KEITHLEY

5th Edition

# Low Level Measurements

Precision DC Current, Voltage and Resistance Measurements

*FIGURE 1-1: Standard Symbols Used In This Text*

| Prefixes | | |
|---|---|---|
| **Symbol** | **Prefix** | **Exponent** |
| y | yocto- | $10^{-24}$ |
| z | zepto- | $10^{-21}$ |
| a | atto- | $10^{-18}$ |
| f | femto- | $10^{-15}$ |
| p | pico- | $10^{-12}$ |
| n | nano- | $10^{-9}$ |
| μ | micro- | $10^{-6}$ |
| m | milli- | $10^{-3}$ |
| (none) | (none) | $10^{0}$ |
| k | kilo- | $10^{3}$ |
| M | mega- | $10^{6}$ |
| G | giga- | $10^{9}$ |
| T | tera- | $10^{12}$ |
| P | peta- | $10^{15}$ |
| E | exa- | $10^{18}$ |
| Z | zetta- | $10^{21}$ |
| Y | yotta- | $10^{24}$ |

| Quantities | | |
|---|---|---|
| **Symbol** | **Unit** | **Quantity** |
| V | volts | EMF |
| A | amperes | current |
| Ω | ohms | resistance |
| C | coulombs | charge |
| s | seconds | time |
| W | watts | power |
| F | farads | capacitance |
| Hz | cycles/s | frequency |
| K | degrees | temperature |



## 1.1 Introduction

DC voltage, DC current, and resistance are measured most often with digital multimeters (DMMs). Generally, these instruments are adequate for measurements at signal levels above 1μV or 1μA, or below 1GΩ. (Refer to **Figure 1-1** for standard symbols used in this text.) However, these instruments do not approach the theoretical limits of sensitivity. For low-level signals, more sensitive instruments such as electrometers, picoammeters, and nanovoltmeters must be used.

### 1.1.1 Theoretical Measurement Limits

The theoretical limit of sensitivity in any measurement is determined by the noise generated by the resistances present in the circuit. As discussed in Sections 2.6.5 and 3.2.2, voltage noise is proportional to the square root of the resistance, bandwidth, and absolute temperature. **Figure 1-2** shows theoretical voltage measurement limits at room temperature with a response time of 0.1 second to 10 seconds. Note that high source resistance limits the theoretical sensitivity of the voltage measurement. While it is certainly possible to measure a 1μV signal that has a 1Ω source resistance, it is not possible to measure that same 1μV signal level from a 1TΩ source. Even with a much lower 1MΩ source resistance, a 1μV measurement is "near theoretical limits," and it would thus be very difficult to make using an ordinary DMM.

In addition to having insufficient voltage or current sensitivity (most DMMs are no more sensitive than 1μV or 1nA/digit), DMMs have high input offset current[1] when measuring voltage and lower input resistance compared to more sensitive instruments meant for low-level DC measurements. These characteristics add more noise to the measurement, disturb the circuit unnecessarily, and cause errors in the measurement. These aspects are discussed in detail in Sections 2 and 3.

### 1.1.2 DMM Limitations

The implication of these DMM characteristics is that it is not possible to use a DMM to measure signals at levels close to theoretical measurement limits, as shown in **Figure 1-3**. If the source resistance is 1MΩ or

[1] Input current flows in the input lead of an active device or instrument. With voltage measurements, the *input current* is ideally zero; thus, any input current represents an error. With current measurements, the *signal current* becomes the *input current* of the measuring instrument. However, some background current is always present when no signal current is applied to the instrument input. This unwanted current is the *input offset current* (often shortened to *offset current*) of the instrument.

Unwanted *offset currents* and *offset voltages* may also be generated by the source and test connections.

A *leakage current* is another unwanted error current resulting from voltage across an undesired resistance path (called *leakage resistance*). This current, combined with the *offset current*, is the total error current.

