.1	≤0.5
10 to 100	1	0.4	0.1	≤0.5
100 to 1k	100	0.4	0.1	≤0.5
1k to 10k	100	0.4	0.1	≤0.5
10k to 100k	10k	0.4	0.35	≤0.8
100k to 1M	10k	0.4	0.5	≤0.9
1M to 10M	1M	8	0.75	≤9
10M to 100M	10M	17	2.5	≤20

The Total Uncertainty specification in Table 1 is based on the availability of 1 ohm, 100 ohm, 10k ohm, 1M ohm and 10M ohm Working Resistance Standards, of sufficient stability and environmental control to be calibrated periodically against Reference Resistance Standards. Refer to section 5. The uncertainties of the Working Resistance Standards in Table 1 are larger than those in Table 3, to account for the additional uncertainty resulting from using the Automated Resistance Measurement System itself to calibrate the Working Resistance Standards against the Reference Resistance Standards, as discussed in section 9.2.

Spare 0.1 ohm, 10 ohm, 1k ohm and 100k ohm Working Resistance Standards are required in support of the Working Set Calibration and System Verification, or, if desired, to perform resistance ratio measurements other than those specified in Table 1.

The Relative Uncertainty specification in Table 1 is the measurement uncertainty of the Automated Resistance Measurement System not including the uncertainty of the Working Resistance Standards. The Total Uncertainty of the Automated Resistance Measurement System is the sum of the uncertainty of the Working Resistance Standard and the Relative Uncertainty. More typically, the square root of the sum of the squares of the two uncertainites is used to determine the Total Uncertainty, and this can be optionally computed using the data acquisition software.

The Total Uncertainty specification in Table 1 is also based on the availability of 1 ohm, 10k ohm, 1M ohm and 100M ohm Reference Resistance Standards, which act as prime standards, with the uncertainties listed in section 6 that are traceable to National Standards, such as provided by the portable Reference Resistance Standards that are described in section 6, for the calibration of the Working Resistance Standards. The DCC Resistance Measurement Bridge along with all other devices in the system should conform to all of the common power and environmental requirements in Table 2.

Table 2. Common power and environmental requirements.

Parameter	Specification
Line Voltage Requirements:	100, 120, 220, 240 VAC +/- 10%
Line Frequency Requirements:	50, 60 Hz ±5%
Operating Ambient Temperature Range:	23° +/- 5°C
Storage Ambient Temperature Range:	-20° to +60°C
Operating Ambient Humidity Range:	20% to 50% RH
Storage Ambient Humidity Range:	15% to 80% RH

3 CURRENT RANGE EXTENDER

The Current Range Extender integrated into the system provides the extra current drive to measure lower resistance values (typically down to 1u ohm) and for measuring resistive devices which are normally expected to pass large currents, such as shunts. Larger currents beyond 150 mA typical, such as 2 A to 100 A used to measure down to 1u ohm, are not usually built into Resistance Bridges. Thus, a separate unit that can be controlled by the measurement process is required to achieve these lower value measurements. The use of a programmable bi-polar current supply along with a fixed direct current transformer ratio, to implement the Current Range Extender, is a proven method for measurement of these lower resistance values. Ideally the current supply and transformer circuit can be packaged together in a rack mountable unit and controlled by the DC Resistance Measurement Bridge directly. Using a larger (100 A) range extender will provide more current for better low unknown resistance measurement stability at the 1u ohm level. However, the current connections of a four-wire measurement must be connected outside of the matrix scanners. This is due to the limitation of how much current can be passed through most matrix switch devices, which is typically 2 A. Therefore, a smaller range extender can also be desirable, using the normal Matrix Scanner circuits of the system which are designed for 2 A capacity. This lower 2 A maximum current range extension capability is still effective down to at least 1m ohm and allows simpler connections for the unknown resistance.

4 MATRIX SCANNERS

The Matrix Scanners to be included in such a system must be of 4-wire switching capacity and have low thermal EMF (typically less than 100 nV), so as not to contribute to the uncertainty to the overall system. These scanners also provide very low leakage and sufficient current/voltage capacity (typically 150 mA – 2 A / 600 V unswitched maximum) for accurate measurements. A communication link to a computer allowing for automated switching of the Matrix Scanners is also required. The automatic switching provides the ability to connect many resistors and multi-resistance devices to the system, using the data acquisition software to set up test sequences. These sequences will automatically select the scanner channels for the desired resistors to be measured. Automating series of measurements in this fashion requires minimum user involvement only at the front end of the measurement sequence. Though the number of channels required for an application varies for each test, there must be adequate channels for the minimum of maintaining the system and standards used. This would typically take 13 channels for full automation of system verification and resistance calibration functions. However, it is recommended to have more channels to allow for other functions, especially for multi-element or multi-range resistance devices. Such devices with 16 switchable channels do exist and using two or more of them in parallel would supply sufficient spare channels to make the system truly effective.

The actual connections to the unknown resistance are provided by a set of test cables, extending from the system, that are permanently connected to the Matrix Scanners. These cables should use unfinished copper wire with high resistance insulation, such as polyethylene, to ensure low thermal EMF connections and negligible leakage. The wire should be sufficiently large, typically 18 AWG, to ensure that it will not be damaged for direct connection to the unknown resistance. Direct connections by unterminated wire give maximum flexibility for a variety of resistive device terminations. For multi-resistive devices, such as transfer standards, a special adapter should be provided which is permanently connected to a dedicated set of channels on a Matrix Scanner.

