

# Troubleshooting Low Voltage Measurement Problems

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*When measuring signals at microvolt levels or lower, there is increased potential for errors. Many of the error sources are caused by thermal effects; an organized troubleshooting approach will speed up correction of these problems to ensure measurement integrity.*

There are many research and production applications that require low level voltage measurements to characterize materials and devices. When signal voltages approach the microvolt level, there are a number of potential error sources that can have a negative impact on measurement integrity. Broadly speaking, these error sources cause voltage offsets and noisy readings, regardless of the type of instrument you are using – digital multimeter (DMM), nanovoltmeter, or electrometer. While there are multiple causes of noise and offset voltages, thermal effects are normally the largest source of error in low voltage measurements. Recognizing

their symptoms can help prioritize your troubleshooting and improve measurement accuracy.

## Offset Voltages

Ideally, when a voltmeter is connected to a relatively low impedance test circuit in which no voltages are present, it should read zero. However, thermal effects in the test circuit may be seen as a non-zero voltage offset. These sources include thermoelectric EMFs and offsets in the voltmeter's input circuitry.

As shown in *Figure 1*, any offset voltage ( $V_{\text{OFFSET}}$ ) between the device under test (DUT) and the voltmeter will add to or subtract from the source voltage ( $V_S$ ), so that the voltage measured by the meter becomes:

$$V_M = V_S \pm V_{\text{OFFSET}}$$

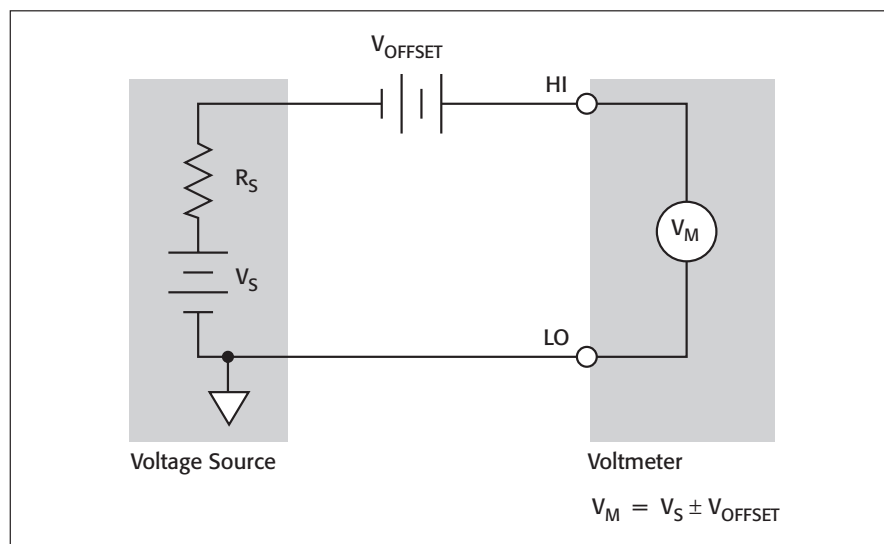
For example, assume  $V_S = 5\mu\text{V}$  and  $V_{\text{OFFSET}} = 250\text{nV}$ . If the voltage polarities are in opposition, the voltmeter reading will be:

$$V_M = (5 \times 10^{-6}) - (250 \times 10^{-9})$$

$$V_M = 4.75 \times 10^{-6}$$

$$V_M = 4.75\mu\text{V} \text{ (an error of } -5\%)$$

*Internal Zero Offset.* A sensitive instrument such as a nanovoltmeter will rarely indicate zero when no voltage is applied to the input, since there are unavoidable offset voltages present in the input circuitry. The first step in troubleshooting, or preparing for voltage measurements, is to check the instrument's zero offset after it has warmed up thoroughly. This is done by disconnecting it from the external measurement circuit, selecting the desired measurement range, and shorting the test leads together. If the meter does not read zero, the offset voltage can be "nulled out" by



*Figure 1. Effects of offset voltages on voltage measurement accuracy.*

pressing the *REL* (for Relative) or *ZERO* button. On some instrument panels, there could be a *ZERO* control that can be adjusted until the meter reads zero. In computer controlled instruments, this is done by invoking the *ZERO* function from the computer.