FIGURE 1-2: *Theoretical Limits of Voltage Measurements*

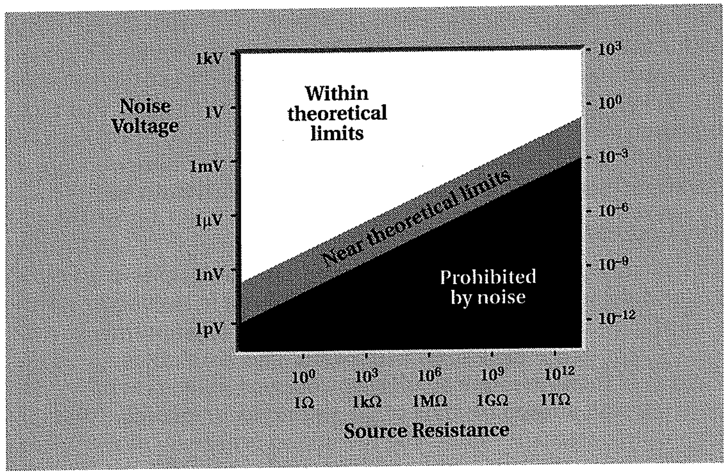
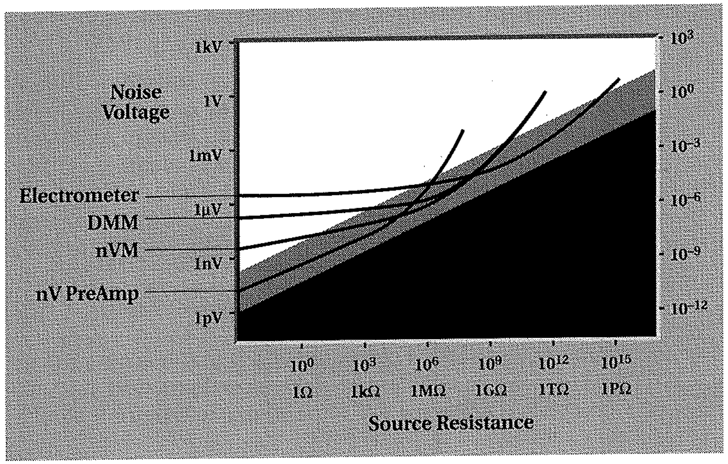



FIGURE 1-3: *Typical Digital Multimeter (DMM, Nanovoltmeter (nVM), and Electrometer Limits of Measurement at Various Source Resistances*




less, or if the desired resolution is no better than 0.1µV (with low source resistance), the signal level is not "near theoretical limits," and the DMM is adequate. If better voltage sensitivity is desired, and the source resistance is low (as it must be because of theoretical limitations), a nanovoltmeter provides a means of measuring at levels much closer to the theoretical limits of measurement. With very high source resistance values (for example, 1TΩ), a DMM is not a suitable voltmeter. DMM input resistance ranges from 10MΩ to 10GΩ—several orders of magnitude less than a 1TΩ source resistance, resulting in severe input loading errors. Also, input currents are typically many picoamps, creating large voltage offsets. However, because of its much higher input resistance, an electrometer can make measurements at levels that approach theoretical limits.

A similar situation exists for low-level current measurements; DMMs generally have a high input voltage drop (input burden), which affects low-level current measurements, and DMM resolution is generally no better than 1nA. Thus, an electrometer or picoammeter with its much lower input burden and better sensitivity will operate at levels much closer to the theoretical (and practical) limits of low-current measurements.

## 1.2 Instrument Definitions

A number of different types of instruments are available to make DC measurements, including electrometers, picoammeters, nanovoltmeters, DMMs, SMUs (source-measure units) and SourceMeter instruments. The following paragraphs discuss and compare the important characteristics of these instruments.

### 1.2.1 The Electrometer

An electrometer is a highly refined DC multimeter. As such, it can be used for virtually any measurement task performed by a conventional DC multimeter. Additionally, the special input characteristics and high sensitivity of an electrometer permit it to perform voltage, current, resistance, and charge measurements far beyond the realm of a conventional DMM.

An electrometer must be used when any of the following conditions exist:

1. Extended range is needed over that of conventional instruments, such as for detecting or measuring:
   - currents below 100pA ($10^{-10}$A), or
   - resistances above 1GΩ ($10^9$Ω).
2. Circuit loading must be minimized, such as when:
   - measuring voltage from a source resistance of 1MΩ or higher or
   - measuring current if input voltage drop (burden) of less than a few hundred millivolts is required (when measuring currents from sources of a few volts or less).
3. Functions not available on general purpose equipment are needed, including:
   - charge measurement,
   - sensitive current measurement or

- measuring signals at or near Johnson noise limitations (as indicated in **Figure 1-2**).

Besides having such versatility, electrometers are easy to operate, reliable, rugged, and many have the speed and interfaceability of system DMMs.

