

# White Paper: The Essentials of Single-Ended and Differential Voltage Measurement

Learn How to Choose Which Method to Apply

*Examining important aspects of single-ended and differential voltage measurement, along with tips on why it might be better to choose one method over the other*



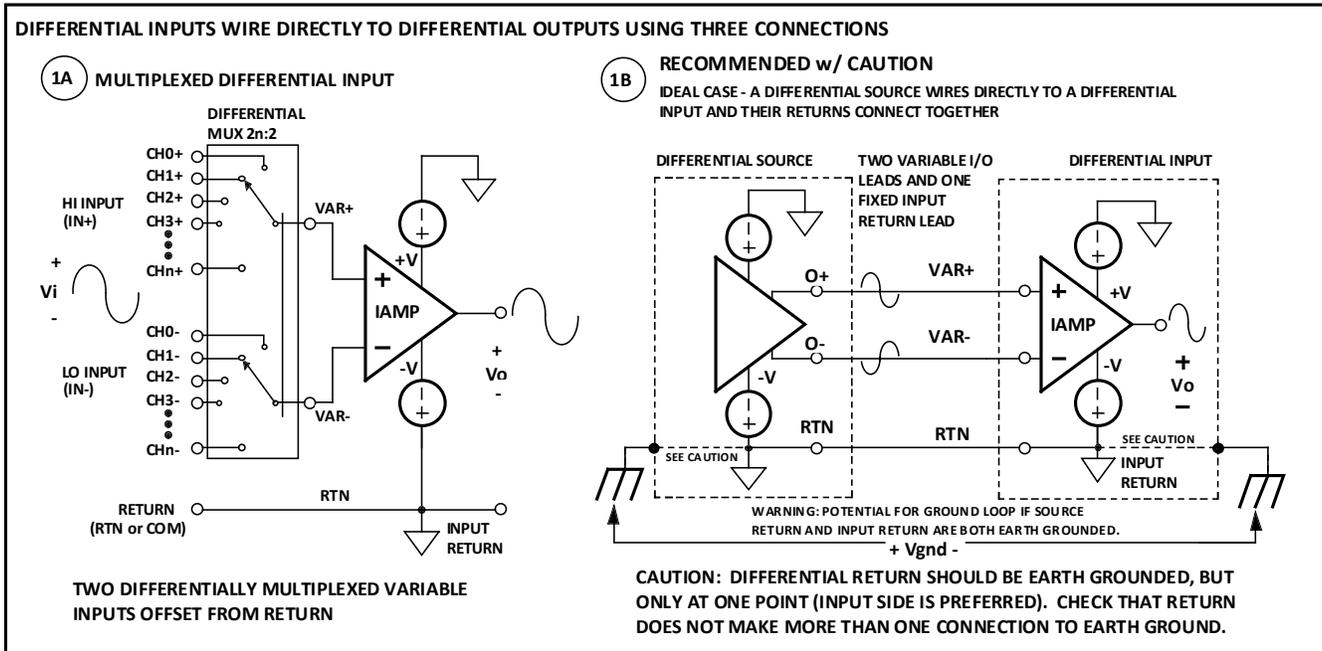
Voltage is a difference in electric potential between two points and is a measure of the force for current flow in a conductor or circuit. You can choose to measure voltage single-ended, or you can measure voltage differentially. Please review this paper [single-ended voltage measurement](#) first (document 8501-035). In this Part, we consider differential voltage measurement. You may download each of these documents and others at <https://acromag.com>. How you measure voltage is important because voltage measurement is at the heart of most of your processes that monitor current, temperature, resistance, and strain, and your method of measurement should be well matched to your application to positively impact your results and avoid error.

## **DIFFERENTIAL INPUT VOLTAGE MEASUREMENT**

Like the single-ended input discussed in [8501-035](#), a differential input also measures the voltage difference between two points, but in this instance, one of the points is not necessarily a fixed common reference point or return. The key differentiator here is that both leads connect to variable potentials and a third connection breaks out the circuit common. That is, a differential input will actually have at least three input connections: signal high or positive, signal low or negative, and a third connection for the signal return or common (return is usually shared by other differential input channels of the same circuit and its connection may be optionally made internal to the circuit if not provided on a third terminal).

The differential input offers more freedom when connecting to earth grounded or non-grounded (isolated) signal sources than the single-ended input, because its signal connections may be offset and separate from signal return, which may or may not also connect to earth ground. However, an earth ground path to return must still be made, and you should be careful not to provide more than one earth ground connection to return to avoid creating a ground loop circuit that could offset or interfere with your measurement.

