

# Digital Multimeter Tutorials

The Agilent 34401A is capable of making highly accurate measurements. In order to achieve the greatest accuracy, you must take the necessary steps to eliminate potential measurement errors. These tutorials describe common errors found in measurements and give suggestions to help you avoid these errors.

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## Thermal EMF Errors

Thermoelectric voltages are the most common source of error in low-level dc voltage measurements. Thermoelectric voltages are generated when you make circuit connections using dissimilar metals at different temperatures. Each metal-to-metal junction forms a *thermocouple*, which generates a voltage proportional to the junction temperature. You should take the necessary precautions to minimize thermocouple voltages and temperature variations in low-level voltage measurements. The best connections are formed using copper-to-copper crimped connections. The table below shows common thermoelectric voltages for connections between dissimilar metals.

Copper-to-	Approx. $\mu\text{V}/\text{C}^\circ$
Copper	<0.3
Gold	0.5
Silver	0.5
Brass	3
Beryllium Copper	5
Aluminum	5
Kovar or Alloy 42	40
Silicon	500
Copper-Oxide	1000
Cadmium-Tin Solder	0.2
Tin-Lead Solder	5

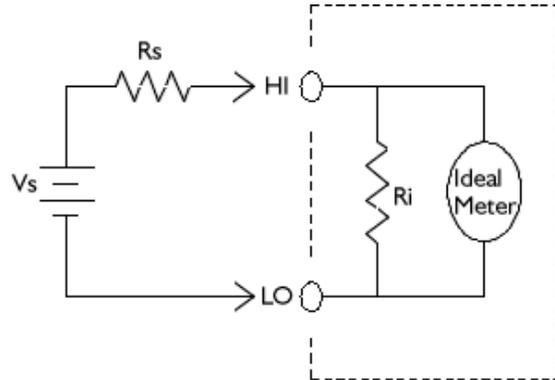
*The Agilent 34401A's input terminals are copper alloy.*

## Loading Errors (dc volts)

Measurement loading errors occur when the resistance of the device-under-test (DUT) is an appreciable percentage of the multimeter's own input resistance. The diagram below shows this error source.

$V_s$  = ideal DUT voltage  
 $R_s$  = DUT source resistance  
 $R_i$  = multimeter input resistance (10 M $\Omega$  or >10 G $\Omega$ )

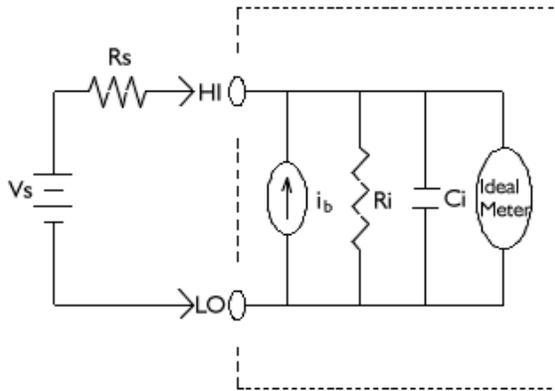
$$\text{Error (\%)} = \frac{100 * R_s}{R_s + R_i}$$



To reduce the effects of loading errors, and to minimize noise pickup, you can set the multimeter's input resistance to greater than 10 G $\Omega$  for the 100 mVdc, 1 Vdc, and 10 Vdc ranges. The input resistance is maintained at 10 M $\Omega$  for the 100 Vdc and 1000 Vdc ranges.

## Leakage Current Errors

The multimeter's input capacitance will "charge up" due to input bias currents when the terminals are open-circuited (if the input resistance is  $10\text{ G}\Omega$ ). The multimeter's measuring circuitry exhibits approximately  $30\text{ pA}$  of input bias current for ambient temperatures from  $0^\circ\text{C}$  to  $30^\circ\text{C}$ . Bias current will double (X2) for every  $8^\circ\text{C}$  change in ambient temperature above  $30^\circ\text{C}$ . This current generates small voltage offsets dependent upon the source resistance of the device-under-test. This effect becomes evident for a source resistance of greater than  $100\text{ k}\Omega$ , or when the multimeter's operating temperature is significantly greater than  $30^\circ\text{C}$ .