*Voltmeter Function*

The input resistance of an electrometer voltmeter is extremely high, typically above 100TΩ ($10^{14}\Omega$) and may be as high as 10PΩ ($10^{16}\Omega$). Furthermore, the input offset current is less than 5fA ($5 \times 10^{-15}$A) and may be as low as 50aA ($5 \times 10^{-17}$A) in some instruments. These characteristics describe a device that can measure voltage with a very small amount of circuit loading.

Because of the high input resistance and low offset current, the electrometer voltmeter has minimal effect on the circuit being measured. As a result, the electrometer can be used to measure voltage in situations where an ordinary multimeter would be unusable. For example, the electrometer can measure the voltage on a 500pF capacitor without significantly discharging the device; it can also measure the potential of piezoelectric crystals and high-impedance pH electrodes.

*Ammeter Function*

As an ammeter, the electrometer is capable of measuring extremely low currents, limited only by theoretical limits or by the instrument's input offset current. It also has a much lower voltage burden than conventional DMMs.

With its extremely low input offset current and minimal input voltage burden, it can measure currents as low as 1fA ($10^{-15}$A). Because of this high sensitivity, it is suitable for measuring the current output of photomultipliers and ion chambers, as well as very low currents in semiconductors, mass spectrometers, and other devices.

*Ohmmeter Function*

An electrometer may measure resistance by using either a constant current or a constant voltage method. If using the constant current method, the electrometer's high input resistance and low offset current enables measurements up to 200GΩ. When using the constant voltage method, the electrometer applies a constant voltage to the unknown resistance, measures the current, and then calculates the resistance. This is the preferred method because it allows the unknown resistor to be tested at a known voltage. The electrometer can measure resistances up to 10PΩ ($10^{16}\Omega$) using this method.

*Coulombmeter Function*

Current integration and measurement of charge are electrometer coulombmeter capabilities not found in multimeters. The electrometer coulombmeter can detect charge down to 800aC ($8 \times 10^{-16}$C). It is equivalent to an active integrator and, therefore, has low voltage burden, typically less than 100μV.

The coulombmeter function is capable of measuring lower current than the ammeter function, since no noise is contributed by internal resistors. Currents as low as 10aA ($10^{-17}$A) may be detected using this function.

### 1.2.2 The DMM

Digital multimeters come in a variety of formats, from low-cost handheld 3½-digit units to high-precision system DMMs costing more than an electrometer or a nanovoltmeter. Many benchtop units and all system DMMs may be interfaced to a computer. While there are many models available from a wide variety of manufacturers, none approaches the theoretical limits of measurement discussed above. These limitations do not imply that DMMs are inadequate instruments; they simply point out the fact that the vast majority of measurements are made at levels far from theoretical limits, and DMMs are designed to meet these more conventional measurement needs.

Although low-level measurements are by definition those that are close to theoretical limits, and are thus outside the range of DMMs, advances in technology are narrowing the gap between DMMs and dedicated low-level instruments. For example, the most sensitive DMMs can detect DC voltages as low as 10nV, resolve DC currents down to 10pA, and measure resistances as high as 1GΩ. While these characteristics still fall far short of the corresponding capabilities of more sensitive instruments like the electrometer described above, all the measurement theory and accuracy considerations in this book apply to DMM measurements as well as to nanovoltmeter, picoammeter, electrometer, or SMU measurements. The difference is only a matter of degree; when making measurements close to theoretical limits, all measurement considerations are vitally important. When measuring at levels far from theoretical limits, only a few basic considerations (accuracy, loading, etc.) are generally of concern.

### 1.2.3 The Nanovoltmeter

A nanovoltmeter is a very sensitive voltmeter. As shown in **Figure 1-3**, this type of instrument is optimized to provide measurements near the theoretical limits of low source resistances, in contrast to the electrometer, which is optimized for use with high source resistances. Compared to an electrometer, the voltage noise and drift are much lower, and the current noise and drift are much higher (but no worse than a DMM). Input resistance is usually similar to that of a DMM and is much lower than that of an electrometer.

As in the case of electrometers, modern nanovoltmeters are just as reliable and easy to operate as DMMs, and many have system DMM interfaceability. Their distinguishing characteristic is their voltage sensitivity, which can be as good as 1nV. Most nanovoltmeters are not multi-function instruments and are correspondingly less complex than electrometers.

### 1.2.4 The Picoammeter

A picoammeter is an ammeter built along the lines of the ammeter function of an electrometer. Generally, it has a lower voltage burden, similar or faster speed than an electrometer, not as much sensitivity, and a lower price. It may also have special characteristics, such as high speed or logarithmic response.