5 WORKING RESISTANCE STANDARDS

Traditionally, the maintenance of resistance standards at the sub-ppm level of uncertainty required the use of temperature stabilized oil baths. Instead, the Reference Resistance Standards and the Working Resistance Standards described herein can each be implemented with the necessary sub-ppm accuracy as integrated sets of resistors in their own temperature stabilized enclosures. These integrated sets of Resistance Standards operate in the normal lab environment. Thus, the Working Resistance Standards can be easily installed with the other components of the Automated Resistance Measurement System in an equipment rack. This approach to packaging the Resistance Standards offers lower acquisition and maintenance costs than use of discrete resistors and an oil bath, without complicating the calibration process.

The Working Resistance Standards unit should be rack mountable to allow easy integration in the Automated Resistance Measurement System. It has been demonstrated that such an instrument is capable of providing a set of up to at least nine precision resistance standards. Resistance values of 0.1 ohms, 1 ohms, 10 ohms, 100 ohms, 1k ohms, 10k ohms, 100k ohms, 1M ohms and 10M ohms can be provided. Optionally, it is expected that at least nine values could be specified from 0.1 ohm to 1G ohm, as applicable for other ranges of unknown resistance or resistance ratios. Each resistance element needs to be electrically isolated and provided with a 4 terminal connection. These connections should be located at the back panel to be suitable for equipment rack mount applications. The resistance elements are enclosed in an iso-thermal chamber, which is typically maintained by an internal heater circuit at 30°C, with a stability of +/- 0.01°C over a one year period. Provision for monitoring of the heater control circuit and the internal temperature is required, without introducing direct thermal bridges to the resistance elements. A corresponding internal cooling circuit is not required, as the Working Resistance Standards unit, along with the rest of the Automated Resistance Measurement System, is expected to operate in a laboratory environment with ambient temperatures of less than 28°C. For facilities with ambient temperatures that can exceed 28°C, the temperature set point can be changed to a higher level up to 40°C. The Working Resistance Standards unit should be powered on whenever possible, to optimize the short and long term stability of the resistances.

Typical technical specifications for the Working Resistance Standards that are known to be achievable are specified in Table 3. The specification for calibration uncertainty in Table 3 is based on the typical capability of a calibration facility. The uncertainty associated with long-term drift will be reduced significantly by use of historical data to extrapolate values between calibration intervals. As Table 3 shows, the temperature coefficients that can be achieved with this approach are equivalent to that which can be achieved using a temperature controlled oil bath, which can reduce the temperature coefficient uncertainties of traditional wire wound resistance standards from the range of 0.5 to 2 ppm per degree C to better than 0.01 ppm per degree C. Greater immunity to the ambient temperature environment will enhance the long term stability of the Working Resistance Standards.

Table 3. Working Resistance Standards technical specification.

Nominal Resistance Value (Ohms)	Nominal Tolerance (+/-PPM)	Calibration Uncertainty (+/-PPM)	Stability Over Any 24 Hour Period (+/-PPM)	Stability First 6 Months (+/-PPM)	Stability Next 12 Months (+/-PPM)	Temperature Coefficient (+/-PPM/°C)	Maximum Voltage (Volts)
0.1	10	0.5	0.1	4	3	0.01	0.1
1	10	0.3	0.005	3	2	0.005	0.32
10	10	0.3	0.005	3	2	0.005	1.0
100	10	0.3	0.005	3	2	0.005	3.2
1k	10	0.3	0.005	3	2	0.005	10
10k	10	0.3	0.005	3	2	0.005	32
100k	15	1	0.02	3	2	0.01	100
1M	25	7	0.04	6	7	0.02	320
10M	35	15	0.2	15	10	0.2	1000

6 PORTABLE REFERENCE RESISTANCE STANDARDS

The Reference Resistance Standards unit is a transportable version of the Working Resistance Standards unit and includes its design and packaging considerations, as described in section V. It has been demonstrated that such an instrument is capable of providing a set of up to at least four precision resistance standards. The instrument has been implemented with resistance values of 1 ohms, 10k ohms, 1M ohms and 100M ohms that are required to calibrate the Working Resistance Standards that are described in section V and verify system accuracy. Optionally, it is expected that any set of up to at least four values can be specified from 0.1 ohm to 1G ohm to be compatible with other ranges of Working Resistance Standards. Each resistance element needs to be electrically isolated and provided with a 4 terminal connection. The resistance elements are enclosed in an iso-thermal chamber, which is typically maintained by an internal heater circuit at 30°C, with a stability of +/- 0.01°C over a one-year period. A corresponding internal cooling circuit is not required, as the Reference Resistance Standards unit, like the Working Resistance Standards unit, is expected to operate in a laboratory environment with ambient temperatures of less than 28°C. For facilities with ambient temperatures that can exceed 28°C, the temperature set point can be changed to a higher level up to 40°C. An internal battery is required to provide power for and maintain the temperature of the unit for a period of up to 100 hours typical, depending on the environment, when transported from one site or workstation to another. The Reference Resistance Standards unit should be powered on whenever possible, to optimize the short and long term stability of the resistances. The unit must provide adequate immunity to shock and vibration during commercial carrier shipment to protect the stability of the resistances.