If the instrument is being used to measure a small voltage resulting from current flow through a DUT, the following procedure will result in a proper zero: First, the instrument should be allowed to warm up for the specified time, usually one to two hours. During this time, the connections should be made between the DUT and the instrument. No current should be supplied to the DUT to allow the temperature gradients to settle to a minimum, stable level. Next, the zero adjustment should be made. When test current is applied, the voltmeter will read the voltage drop across the DUT.

In some applications, the voltage to be measured is always present and the procedure above cannot be used. For example, the voltage difference between two standard cells or two thermocouples is best observed by reversing the instrument connections to the DUTs and averaging the two readings, as described in a later paragraph on *Reversing Sources to Cancel Thermoelectric EMFs*.

**Zero Drift.** While an instrument's input stage voltage offset can be relatively steady, it is apt to change with the operating temperature. Over time, a change in the meter reading with no input signal (typically with input leads shorted) is referred to as zero drift. You may notice that the zero reading varies as ambient temperature changes; the magnitude of this effect is usually referred to as the temperature coefficient of voltage offset.

Good measurement practice dictates periodic checking and adjustment of the zero offset. Instruments that have a low temperature coefficient of voltage offset will require less frequent zero adjustments.

In some measurement environments, a rapid change in ambient temperature can cause a different kind of zero offset symptom. After a step change in the ambient temperature, the voltage offset may change by a fairly large amount, possibly exceeding the instrument's published specifications. If you are measuring a stable voltage source, you might see the voltmeter reading make a relatively rapid shift up or down. The transient offset

will then gradually decrease and your meter reading eventually settles close to the original value. This effect is the result of dissimilar metal junctions in the instrument having different thermal time constants. While one junction will adjust to the new ambient temperature quickly, another changes slowly, resulting in a temporary change in voltage offset.

If your measurement environment is prone to such rapid temperature changes, it may be a good idea to monitor them with a fast acting temperature sensor, or even record voltage measurements and temperature readings simultaneously. Once the temperature has settled to a steady value, you can check the zero offset again.

**Thermoelectric EMFs.** As noted earlier, steady offsets can be nulled out by shorting an instrument's input leads and using its *ZERO* or *REL* feature. However, thermoelectric EMFs pose additional problems. If the shorted input leads encompass a thermoelectric EMF (*Figure 2*), ambient temperature variations can require frequent zeroing.

Thermoelectric EMFs (voltages) are the most common source of errors in low-voltage measurements. These voltages are generated when different parts of a circuit are at different temperatures, and conductors made of dissimilar metals are joined together (*Figure 2*). This causes such connections to act as

thermocouple pairs. The voltage generated depends on the ambient temperature and the metals' Seebeck coefficient ( $Q_{AB}$  in *Table 1*). This table lists the coefficients for various metals with respect to copper, the most common electrical conductor material.

TABLE 1: Seebeck Coefficients

Paired Materials*	Seebeck Coefficient, $Q_{AB}$
Cu – Cu	$\leq 0.2 \mu\text{V}/^\circ\text{C}$
Cu – Ag	$0.3 \mu\text{V}/^\circ\text{C}$
Cu – Au	$0.3 \mu\text{V}/^\circ\text{C}$
Cu – Pb/Sn	$1\text{--}3 \mu\text{V}/^\circ\text{C}$
Cu – Si	$400 \mu\text{V}/^\circ\text{C}$
Cu – Kovar	$40\text{--}75 \mu\text{V}/^\circ\text{C}$
Cu – CuO	$1000 \mu\text{V}/^\circ\text{C}$

\* Ag = silver; Au = gold; Cu = copper; CuO = copper oxide; Pb = lead; Si = silicon; Sn = tin

To diagnose this problem, start with a "cold" test instrument that has been turned off overnight. Then locate the parts of the test circuit where there are connections between different metallic conductors. Short the instrument input leads across the portion of the test circuit that encompasses these connections (*Figure 2*). Turn on all the test equipment and observe the voltmeter reading as it and the ambient temperature increases. When the voltmeter reaches thermal equilibrium you should see the reading stabilize.

