Modern precision multimeter measurements
- putting theory to the test.

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In a controlled experiment we asked five laboratory personnel to perform some basic measurements using the same precision digital multimeter the results yield an unusually wide spread of readings – why? Is the operator or the instrument to blame or were the results within an acceptable measurement uncertainty! Modern precision multimeters have numerous measurement modes to cater for a diverse range of applications, but which mode is right. This paper unravels the confusion over choice of instrument operating modes and promotes best measurement practices to maintain consistent and repeatable measurements.

Background
This paper was developed from a growing concern that basic metrology principles are being overlooked by demands for greater lab efficiency. Calibration software, measuring instrument design, metrology training and documentation all (to a greater or lesser degree) influence our implementation of best measurement practices.

The process (see figure 1) of performing what can be sometimes viewed as a simple measurement using a Digital Multimeter, when broken down into a process flow chart is often quite complex, involving a ten or more decisions.
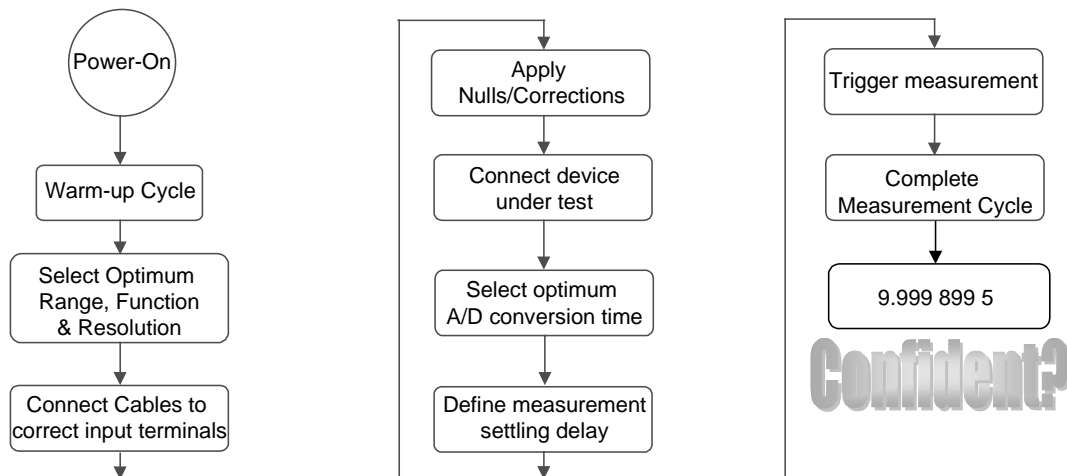

Figure 1

Each step in the set-up configuration process requires the user to have sound metrology knowledge covering a range of issues, sometimes only gained through basic hands-on experience.

Source of Measurement Error

In practice factors influencing the repeatability of a measurement can be broken down on a check-list. The significance of each should be considered relative to the overall resolution or scale (least significant digit) requirement.

An example of this can be demonstrated in the following experiment. Time is a common component in every day measurement. The analog clock is the measuring hardware, the clocks ability to remain accurate is dependent upon its specification and the Standard used to set the time in the first place. But let's for the sake of this experiment assume we have the perfect time-piece!

So what's the time?

The results may vary based on the following potential error sources.

1) Ability see the clock
2) Ability to tell the time
3) Maintenance of the clock
4) Resolution of the clock
5) Parallax

Points 1,2 & 3 are user influenced and 4 & 5 are hardware related, although it could be argued that point 5 is an error associated with the user. Everyone knows that analog displays have parallax problems - don't they!!

Extend this experiment to a more complex measuring instruments, such as a precision DMM. Where increased sensitivity of a few parts per million make many errors significant. The following list (figure 2) of potential influences could, like the previous example, be broken down into hardware and operator influences. The experiment is further compounded by the fact that the measuring instrument is multi-function. This in turn leads to compromises being made as the user is presented with even greater choice - not always specific to the actual application.