FIGURE 1: SIMPLIFIED DIFFERENTIAL INPUT CONNECTIONS



In Figure 1A, each channel pair is differentially multiplexed to an instrumentation amplifier. A third lead carries the input circuit common or return, which may or may not also be connected to earth ground. Figure 1B shows a differential output connected to a differential input with the third leads (the I/O Return leads) connected together. A connection to earth ground at Return will help to keep the signals from floating and is also needed for protection purposes, but making two connections to earth ground should be avoided. Unfortunately, for most applications, outputs will not connect to differential inputs this simply and Figure 1B is perhaps an ideal case that rarely happens in industry. *That is, differential inputs usually connect to single-ended sources having only two signal leads with no separate return lead as shown in Figure 2 of the following page.*

You may have read something like, *a differential voltage is “floating”, in that it has no reference to ground.* This definition is partially correct, but misleading. The term “floating” should not be used to describe differential input measurement. Likewise, the differential potentials must have an indirect or direct reference to the input measurement return lead which may connect to earth ground. This is because no differential input potential can truly float, nor is it good practice to allow an instrument’s inputs to float. In fact, no meaningful measurement can even be made if either of the differential input potentials are floating. It is best to avoid the use of the term floating and instead describe a differential input voltage measurement as a voltage difference between two potentials that are offset from return. That is, a differential voltage is measured as a voltage difference between two voltage levels, and neither of the levels must be fixed to signal common or return. Contrast this to single-ended voltage measurement covered in Part 1 of this paper, which is measured as the voltage difference between one point and a fixed reference or signal return (i.e. single-ended).

## Beware of Ground Loops

*Because differential inputs can also connect to earth grounded source signals, you need to be aware of your instrument and determine if its Return connection is also connected to earth ground in order to avoid situations where two separate connections to earth ground may create a ground loop, which can lead to measurement error and equipment failure.*

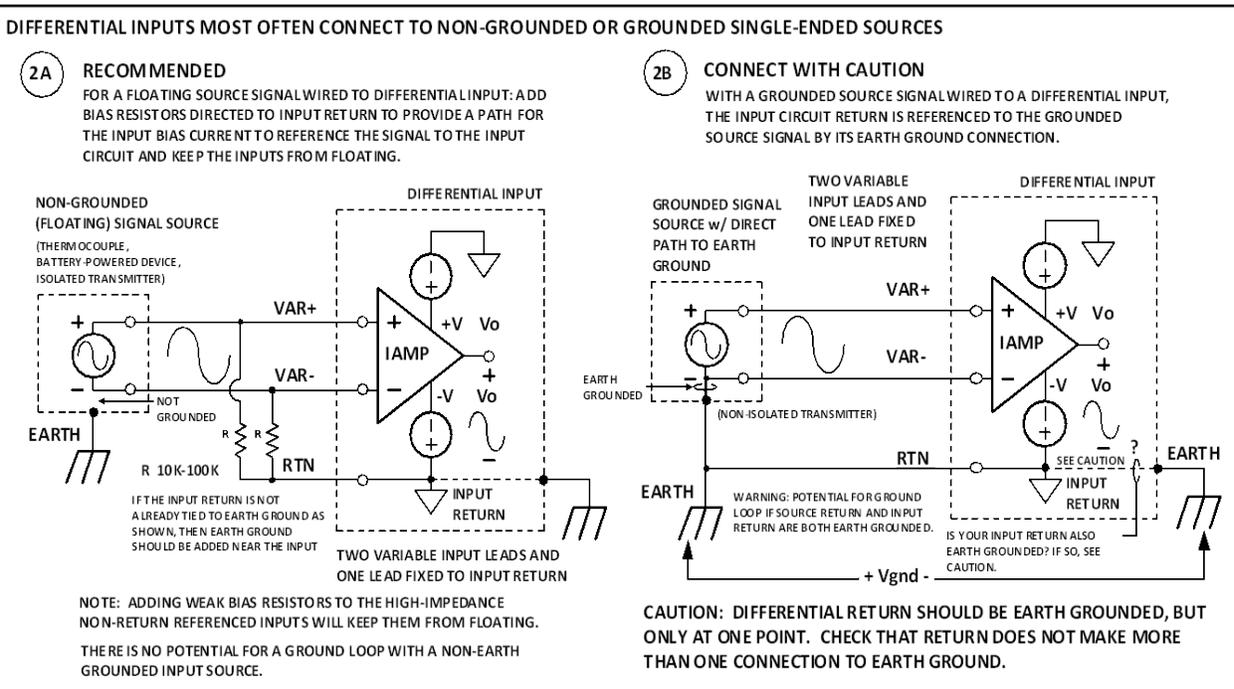
Instrument instructions will normally tell you to limit yourself to one earth ground connection in a circuit in an effort to avoid generating a ground loop which can interfere with your measurement, but this is really only required when the earth grounds are at different potentials which would push error current between them (not likely for closely spaced I/O). Be aware of where your output and input connect to earth ground—if they each connect separately to earth, how far apart are their connections to earth? If the distance between the output and the input is larger than about 3 meters, or the distance between the earth grounding points is long, you may have to introduce an isolation barrier between the signal source and measurement device. The presence of isolation between the output and input circuits will “break the ground loop” by allowing the earth grounds of each circuit on each side of the barrier to be at different potentials (within the limits of the isolation rating).