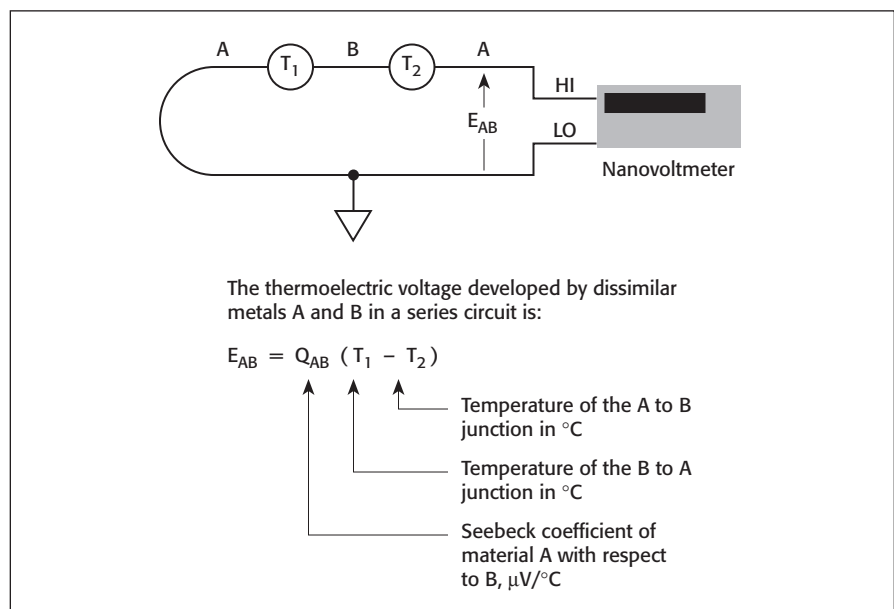


Figure 2. Thermoelectric EMFs in a nanovoltmeter test circuit caused by the Seebeck coefficient of different metallic circuit elements.

Allowing adequate warm up time for the test equipment and stabilization of the ambient temperature minimizes thermoelectric EMF effects. Any remaining thermoelectric EMF, provided it is relatively constant, can be nulled out with the instrument's ZERO feature. As noted earlier, frequent zeroing of the voltmeter may be required if temperatures are not stable.

*Minimizing Thermoelectric EMF Errors.* To minimize thermoelectric EMFs, keep ambient temperatures constant. Equipment should be kept away from direct sunlight, exhaust fans, and similar sources of heat flow or moving air. Wrapping connections in insulating foam (e.g., polyurethane) also minimizes ambient temperature fluctuations caused by air movement.

Constructing circuits using the same material for all conductors further reduces thermoelectric EMF generation. For example, connections made by crimping copper sleeves or lugs on copper wires results in cold-welded copper-to-copper junctions, which generate minimal thermoelectric EMFs. Also, connections must be kept clean and free of oxides. For example, clean Cu-Cu connections typically have a Seebeck coefficient of  $\leq 0.2\mu\text{V}/^\circ\text{C}$ , while Cu-CuO connections may have a coefficient as high as  $1\text{mV}/^\circ\text{C}$ .

Sometimes, dissimilar metals cannot be avoided. For example, test fixtures often use spring contacts, which may be made of phosphor-bronze, beryllium-copper, or other materials with high Seebeck coefficients. In these cases, a small temperature difference may generate a large enough thermoelectric voltage to affect measurement accuracy. In that case an effort should be made to reduce the temperature gradients throughout the test circuit by placing all junctions in close proximity to one another and shielding the circuit from heat sources.