Hardware Specifications	Environment (changes in)
Uncertainty Relative to Standards	Temperature
Calibration Uncertainty	Humidity
Calibration Interval	Pressure
Confidence level	
Stability	
Internal Nulls/Offset corrections	
Cables and Connections	**Measurement**
Thermal Errors	Load Errors
Sensing Techniques	A/D conversion times
Guarding	Measurement Settling times
Shielding	Bias current
	Burden Voltage/Current
	Settling times
	Interference
Figure 2	

More thorough analysis of each of the items in figure 2 would provide a better appreciation of the magnitude of the error associated with each of the contributions. As an example those errors that are more easily accessible can be found in the specifications for the measuring instrument. The figures in the following table are based on a range of specifications covering the more popular precision multimeters.

Parameter	Typical Specification Range	Error Contribution
Warm-up time	25 minutes - 4 hours	0 - 100 ppm
DC Uncertainty (Absolute)	3 - 8 ppm	3 - 8 ppm
DC Uncertainty (Cal Uncertainty)	1 - 5 ppm	1 - 5 ppm
Confidence Level 95% or 99%	1 - 1.25 multiplier	1 - 10 ppm
DC Stability	0.5 - 2 ppm	0.5 - 2 ppm
Temperature Co-efficients	$0.25\mu V/°C$ - $4\mu V/°C$	0.25 - 4ppm for 1°C change
Counts	120 - 200 million	n/a
Linearity	0.05 - 0.1ppm	0.05 - 0.1ppm
A/D Conversion Cycle	$10\mu sec$ - 25 seconds	0 - 50 ppm

From the specification alone we've identified a potential spread of error (uncertainty) contribution ranging from 5 ppm to 180 ppm, with the largest contributions associated with warm-up time and measurement time. Those listed in figure 2 are the more easily identified sources of error. The resultant uncertainty will be greater when combined with the uncertainty associated with the process, connections and interference is further considered.

Interconnections
Probably the single largest contributor of uncertainty (outside that of the instrument) is the way we interface the measuring instrument to the device to be measured. Multi-function instruments are designed to be versatile – cables supplied with the instrument are often designed for general-purpose use therefore compromise one or more

applications. What might be the best cable for sensitive low voltage high frequency ac measurements may not be ideal for high voltage or high current applications.

Errors associated with thermal emfs generated from use of cable conductors of different materials can be significant. Using measurement techniques including Nulling, True-Ohms and Reversal measurements help reduce the effects of thermals. The best approach is not to rely too heavily on the instrument or technique but to use materials where the magnitude of emf generated per degree change in temperature is insignificant.

Figure 3 provides a useful table of Thermal emf for different material relative to copper.

| Thermal EMF to Hard-Drawn Copper in Microvolts per Degree Celsius at an ambient temperature of 23°C	
Metal	Thermal EMF (µV/°C@23°C)
Evanohm	+0.20
Gold	+0.01
Anneald Silver	-0.30
Brass	-1.60
Manganin	-1.70
Tin	-2.98
Lead	-3.05
Mecury	-9.57
Constantin	~40

Figure 3

Most precision DMM terminals are of Gold flashed copper in construction. Copper being the cheaper however the gold flashing helps prevent tarnish. Tarnished connections bring with it other errors associated with contact resistance.

Once the optimum material is used we're left with describing the different thermal effects as well as recommended practices.
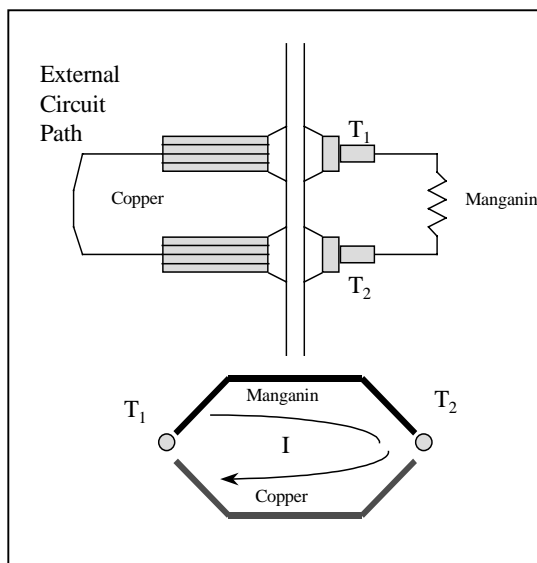