### 1.2.5 The Source-Measure Unit

As the name implies, the source-measure unit (SMU) has both measuring and sourcing capabilities. Adding current and voltage sourcing capabilities to a measuring instrument provides an extra degree of versatility for many low-level measurement applications. For example, very high resistance values can be determined by applying a voltage across a device and measuring the resulting current. The added sourcing functions also make a SMU more convenient and versatile than using separate instruments for such applications as generating I-V curves for semiconductors and other types of devices.

The typical SMU provides the following four functions:

- Measure voltage
- Measure current
- Source voltage
- Source current

These functions can be used separately or they can be used together in the following combinations:

- Simultaneously source voltage and measure current or
- Simultaneously source current and measure voltage.

Modern SMUs have a number of electrometer-like characteristics that make them suitable for low-level measurements. The input resistance is very high (typically 100TΩ or more), minimizing circuit loading when making voltage measurements from high-impedance sources. The current-measurement sensitivity is also similar to that of the electrometer picoammeter section—typically as low as 10fA.

Another important advantage of many source-measure units is their sweep capability. Either voltage or current can be swept across the desired range at specified increments, and the resulting current or voltage can be measured at each step. Built-in source-delay-measure cycles allow measurement speed to be optimized while ensuring sufficient circuit settling time to maintain measurement integrity.

### 1.2.6 The SourceMeter®

The SourceMeter is very similar to the source-measure unit in many ways, including its ability to source and measure both current and voltage and to perform sweeps. In addition, a SourceMeter can display the measurements directly in resistance, as well as voltage and current.

The typical SourceMeter does not have as high an input impedance or as low a current capability as a source-measure unit. The SourceMeter is designed for general-purpose, high speed production test applications. The SourceMeter can be used as a source for moderate to low level measurements and for research applications.

Unlike a DMM, which can make a measurement at only one point, the SourceMeter can be used to generate a family of curves, because it has a built-in source. This is especially useful when studying semiconductor devices and making materials measurements.

The SourceMeter, as a current source, can be used in conjunction with a nanovoltmeter to measure very low resistances. The polarity of the source can be automatically reversed to correct for offsets.

### 1.2.7 The Micro-ohmmeter

A micro-ohmmeter is a special type of ohmmeter designed especially for making low-level resistance measurements. While the techniques used for making resistance measurements are similar to those used in a DMM, micro-ohmmeter circuits are optimized for making low-level measurements. The typical micro-ohmmeter can resolve resistances as low as 10μΩ.

Measurements made using the micro-ohmmeter are always performed using the 4-wire technique in order to minimize errors caused by test leads and connections. The typical micro-ohmmeter also has additional features such as offset compensation and dry circuit testing to optimize low-resistance measurements. Offset compensation is performed by pulsing the test current to cancel offsets from thermoelectric EMFs. The dry circuit test mode limits the voltage across the unknown resistance to a very small value (typically <20mV) to avoid puncturing oxides when testing such devices as relay contacts, connectors and switches.

## 1.3 Understanding Instrument Specifications

An important aspect of making good low-level measurements is a proper understanding of instrument specifications. Although instrument accuracy is probably the most important of these specifications, there are several other factors to consider when reviewing specifications, including noise, deratings, and speed.

### 1.3.1 Definition of Terms

A number of terms often used in defining instrument specifications are briefly summarized below. Some of these terms are further discussed in subsequent paragraphs. **Table 1-1** summarizes conversion factors for various specifications associated with instruments.

SENSITIVITY - the smallest *change* in the signal that can be detected.

RESOLUTION - the smallest *portion* of the signal that can be observed.

REPEATABILITY - the closeness of agreement between *successive* measurements carried out under the same conditions.

REPRODUCIBILITY - the closeness of agreement between measurements of the same quantity carried out with a stated *change in conditions.*

ABSOLUTE ACCURACY - the closeness of agreement between the result of a measurement and its true value or accepted *standard value.* Accuracy is often separated into gain and offset terms.

RELATIVE ACCURACY - the extent to which a measurement accurately reflects the *relationship* between an unknown and a *reference value.*

ERROR - the *deviation* (difference or ratio) of a measurement *from its true value.* Note that true values are by their nature indeterminate.

RANDOM ERROR - the *mean* of a large number of measurements influenced by random error *matches the true value.*

SYSTEMATIC ERROR - the *mean* of a large number of measurements influenced by systematic error *deviates from the true value.*

UNCERTAINTY - an estimate of the *possible* error in a measurement, i.e. the estimated possible deviation from its actual value. This is the opposite of accuracy.