Typical technical specifications and general specifications for the Reference Resistance Standards that are known to be achievable are specified in Tables 4 and 5. The specification for calibration uncertainty in Table 4 is based on the typical capability of a calibration facility. The uncertainty associated with long-term drift will be reduced significantly by use of historical data to extrapolate values between calibration intervals. It is expected that the prime Reference Resistance Standards discussed herein will be calibrated against National Standards. A set of battery backed up, portable Reference Resistance Standards provides a mechanism for the transport of these standards from one location to another. This includes a National Laboratory or equivalent for calibration of the Reference Resistance Standards themselves. This results in the reduced possibility of thermal shock affecting their stability. Greater immunity to the ambient environment, including temperature, shock and vibration, will enhance the long-term stability of the Reference Resistance Standards.

Table 4. Reference Resistance Standards technical specification.

Nominal Resistance Value (Ohms)	Nominal Tolerance (+/-PPM)	Calibration Uncertainty (+/-PPM)	Stability Over Any 24 Hour Period (+/-PPM)	Stability First 6 Months (+/-PPM)	Stability Next 12 Months (+/-PPM)	Temperature Coefficient (+/-PPM/°C)	Maximum Voltage (Volts)
1	10	0.2	0.004	2	1.5	0.005	0.32
10k	10	0.2	0.004	2	1.5	0.005	32
1M	25	5	0.03	5	6	0.01	320
100M	50	18	0.5	18	21	0.3	1000

Table 5. Reference Resistance Standards general specification.

Parameter	Specification
Dimensions:	35 (D) x 28 (W) x 19 (H) cm [13.8 (D) x 11 (W) x 7.5 (H) inch]
Weight:	14 kg (30.8 lbs.)

7 TEMPERATURE STABILIZED AIR BATH

Provision of a Temperature Stabilized Air Bath (air bath) in the Automated Resistance Measurement System provides the capability to stabilize the temperature of the unknown resistor, where required to fulfil calibration requirements and to minimize its temperature related contribution to its resistance measurement uncertainty. The air bath provides the capability to temperature stabilize devices in the air that would normally require a constant temperature oil bath for temperature stabilization. It is required to provide precision, constant air temperature control with a variable temperature set point. It shall be possible to set the temperature within the air bath chamber of the air bath under the control of the data acquisition software program in the Computer System by means of an IEEE 488 bus (see section 9). Forced air circulation within the temperature controlled air bath chamber by fans ensures uniformity of temperature. Electrical cooling modules provide temperature control below the ambient room temperature, while incandescent lamps provide temperature control above the ambient room temperature. The air bath must be suitable for bench top use and incorporate an air bath chamber that is large enough to accommodate several resistive devices. It should typically be provided with a hinged, front access door for access to the air bath chamber by the user and a side access port for test lead entry into the air bath chamber. Temperature monitoring by the Environmental Monitor (see section 8) shall be by means of this side access port. The critical specifications for the Temperature Stabilized Air Bath are identified in Table 6.

Table 6. Temperature Stabilized Air Bath technical specification.

Parameter	Specification
Temperature Set Range:	+15°C to +50°C, with the restriction that it be no more than 6°C below the ambient room temperature
Set Point Temperature Accuracy (24 hours):	±0.06°C
Set Point Temperature Accuracy (1 year):	±0.08°C
Temperature Stability (24 hours):	±0.03°C
Temperature Stability (1 year):	±0.06°C
Ambient Temperature Attenuation:	±0.04°C/°C
Cold Power on Stabilisation Time to Specified Accuracy:	6 hours
Inside Dimensions of Air Bath Chamber:	61 (H) x 38.1 (W) x 35.6 (D) cm [24 (H) x 15 (W) x 14 (D) inches]
Outside Dimensions:	86.4 (H) × 53.3 (W) × 66.0 (D) cm [34 H × 21 W × 26 D inches]
Weight:	78 kg (172 lb.)

8 ENVIRONMENTAL MONITOR

The Environmental Monitor provides the capability of automatically recording the ambient environmental conditions of the unknown resistor. The ambient environmental conditions of interest are typically temperature, humidity and air pressure. A record of these conditions is typically required for calibration record purposes. They are also of use for the analysis of the affects of different environmental conditions on the unknown resistor. The core of the

Environmental Monitor is a data logger that is capable of accepting inputs from a variety of environmental sensors and transmitting the resulting data to the Computer System for integration and processing by the data acquisition software program. The data acquisition software program is required to correlate and save the environmental data with the resistance measurement test data. Thus, the maximum sampling rate of the data logger must be similar to the maximum sampling rate for the resistance measurement of the DCC Resistance Measurement Bridge, which is typically 2 seconds. At this speed, it is not necessary for the data logger speed to be as fast as the DCC Resistance Measurement Bridge, as the ambient environmental conditions do not change that quickly. However, it is desirable to have one to one correspondence for slower sample rates, such as 30 seconds. For the preparation of test reports, the data acquisition software program is required to automatically generate averages of the environmental measurements over the time period of the of the average resistance measurement.

A suitable data logger for this application is the SmartReader Plus 4™ that is manufactured by ACR Systems. The air pressure sensor is integrated into the main module of this data logger, while the temperature and humidity sensors are probes that are separately wired to it. This data logger is easily movable to the location of the unknown resistor. It communicates with the Computer System over a standard serial port. The critical specifications for this version of the SmartReader Plus 4™ that are applicable to the Automated Resistance Measurement System are identified in Table 7.

Table 7. Environmental Monitor technical specification.

