Using High Resistance Meters Effectively

Speaker: Behnam Dizaji
Authors: Behnam Dizaji, Nick Allen, and Lawrence Heal
Guildline Instruments Limited
P.O. Box 99, 21 Gilroy Street
Smiths Falls, Ontario, Canada, K7A 4S9
Phone: (613) 283-3000; Fax: (613) 283-6082
E-mail: sales@guildline.ca

ABSTRACT

You have a high resistance meter (typical measurement range of 1 megaohm to 100 petaohm), but want to obtain more repeatable resistance measurements from it. This paper describes new developments in the features of high resistance meters that improve the meter's measurement uncertainty. However, to make effective use of such a meter, the operator must follow stringent measurement procedures to minimize total measurement uncertainty. Appropriate measurement techniques are presented to characterize the performance of the meter and to use the meter effectively to perform resistance measurements or calibrations.

1   INTRODUCTION

The total measurement uncertainty for a high resistance measurement can be divided into three categories:

1) inherent uncertainties
2) environmental factors
3) measurement methods

The inherent uncertainties are the specified or calibrated uncertainties of the high resistance meter and, if applicable, the reference resistor. The environmental factors are the result of the affect of variances in the ambient environment on the test setup and specified changes in the electrical value that can be expected to occur from defined environmental conditions. The measurement methods themselves can have a significant affect on the noise level and the actual mean value of the measurement. Methods to minimize the effects of these three uncertainty categories, including improvements in the design of high resistance meters, along with best measurement practices, in the performance of high resistance measurements are presented.

2   PRESENT MEASUREMENT CIRCUIT

A typical, presently available, high resistance meter design is first presented. The Guildline Model 6500A Digital Teraohmmeter is a microprocessor based, fully automated, high precision device for measuring high value resistors or very small DC currents. The simplified block diagram of Figure 1 details the major components of the Digital Teraohmmeter.

When measuring resistance, a known DC test voltage is supplied by the model 6500A, which causes a current to flow through the unknown resistor into an integrator. The magnitude of this current is determined by the time required for the integrator output to pass between two different threshold voltage points. Knowing the test voltage and magnitude of the current, the microprocessor can determine the value of the unknown resistor. The test voltage is selectable from 10 standard values in the range ±1 to ±1000 volts. The standard values are 1, 2, 5, 10, 20, 50, 100, 200, 500, and 1000 volts.

Unknown currents can be measured by connecting the unknown current source output directly to the integrator input (the internal test voltage source is not used when measuring currents).

The stability of the model 6500A depends on the stability of the applied test voltage, the integrator, the timing circuit and the threshold voltage detector at the integrator output. Fixed errors in the absolute values of these parameters are compensated during calibration by using a software calibration routine in conjunction with a set of external calibration reference resistors of known value.

The model 6500A is fully automated with an internal microprocessor to compute the measurements and make the error compensations. The calculated value of the unknown resistor is displayed on the front panel and is made available to instruments attached to the control bus. The microprocessor can be operated from the front panel manual controls or from either one of the two communication control buses (GPIB or RS-232C). When measuring resistance, a front panel selectable option allows the model 6500A to provide increased accuracy by automatically computing the average of four sequential measurements made with test voltage polarity alterations. The computer average is displayed on the front panel and is made available to instruments on the control bus.
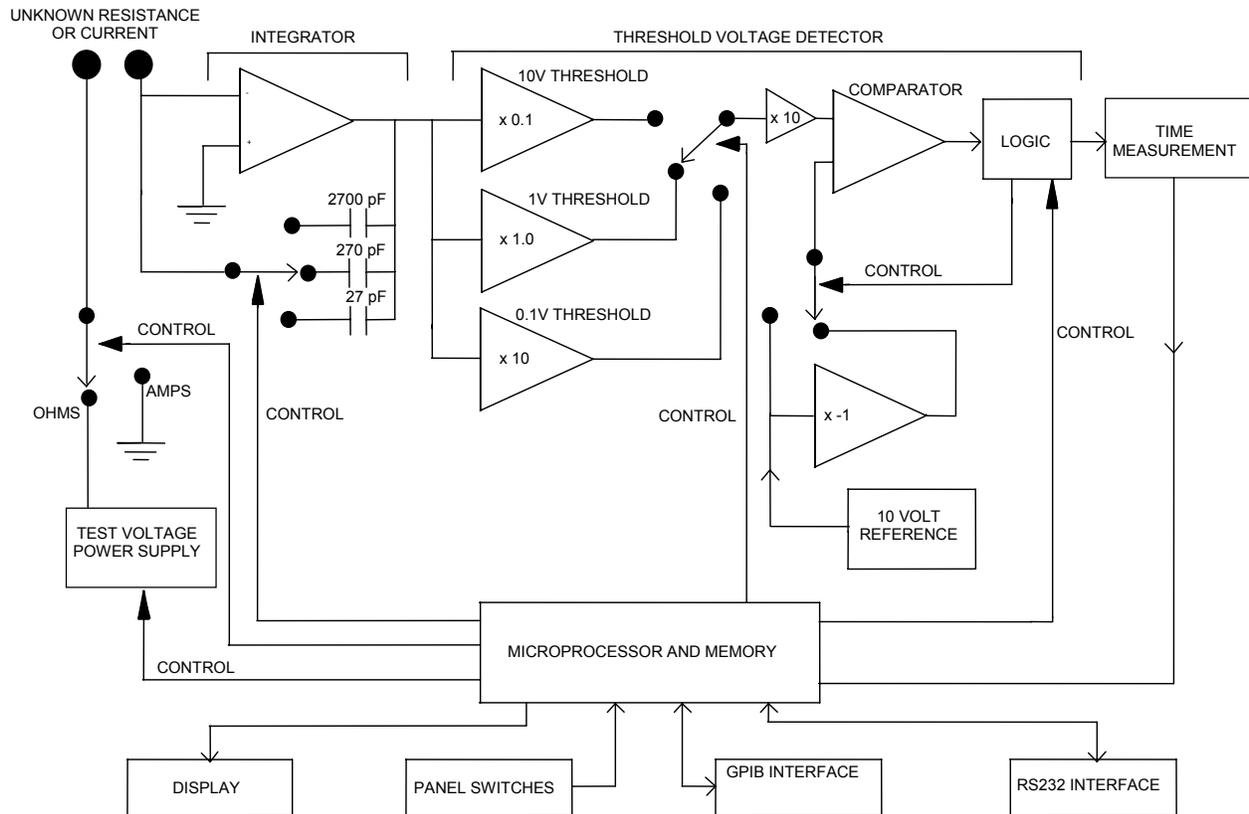
Figure 1. Model 6500A Digital Teraohmmeter block diagram.