Another technique is to provide good thermal coupling between the test fixtures and a common, massive heat sink. Electrical insulators having high thermal conductivity must be used. Since most electrical insulators do not conduct heat very well, special insulator materials such as hard anodized aluminum, beryllium oxide, specially filled epoxy resins, sapphire, or diamond are needed to couple junctions to the heat sink.

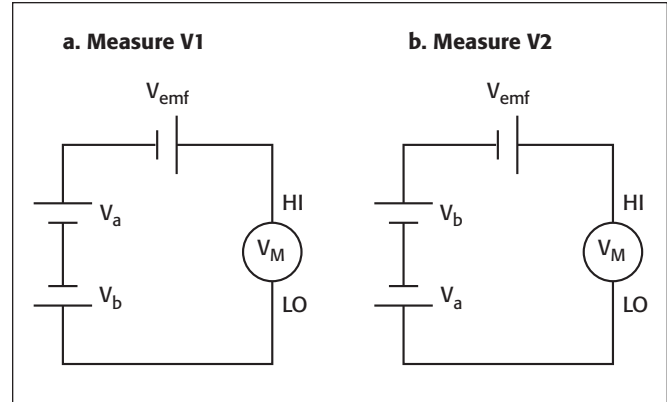
*Reversing Sources to Cancel Thermoelectric EMFs.* There may be cases where it's not practical to eliminate all the thermoelectric EMFs in a test circuit, and a low source voltage will be prone to measurement error. For example, when measuring a small voltage difference between two standard cells or between two thermocouples connected back-to-back, the error caused by stray thermoelectric EMFs can be excessive. However, the thermoelectric EMF can be cancelled by taking one measurement, and then carefully reversing the two sources and taking a second measurement (*Figure 3*). The average of the difference between these two readings is the desired voltage difference.

In *Figure 3*, the voltage sources,  $V_a$  and  $V_b$ , represent two standard cells (or two thermocouples). The voltage measured in *Figure 3a* is:

$$V_1 = V_{emf} + V_a - V_b$$

The two cells are reversed in *Figure 3b* and the measured voltage is:

$$V_2 = V_{emf} + V_b - V_a$$



*Figure 3. Reversing sources to cancel thermoelectric EMFs.*

The average of the difference between these two measurements is:

$$(V_1 - V_2) / 2 = (V_{emf} + V_a - V_b - V_{emf} - V_b + V_a) / 2 = V_a - V_b$$

Notice that this measurement technique effectively cancels out the thermoelectric EMF term ( $V_{emf}$ ), which represents the algebraic sum of all thermoelectric EMFs in the circuit.

*Input Offset Current Loading.* Another consideration when measuring voltages from sources with high impedance is the input offset current of a voltmeter. The input offset current develops an error voltage (offset) across the source resistance ( $R_s$ ). This causes the actual measured voltage to differ from the source voltage, i.e.,

$$V_m = V_s \pm (I_{offset} \times R_s)$$

For instance, if the offset current is  $1\text{pA}$  into a source resistance of  $10\text{G}\Omega$ , and the source voltage is  $10\text{V}$ , then the actual voltage measured by the instrument is:

$$V_m = 10\text{V} \pm (10^{-12}\text{A} \times 10^{10}\Omega)$$

$$V_m = 10\text{V} \pm 0.01\text{V}$$

The error caused by the input offset current in this example is about 0.1%.

Digital multimeters and nanovoltmeters have offset currents from about  $1\text{pA}$  to  $1\text{nA}$ . Electrometers are known for their low input offset current, from about  $10\text{fA}$  ( $10^{-14}\text{A}$ ) down to  $50\text{aA}$  ( $5 \times 10^{-17}\text{A}$ ). The lower the input offset current the more accurate the voltage measurement. Electrometers are the instruments to use for precise voltage measurements with high source resistance.