Parameter	Specification
Air Pressure Measurement Range:	0 to 207 kPa ±0.5%
Humidity Measurement Range:	10% to 90% RH
Temperature Measurement Range:	-35° to +70°C ±0.5°C, except 0° to +70°C ±0.2°C
Maximum Sampling Rate:	25 samples per second
Sampling Method:	Continuous (for sample rate of 8 seconds minimum)
Resolution:	12 bit (1 part in 4096)
Operating Ambient Temperature Range (exclusive of temperature sensor):	-40 to +70°C
Operating Ambient Humidity Range:	0% to 95% RH
Dimensions:	10.7 (D) x 7.4 (W) x 2.2 (H) cm [4.2 (D) x 2.9 (W) x 0.9 (H) inch]
Weight:	110 gm (3.8 ounces)

9 DATA ACQUISITION SOFTWARE

9.1 General Requirements

The data acquisition software program provides a simple user interface at the system level. It provides the means to integrate all of the separate components into a single system. Having the software programmed to run in a globally accepted familiar environment such as Microsoft®

Windows 9X/NT™, helps create familiarity and ease of use. It has been demonstrated that the National Instruments™ LabVIEW™ data acquisition software provides a suitable operating environment for the real time application software program. This software program must be able to exploit all of the hardware capability within the system, but maintain the ability to be easy to use through a graphic user interface. Through the software program, full automation is achieved through remote commands sent over a communication link from a personal computer to all of the devices in the system. A common link used for this purpose is the IEEE 488 bus, allowing for up to 30 uniquely addressed devices to be all connected on the same communication link. This link is also used to retrieve data from the system to be processed into reports and analysed. As discussed in section 8, an exception to the use of the IEEE 488 bus is the use of a serial link for communication between the Environmental Monitor and the Computer System, which is a result of the available data logger for this application. The ability to retrieve the measurement data to process and generate reports is also a functional requirement to the software package. The software package must be flexible enough for the user to create custom tests and allow for custom processing of data. The program must allow control of all test parameters in the series of tests and be capable of exporting the test data to a program such as Microsoft® Excel for processing, give full control of all aspects of the tests conducted by the system.

As an example of how the software program simplifies the test process, when using the DCC Resistance Measurement Bridge with a specified accuracy from only 1:1 to 100:1 for Rx:Rs, the user can have the software automatically reverse measurements that are of ratios less than 1:1, so that a desired 0.1:1 ratio is actually electrically measured as 10:1. The software will display the reciprocal of the actual measurement, with the Rx, rather than the usual Rs, as the reference resistance. The end result is identical to the approach of measuring the 0.1:1 ratio directly, but instead the bridge is using the specified ratio range where superior performance is achieved.

Use of the software, as in the previous example, should remove such unnecessary manual tasks to optimise the user's time, improving productivity. The user can prepare and execute a sequence file that results in one or more resistance measurements being automatically performed and saved. In addition, through the use of various dedicated utilities, more common or standardized tasks can be simplified even further. Some common examples are explained in the next paragraphs. These procedures, within the real time application software program, has been demonstrated to remove a lot of the configuration and post-processing manual work involved in calibrating the full working set of resistors. In the real time application software program, resistor files can be created which specify the characteristics of each of the resistors used for Rx and Rs that are required for the test; in terms of resistance, uncertainty, test current, maximum current, test voltage and maximum voltage. The applicable resistor files are loaded to their associated Matrix Scanner channels via the Computer System to complete the definition of the test parameters for the test. Other potential procedures can address the test of specific resistance measurement test equipment, such as automated resistance calibrators.

9.2 Working Set Calibration

The following Working Set Calibration procedure is a simplified approach to calibrating a full set of Working Resistance Standards from 1 ohm to 10M ohms, by using the Automated Resistance Measurement System and the Reference Resistance Standards to perform a series of measurements. The methodology of this procedure can be changed to be compatible with other resistance values. Upon completion, the Working Set Calibration utility will generate a report so that the data can be reviewed for acceptance or rejection of the test results and update of the Rx resistor files.

The following Figure 2 illustrates and Table 8 describes the test variables for the predetermined test schedule for the complete calibration of the Working Resistance Standards used by the Automated Resistance Measurement System. The sample depth and the number of samples used for the calculations are predetermined based on the performance of the Automated Resistance Measurement System (for example, take 100 readings for a test, with only the last 50 readings used for the calculations). This allows proper settling time to acquire the quality of measurement as specified for the Automated Resistance Measurement System. The test variables in Table 8 can be changed accordingly to match other resistance values.