The model 6500A measures high values of resistance by charging a small capacitor through the resistance to be measured. An operational integrator of the model 6500A is shown in Figure 2. The equations for this integrator are as follows:

$$\frac{\text{delta } V_{out}(t)}{\text{delta } t} = \frac{V_{in}}{R * C} \qquad \text{(The equality is not exact, but is extremely close when the voltage gain is high)} \qquad (1)$$

or:

$$R = \frac{V_{in} \text{ x delta } t}{C * \text{delta } V_{out}} \qquad (2)$$

Where delta t = a change in time and delta V_{out} = a change in output voltage V_{out} over time delta t.

When current is being measured, V_{in} can be replaced by iR which simplifies (1) to the form:

$$i = \frac{C * \text{delta } V_{out}}{\text{delta } t} \qquad (3)$$

In the model 6500A:

V_{in} is the test voltage for resistance measurement.

C is a stable capacitor selected from the nominal values of 27 pF, 270 pF & 2700 pF.

delta V_{out} is the potential difference between two threshold voltages placed symmetrically above and below ground ($V_{out} = 2 * V_{thresh}$, where V_{thresh} is selectable from 0.1 volt, 1 volt and 10 volts).

In equations (2) and (3), all terms are constant except R, i and delta t. Therefore, delta t is proportional to R or inversely proportional to the current i. During normal operation, the model 6500A calculates the unknown resistance R or current i by taking measurements of the time delta t.
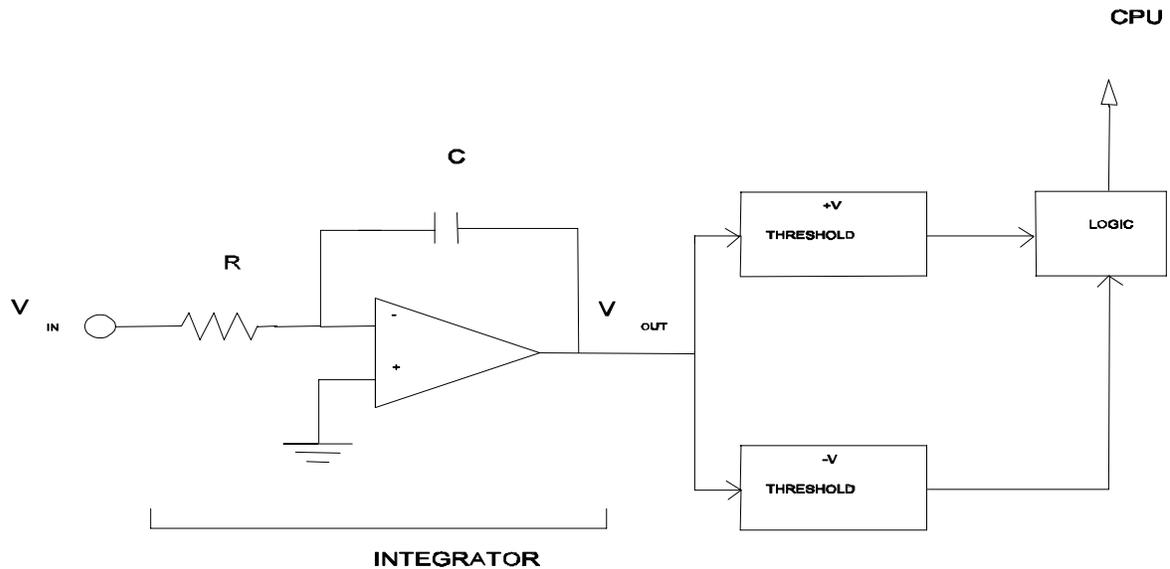

Figure 2. Model 6500A operational integrator.

The maximum resistance and current measurement uncertainties using the model 6500A are documented in Tables 1 and 2, respectively.