$i_b$  = multimeter bias current  
 $R_s$  = DUT source resistance  
 $C_i$  = multimeter input capacitance

Voltage Ranges	$C_i$ (multimeter input capacitance)
dc: 0.1V, 1 V, 10 V	< 700 pF
dc: 100 V, 1000 V	< 50 pF
all ac ranges	< 50 pF

## Rejecting Power-Line Noise Voltages

A desirable characteristic of integrating analog-to-digital (A/D) converters is their ability to reject spurious signals. Integrating techniques reject power-line-related noise present with dc signals on the input. This is called *normal mode rejection* or *NMR*. Normal mode noise rejection is achieved when the multimeter measures the average of the input by "integrating" it over a fixed period. If you set the integration time to a whole number of power line cycles (PLCs) of the spurious input, these errors (and their harmonics) will average out to approximately zero.

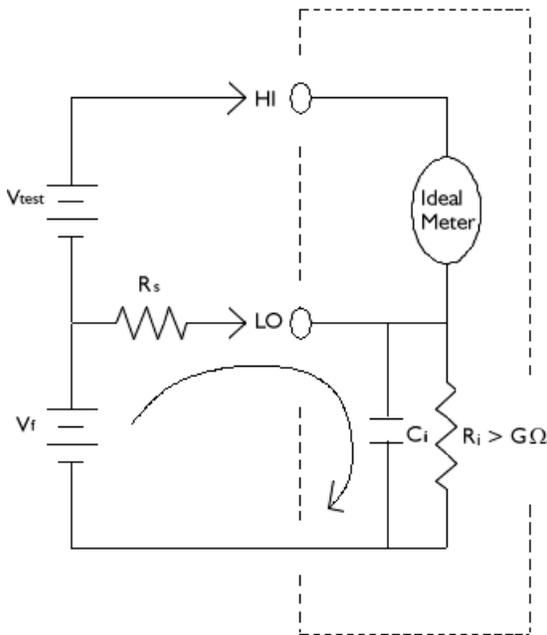
The Agilent 34401A provides three A/D integration times to reject power-line frequency noise (and power-line frequency harmonics). When you apply power to the multimeter, it measures the power-line frequency (50 Hz or 60 Hz), and then determines the proper integration time. The table below shows the noise rejection achieved with various configurations. For better resolution and increased noise rejection, select a longer integration time.

Digits	NPLCs	Integration Time 60 Hz (50 Hz)	NMR
4½ Fast	0.02	400.7µs (400 µs)	-
4½ Slow	1	16.7 ms (20 ms)	60 dB
5½ Fast	0.2	3 ms (3 ms)	-
5½ Slow	10	167 ms (200 ms)	60 dB
6½ Fast	10	167 ms (200 ms)	60 dB
6½ Slow	100	1.67 sec (2 sec)	70 dB

## Common Mode Rejection (CMR)

Ideally, a multimeter is completely isolated from earth-referenced circuits. However, there is finite resistance between the multimeter's input LO terminal and earth ground as shown below. This can cause errors when measuring low voltages that are floating relative to earth ground.

*Note: below,  $R_i$  is greater than  $10\text{ G}\Omega$ .*



$V_f$  = float voltage

$R_s$  = DUT source resistance imbalance

$R_i$  = multimeter isolation resistance (LO-Earth)

$C_i$  = multimeter input capacitance:  $\approx 200\text{ pF}$  (LO-Earth)

$$\text{Error (V)} = \frac{V_f * R_s}{R_s + R_i}$$

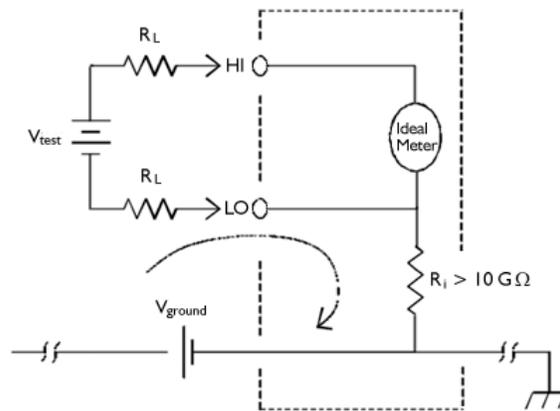
## Noise Caused by Magnetic Loops

If you are making measurements near magnetic fields, you should take the necessary precautions to avoid inducing voltages in the measurement connections. You should be especially careful when working near conductors carrying large currents. Use twisted-pair connections to the multimeter to reduce the noise pickup loop area, or dress the test leads as close together as possible. Loose or vibrating test leads will also induce error voltages. Make sure your test leads are tied down securely when operating near magnetic fields. Whenever possible, use magnetic shielding materials or physical separation to reduce problem magnetic field sources.