In the absence of isolation, limiting yourself to a single connection to earth ground can be difficult. Often wiring diagrams will assume that the local (input) earth ground and the remote earth ground (at the sensor or signal source) are at the same potential, which is often not the case. To complicate matters, your equipment will typically recommend you have a local connection to earth ground at each piece of equipment for protection purposes. This can be a source of confusion in the sense that following the letter of the law appears to introduce “more than one connection to earth ground”. But what you really need to avoid is not having more than one earth ground connection, but having more than one earth ground potential. In general, for short distances (3 meters or less), the remote and local earth grounds will be nearly the same potential and having two connection points to earth will normally not present a problem. If your signal source is earth grounded and the mating input is not, you may need to add earth ground to the circuit near the input, as relying on an indirect common connection to earth ground via the output circuit may not be suitable because of the potentially high inductance of the input path wiring to earth ground at the source, which will impede transient energy at the input from reaching earth ground efficiently and may even damage your input circuit.

## Differential Input Myth

One common misconception regarding multiple differential input pairs, is that they are somehow isolated, because they can be taken offset from one another. **Differential inputs are not isolated.** This is a misuse of the term and it instead refers to the degree to which they may be offset from each other and from the circuit return. As already stated, multiple differential inputs of the same circuit actually share a common signal reference point in a required extra connection (usually Return) and none of the differential input pairs can be converted without a direct or indirect reference to that point.

FIGURE 2: SIMPLIFIED DIFFERENTIAL INPUT CONNECTIONS



Most instruments will connect an analog to digital converter (A/D), an instrumentation amplifier or buffer, an input multiplexer, or some combination of this circuitry at their input terminals to measure voltage. Differential inputs provide two input connection points for measuring voltage, and a third connection to signal return or some reference voltage biased from return (which may be hidden inside the circuit). Where provided, the application of the third RTN (Return) or COM (Common) connection of differential inputs is a source of confusion. No differential A/D or amplifier can convert a voltage input signal without a direct or indirect reference between the field potentials at its inputs and its own common or measurement return. That is, it must measure each  $\pm$ input potential simultaneously relative

to its own return or it cannot resolve the voltages or their difference (its differential measurement is relative to what?). Do not leave the third connection (Return) floating, the I/O signals must be referenced to it as shown in Figure 2.

One of its most significant benefits is not just that the potentials at each lead and between channels may be offset from one another and return, but that each channel's signal leads are measured separately and simultaneously, which offers much greater noise suppression. This is important because noise in an electrical circuit is typically present on all conductors and in synchrony. **This makes the same noise common to both differential signal leads at the same time (there may still be small differences in magnitude), which as a result will be largely rejected via the high common mode noise rejection offered by the differential input.** This benefit also makes differential conversion the preferred technique in noisy environments.