Thermal gradients across dissimilar metals in contact with each other is known as the **Seebeck effect**. A net thermal emf is generated that induces continuous electrical current that will vary as the temperature changes. (see figure 3)

Converse to the Seebeck effect is the **Peltier effect**. In this case the current flow through the circuit causes one junction to be heated, and the other to be cooled. This effect is dependent on both magnitude and direction of current flow.
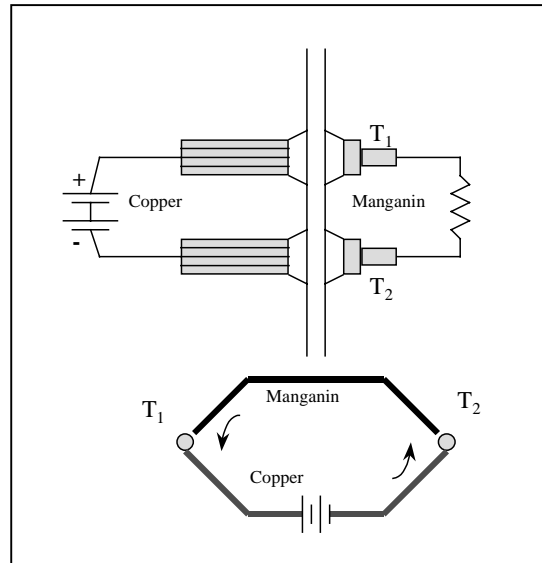
The **Thomson effect** is when a voltage is developed between points on a wire of uniform composition when a temperature gradient exists along its length
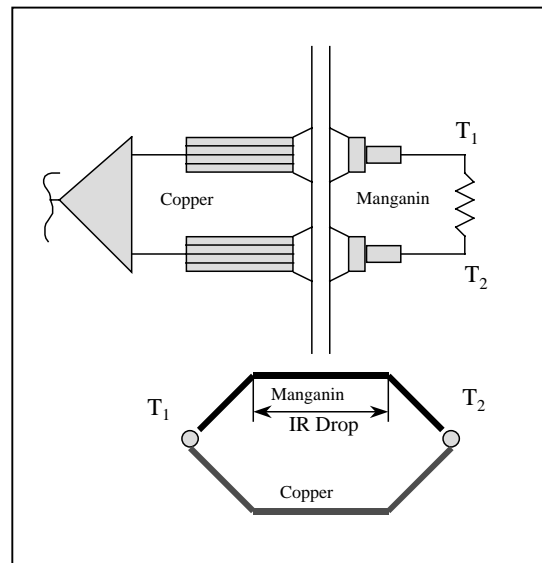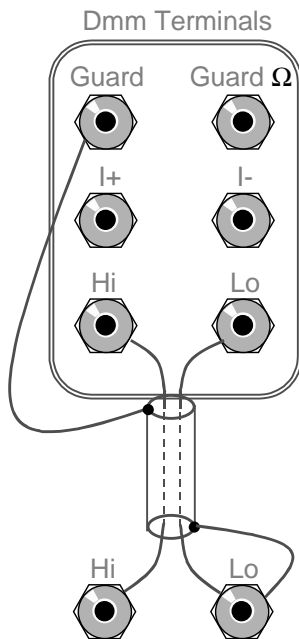
Thermal emf cannot be removed completely however through better understanding and proper care they can be at least minimized. To summarze, give consideration to material type, maintain connections at a constant temperature, use offset null techniques to remove residual thermals and employ reversal techniques to dynamically remove offsets (more on reversal techniques later) that change during repeated measurements.
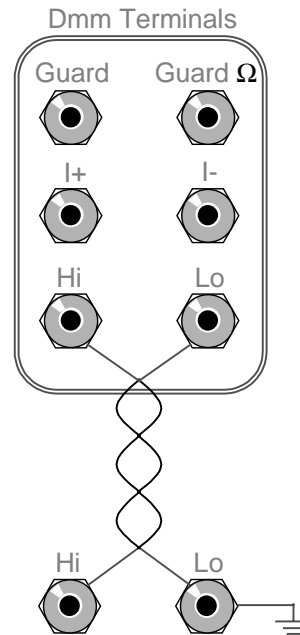
Interconnections

Most laboratory Dmms are six input terminal devices. Signal High (Hi), Low (Lo), Sense High (I+), Sense Lo, Guard and Ohms Guard make up the front and/or rear terminal configuration. The mix of connection type, cable topology and cable lengths suggests a range of cables for different applications. The following diagrams help identify those that offer the optimum performance based on type of signal being measured.