## Noise Caused by Ground Loops

When measuring voltages in circuits where the multimeter and the device-under-test are both referenced to a common earth ground, a "ground loop" is formed. As shown below, any voltage difference between the two ground reference points ( $V_{\text{ground}}$ ) causes a current to flow through the measurement leads. This causes errors, such as noise and offset voltage (usually power-line related), which are added to the measured voltage.

The best way to eliminate ground loops is to maintain the multimeter's isolation from earth; do not connect the input terminals to ground. If the multimeter must be earth-referenced, be sure to connect it, and the device-under-test, to the same common ground point. This will reduce or eliminate any voltage difference between the devices. Also make sure the multimeter and device-under-test are connected to the same electrical outlet whenever possible.



$R_L$  = lead resistance

$R_i$  = multimeter isolation resistance

$V_{\text{ground}}$  = voltage drop on ground bus

## Resistance Measurements

The Agilent 34401A offers two methods for measuring resistance: *2-wire* and *4-wire* ohms. For both methods, the test current flows from the input HI terminal and then through the resistor being measured. For 2-wire ohms, the voltage drop across the resistor being measured is sensed internal to the multimeter. Therefore, test lead resistance is also measured. For 4-wire ohms, separate "sense" connections are required. Since no current flows in the sense leads, the resistance in these leads does not give a measurement error.

*The errors mentioned earlier in this chapter for dc voltage measurements also apply to resistance measurements. Additional error sources unique to resistance measurements are discussed on the following pages.*

## 4-Wire Ohms Measurements

The 4-wire ohms method provides the most accurate way to measure small resistances. Test lead resistances and contact resistances are automatically reduced using this method. The four-wire ohms method is often used in automated test applications where long cable lengths, numerous connections, or switches exist between the multimeter and the device-under-test. The recommended connections for 4-wire ohm measurements are shown below.

$$R = \frac{V_{\text{meter}}}{I_{\text{test}}}$$

## Removing Test Lead Resistance Errors

To eliminate offset errors associated with the test lead resistance in 2-wire ohm measurements, follow the steps below.

1. Short the ends of the test leads together. The multimeter displays the test lead resistance.
2. Press **Null** from the front panel. The multimeter displays "0" ohms with the leads shorted together.

## Power Dissipation Effects

When measuring resistors designed for temperature measurements (or other resistive devices with large temperature coefficients), be aware that the multimeter will dissipate some power in the device-under-test. If power dissipation is a problem, you should select the multimeter's next higher measurement range to reduce the errors to acceptable levels. The following table shows several examples.

Range	Test Current	DUT (Power at Full Scale)
100 $\Omega$	1 mA	100 $\mu$ W
1 k $\Omega$	1 mA	1 mW
10 k $\Omega$	100 $\mu$ A	100 $\mu$ W
100 k $\Omega$	10 $\mu$ A	10 $\mu$ W
1 M $\Omega$	5 $\mu$ A	30 $\mu$ W
10 M $\Omega$	500 na	3 $\mu$ W

## Settling Time Effects

The Agilent 34401A has the ability to insert automatic measurement settling delays. These delays are adequate for resistance measurements with less than 200 pF of combined cable and device capacitance. This is particularly important if you are measuring resistances above 100 kΩ. Settling due to RC time constant effects can be quite long. Some precision resistors and multi-function calibrators use large parallel capacitors (1000 pF to 0.1 mF) with high resistor values to filter out noise currents injected by their internal circuitry. Non-ideal capacitances in cables and other devices may have much longer settling times than expected just by RC time constants due to dielectric absorption (soak) effects. Errors will be measured when settling after the initial connection and after a range change.