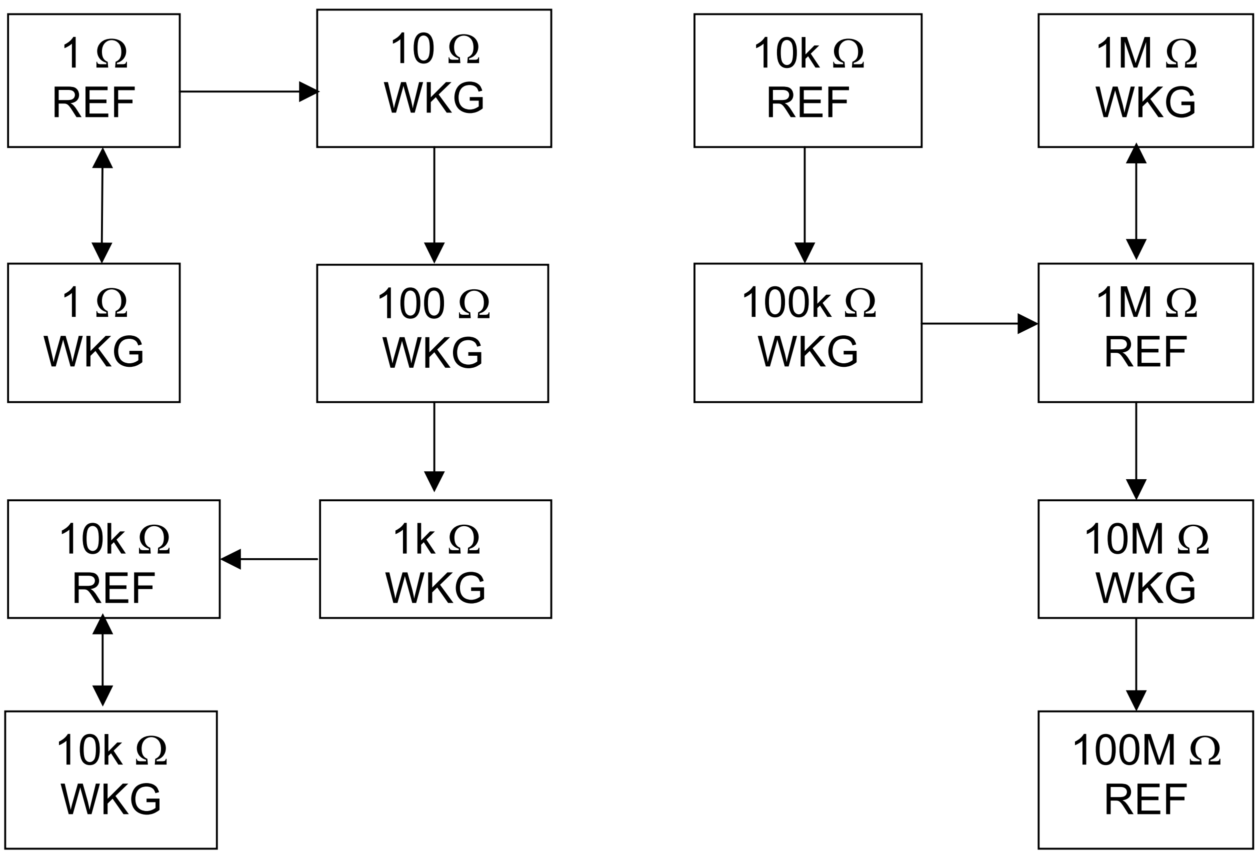

Figure 2. Automated working set calibration block diagram.

Table 8. Working set calibration test schedule.

Rx (Ω)	Rs (Ω)	Typical Rx Excitation Current/Voltage	Ratio / Comment
10 ws (ch. 18)	1 ref (ch. 13)	10 mA	R_1 / Calibrate 10 ws and 100 ws
100 ws (ch. 19)	10 ws (ch. 18)	3 mA	R_2 / Calibrate 100 ws
10k ref (ch. 14)	1k ws (ch. 20)	0.3 mA	R_3 / Calibrate 1k ws
1k ws (ch. 20)	100 ws (ch. 19)	1 mA	R_4 / Closure on 100 ws
1 ws (ch. 17)	1 ref (ch. 13)	100 mA	R_5 / Calibrate 1 ws
1 ref (ch. 13)	1 ws (ch. 17)	100 mA	R_6 / Calibrate 1 ws
10k ws (ch. 21)	10k ref (ch. 14)	1 mA	R_7 / Calibrate 10k ws
10k ref (ch. 14)	10k ws (ch. 21)	1 mA	R_8 / Calibrate 10k ws
100k ws (ch. 22)	10k ref (ch. 14)	0.1 mA	R_9 / Calibrate 100k ws
1M ref (ch. 15)	100k ws (ch. 22)	30 V	R_{10} / Closure on 100k ws
1M ws (ch. 23)	1M ref (ch. 15)	100 V	R_{11} / Calibrate 1M ws
1M ref (ch. 15)	1M ws (ch. 23)	100 V	R_{12} / Calibrate 1M ws
10M ws (ch. 24)	1M ref (ch. 15)	100 V	R_{13} / Calibrate 10M ws
100M ws (ch. 25)	10M ws (ch. 24)	300 V	R_{14} / Closure on 10M ws

Notes:

1. In Table 8, “ref” refers to a Reference Resistance Standard and “ws” refers to a Working Resistance Standard.
2. In Table 8, the channel numbers (i.e., ch. 13) are examples only of the channel number of the Matrix Scanner to which that particular Working or Reference Resistance Standard is connected.

When using 1:1 resistance ratio measurements, both the measurement against the applicable Reference Resistance Standard (Rx:Rs ratio) and the corresponding interchange ratio measurement (Rs:Rx ratio) are used to determine the measured resistance value of the Working Resistance Standard. As both measurements are equally accurate, this removes systemic measurement error. When using non-1:1 resistance ratio measurements (typically 10:1), the measurement against the more accurate Reference Resistance Standard for which the Automated Resistance Measurement System typically provides the most accurate measurement is used to determine the value of the Working Resistance Standard. Another measurement of the resistance value of the Working

Resistance Standard using a different Reference Resistance Standard is performed as a closure check to verify the accuracy of the first measurement.