Precision is a more qualitative term than many of those listed above. It refers to the freedom of uncertainty in the measurement. It is often applied in the context of repeatability or reproducibility but should not be used in place of "accuracy."

*TABLE 1-1: Specification Conversion Factors*

| Percent | PPM | Digits | Bits | dB | Portion of 10V | # $\tau$ to Settle* |
|---|---|---|---|---|---|---|
| 10% | 100000 | 1 | 3.3 | –20 | 1 V | 2.3 |
| 1% | 10000 | 2 | 6.6 | –40 | 100 mV | 4.6 |
| 0.1% | 1000 | 3 | 10 | –60 | 10 mV | 6.9 |
| 0.01% | 100 | 4 | 13.3 | –80 | 1 mV | 9.2 |
| 0.001% | 10 | 5 | 16.6 | –100 | 100 µV | 11.5 |
| 0.0001% | 1 | 6 | 19.9 | –120 | 10 µV | 13.8 |
| 0.00001% | 0.1 | 7 | 23.3 | –140 | 1 µV | 16.1 |
| 0.000001% | 0.01 | 8 | 26.6 | –160 | 100 nV | 18.4 |
| 0.0000001% | 0.001 | 9 | 29.9 | –180 | 10 nV | 20.7 |

* $\tau$ = RC time constant



### 1.3.2 Accuracy

One of the most important considerations in any measurement situation is reading accuracy. For any given test setup, a number of factors can affect accuracy. The most important factor is the accuracy of the instrument itself, which may be specified in several ways, including a percentage of full scale, a percentage of reading, or a combination of both. Instrument accuracy aspects are covered in the following paragraphs.

Other factors such as input loading, leakage resistance and current, shielding, and guarding may also have a serious impact on overall accuracy. These important measurement considerations are discussed in detail in Sections 2 and 3.

#### *Analog Meter Accuracy Specifications*

Analog meter accuracy specifications are usually given as a percentage of full scale, such as ±1%. The major consideration here is that accuracy of the reading decreases as the reading becomes a smaller percentage of full scale. For example, with a ±1% full-scale accuracy specification on a 1V range, the reading error with a 0.5V input will be 2%.

#### *Digital Meter Accuracy Specifications*

Digital meter accuracy is usually specified as a percent of reading, plus a percentage of range (or a number of counts of the least significant digit). For example, a typical DMM accuracy specification may be stated as: ±(0.005% of reading + 0.002% of range). Note that the percent of reading is most significant when the reading is close to full scale, while the percent of range is most significant when the reading is a small fraction of full scale.

Accuracy may also be specified in ppm (parts per million). Typically, this accuracy specification is given as ±(ppm of reading + ppm of range). For example, the DCV accuracy of a higher resolution DMM might be specified as ±(25ppm of reading + 5ppm of range).

#### *Resolution*

The resolution of a digital instrument is determined by the number of counts that can be displayed, which depends on the number of digits. A typical digital electrometer might have 4½ digits, meaning four whole digits (each with possible values between 0 and 9) plus a leading half digit that can take on the values 0 or ±1. Thus a 4½-digit display can show 0 to 19999, a total of 20,000 counts. The resolution of the display is the ratio of the smallest count to the maximum count (1/20,000 or 0.005% for a 4½-digit display).

For example, the specification of ±(0.05% + 1 count) on a 4½-digit meter reading 10.000 volts corresponds to a total error of ±(5mV + 1mV) out of 10V, or ±(0.05% of reading + 0.01% of reading), totaling ±0.06%. Generally, the higher the resolution, the better the accuracy.

### *Sensitivity*

The sensitivity of a measurement is the smallest change of the measured signal that can be detected. For example, voltage sensitivity may be 1µV, which simply means that any changes in input signal less than 1µV will not show up in the reading. Similarly, a current sensitivity of 10fA implies that only changes in current greater than that value will be detected.

The ultimate sensitivity of a measuring instrument depends on both its resolution and the lowest measurement range. For example, the sensitivity of a 5½-digit DMM with a 200mV measurement range is 1µV.