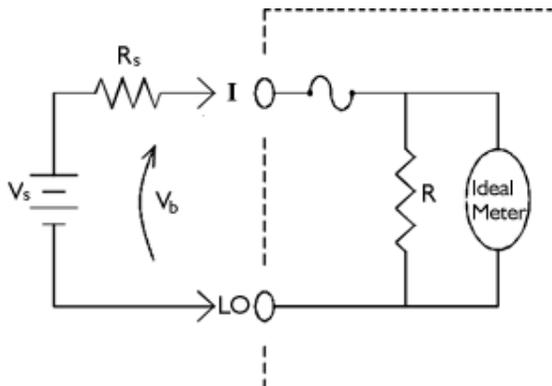
## Errors in High Resistance Measurements

When you are measuring large resistances, significant errors can occur due to insulation resistance and surface cleanliness. You should take the necessary precautions to maintain a "clean" high-resistance system. Test leads and fixtures are susceptible to leakage due to moisture absorption in insulating materials and "dirty" surface films. Nylon and PVC are relatively poor insulators ( $10^9$  ohms) when compared to PTFE Teflon<sup>®</sup> insulators ( $10^{13}$  ohms). Leakage from nylon or PVC insulators can easily contribute a 0.1% error when measuring a 1 MΩ resistance in humid conditions.

*Teflon is a registered trademark of E.I. DuPont de Nemours and Co.*

## DC Current Measurement Errors

When you connect the multimeter in series with a test circuit to measure current, a measurement error is introduced. The error is caused by the multimeter's series *burden voltage*. A voltage is developed across the wiring resistance and current shunt resistance of the multimeter as shown below.



$V_s$  = source voltage  
 $R_s$  = DUT source resistance  
 $V_b$  = multimeter burden voltage  
 $R$  = multimeter current shunt

$$\text{Error (\%)} = \frac{-100\% * V_b}{V_s}$$

## True RMS AC Measurements

True RMS responding multimeters, like the Agilent 34401A, measure the "heating" potential of an applied voltage. Unlike an "average responding" measurement, a true RMS measurement is used to determine the power dissipated in a resistor. The power is proportional to the square of the measured true RMS voltage, independent of waveshape. An average responding ac multimeter is calibrated to read the same as a true RMS meter for *sinewave inputs only*. For other waveform shapes, an average responding meter will exhibit substantial errors as shown below.

Waveform Shape	Crest Factor (C.F.)	AC RMS	AC+DC RMS	Average Responding Error
	1.414	$\frac{V}{1.414}$	$\frac{V}{1.414}$	Calibrated for 0 error
	1.732	$\frac{V}{1.732}$	$\frac{V}{1.732}$	-3.9%
	$\sqrt{\frac{T}{t}}$	$\frac{V}{C.F.} \times \sqrt{1 - \left(\frac{1}{C.F.}\right)^2}$	$\frac{V}{C.F.}$	-46% for C.F. = 4

The multimeter's ac voltage and ac current functions measure the ac-coupled true RMS value. This is in contrast to the ac + dc true RMS value shown above. Only the "heating value" of the ac components of the input waveform are measured (dc is rejected). For sinewaves, triangle waves, and square waves, the ac and ac + dc values are equal since these waveforms do not contain a dc offset. Non-symmetrical waveforms, such as pulse trains, contain dc voltages that are rejected by ac-coupled true RMS measurements. An ac-coupled true RMS measurement is desirable in situations where you are measuring small ac signals in the presence of large dc offsets. For example, this situation is common when measuring ac ripple present on dc power supplies. There are situations, however, where you might want to know the ac + dc true RMS value. You can determine this value by combining results from dc and ac measurements as shown below. You should perform the dc measurement using at least 10 power line cycles of integration (6-digit mode) for best ac rejection.

$$ac + dc = \sqrt{ac^2 + dc^2}$$

## Crest Factor Errors (non-sinusoidal inputs)

A common misconception is that "since an ac multimeter is true RMS, its sinewave accuracy specifications apply to all waveforms." Actually, the shape of the input signal can dramatically affect measurement accuracy. A common way to describe signal waveshapes is *crest factor*. Crest factor is the ratio of the peak value to RMS value of a waveform.

For a pulse train, for example, the crest factor is approximately equal to the square root of the inverse of the duty cycle as shown in the table on the previous page. In general, the greater the crest factor, the greater the energy contained in higher frequency harmonics. All multimeters exhibit measurement errors that are crest factor dependent. Crest factor errors for the Agilent 34401A are shown in the specifications in chapter 8. Note that the crest factor errors do not apply for input signals below 100 Hz when using the slow ac filter.