Twisted pair (1) for two-wire applications where any voltage drop in the cable is insignificant The E-M environment is quiet and common mode voltages are insignificant. Suitable for DC and AC voltages over 100mV and where frequencies are less than 100kHz.

Dmm Terminals

Guard   Guard Ω

I+   I-

Hi   Lo

Hi   Lo

Dmm Terminals

Guard   Guard Ω

I+   I-

Hi   Lo

Hi   Lo

Twin-Axial (2) for sensitive measurement applications where E-M and Common mode voltages are significant. DC & AC Voltage >10μV and <1MHz

Twin-Axial (3) for resistance measurement applications where lead resistance is insignificant and E-M environment is quite. Suitable for 1k and 1M Ohm.

Dmm Terminals

Guard   Guard Ω

I+   I-

Hi   Lo

Hi   Lo
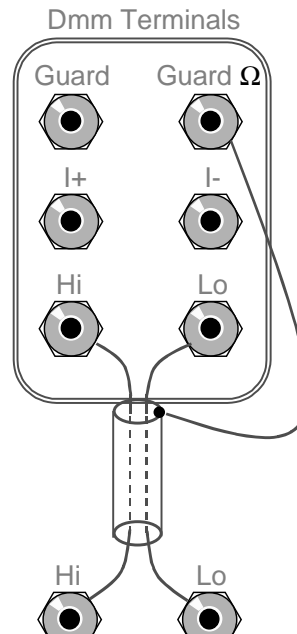
Twin-Axial pair (4) used when lead resistance is significant, relatively noisy E-M environment and Common mode voltages are significant. Resistance measurement <1MOhm
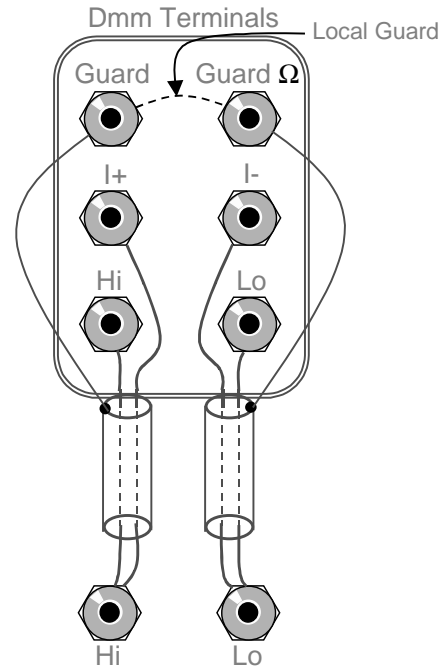
The right cable type and connection is an important consideration when making precision measurements. Lead lengths should be kept as short as possible the recommended cable type for most precision Dmm measurements is ptfe low leakage twin-axial cable. Individual twin cable should carry the Hi and Sense Hi conductors the second cable should carry the Lo and Lo Sense conductors (see Twin-Axial pair [4]).