Table 1. Model 6500A resistance measurement uncertainty.

Resistance Measurement Range (Ohms)	Uncertainty (±% of reading)
10^6 - 10^7	0.035
10^7 - 10^8	0.035
10^8 - 10^9	0.05
10^9 - 10^{10}	0.07
10^{10} - 10^{11}	0.1
10^{11} - 10^{12}	0.2
10^{12} - 10^{13}	0.3
10^{13} - 10^{14}	0.5
10^{14} - 10^{15}	1.0
10^{15} - 10^{16}	10.0
10^{16} - 10^{17}	50.0

Table 2. Model 6500A current measurement uncertainty.

Current Measurement Range (Amps)	Uncertainty (±% of reading)
10^{-4} - 10^{-3}	0.25
10^{-5} - 10^{-4}	0.35
10^{-6} - 10^{-5}	0.5
10^{-7} - 10^{-6}	0.7
10^{-8} - 10^{-7}	1.0
10^{-9} - 10^{-8}	1.0
10^{-10} - 10^{-9}	1.0
10^{-11} - 10^{-10}	1.0
10^{-12} - 10^{-11}	1.0
10^{-13} - 10^{-12}	10.0
10^{-14} - 10^{-13}	50.0

In Tables 1 and 2, uncertainty is over ± 4 ^{0}C from the calibration temperature for 1 year in the ambient operating temperature range of 18°C to 28°C.

3   MEASUREMENT CIRCUIT ENHANCEMENTS

The greatest contribution to measurement uncertainty in the model 6500A is provided by the analog measuring circuit and the high voltage source. Within these circuits, the most significant contributor is the effect of the ambient environment on its three selectable 27 pF, 270 pF and 2700 pF integration capacitors. Note that these capacitances are created by three 27 pF, 240 pF and 2700 pF capacitors, with the 27 pF capacitor always connected to the integrator, while the 240 pF and 2700 pF capacitors are selected as required. The effect of the ambient environment is due to the temperature coefficient of these capacitors. The model 6500A uses glass capacitors with values of 27 pF and 240 pF, and a metallized teflon 2700 pF capacitor. Although these are extremely stable capacitors, their temperature coefficients are the most significant variable in the measurement circuit. The 27 pF and 240 pF capacitors have a temperature coefficient of +140 ppm/°C ±25 ppm/°C, while the 2700 pF capacitor has a temperature coefficient of ±50 ppm/°C. Stabilizing their capacitances would result in significantly improved performance. This was one of the design goals of the new Guildline model 6520 Digital Teraohmmeter. To improve the stability of the model 6520, an iso-thermal chamber is incorporated within it to house the analog measuring circuit and the high voltage source. A precision temperature regulation circuit maintains the temperature within the iso-thermal chamber to a level that is designed to be within 26°C ±1°C over the ambient temperature range of 17°C to 29°C. This covers the ambient temperature of a typical measurement facility. The temperature regulation over the full operating ambient temperature range of 15°C to 30°C is with reduced stability. With the resulting temperature attenuation of a factor of six, the three integration capacitors are expected to have a total temperature drift over the ambient temperature range of 17°C to 29°C of +280 ppm ±50 ppm for the 27 pF and 240 pF capacitors, and ±100 ppm for the 2700 pF capacitor. Testing of the temperature regulation of the iso-thermal chamber is ongoing at the time of this paper. The choice of the stabilized temperature within the iso-thermal chamber represents a trade-off of thermal management, circuit complexity and performance. Increasing the stabilized temperature would result in excessive temperature induced noise being created in the measurement circuit. By maintaining the temperature within the iso-thermal chamber above the typical ambient temperature range, a heater circuit is not required. The temperature regulation circuit is designed such that it maintains a constant temperature within the iso-thermal chamber by drawing off excess heat that is dissipated by the enclosed circuits with an electrical cooling module based on the Peltier effect. This approach minimizes the complexity, size and cost of the model 6520. The resulting overall improved performance that is expected to be achieved by the model 6520 is documented in the following Tables 3 and 4 for expected resistance and current measurement uncertainties, respectively.

Table 3. Model 6520 resistance measurement uncertainty.

Resistance Measurement Range (Ohms)	Uncertainty (±% of reading over 1 year, 23°C ±2°C)	Transfer Uncertainty (±% of reading over 4 hours, 23°C ±2°C)	Temperature Coefficient (±% of reading/°C, 15°C to 21°C, 25°C to 30°C)	Uncertainty (±% of reading over 1 year, 23°C ±4°C)
$10^5 - 10^6$	0.025	0.005	0.01	0.045
$10^6 - 10^7$	0.025	0.0025	0.0025	0.030
$10^7 - 10^8$	0.015	0.0025	0.0035	0.022
$10^8 - 10^9$	0.02	0.0025	0.005	0.03
$10^9 - 10^{10}$	0.06	0.0025	0.007	0.074
$10^{10} - 10^{11}$	0.08	0.0025	0.01	0.10
$10^{11} - 10^{12}$	0.1	0.005	0.02	0.14
$10^{12} - 10^{13}$	0.2	0.0075	0.03	0.26
$10^{13} - 10^{14}$	0.3	0.0125	0.05	0.4
$10^{14} - 10^{15}$	1.0	0.05	0.1	1.2
$10^{15} - 10^{16}$	5.0	0.1	1.0	7.0
$10^{16} - 10^{17}$	50.0	0.2	5.0	60.0

In Table 3, the transfer uncertainty is the stability of the measurements of the 6520 over the specified time period. The last column in Table 3 provides a direct comparison to the 1 year resistance uncertainty of the model 6500A in Table 1.