### KEY POINT 1 - Make that "Third" Connection to Differential Input Return

We have already stated that a differential input really requires a minimum of three connections: signal high or positive, signal low or negative, and Return or Common (I/O signal common). Differential measurement is really the difference between two simultaneous voltage measurements (one at each input lead) taken with respect to measurement return. Differential outputs with three wires will wire directly to differential inputs with three wires without confusion. But problems arise when the *third* connection (Return) is not made. When a third connection cannot be easily identified, it is likely that the circuit is making an indirect connection to its Return for you. Be aware that a sensor or instrument with a differential output (three-wires) can be wired single-ended by connecting its signal low lead (OUT-) to the signal common reference or return. And a differential input that connects its input low (IN-) signal directly to its common reference or return is essentially wired for single-ended input. For some of our differential instruments, the following instruction may be present in the manual:

**IMPORTANT:** *If your input source is not already grounded, connect IN- to Return & connect input Return to earth ground.*

This only addresses what can be done to connect a floating or isolated single-ended output signal to a single differential input and will actually make the differential input single-ended by connecting IN- to signal Return. Applied to all the differential inputs, it prevents the separate input channels from measuring offset from return and each other. The intent of breaking Return or Common out as a separate connection is to connect it directly to the third lead of a mating differential output. Unfortunately in practice, the output signal you wish to measure differentially is often not differential at all and may only have two leads (the differential input is instead connected to a single-ended output that may be floating). Connecting differential IN- to Return yields a meaningful measurement, and additionally connecting Return or Common to earth ground ensures the signal will never float and is needed for protection purposes (connecting it to earth ground is not required to convert the signal). For other single-ended output channels, you can choose to reference their signals to differential Return indirectly via another circuit tied to Return, or via the first channel connected to Return (refer to the discussion of Figure 4 and Differential Application Trap 2 later in

this paper for some examples of how to do this). Perhaps a more complete manual instruction for our differential input instruments should read as follows:

**IMPORTANT:** *You must reference channel signals to input Return. Either connect input Return to your differential output signal return directly, or reference a single-ended output signal pair to input Return. You can do this by connecting output minus to Return directly, or by connecting one output minus to Return and then connecting the other single-ended channels in series with it or along a series path of the same circuit (this provides an indirect path to input Return for each channel so that the input circuit can make a measurement). In addition, if your input signals do not already connect to earth ground, you should additionally connect earth ground to input Return at one point for protection purposes.*

## **KEY POINT 2 - Sometimes the third Return connection of a Differential Input is not readily apparent because this connection is instead made internal to the circuit.**

To avoid confusion when you try to discern a differential from a single-ended input by looking for the third connection to Return, please note that some differential products will not include a third wire connection to differential input Return. Rather its connection to the differential input is hidden from the user and an indirect reference to return is made internally. For example, some differential circuits may separately multiplex the  $\pm$ channel inputs to a differential A/D while simultaneously measuring a CJC reference or voltage reference with respect to return to get a stable measurement. These circuits will usually include small input bias leakage paths to return at each input lead via filtering that helps keep the inputs from free-floating when not connected to the A/D, acting similar to using weak pull-downs to return as illustrated in Figure 2A. Because the input pairs connect to the A/D separately, they may still be offset from each other.

## **SOME APPLICATIONS OF DIFFERENTIAL INPUT MEASUREMENT**

- Used to measure voltage outputs that are not inherently referenced to a common return (i.e. outputs that are independent and offset from each other). Generally used where the output has two individual connections each separate from common or return.
- Useful where many independent voltages (or cells) must be measured, or where many voltages are connected in series, such as those in solar cell, fuel cell, and hybrid-vehicle battery applications (this will additionally require a high common-mode range differential input type—more on this below).
- Preferred where sensors are coupled over distances greater than 3 meters, or where unshielded or untwisted pair wiring is utilized (not recommended).

- Its high common mode rejection makes it especially useful in noisy environments with strong electric fields, lots of 50-60Hz power line feed-through noise, and high EMI or RFI.
- Preferred for low level signals with full-scale ranges below 1V (thermocouples, strain gages, bridge sensors, etc).
- Used with instruments designed for wide common mode input measurement applications.

Before delving deeper into differential voltage measurement, we need to explore a few important terms applicable to differential inputs—Common-Mode Signal, Common Mode Rejection, and Common Mode Range.

## WHAT IS THE COMMON-MODE SIGNAL AND COMMON-MODE REJECTION?

Noise in any circuit will generally permeate the circuit entirely and appear on both I/O leads of differential inputs making it common mode. Even an earth grounded sensor can induce noise on both differential leads from a less than ideal connection to earth ground. The common mode voltage of a differential input is computed as the sum of the voltage potential at the positive lead with respect to input return and the voltage potential at the negative lead with respect to input return divided by 2 ( $V_{cm}=[V_{in+} + V_{in-}]/2$ ). The high common mode rejection of the differential input will do a great job of rejecting noise common to both input leads, helping discriminate the signal from unwanted noise.