Common mode interference is generally disturbances at line frequency generated when circulating currents exist between the source and the measuring instrument. The disturbance is common to both Lo and high terminals. Appropriate guarding techniques should be applied where measurements are made in an environment where common mode voltages exist – if in doubt always use remote guard. The Guard terminal on most precision Dmms is connected to internal shielding as well as pcb tracking to screen susceptible signal input lines and input circuits. In most cases the Dmms default setting is to internally connect the Dmm Guard to the Dmm Lo terminal. In the event that common mode exists the Dmm Guard should be switched to Remote with a connection (see figure 4) made to the source of the common mode voltage.
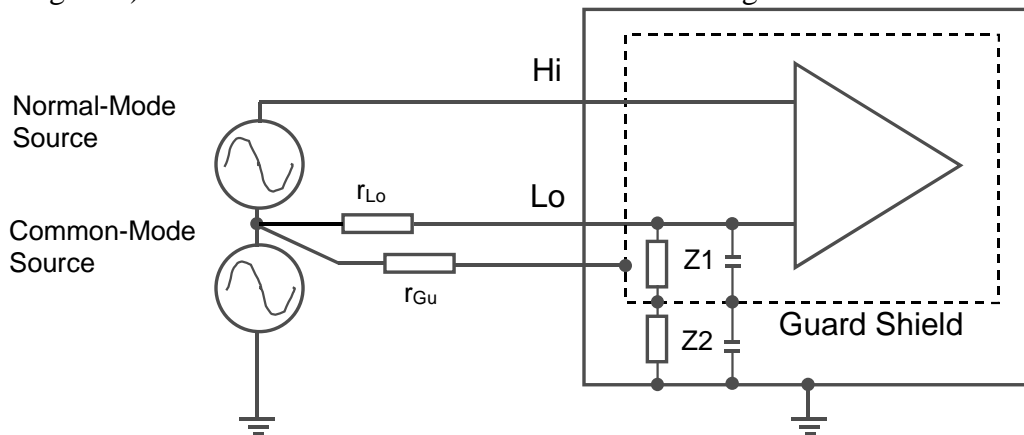

Figure 4

Select Remote Guard on Dmm

Common mode currents that would normally flow through the Hi/Lo terminals to earth are shunted via the guard shield to earth.

Series mode interference normally resides between the Hi and Lo terminals of the Source/Dmm. Similar to Common mode the interference is generally at line frequency. The measuring instrument has analog filters for maximum rejection of the series mode interference. Most precision Dmms have frequency selectable filter functions. The filter type is normally a two or three-pole low pass analog filter that provides typically 120dB of rejection at the selected frequency.

Additional rejection is achieved by setting the A/D conversion time to greater than the 16 or 20milli-second line period. A/D conversion time is often referred to as Number of Power Line Cycles (NPLC). Measurements requiring the greatest resolution typically integrate over 25 or more power line cycles. Maximum rejection is inversely proportional to the speed of A/D conversion.

Use of **Remote Sensing** often applies to source device such as a multifunction calibrator. The calibrator voltage output amplifier delivers the required value to the measuring device. Circumstances may arise where the calibrator is being loaded – this in part maybe due to cable impedances or the actual input impedance of the device itself. To overcome these effects (within specified burden current) the calibrator uses sense amplifier that acts as a feedback mechanism. If the sense wires are connected at the measuring device terminals at the same point the Hi and Lo terminals are connected the errors are reduced. The same configuration applies to measuring devices, specifically when using the Resistance measurement function.

Figure 5 describes a 4-wire Resistance measurement configuration. The Dmms constant current is applied via the Current Source cable while the Voltage is sensed at the resistor under test.
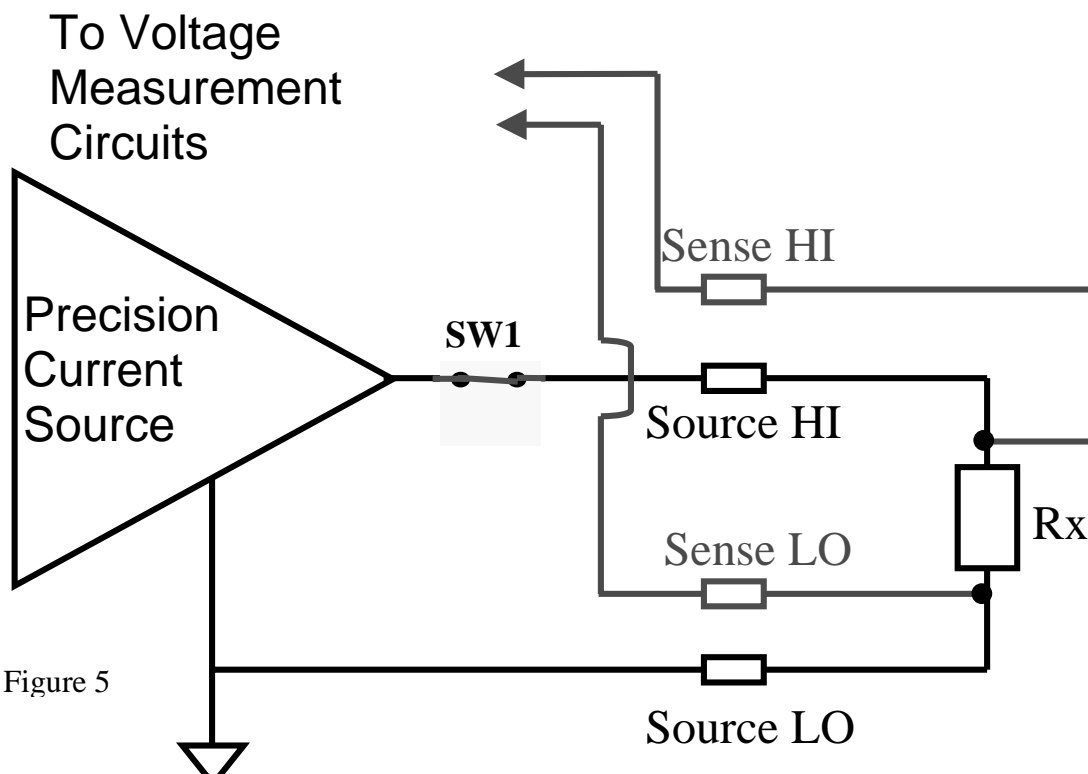