Table 4. Model 6520 current measurement uncertainty.

Current Measurement Range (Amps)	Uncertainty (±% of reading over 1 year, 23°C±2°C)	Temperature Coefficient (±% of reading/°C, 15°C to 21°C, 25°C to 30°C)
$10^{-2} - 10^{-1}$	0.1	0.01
$10^{-3} - 10^{-2}$	0.1	0.008
$10^{-4} - 10^{-3}$	0.1	0.008
$10^{-5} - 10^{-4}$	0.1	0.005
$10^{-6} - 10^{-5}$	0.1	0.005
$10^{-7} - 10^{-6}$	0.1	0.005
$10^{-8} - 10^{-7}$	0.2	0.03
$10^{-9} - 10^{-8}$	0.2	0.03
$10^{-10} - 10^{-9}$	0.2	0.1
$10^{-11} - 10^{-10}$	1.0	0.1
$10^{-12} - 10^{-11}$	1.0	0.1
$10^{-13} - 10^{-12}$	10.0	1
$10^{-14} - 10^{-13}$	50.0	5

A comparison of measurement uncertainties (this is the variance of the actual measurement itself, not the total measurement uncertainty) between three model 6500A Digital Teraohmmeters and a prototype model 6520 Digital Teraohmmeter, when measuring a 100M (10^8) ohm resistor in a stable ambient temperature environment, are documented in Table 5. This demonstrates that the model 6520 is capable of performing at least as well as the model 6500A under stable ambient environmental conditions.

Table 5. Models 6500A and 6520 100M ohm measurement uncertainties.

Meter	Applied Voltage (Volts)	Measurement Uncertainty (last 12 samples) (±ppm)
6500A no. 1	1	6
6500A no. 1	1	5
6500A no. 2	1	16
6500A no. 3	5	11
6500A no. 3	5	7
6520	1	4

The following test results in Tables 6 and 7 for this same prototype model 6520 Digital Teraohmmeter illustrate its performance over a large part of its specified resistance measurement range. Again, the measurement uncertainties are the variance of the actual measurements themselves, not the total measurement uncertainty, in a stable ambient temperature environment. The measurements are the average of the last 12 samples after the measurement has stabilized. The measurement modes are described in section 4.3.2. The test results in Table 6 are the result of using the model 6520 in the auto reverse mode, where the best measurement accuracy is attained for values less than approximately 1T ohm. The test results in Table 7 are the result of using the model 6520 in the single polarity mode, where the best measurement accuracy is attained for values greater than approximately 1T ohm. The single polarity mode is also applicable if the test sample stores electrical charges and has a long time constant (which is applicable for very large resistance values or resistance standards which include compensating reactive components). The measurement uncertainties in Tables 6 and 7 are well within the expected one year resistance measurement uncertainties in Table 3. The measurements for the same 1T ohm resistor that was tested in both Tables 6 and 7 agree quite closely. The average measurements for the larger resistances in Table 7 do show significant differences, which demonstrates the need for averaging the results of consecutive positive and negative polarity mode measurements to properly characterize the unit under test.

Table 6. Model 6520 auto reverse mode measurements.

Nominal Resistance (Ohms)	Applied Voltage (Volts)	Average Measured Resistance (Ohms)	Measurement Uncertainty (±ppm)
100M (10^8)	1	100.0004M	4
1G (10^9)	10	1.000149G	2
10G (10^{10})	100	10.00137G	6
100G (10^{11})	1000	99.9844G	2
1T (10^{12})	1000	0.99061T	59

Table 7. Model 6520 single polarity mode measurements.

Nominal Resistance (Ohms)	Applied Voltage (Volts)	Positive Polarity Mode Measurement		Negative Polarity Mode Measurement	
		Average Measured Resistance (Ohms)	Measurement Uncertainty (±ppm)	Average Measured Resistance (Ohms)	Measurement Uncertainty (±ppm)
1T (10^{12})	1000	0.99051T	51	0.99051T	48
10T (10^{13})	1000	10.083T	170	10.110T	100
100T (10^{14})	1000	103.6T	1,300	105.3T	1,200
1P (10^{15})	1000	0.934P	3,200	1.238P	3,700
4P ($4 * 10^{15}$)	1000	3.71P	21,000	-	-

Further testing of the model 6520 to fully verify and characterize its performance at the time of this paper is still ongoing.

4   MEASUREMENT TECHNIQUES AND CONSIDERATIONS

To make effective use of such a high resistance meter as either the model 6500A or the model 6520 Digital Teraohmmeters, the operator must follow stringent measurement procedures to minimize total measurement uncertainty. The following measurement techniques and practices are presented to characterize the performance of the meter and to use the meter effectively to perform resistance measurements or calibrations. Although the models 6500A and 6520 are referred to in particular, these techniques and practices are generally applicable to any high resistance meter.