Input offset current errors will not be obvious. The solution is to get the instrument specifications from the manufacturer, find the source impedance, and calculate the potential measurement error.

## Johnson Noise

The ultimate limit on resolution in an electrical measurement is defined by Johnson or thermal noise. This noise is the voltage associated with the motion of electrons due to their thermal energy at temperatures above absolute zero ( $0\text{K}$ ). All voltage sources have internal resistance, so all voltage sources develop Johnson noise.

A plot of thermal noise voltage as a function of resistance and bandwidth at a temperature of  $290\text{K}$  is shown in *Figure 4*. This

voltage is related to the temperature, noise bandwidth and the source resistance. The noise voltage developed by a metallic resistance can be calculated from the following equation:

$$V = \sqrt{4kTBR}$$

where:

V = rms noise voltage developed in source resistance

k = Boltzmann's constant,  $1.38 \times 10^{-23}$  joule/K

T = absolute temperature of the source in Kelvin

B = noise bandwidth in hertz

R = resistance of the source in ohms

For example, at room temperature (293K), a source resistance of 10kΩ with a bandwidth of 5kHz will have almost 1μV rms of noise. For low level voltage measurements that are approaching the Johnson noise limit, troubleshooting and eliminating error is a matter of controlling whatever test system variables are possible. For example, you can reduce Johnson noise by lowering the temperature of the source resistance and by decreasing the bandwidth of the measurement. Cooling the sample from room temperature (293K) to liquid nitrogen temperature (77K) decreases the voltage noise by approximately a factor of 2.

If the voltmeter has adjustable filtering and integration, the bandwidth can be reduced by increasing the amount of filtering and/or by integrating over multiple power line cycles. Decreasing the bandwidth of the measurement is equivalent to increasing the response time of the instrument, and as a result, the measurement time is much longer.

However, if the measurement response time is long, thermoelectric EMFs associated with the temperature gradients in the circuit become more important. Sensitive measurements may not be achieved if the thermal time constants of the measurement circuit are the same order of magnitude as the response time. When this occurs, distinguishing between a change in signal voltage and a change in thermoelectric EMFs becomes impossible.

### Other Error Sources to Consider

RFI/EMI. Significant errors can also be generated by noise sources, which include RFI/EMI, magnetic fields, and ground loops.

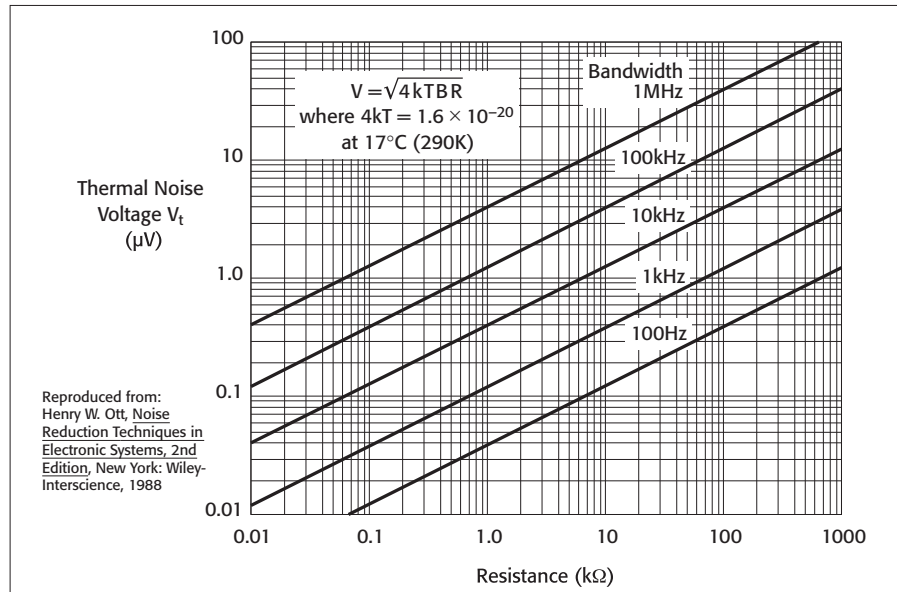


Figure 4. Thermal noise voltage as a function of resistance and bandwidth.