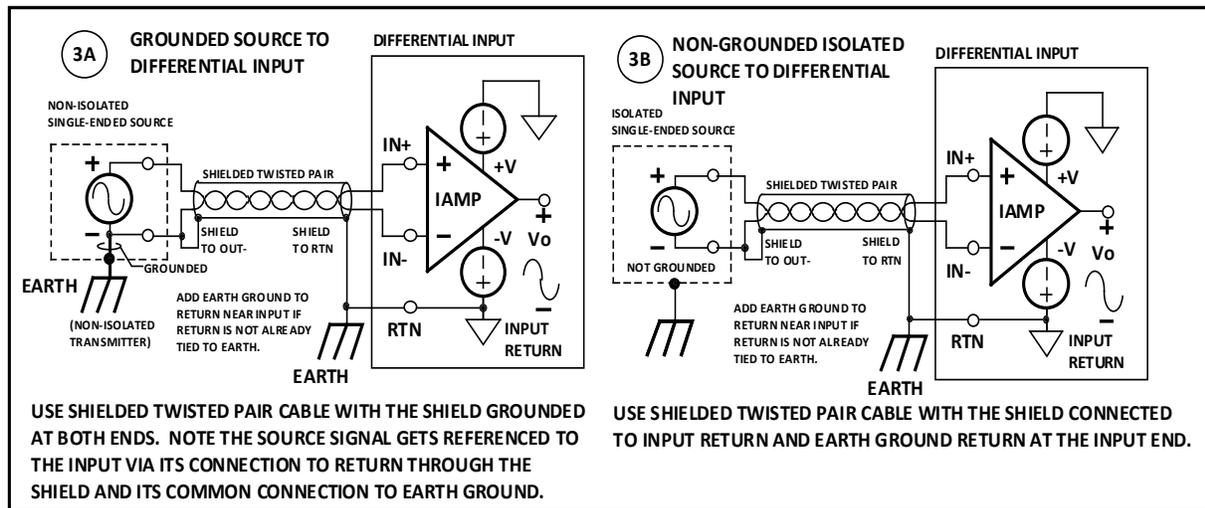
A good instrumentation amplifier is optimized to amplify the *differential* normal-mode signal and reject the common-mode signal (the noise) common to both inputs (normal mode signal refers to the signal that appears normally between the two wires of the circuit). The Common-Mode Rejection Ratio (CMRR) is a measure of the instrumentation amplifier's ability to reject common mode noise (look for 100dB or better). Think of CMRR as equivalent to the multiple of gain applied to the differential signal relative to gain applied to the common-mode noise ( $CMRR=\text{signal gain}/\text{common-mode gain}$ )—a very high number. Expressed in dB, this is  $20*\text{LOG}[CMRR]$ . Thus,  $20*\text{LOG}[CMRR]=100\text{dB}$  implies  $CMRR=\text{LOG}^{-1}[100/20]=100,000$  or 100000:1 signal to noise. This means that the common-mode noise that can appear at the output is reduced to 1 part in 100,000, or less than 1lsb of a 16-bit signal (1lsb of 16bits=1/65535). Unfortunately, CMR normally starts to roll off above 100KHz and may not be effective for very high frequency common mode noise—so other measures must still be taken (like the use of shielded twisted pair cable to make the connection, see Figure 3).

Think of differential measurement as two simultaneous voltage measurements taken at each lead with respect to return and subtracted according to polarity. The high Common-Mode Rejection offered by the differential input is one of its most significant advantages over single-ended measurement, making differential measurement the favorite for small voltage signals with full-scale spans below 1V, such as those driven by thermocouples, thermistors, strain gages, and bridge type sensors. Additionally, the fact that a differential measurement is two measurements independent of a common physical connection between them makes it even more immune to noise pickup (a common connection could add common-mode noise).

Contrast this to single-ended or unbalanced inputs which generally have no common-mode range because one input is fixed to a relatively stable common or signal return. The opposite variable input does not reject the noise present on its signal line and will instead pass it through the circuit and possibly amplify it with the normal-mode signal resulting in increased signal noise.

To maximize the positive effect of Common Mode Rejection with differential inputs, it is best to wire a signal source to the input using a wiring scheme that helps to couple the noise equally into both leads (that helps to make the noise common-mode). This is best accomplished with **shielded twisted-pair** wiring as shown in Figure 3.