### *Absolute and Relative Accuracy*

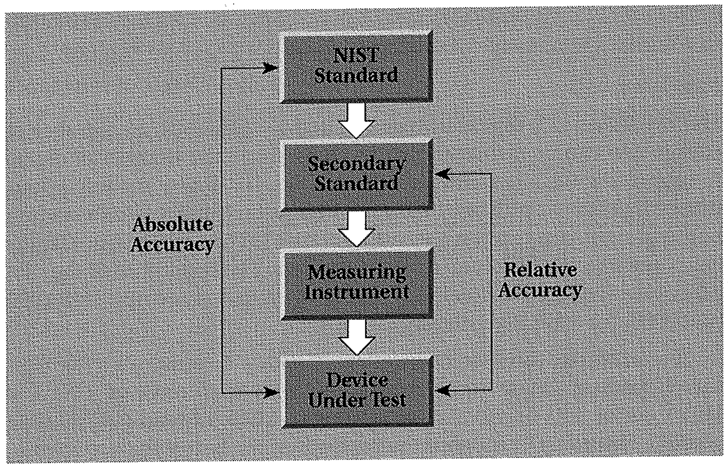
As shown in **Figure 1-4**, absolute accuracy is the measure of instrument accuracy that is directly traceable to the primary standard at the National Institute of Standards and Technology. Absolute accuracy may be specified as ±(% of reading + counts), or it can be stated as ±(ppm of reading + ppm of range), where ppm signifies parts per million of error.

Relative accuracy (see **Figure 1-4**) specifies instrument accuracy to some secondary reference standard. As with absolute accuracy, relative accuracy can be specified as ±(% of reading + counts) or it may be stated as ±(ppm of reading + ppm of range).

### *Transfer Stability*

A special case of relative accuracy is the transfer stability, which defines instrument accuracy relative to a secondary reference standard over a very short time span and narrow ambient temperature range (typically within five minutes and ±1°C). The transfer stability specification is useful in situations where highly accurate measurements must be made in reference to a known secondary standard.

*FIGURE 1-4: Comparison of Absolute and Relative Accuracy*






### *Calculating Error Terms from Accuracy Specifications*

As an example of how to calculate measurement errors from instrument specifications, assume the following measurement parameters:

Accuracy: ±(25ppm of reading + 5ppm of range)

Range: 2V

Input signal: 1.5V

The error is calculated as follows:

$$\begin{aligned}\text{Error} &= 1.5(25 \times 10^{-6}) + 2(5 \times 10^{-6})\\ &= (37.5 \times 10^{-6}) + (10 \times 10^{-6})\\ &= 47.5 \times 10^{-6}\end{aligned}$$

Thus, the reading could fall anywhere within the range of 1.5V ± 47.5µV, an error of ±0.003%.

## 1.3.3 Deratings

Accuracy specifications are subject to deratings for temperature and time drift, as discussed in the following paragraphs.

### *Temperature Coefficient*

The temperature of the operating environment can affect accuracy. For this reason, instrument specifications are usually given over a defined temperature range. Keithley accuracy specifications on newer electrometers, nanovoltmeters, DMMs, and SMUs are usually given over the range of 18° to 28°C. For temperatures outside of this range, a temperature coefficient such as ±(0.005 % + 0.1 count)/°C or ±(5ppm of reading + 1ppm of range)/°C is specified. As with the accuracy specification, this value is given as a percentage of reading plus a number of counts of the least significant digit (or as a ppm of reading plus ppm of range) for digital instruments. If the instrument is operated outside the 18°C to 28°C temperature range, this figure must be taken into account, and errors can be calculated in the manner described above for every degree below 18°C or above 28°C.

### *Time Drift*

Most electronic instruments, including electrometers, picoammeters, nanovoltmeters, DMMs, SMUs and SourceMeter instruments, are subject to changes in accuracy and other parameters over a long period of time, whether or not the equipment is operating. Because of these changes, instrument specifications usually include a time period beyond which the instrument's accuracy cannot be guaranteed. The time period is stated in the specifications, and is typically over specific increments such as 90 days or one year. As noted above, transfer stability specifications are defined for a much shorter period of time—typically five or 10 minutes.

### 1.3.4 Noise and Noise Rejection

Noise is often a consideration when making virtually any type of electronic measurement, but noise problems can be particularly severe when making low-level measurements. Thus, it is important that noise specifications and terms are well understood when evaluating the performance of an instrument.

*NMRR*

NMRR stands for normal-mode rejection ratio, and it defines how well the instrument rejects or attenuates noise that appears between the HI and LO input terminals. As shown in **Figure 1-5**, normal-mode noise is an error signal that adds to the desired input signal.