4.1 Setup

The proper setup for the test must first be addressed. For the high resistance, low current measurements being performed, it is especially important to minimize any electromagnetic interference (EMI) or ambient environmental influence that could add noise or an offset to the measurement. Noise will appear in the measurement uncertainty in the form of standard

deviation. As the temperature and voltage coefficient uncertainties are reduced, the noise levels in the measurement take on a more pronounced role.

4.1.1. Grounding and Noise Pickup

Grounding or guarding of resistors not only reduces noise levels, in some cases the apparent value of the resistor will change. One must be absolutely specific when having a resistor calibrated to indicate the requirements for grounding. For example, if a national laboratory has calibrated a working or reference standard resistor, a very detailed description of the conditions and configuration used to achieve the result will be provided. The stated uncertainty is valid only under the stated conditions, so that it is required that the test conditions be duplicated as closely as possible. If the manufacturer has provided a shielded enclosure with a ground or guard terminal, it should be used. One should check the operating manual for the measurement equipment to avoid possible incompatibilities. In addition, one should watch for periodic noise in the test data. Despite shielded rooms and electrical isolation, sometimes equipment interacts. Measurement systems that integrate data over time may include periodic noise as part of the data.

Proximity can generate a noise problem with lower signal to noise ratios. This will have to be evaluated on site where the measurement actually occurs.

Random noise may show up as a lack of repeatability. By making a test measurement repeatedly (at least five times), it is possible to generate a spread of values that is representative of the repeatability. The standard deviation of this spread will have to be added to the uncertainty budget. Again, the cause will have to be determined in each case.

The recommended shielded leads with the required mating connections should always be used. Shielded test leads shunt unwanted leakage current away from the measurement circuit. These leads must be well maintained. Damage to the cable shield or insulation can result in significant measurement errors. Ensure that good connections are made also. Poor connections will generally result in a higher resistance value and a noisier measurement, due to the additional contact resistance. This is definitely applicable to the models 6500A and 6520. As an example, in one case, a poor connection at the 100M ohm resistor under test end of the test setup resulted in a measurement of 47 ppm above nominal with a measurement uncertainty of ±13 ppm (this is the variance of the actual measurement itself, not the total measurement uncertainty). When the test was repeated with tightened connections, a measurement of 33 ppm above nominal with a measurement uncertainty of ±4 ppm resulted.

The unit under test (UUT) should be installed in a metal shielded enclosure that is grounded to the chassis of the Digital Teraohmmeter. The models 65205 and 65223 Shielded Sample Enclosures are available for this purpose to be used with the models 6500A and 6520, respectively. The Shielded Sample Enclosures should be located on the right side of either the models 6500A or 6520 to avoid heat from their internal power supplies, which can change the ambient temperature in the area of the UUT. Similar considerations for the physical location of the various components of a test setup apply when using other high resistance meters.

4.1.2. Test Sample Preparation

It is important to prepare the test sample properly so that unwanted parallel leakage paths are reduced as much as possible. The condition of the insulation surface between the sample terminals is very critical, since this usually forms a significant source of electrical leakage. The surface must be dry and free of conductive salts or other deposits.

4.1.3. Test Environment

The ambient temperature, humidity and air pressure of the test facility in the vicinity of the UUT can all have an effect on the electrical characteristics, such as resistance, of the UUT. For example, resistor elements that are hermetically sealed are much less susceptible to humidity and air pressure changes. Likewise, ionized air and ionizing radiation should not be present in the test facility. Care should be taken to check the environmental specifications of the measuring system and include additional uncertainties as conditions dictate. The environment of the test facility should be as well controlled as possible, to minimize these effects and the resulting measurement uncertainty that they induce. Typically, the environment should be controlled to within 45% ±5% relative humidity and 23° ±1° C. Usually, there is no control over the air pressure, unless the UUT is mounted within a special air pressure regulated environmental chamber provided for the specific purpose of assessing the impact of air pressure on the UUT. In order to fully document and account for the affects of the ambient environment on the measurement of the UUT, it is necessary to record the ambient temperature, humidity and air pressure in the vicinity of the UUT. Typically, the test facility will include a thermometer, hygrometer and a barometer to measure and record the ambient temperature, humidity and air pressure, respectively. The location of the hygrometer and barometer are not critical, as the difference in humidity and air pressure throughout the test facility will be negligible. The location of the thermometer is more important, as it is often very difficult to prevent temperature differences, even in a well-regulated test facility. For best temperature reporting, it is best to monitor the ambient temperature in the immediate vicinity of the UUT. The Guildline model 9540 is an example of a Digital Platinum Resistance Thermometer that can measure the air temperature within the Shielded Sample Enclosure containing the UUT. In a different approach to environmental data logging, the optional model 65220 Environmental Monitor can monitor all of the ambient temperature, humidity and air pressure and report them to the model 6520. The Environmental Monitor provides the capability of automatically recording the ambient environmental conditions of 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 model 6520. The model 6520 can display this environmental data directly, as well as transmit it to a personal computer that runs the model 6520's TeraCal data acquisition software program. The data acquisition software program is required to correlate and save the environmental data with the resistance or current measurement test data.