You can estimate the measurement error due to signal crest factor as shown below:

$$\text{Total Error} = \text{Error (sine)} + \text{Error (crest factor)} + \text{Error (bandwidth)}$$

Error (sine): error for sinewave.

Error (crest factor): crest factor additional error.

Error (bandwidth): estimated bandwidth error as shown below.

Bandwidth	$\frac{-C.F.^2 * F}{4\pi * BW}$	C.F. = signal crest factor
Error =		F = input fundamental frequency
		BW = multimeter s -3 dB bandwidth (1 MHz for the Agilent 34401A)

Example: Calculate the approximate measurement error for a pulse train input with a crest factor of 3 and a fundamental frequency of 20 kHz. For this example, assume the multimeter's 90-day accuracy specifications: +/- (0.05% + 0.03%).

$$\text{Total Error} = 0.08\% + 0.15\% + 1.4\% = 1.6\%$$

## Loading Errors (ac volts)

In the ac voltage function, the input of the Agilent 34401A appears as a 1 M [see image 1] resistance in parallel with 100 pF of capacitance. The cabling that you use to connect signals to the multimeter will also add additional capacitance and loading. The table below shows the multimeter's approximate input resistance at various frequencies.

Input Frequency	Input Resistance
100 kHz	1 M $\Omega$
1 kHz	850 k $\Omega$
10 kHz	160 k $\Omega$
100 kHz	16 k $\Omega$

For low frequencies:

$$\text{Error (\%)} = \frac{-100 \times R_s}{R_s + 1 \text{ M}\Omega}$$

Additional error for high frequencies:

$$\text{Error (\%)} = 100 \times \left[ \frac{1}{\sqrt{1 + (2\pi \times F \times R_s \times C_{in})^2}} - 1 \right]$$

$R_s$  = source resistance  
 $F$  = input frequency  
 $C_{in}$  = input capacitance (100 pf)  
plus cable capacitance

## Measurements below Full Scale

You can make the most accurate ac measurements when the multimeter is at full scale of the selected range. Autoranging occurs at 10% and 120% of full scale. This enables you to measure some inputs at full scale on one range and 10% of full scale on the next higher range. The accuracy will be significantly different for these two cases. For highest accuracy, you should use manual range to get to the lowest range possible for the measurement.

## High-Voltage Self-Heating Errors

If you apply more than 300 Vrms, self-heating will occur in the multimeter's internal signal-conditioning components. These errors are included in the multimeter's specifications. Temperature changes inside the multimeter due to self-heating may cause additional error on other ac voltage ranges. The additional error will be less than 0.02% and will dissipate in a few minutes.

## Temperature Coefficient and Overload Errors

The Agilent 34401A uses an ac measurement technique that measures and removes internal offset voltages when you select a different function or range. If you leave the multimeter in the same range for an extended period of time, and the ambient temperature changes significantly (or if the multimeter is not fully warmed up), the internal offsets may change. This temperature coefficient is typically 0.002% of range per °C and is automatically removed when you change functions or ranges.

When manual ranging to a new range in an *overload condition*, the internal offset measurement may be degraded for the selected range. Typically, an additional 0.01% of range error may be introduced. This additional error is automatically removed when you remove the overload condition and then change functions or ranges.

## Low-Level Measurement Errors

When measuring ac voltages less than 100 mV, be aware that these measurements are especially susceptible to errors introduced by extraneous noise sources. An exposed test lead will act as an antenna and a properly functioning multimeter will measure the signals received. The entire measurement path, including the power line, act as a loop antenna. Circulating currents in the loop will create error voltages across any impedances in series with the multimeter's input. For this reason, you should apply low-level ac voltages to the multimeter through shielded cables. You should connect the shield to the input LO terminal.

Make sure the multimeter and the ac source are connected to the same electrical outlet whenever possible. You should also minimize the area of any ground loops that cannot be avoided. A high-impedance source is more susceptible to noise pickup than a low-impedance source. You can reduce the high-frequency impedance of a source by placing a capacitor in parallel with the multimeter's input terminals. You may have to experiment to determine the correct capacitor value for your application.