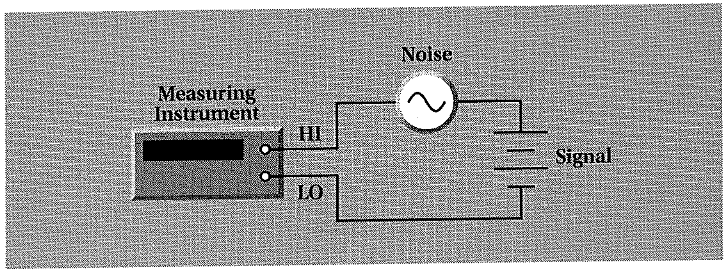
Normal mode noise is detected as a peak noise or deviation in a DC signal. The ratio is calculated as follows:

$$\text{NMRR} = 20 \log \left[ \frac{\text{peak normal mode noise}}{\text{peak measurement deviation}} \right]$$

Normal-mode noise can seriously affect measurements unless steps are taken to minimize effects. Careful shielding will usually attenuate normal-mode noise, and many instruments have internal filtering to reduce noise even further.

NMRR is given for specific frequencies and frequency ranges so as to reject noise (50Hz, 60Hz, high-frequency noise) while not rejecting low-frequency or DC normal-mode signals.

*FIGURE 1-5: Normal Mode Noise*



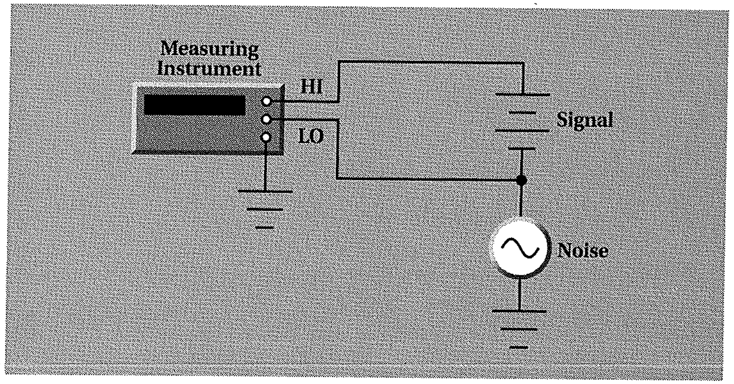

*CMRR*

CMRR (common mode rejection ratio) specifies how well an instrument rejects noise signals that appear between both input high and input low and chassis ground, as shown in **Figure 1-6**. CMRR is usually measured with a 1kΩ resistor imbalance in one of the input leads.



Although the effects of common mode noise are usually less severe than normal mode noise, this type of noise can still be a factor in sensitive measurement situations. To minimize common-mode noise, connect shields only to a single point in the test system.

*FIGURE 1-6: Common Mode Noise*




*Noise Specifications*

Both NMRR and CMRR are generally specified in dB at 50 and 60Hz, which are the interference frequencies of greatest interest. (CMRR is often specified at DC as well.) Typical values for NMRR and CMRR are >80dB and >120dB respectively.

Each 20dB increase in noise rejection ratio reduces noise voltage or current by a factor of 10. For example, a rejection ratio of 80dB indicates noise reduction by a factor of 10,000, while a ratio of 120dB shows that the common-mode noise would be reduced by a factor of $10^6$. Thus, a 1V noise signal would be reduced to 100μV with an 80dB rejection ratio and down to 1μV with a 120dB rejection ratio.

### 1.3.5 Speed

Instrument measurement speed is often important in many test situations. When specified, measurement speed is usually stated as a specific number of readings per second for given instrument operating conditions. Certain factors such as integration period and the amount of filtering may affect overall instrument measurement speed. However, since changing these operating modes may also alter resolution and accuracy, there is often a tradeoff between measurement speed and accuracy.

Instrument speed is most often a consideration when making low-impedance measurements. At higher impedance levels, circuit settling times become more important and are usually the overriding factor in determining overall measurement speed. Section 2.6.4 discusses circuit settling time considerations in more detail.