It is important not to ignore the effects of temperature, in particular, on the UUT. For example, to be stable and therefore better suited to bench top use, air resistors, which comprise the vast majority of high value resistances, are designed with "Thermal Inertia". Basically, this means that the air resistor will not change temperature quickly. While this is desirable during a

measurement, the air resistor must be allowed to stabilize (for up to 90 minutes typically). Ideally, since the test facility environment is homogeneous, the air resistor is ready to be used at any time. However, that may not be the real situation. If the storage area for the resistor is at a different temperature from the workstation, then the problem of the resistor being at the wrong temperature occurs. Since the air resistor will be slow to change temperature, it is possible to run a 30 or 45 minute measurement and not be aware of the temperature difference. A longer measurement would show the resistor moving and settling at the value associated with the temperature of the workstation.

Two practical solutions present themselves. Either keep the air resistor at the workstation and allow the resistor to stabilize, or monitor the temperature at different points in the test facility and find a storage location that closely tracks the temperature at the workstation. If the uncertainty caused by the temperature coefficient is still too large for the test application, it will be necessary to use some form of temperature controlled enclosure. For example, automated control of the air temperature about the UUT can be provided by the Guildline model 5032 Variable Temperature Air Bath.

It is important to be aware of changing the airflow patterns in the test facility. Leaving an instrument on a cart may deflect air currents, and cause a warm or cool spot. Air resistors left in such a location will adjust to the new temperature. The same problem can occur if the test equipment is moved and the effect of the exhaust from the unit's cooling fan is not accounted for. For example, a simple metal shielded enclosure left in the airflow from an air bath can warm up by 3-5°C.

4.1.4. Working Resistance Standards

All of the working resistance standards required for use with the high resistance meter should be available at the same ambient temperature. A typical set of such standards would include all of the decade values from 100M ohm to 1P ohm. Traceable values for these standards should be available at the required voltages. For example, if a 100M ohm resistor to be calibrated is normally measured with a precision digital multimeter (DMM), a low voltage (typically less than 10 V) will be used by this meter. If this resistor is going to be calibrated by a model 6500A or 6520 Digital Teraohmmeter, then the applied voltage is selectable up to 1000 V. If the manufacturer's specification for this resistor indicated a voltage coefficient of <0.5 ppm/volt, you could have a difference of 500 ppm between the two measurement systems, if 1000 V was used by the model 6500A or 6520, and still be within specification. Thus, the required applied voltage should be used, whenever possible, to minimize the effect of the voltage coefficient. If the actual voltage coefficient is not known, then it will be necessary to include the possible (maximum) value as defined by the specifications in the uncertainty budget. Again, the importance of calibrating this resistor at two or more voltages becomes plain. If it is planned to use the standard for 1:1 ratios as well as 10:1 ratios for laddering with a Direct Current Comparator (DCC) Bridge, it will be necessary to know the actual voltage coefficient or actual value at both points in order to minimize the uncertainty.

4.2 Process

The following process should be followed by the operator, in order to characterize the performance of the high resistance meter and the reference resistors used. Connect the resistance standard to the high resistance meter and allow time for the resistance standard to stabilize. The operator must be aware of the time frame that is required to achieve stability. Record the data from a long measurement (typically 12 hours). Following the test, analyze the data, looking for spurious readings and cyclic drift of the meter. Next, use the resistance standard to determine the meter error. The determination of meter error should be repeated a minimum of 5 times in a one day period. Review the change in value over time and determine the random error based on the meter drift. Repeat this daily meter error determination on 3 consecutive days and compare any change in the ambient temperature, humidity and, particularly, air pressure to change in meter error, allowing for previous random error and stability of the resistance standard. In particular, determine if a relationship exists between air pressure and the value of the resistance standard, as this is not an environmental parameter that is usually controlled. Some resistors will have a negligible air pressure coefficient, whereas it will be significant for others. Experience at Guildline has shown that the model 6500A itself has a negligible air pressure coefficient. This has been demonstrated by tracking the resistance versus air pressure for a resistor that appears to be sensitive to air pressure and comparing the results with a reference resistor which showed negligible change in resistance at different air pressures, using the same model 6500A Teraohmmeter.

4.3 Test Methods

Two methods are generally available to perform a resistance measurement using a high resistance meter, such as the model 6500A or 6520 Digital Teraohmmeter. One method is to directly measure the resistance of the unit under test (UUT), and take the published or (more accurately) the previously calibrated long term measurement uncertainty of the high resistance meter. The second, more accurate, method is to use the transfer method.

4.3.1.   Transfer Method

In the transfer method, the resistance of the UUT is measured and compared with a known resistance standard that has been measured by the same high resistance meter, with minimum time separation between measurements, as follows. Always use the best resistance standards available to the operator. When transferring a resistance value, have both resistors housed in the shielded enclosure together, to avoid delays waiting for the UUT to stabilize after measuring the resistance standard. This will speed up the measurement cycle and reduce the time for the meter to drift. Keep the measurement cycle time longer rather than shorter, as speeding up a measurement will result in more noise. However, the operator must not take too long a measurement (many samples), as this will allow more time for meter or resistance drift. The operator must ensure that the resistance standard is calibrated at the required voltage. Otherwise, the voltage coefficient must be used when determining the meter error at voltages other than the calibrated point of the standard, resulting in increased uncertainty. If the operator changes a parameter, then the meter must be re-standardized. Assuming that there is negligible

environmental variation and that the test parameters are the same, then the ratios of the calibrated and measured resistance of the UUT versus the resistance standard by the transfer method are equivalent in accordance with the following equation (4):

$$R_{xc} / R_{sc} = R_{xm} / R_{sm} \qquad (4)$$

Where
R_{xc} = Calibrated resistance value of the UUT
R_{sc} = Previously known calibrated resistance value of the resistance standard
R_{xm} = Measured resistance value of the UUT by the high resistance meter
R_{sm} = Measured resistance value of the resistance standard by the high resistance meter