The first stage of the Working Set Calibration is to measure the 100 ohm Working Resistance Standard against the 1 ohm Reference Resistance Standard through calibration of the 10 ohm Spare Working Standard Resistor. Then, the 100 ohm Working Resistance Standard is also measured in from the 10k ohm Reference Resistance Standard through calibration of the 1k ohm Working Resistance Standard to have a closure. The closure for this series of measurements is determined by the agreement, within the uncertainties, of the two measured values of the 100 ohm Working Resistance Standard.

Note that in the following formulas, R_1 through R_{14} are the measured resistance ratios listed in Table 5, Raws is the working standard (ws) resistance and Raref is the reference standard (ref) resistance, where ‘a’ is the nominal resistance value in ohms.

The value of the 10 ohm Working Resistance Standard is calculated by,

$$R_{10ws} = R_1 \times R_{1ref} \qquad (1)$$

The value of the 100 ohm Working Resistance Standard is calculated by,

$$R_{100ws} = R_1 \times R_2 \times R_{1ref} \qquad (2)$$

The value of the 1k ohm Working Resistance Standard is calculated by,

$$R_{1kws} = \tfrac{1}{R_3} \times R_{10kref} \qquad (3)$$

The closure of the 100 ohm Working Resistance Standard measurement, which includes the 10 ohm and 1k ohm Working Resistance Standards as well, is calculated by,

$$e_c = |\,(R_1 \times R_2 \times R_{1ref}) - (\tfrac{1}{R_3} \times \tfrac{1}{R_4} \times R_{10kref})\,| \qquad (4)$$

The second stage of the Working Set Calibration is to measure the 1 ohm Working Resistance Standard against the 1 ohm Reference Resistance Standard. The closure for this series of measurements is based on the interchange of the two measured values of the 1 ohm Working Resistance Standard.

The value of the 1 ohm Working Resistance Standard is calculated by,

$$R_{1ws} = [(R_5 + \tfrac{1}{R_6}) \times R_{1ref}] \div 2 \qquad (5)$$

The closure of the 1 ohm Working Resistance Standard measurement is calculated by,

$$e_c = |\,(\tfrac{1}{R_6} \times R_{1ref}) - (R_5 \times R_{1ref})\,| \qquad (6)$$

The third stage of the Working Set Calibration is to measure the 10k ohm Working Resistance Standard against the 10k ohm Reference Resistance Standard. The closure for this series of measurements is based on the interchange of the two measured values of the 10k ohm Working Resistance Standard.

The value of the 10k ohm Working Resistance Standard is calculated by, $R_{10kws} = [(R_7 + \frac{1}{R_8}) \times R_{10kref}] \div 2$ (7)

The closure of the 10k ohm Working Resistance Standard measurement is calculated by, $e_c = |(\frac{1}{R_8} \times R_{10kref}) - (R_7 \times R_{10kref})|$ (8)

The fourth stage of the Working Set Calibration is to measure the 100k ohm Working Resistance Standard against the 10k ohm Reference Resistance Standard. The 100k ohm Working Resistance Standard is then verified through a closure measurement against the 1M ohm Reference Resistance Standard. The closure for this series of measurements is determined by the agreement, within the uncertainties, of the two measured values of the 100k ohm Working Resistance Standard.

The value of the 100k ohm Spare Working Resistance Standard is calculated by, $R_{100kws} = R_9 \times R_{10kref}$ (9)

The closure of the 100k ohm Spare Working Resistance Standard is calculated by, $e_c = |(\frac{1}{R_{10}} \times R_{1Mref}) - (R_9 \times R_{10kref})|$ (10)

The fifth stage of the Working Set Calibration is to measure the 1M ohm Working Resistance Standard against the 1M ohm Reference Resistance Standard. The closure for this series of measurements is based on the interchange of the two measured values of the 1M ohm Working Resistance Standard.

The value of the 1M ohm Working Resistance Standard is calculated by, $R_{1Mws} = [(R_{11} + \frac{1}{R_{12}}) \times R_{1Mref}] \div 2$ (11)

The closure of the 1M ohm Working Resistance Standard is calculated by, $e_c = |(\frac{1}{R_{12}} \times R_{1Mref}) - (R_{11} \times R_{1Mref})|$ (12)

The sixth and last stage of the Working Set Calibration is to measure the 10M ohm Working Resistance Standard against the 1M ohm Reference Resistance Standard. The 10M ohm Working Resistance Standard is then verified through a closure measurement against the 100M ohm Reference Resistance Standard. The closure for this series of measurements is determined by the agreement, within the uncertainties, of the two measured values of the 10M ohm Working Resistance Standard.

The value of the 10M ohm Working Resistance Standard is calculated by,
$R_{10Mws} = R_{13} \times R_{1Mref}$ (13)

The closure of the 10M ohm Working Resistance Standard is calculated by,
$e_c = |(\frac{1}{R_{14}} \times R_{100Mref}) - (R_{13} \times R_{1Mref})|$ (14)

For the Working Resistance Standard resistance values determined by the 1:1 resistance ratio interchanges, the corresponding calculated uncertainty is the sum of the Reference Resistance Standard uncertainty and the random component of measurement uncertainty. The Automated Resistance Measurement System calibration uncertainty does not have to be accounted for in this case, as 1:1 resistance ratio interchanges intrinsically account for this factor, since the same ratio is being measured twice in a short time period. Thus, the difference in the two ratios already fully includes the measure of the error induced by the measurement system. For the Working Resistance Standard resistance values determined by non-1:1 resistance ratio measurements (typically 10:1), the corresponding calculated uncertainty is the sum of the Reference Resistance Standard uncertainty, the Automated Resistance Measurement System calibration uncertainty and the random component of measurement uncertainty. These calculated uncertainties could be either the direct sum or the RMS sum of the contributing uncertainty factors, depending on the calibration requirements.