## 1.4 Circuit Design Basics

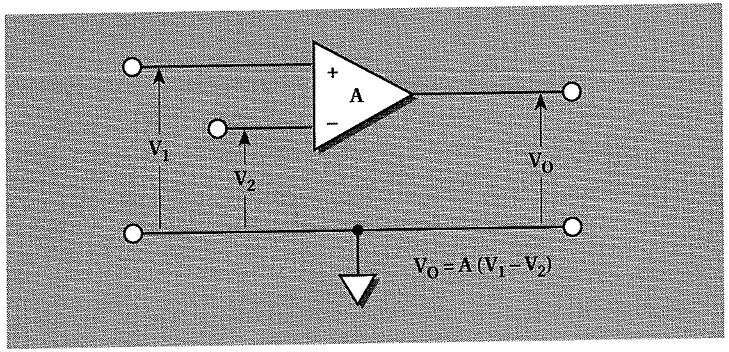
Circuits used in the design of many low-level measuring instruments, whether a voltmeter, ammeter, ohmmeter, or coulombmeter, generally use circuits that can be understood as operational amplifiers.

**Figure 1-7** shows a basic operational amplifier. The output voltage is given by:

$$V_O = A\,(V_1 - V_2)$$

The gain (A) of the amplifier is very large, a minimum of 10,000 to 100,000, and often one million. The amplifier has a power supply (not shown) referenced to the common lead.

*FIGURE 1-7: Basic Operational Amplifier*




Current into the op amp inputs is ideally zero. The effect of feedback properly applied is to reduce the input voltage difference ($V_1 - V_2$) to zero.

### 1.4.1 Voltmeter Circuits

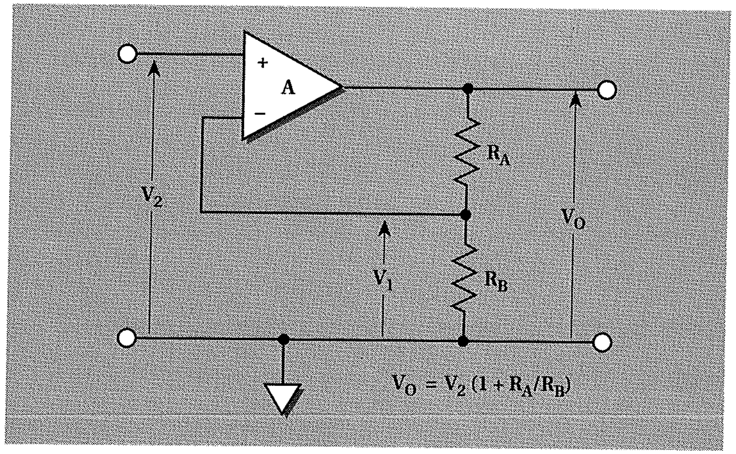
*Electrometer Voltmeter*

The operational amplifier becomes a voltage amplifier when connected as shown in **Figure 1-8**. Since the offset current is low, the current flowing through $R_A$ and $R_B$ is the same. Assuming the gain (A) is very high, the voltage gain of the circuit is defined as follows:

$$V_O = V_2\,(1 + R_A/R_B)$$

Thus, the low-impedance output voltage ($V_O$) is determined both by the input voltage ($V_2$), and amplifier gain set by resistors $R_A$ and $R_B$. Since $V_2$ is applied to the amplifier input lead, the high input resistance of the operational amplifier is the only load on $V_2$, and the only current drawn from the source is the very low input offset current of the operational amplifier. In many electrometer voltmeters, $R_A$ is shorted and $R_B$ is open, resulting in unity gain.

*FIGURE 1-8: Voltage Amplifier*




*Nanovoltmeter Preamplifier*

The same basic circuit configuration shown in **Figure 1-8** can be used as an input preamplifier for a nanovoltmeter. Since much higher voltage gain is required, the values of $R_A$ and $R_B$ are set accordingly; a typical voltage gain for a nanovoltmeter preamplifier is 1,000.

Since electrometer and nanovoltmeter characteristics differ, operational amplifier requirements for the two types of instruments are somewhat different. While the most important characteristics of the electrometer voltmeter operational amplifier are low input offset current and high input impedance, the most important requirement for the nanovoltmeter input preamplifier is low input noise voltage.

### 1.4.2 Ammeter Circuits

There are two basic techniques for making current measurements: these use the shunt ammeter ("NORMAL" mode) and the feedback ammeter ("FAST" mode) techniques. DMMs and older electrometers use the shunt method, while picoammeters and the AMPS function of the newer electrometers use the feedback ammeter configuration only. The major difference between picoammeters and electrometers is that electrometers are multi-function instruments, while picoammeters measure only current.

***Shunt Picoammeter***

Shunting the input of an electrometer voltmeter with a resistor forms a shunt picoammeter, as shown in **Figure 1-9**. The input current ($I_{IN}$)