It is recommended that an average value for R_{sm} be determined, as described in the following equation (5):

$$R_{sm} = (R_{sm1} + R_{sm2}) / 2 \qquad (5)$$

Where
R_{sm1} = Measured resistance value of the resistance standard by the high resistance meter, before measuring the UUT
R_{sm2} = Measured resistance value of the resistance standard by the high resistance meter, after measuring the UUT

Inserting equation (5) into equation (4) gives the following equation (6) for the calibrated resistance value of the UUT, R_{xc}:

$$R_{xc} = 2 * R_{sc} * R_{xm} / (R_{sm1} + R_{sm2}) \qquad (6)$$

The corresponding measurement uncertainty of the UUT by the transfer method is characterized by the following equation (7), based on the standard square root of the sum of the squares calculation:

$$U_{Rxc} = (U_{Rsc}^2 + U_{Rsm}^2 + U_{Rxm}^2)^{1/2} \qquad (7)$$

Where
U_{Rxc} = Measurement uncertainty of the calibrated resistance value of the UUT
U_{Rxm} = Measurement uncertainty of the measured resistance value of the UUT by the high resistance meter (2 times the standard deviation)
U_{Rsc} = Measurement uncertainty of the previously known calibrated resistance value of the resistance standard (typically k = 2)
U_{Rsm} = Measurement uncertainty of the measured resistance value of the resistance standard by the high resistance meter (2 times the standard deviation)

Because R_{sm} is the average of two measurements; its uncertainty, U_{Rsm}, is the average of its component uncertainties, as follows in equation (8):

$U_{Rsm} = (U_{Rsm1} + U_{Rsm2}) / 2$ (8)

Where

U_{Rsm1} = Measurement uncertainty of the measured resistance value of the resistance standard by the high resistance meter (2 times the standard deviation), before measuring the UUT

U_{Rsm2} = Measurement uncertainty of the measured resistance value of the resistance standard by the high resistance meter (2 times the standard deviation), after measuring the UUT

Inserting equation (8) into equation (7) gives the following equation (9) for the measurement uncertainty of the calibrated resistance value of the UUT, U_{Rxc}:

$$U_{Rxc} = (U_{Rsc}^2 + (U_{Rsm1} + U_{Rsm2})^2 / 4 + U_{Rxm}^2)^{1/2}$$ (9)

The transfer method characterized by equations (6) and (9) is based on measuring the resistance standard immediately before and after the UUT. The two measurements of the resistance standard verify that the resistance standard is stable. Additional measurements are not recommended, as the additional time can result in drift of the resistances, primarily due to environmental factors. This is the method used by the model 6520's TeraCal data acquisition software program in its Transfer Calibration Utility. For each measurement, it is recommended that only about the last 12 samples be used to determine the average and the standard deviation of the measurement. The total number of samples should be about 50 for the UUT and the following reference resistor measurements. For the reference resistor measurement before the UUT, a sufficient number of samples should be taken to ensure that the resistor, the test setup and the environment are stable. These sample sizes have been found to give the most accurate results when using the model 6500A.

4.3.2. Test Method Practices

For either test method, always follow these practices to minimize noise and the resulting measurement uncertainty:

1) Use the shielded enclosure to house the resistor and be sure that the enclosure and the resistor are grounded.
2) Use shielded leads.
3) Tighten the connections securely. Poor connections will show up as a noisy measurement.
4) Avoid sources of electrical noise, such as automating switching equipment (unless it is known to provide a negligible noise contribution) as part of the test setup and small electrical heaters with thermostat controls. Keep any computer, even one required for use with the meter, as far from the meter as possible (certainly not directly adjacent). Have all test equipment turned on before the test, particularly to prevent noise spikes. This includes such items as a chart recorder.
5) Even the proximity of the operator can be a problem for high resistance measurements. Moving around near the unit can add to the measurement noise.

Always remember the following concerns for either test method:

1) If the measurement can not be repeated, then there is no point in measuring in the first place.
2) Precise measurements require precise conditions.
3) Always document the environmental and test conditions for each measurement.
4) A history of the resistance standards is required to predict a value during the calibration interval.
5) The uncertainty caused by time from calibration date of the resistance standard can be as large as any other factor in a high value resistor measurement.
6) The temperature coefficient of the UUT can be as large or larger as the yearly drift of the resistance standard. Thus, the operator must be sure of the ambient temperature. It should be within ±100m°K from the calibrated temperature of the resistance standard.
7) Air resistors, such as the Guildline models 9334A, 9336 and 9337, have thermal inertia and will not change temperature quickly. These resistors should be stored at the same temperature they are used within ±100m°K. The best storage location is in the shielded enclosure that they will be used in.
8) Never connect a resistance standard or UUT directly to the connectors of the high resistance meter, unless the manufacturer's test practices specifically require it under special circumstances. A thermal transfer may occur. In addition, damage to the high resistance meter can occur if the resistor in accidentally hit while connected in this fashion.
9) Use the recommended polarity test method for the nominal resistance value. For the models 6500A and 6520, the best measurement accuracy is attained in the auto reverse mode for values less than approximately 1T ohm. In the auto reverse mode, each measurement sample is the average of four separate measurements with first the positive test voltage, then the negative test voltage, then the negative test voltage again, and finally the positive test voltage again applied to the resistance. For the models 6500A and 6520, the best measurement accuracy is attained in the single polarity mode for values greater than approximately 1T ohm. The single polarity mode is also applicable if the test sample stores electrical charges and has a long time constant (which is applicable for very large resistance values or resistance standards which include compensating reactive components). In the single polarity mode, each measurement sample is taken with either the positive or negative test voltage always applied to the resistance. In this case, separate measurements should be taken with both positive and negative test voltages applied, and the resulting average resistance value then computed.

4.3.3. Test Results

In a test conducted by Guildline using a model 6500A Digital Teraohmmeter, a 10G ohm model 9334AH-10G resistance standard was calibrated in accordance with the transfer method described in section 4.3.1, with the following results.

1) 10G ohm reference standard calibrated mean value from nominal = 680 ppm, with an uncertainty of ±40 ppm
2) First 10G ohm reference standard measurement: 10.007545G ohm mean value, standard deviation = ±4.4 ppm

3) 6500A meter error per first reference measurement= 74.5 ppm, based on calibrated mean value of the 10G ohm reference standard
4) 9334AH-10G UUT measurement: 9.999876G ohm mean value, standard deviation = ±3.5 ppm
5) 9334AH-10G UUT deviation from nominal = -12.4 ppm
6) Second 10G ohm reference standard test: 10.007423G ohm mean value, standard deviation = ±3.2 ppm
7) 6500A meter error per second reference measurement= 62.3 ppm, based on calibrated mean value of the 10G ohm reference standard
8) Average 6500A meter error = (74.5 ppm + 62.3 ppm) / 2 = 68.4 ppm
9) 9334AH-10G UUT calibrated mean value from nominal = (74.5 ppm – 68.4 ppm) – 12.4 ppm = -6.3 ppm
10) 9334AH-10G UUT calibrated uncertainty, not including reference standard uncertainty = $\pm(40^2 + (4.4 + 3.2)^2 / 4 + 3.5^2)^{1/2}$ ppm = ±40.3 ppm

Thus, the 9334AH-10G UUT was calibrated to have a mean value from nominal of –6.3 ppm with a measurement uncertainty of ±40.3 ppm, with negligible environmental variation. This is a factor of 17 better than using the nominal 10G ohm uncertainty of ±700 ppm listed in Table 1.

Typical reported test results for the direct and similar transfer methods using the model 6500A Digital Teraohmmeter are documented in Table 8 as reported by Shiv Kumar Jaiswal, Ajeet Singh and V. N. Ojha [1], indicating the improvements in measurement uncertainty that can be achieved by the transfer method. The transfer method uncertainty of ±122 ppm for the 10G ohm resistor in Table 8 is similar in magnitude to the above ±40.3 ppm uncertainty for the 9334AH-10G UUT measured by Guildline.

Table 8. Model 6500A direct and transfer measured values.

Nominal Value Of Resistor (Ohms)	Test Voltage (V)	Measured Value By Model 6500A (k = 2)		
		Direct Method With Guildline Published Uncertainty (Ohms)	Direct Method With Meter Previously Calibrated (Ohms)	Transfer Method (Ohms)
100M	5	100.0253M ±0.0350M	100.0253M ±0.0077M	100.0269M ±0.0064M
1G	50	1.005782G ±0.000500G	1.005782G ±0.000407G	1.005807G ±0.000120G
10G	100	10.10939G ±0.00700G	10.10939G ±0.00561G	10.10954G ±0.00122G

5   CONCLUSION

The test results show that the models 6500A and 6520 Digital Teraohmmeters achieve comparable resistance measurement performance in a very stable ambient temperature environment. The test results for the model 6520 show that it can maintain the temperature stability of its critical measurement electronic circuits over a wide range of ambient temperatures. Thus, it is expected that the model 6520 will be able to perform resistance and current measurements with a much smaller temperature coefficient over the full operating ambient temperature range as compared to the model 6500A. Verification of this improved immunity to the environment of the model 6520 Digital Teraohmmeter is ongoing at this time. This improved performance allows the model 6520 to be used in test facilities that have poorly regulated environments. However, to achieve the best measurement accuracy, it is still necessary to follow stringent and thorough test practices. Thus, the environment of the unit under test must still be monitored and well regulated. This may require the use of a temperature regulated bath. Best measurement uncertainty can be achieved with the transfer method approach.

6   REFERENCES

1) Shiv Kumar Jaiswal, Ajeet Singh and V. N. Ojha, Uncertainty Evaluation of High Value Standard Resistors Using Automatic High Resistance Bridge and Digital Teraohmmeter, MAPAN – Journal of Metrology Society of India, volume 18, supplementary issue, 2003, pages 81-85