The uncertainty of the Reference Resistance Standard, like its measured resistance value, is determined by calibration that is traceable to National Standards. It is obtained by the data acquisition software from the corresponding resistor file.

The uncertainty of the Automated Resistance Measurement System is determined by separate calibration of the system itself. It is obtained by the data acquisition software from the system calibration information stored in the DCC Resistance Measurement Bridge.

The random component of measurement uncertainty is typically two times the standard deviation of the measurement. The standard deviation is computed using the following formula:

Standard Deviation, $\sigma_x = \sqrt{\frac{1}{n}\sum_{i=0}^{n-1}(x_i - \mu)^2}$ (15)

Where the Measurement Mean, $\mu = \frac{1}{n}\sum_{i=0}^{n-1} x_i$ (16)

And n is the number of elements of the measurement samples, x.

The accuracy of the measured resistance value of each Working Resistance Standard can be verified by checking that the corresponding closure is no greater than the sum of the calculated uncertainties of its two measured resistance values. Failure of this check will indicate to the user that either the Automated Resistance Measurement System has performed inaccurate measurements, or that the calibration of one or more of the Reference Resistance Standards is no longer valid.

9.3 System Accuracy Verification

Calibration of a resistance measurement system involves three steps. These are initial alignment, calibration and calibration verification. The Verification procedure is a simplified approach to performing this last step, by verifying the performance of a Resistance Measurement System that is capable of 100:1 ratio measurements, exclusive of the calibration of the Working Resistance Standard itself. The methodology of this procedure can be changed to be compatible with other resistance values. Upon completion, the Verification utility will generate a report so that the data can be reviewed for determining the validity of the Automated Resistance Measurement System's calibration.

The following Figure 3 gives sample illustrations of an interchange test and a closure test, while Table 9 describes the test variables, for the predetermined test schedule for the complete verification of the Automated Resistance Measurement System. The sample depth and the number of samples used for the calculations are predetermined based on the performance of the Automated Resistance Measurement System (for example, take 100 readings for a test, with only the last 50 readings used for the calculations). This allows proper settling time to acquire the quality of measurement as specified for the Automated Resistance Measurement System. The test variables in Table 9 can be changed accordingly to match other resistance values.

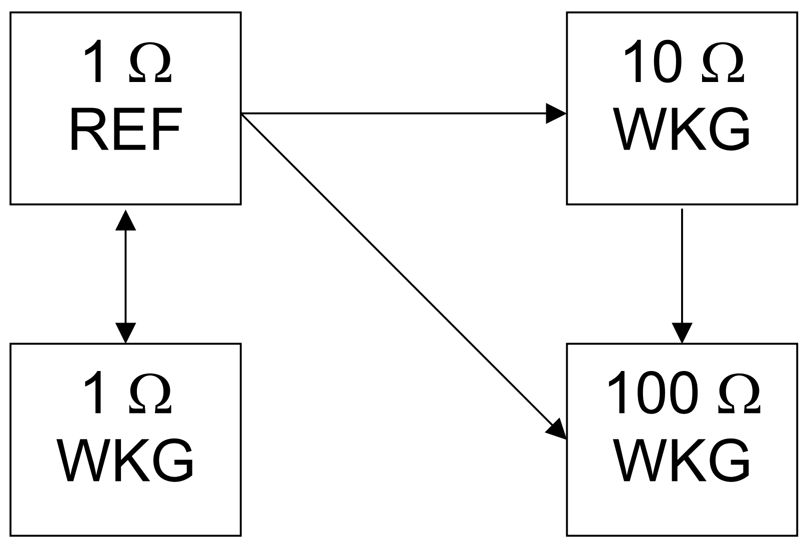

Figure 3. Sample system accuracy verification block diagram.

Table 9. Verification test schedule.

Meas. No.	R_X		R_s		Typical Rx Excitation Current/Voltage
	Resistor	Channel	Resistor	Channel	
1	0.1 Ω	26	1 Ω	13	140 mA
2	1 Ω	13	0.1 Ω	26	14 mA
3	1 Ω	17	1 Ω	13	100 mA
4	1 Ω	13	1 Ω	17	100 mA
5	10k Ω	21	10k Ω	14	1 mA
6	10k Ω	14	10k Ω	21	1 mA
7	1M Ω	23	1M Ω	15	100 V
8	1M Ω	15	1M Ω	23	100 V
9	10 Ω	18	1 Ω	13	14 mA
10	100 Ω	19	10 Ω	18	4.2 mA
11	100 Ω	19	1 Ω	13	1.4 mA
12	1k Ω	20	100 Ω	19	1.4 mA
13	10k Ω	14	1k Ω	20	0.42 mA
14	10k Ω	14	100 Ω	19	0.14 mA
15	100k Ω	22	10k Ω	14	0.14 mA
16	1M Ω	15	100k Ω	22	42 V
17	1M Ω	15	10k Ω	14	14 V
18	10M Ω	24	1M Ω	15	140 V
19	100M Ω	16	10M Ω	24	420 V
20	100M Ω	16	1M Ω	15	140 V

Notes:

1. In Table 9, "ref" refers to a Reference Resistance Standard and "ws" refers to a Working Resistance Standard.
2. In Table 9, the channel numbers (i.e., ch. 13) are examples only of the channel number of the Matrix Scanner to which that particular Working or Reference Resistance Standard is connected.
3. It has been demonstrated that even with the different power levels applied to the same Rx as described in Table 9, using the Working and Portable Resistance Standards described herein, it is possible to achieve the following interchange and closure errors, which are based on the relative uncertainties of the system that are specified in Table 1.