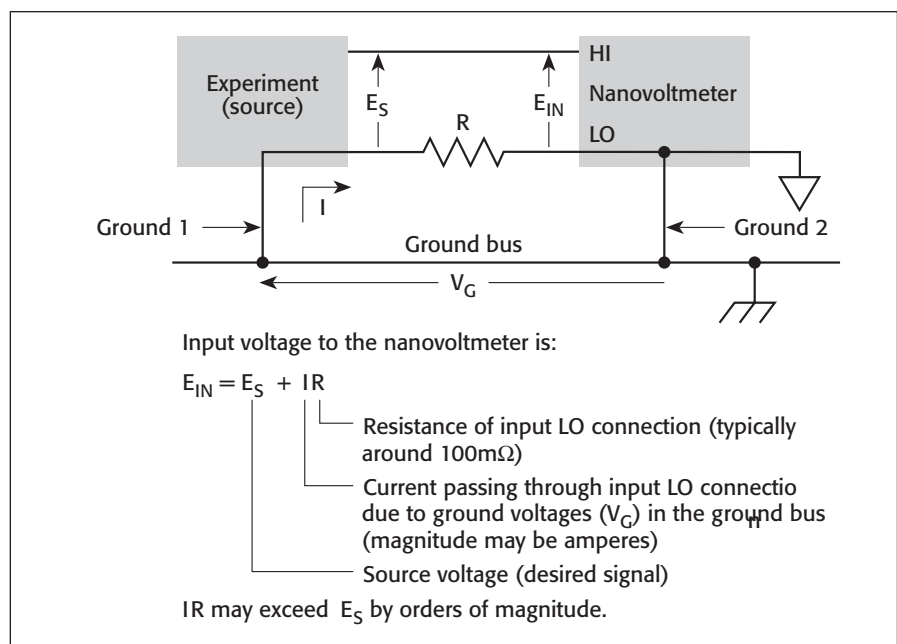


Figure 5. Multiple equipment grounds can form ground loops.

Typically, these are manifested as unstable (noisy) readings, but they can also cause offset voltages. For example, DC rectification of RFI (Radio Frequency Interference) and EMI (Electromagnetic Interference) by test equipment circuitry can cause a relatively steady reading offset.

Well-known techniques for alleviating these error sources are locating the test equipment some distance from RFI/EMI radiators, plus shielding of wire, cables, and the entire test set-up (i.e., a screen room). Twisted and shielded test leads are standard

practice for minimizing electromagnetically induced voltages. If all else fails, external filtering of the device input paths may be required.

**Ground Loops.** Noise and error voltages also arise from ground loops. When the source and measuring instruments are both connected to a common ground bus, a loop is formed as shown in Figure 5. A voltage ( $V_G$ ) between the source and instrument grounds will cause a current ( $I$ ) to flow around the loop. This current will create an unwanted

voltage in series with the source voltage. From Ohm's law:

$$E = IR$$

where E = ground loop interfering voltage, R = the resistance in the signal path through which the ground loop current flows, and I = the ground loop current.

A typical example of a ground loop can be seen when a number of instruments are plugged into power strips on different instrument racks. Frequently, there is a small difference in potential between the ground points. This potential difference can cause large currents to circulate and create unexpected

voltage drops. A fairly obvious sign of a ground loop noise voltage is when the voltmeter reading is much larger than anything expected from the DUT. Sometimes it can be orders of magnitude larger than the DUT source voltage. The cure for ground loops is to ground all equipment at a single point. The easiest way is to use isolated power sources and instruments, and then find a single, good earth-ground point for the entire system.

There are many other potential error sources in low voltage measurements, but those just discussed are the most common, and tend to create the largest magnitude errors. KEITHLEY

## About the Author

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