Figure 5

This configuration reduces the effect of any lead resistance contributing to the value of the unknown resistor. The addition of SW1 provides a means whereby the constant current can be removed. Thermal emfs where described in a previous chapter, by removing the current from the unknown resistor any voltages present at the Dmm Sense Hi/Lo terminals are error sources and can be stored within the Dmms memory. With the current switched back on the next Dmm reading will measure the voltage drop across the unknown resistor as well as the error source. The true reading can be mathematically calculated by subtracting the error source reading from the new result. This function is often referred to as **True Ohms**. The downside to this approach is firstly switching often requires greater settling time, particularly if the load is capacitive. And secondly the switched approach is not the optimum method for resistance values that are susceptible to self-heating (i.e. RTDs). In these applications the current through the resistor should be ideally maintained constant therefore an alternate approach is to reverse the current flow and mathematically bring the two readings together to determine the true result.

Measurement Corrections

Most Dmm users are familiar with nulling or zeroing offsets prior to performing a measurement. Precision Dmms generally store the offset value in memory and subtract it from subsequent readings. This approach removes voltage offsets caused by the many anomalies covered in previous chapters.

Care should be taken when using the Null function;

1) The offset value is often maintained in memory until the instrument is switched off. You maybe working with a previously stored offset.

2) Nulls are range dependent.

3) If the Dmm has multiple channels it may have individual Null stores for each channel.

4) Use the appropriate Null, shorting the Dmm terminals and then connecting to the device under test may not be the right approach.

5) Nulls or corrections are sometimes used to remove component drift in poorly designed meters.

6) A null only removes the offset when the function is selected. If you believe the offsets change (due to temperature variation) then repeating the null maybe appropriate or use alternate techniques as described in the chapter on True Ohms measurements.

Finally – software automation may help improve the bottom line through greater efficiency. However all the points discussed thus far should be considered part of any procedure or process.

The best precision Dmm and range of cable accessories available from manufacturers are often compromised by the wide variety of functions and applications. What might be good for low millivolt ACV measurements maybe compromised for Resistance and vice versa. Manufactures may wish to take a closer look at how the design of future products might be improved - particularly around the measurement interface.

Nothing will replace the benefit of on-the-job training particularly along side a good mentor. The fundamentals I agree have not change significantly for many years but technology has. Metrology training classes generally cater for new students but there's no shame in attending refresher courses particularly for the long terms like myself! The Fluke Calibration Book is now in the process of being rewritten. The techniques described here along with more great practical advice for the metrologist will be incorporated in the third edition.

The use of the Internet as a tool for developing remote (error free?) measurement is growing. The benefits of remote control and video will extend the experts control and vision anywhere in the world. Maybe the next time we run this experiment we'll choose to use the Internet as an aid to measurement and compare results.

Further References

Calibration - Philosophy in Practice, copyright Fluke Precision Measurement.

Floating Measurements and Guarding, copyright Agilent.

Sources of Error in ac Measurement – Paul Roberts Fluke Precision Measurement.