Most extraneous noise is not correlated with the input signal. You can determine the error as shown below.

$$\text{Voltage measured} = \text{sqrt} (V_{\text{in}}^2 + \text{Noise}^2)$$

Correlated noise, while rare, is especially detrimental. Correlated noise will always add directly to the input signal. Measuring a low-level signal with the same frequency as the local power line is a common situation that is prone to this error.

## Common Mode Errors

Errors are generated when the multimeter's input LO terminal is driven with an ac voltage relative to earth. The most common situation where unnecessary common mode voltages are created is when the output of an ac calibrator is connected to the multimeter "backwards." Ideally, a multimeter reads the same regardless of how the source is connected. Both source and multimeter effects can degrade this ideal situation.

Because of the capacitance between the input LO terminal and earth (approximately 200 pF for the Agilent 34401A), the source will experience different loading depending on how the input is applied. The magnitude of the error is dependent upon the source's response to this loading. The multimeter's measurement circuitry, while extensively shielded, responds differently in the backward input case due to slight differences in stray capacitance to earth. The multimeter's errors are greatest for high-voltage, high-frequency inputs. Typically, the multimeter will exhibit about 0.06% additional error for a 100 V, 100 kHz reverse input. You can use the grounding techniques described for dc common mode problems to minimize ac common mode voltages (see page 195).

## AC Current Measurement Errors

Burden voltage errors, which apply to dc current, also apply to ac current measurements. However, the burden voltage for ac current is larger due to the multimeter's series inductance and your measurement connections. The burden voltage increases as the input frequency increases. Some circuits may oscillate when performing current measurements due to the multimeter's series inductance and your measurement connections.

## Frequency and Period Measurement Errors

The multimeter uses a reciprocal counting technique to measure frequency and period. This method generates constant measurement resolution for any input frequency. The multimeter's ac voltage measurement section performs input signal conditioning. All frequency counters are susceptible to errors when measuring low-voltage, low frequency signals. The effects of both internal noise and external noise pickup are critical when measuring "slow" signals. The error is inversely proportional to frequency. Measurement errors will also occur if you attempt to measure the frequency (or period) of an input following a dc offset voltage change. You must allow the multimeter's input dc blocking capacitor to fully settle before making frequency measurements.

## Making High-Speed dc and Resistance Measurement Errors

The multimeter incorporates an automatic zero measurement procedure (autozero) to eliminate internal thermal EMF and bias current errors. Each measurement actually consists of a measurement of the input terminals followed by a measurement of the internal offset voltage. The internal offset voltage error is subtracted from the input for improved accuracy. This compensates for offset voltage changes due to temperature. For maximum reading speed, turn autozero off. This will more than double your reading speeds for dc voltage, resistance and dc current functions. Autozero does not apply to other measurement functions.

## Making High-Speed ac Measurements

The multimeter's ac voltage and ac current functions implement three different low-frequency filters. These filters allow you to trade-off low frequency accuracy for faster reading speed. The *fast filter* settles in 0.1 seconds, and is useful for frequencies above 200 Hz. The *medium filter* settles in 1 second, and is useful for measurements above 20 Hz. The *slow filter* settles in 7 seconds, and is useful for frequencies above 3 Hz. With a few precautions, you can perform ac measurements at speeds up to 50 readings per second. Use manual ranging to eliminate autoranging delays. By setting the preprogrammed settling (trigger) delays to 0, each filter will allow up to 50 readings per second. However, the measurement might not be very accurate since the filter is not fully settled. In applications where sample-to-sample levels vary widely, the medium filter will settle at 1 reading per second, and the fast filter will settle at 10 readings per second. If the sample-to-sample levels are similar, little settling time is required for each new reading. Under this specialized condition, the medium filter will provide reduced accuracy results at 5 readings per second, and the fast filter will provide reduced accuracy at 50 readings per second. Additional settling time may be required when the dc level varies from sample to sample. The multimeter's dc blocking circuitry has a settling time constant of 0.2 seconds. This settling time only affects measurement accuracy when dc offset levels vary from sample to sample. If maximum measurement speed is desired in a scanning system, you may want to add an external dc blocking circuit to those channels with significant dc voltages present. This circuit can be as simple as a resistor and a capacitor.