For each resistor pair, the software will calculate and report the interchange error. For example, if the Rx:Rs ratio of the first measurement is R_a and the Rx:Rs ratio of the second measurement, where the two resistors are exchanged with one another, is R_b, then the interchange error e_i in ppm of the nominal ratio is:

$$e_i = (1/2) \times \left| R_a \times R_b - 1 \right| \times 10^6 \qquad (17)$$

Note that the interchange or closure error, e_i, for this Verification is similar to the closure error, e_c, for the Working Set Calibration, except that e_c includes the uncertainty of the reference resistor as well.

The typical maximum allowable interchange errors (ppm) for resistor pairs are specified in Table 10.

Table 10. Maximum allowable interchange errors for resistor pairs.

Resistor	Resistor	Interchange Error (±ppm)
0.1 Ω	1 Ω	0.9
1 Ω	1 Ω	0.1
10k Ω	10k Ω	0.1
1M Ω	1M Ω	0.8

For the 100:1 closures, the 100:1 ratio must agree to within the specification of the nominal ratio for either directly measuring the 100:1 ratio, or calculating the ratio from the product of the 100:10 ratio and the 10:1 ratio, as follows:

$$e_i = (1/3) \times \left| R_a - R_b \times R_c \right| / 100 \times 10^6 \qquad (18)$$

Where:

R_a is the 100:1 ratio
R_b is the 100:10 ratio
R_c is the 10:1 ratio

The typical maximum allowable closure errors (ppm) for resistor sets are specified in Table 11.

Table 11. Maximum allowable closure errors for resistor sets.

Resistor	Resistor	Resistor	Closure Error (±ppm)
1 Ω	10 Ω	100 Ω	0.1
100 Ω	1k Ω	10k Ω	0.1
10k Ω	100k Ω	1M Ω	0.5
1M Ω	10M Ω	100M Ω	2

9.4 Decade Box Calibration

The Decade Box Calibration procedure is a simplified approach to calibrating a decade box resistance device using an Automated Resistance Measurement System that is capable of 100:1 ratio measurements. The methodology of this procedure can be changed by the user to be compatible with any decade range. In the real time application software program, profiles of the decade box can be created and stored to outline the ranges, characteristics, and pass criteria of a given decade box type. The applicable reference resistor files are loaded to their associated Matrix Scanner channels via the Computer System and the user is prompted to select manually on the decade box each value to be tested. Upon completion, the Decade Box Calibration program will generate a report so that the data can be reviewed for determining the calibration of the decade box.

9.5 Transfer Standard Calibration

The Transfer Standard Calibration procedure is a simplified approach to calibrating a transfer standard resistance device using a Resistance Measurement System. This generally requires considerable wiring and can be assisted through the use of pre-assembled adapters that can be indexed via the scanners. The adapter for ESI's SR1010 series of resistors already exists. The methodology of this procedure can be changed to be compatible with any resistance value or quantity of elements in the transfer standard. The applicable reference resistor files are loaded to their associated Matrix Scanner channels via the Computer System and the transfer standard is then automatically tested. If the transfer standard is of the type that requires, like a decade box, manual changes, then the user is prompted to manually select on the transfer standard each value to be tested. Upon completion, the Transfer Standard Calibration program will generate a report so that the data can be reviewed for determining the calibration of the transfer standard.

10 CONCLUSION

An Automated Resistance Measurement System can integrate all of the essential components required to perform DC resistance measurements. Such an integrated system provides a turnkey approach that simplifies the performance of DC resistance measurements to sub ppm accuracy with a minimum of set up. Sets of integrated, temperature stabilized Resistance Standards eliminate the need for oil bath temperature stabilized resistance standards or other discrete wired resistance standards of comparable performance. A set of battery backed up, portable Reference Resistance Standards provides a mechanism for the transport of these standards from one location to another, with reduced possibility of thermal shock affecting their stability, for the calibration of the corresponding set of the Working Resistance Standards described herein. Greater immunity to the ambient environment, including temperature, shock and vibration, will enhance the long term stability of the Resistance Standards. Provision of a Temperature Stabilized Air Bath provides the capability to stabilize the temperature of the unknown resistor, in order to achieve stable ambient temperature requirements where required for calibration and to minimize its temperature related contribution to its resistance measurement uncertainty. An Environmental Monitor provides the capability of recording the ambient environmental conditions of the unknown resistor for calibration record purposes and to allow analysis of the affects of different environmental conditions on the unknown resistor. The computerized control of the system through the use of a dedicated data acquisition software program results in the ability of the user to perform automated measurements required for calibration and accuracy verification of the system itself, as well as general and specialized resistance measurements, historical analysis and preparation of calibration reports with minimal user involvement. This results in equivalent performance to existing discrete test set-ups; with lower attainable acquisition, set up, maintenance and running costs. This is of particular benefit to manufacturers of precision resistive devices and resistance measurement test equipment, and calibration laboratories that process large volumes of resistive devices, where the capital expenditure for such a system is justified by the resulting improvements in running operating costs.

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