FIGURE 3: SIMPLIFIED DIFFERENTIAL INPUT CONNECTIONS TO NON-ISOLATED AND ISOLATED SOURCES USING TWISTED PAIR CABLE



As shown in Figure 3A, connect the shield of the twisted pair cable to the negative lead and to the earth ground at the earth grounded single-ended source. At the differential input end of the cable, connect the shield to the third lead of the differential input (its Return lead) and to earth ground. Note that Return uses the shield to reference differential input Return to the earth grounded output signal and the shield current is very small. While it's normally not accepted to allow two separate connections to earth ground, in this instance, connecting earth ground to the cable shield at both ends has been shown to significantly reduce noise levels and is the recommended approach of many instrumentation amplifier manufacturers (this can also lower radiated emissions by the circuit).

Best performance is obtained using isolated sources with no direct-connection to earth ground as shown in Figure 3B. In this instance, connect the shield of the twisted pair cable to the negative lead of the isolated single-ended source. At the differential input end of the cable, connect the shield to the third lead of the differential input (its Return lead) and connect Return to earth ground. Note that Return uses the shield to reference the differential I/O potentials to itself.

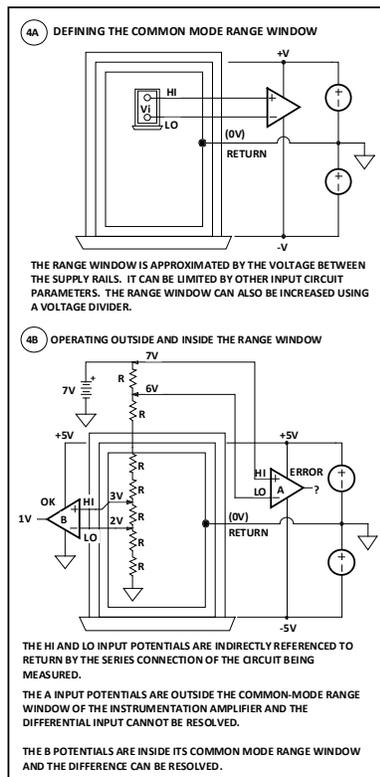
## WHAT IS COMMON MODE RANGE?

A differential input will only measure the voltage between two individual points within its common mode range. The common-mode voltage range is defined as the maximum allowable voltage swing on each input with respect to the signal return of the measurement circuit (the third connection). This parameter will be very important to your application as it defines your *window* of possible signal measurement.

To explain, most differential inputs that break out return separately will actually be used to measure outputs with only two connections per channel (single-ended outputs with no third Return or Common connection). Some modern applications will utilize differential inputs to measure many voltages in series, like individual cells of a large solar or hybrid battery, or several voltages along a series connected circuit (maybe the voltages across many series connected resistors as illustrated in Figure 4B). The input return must be referenced to your signals. Thus, it will be necessary to reference the IN- signal to Return either directly (connect one IN- to return and connect the other channels in series), or indirectly (connect each channel along a series connected circuit with a return path).

If your differential voltages are taken independent of a series circuit connection, then you would need to series connect multiple channels by connecting one IN1- to Return, then connecting IN2- to IN1+ to reference channel 2 indirectly to return, and so on (the differential input channels connect in series to return). If the voltages you are measuring are at different points along a series connected circuit, then you don't have to connect IN2- to IN1+ directly (the circuit itself will complete the path between the inputs). However, in both cases, you must exercise caution and make sure that the potentials of all channel  $\pm$ inputs do not go outside of their differential common-mode range of measurement, as problems will arise when multiple channels that connect in series directly, or along a series circuit, allow one or more of the channels to connect to potentials outside the common-mode range.

FIGURE 4: THE COMMON MODE RANGE WINDOW OF MEASUREMENT



It is helpful to think of a differential input as having a window of voltage measurement defined within a larger window of measurement corresponding to its common-mode range as illustrated in Figure 4. Envision the differential measurement as a smaller window inside the larger common mode range and completely over-lapping it. You are restricted to measuring voltage between any two points inside the larger window. If either of your measurement points connect to potentials outside of the larger range window, measurement error or failure will occur and you may permanently damage the input circuit.

Differential measurement problems happen if instrument inputs are taken to potentials outside their common-mode range window. Most instruments will employ clamps to shunt over-voltage safely to the internal voltage rails, and without clamping,

the input could be damaged. But no meaningful measurement can be made if the potential at either input lead is not directly or indirectly referenced to the differential input Return.

The differential input is different from a single-ended input in that its "difference window" can be taken anywhere inside its common-mode input signal range. A single-ended input could only measure a voltage relative to its own signal return. The differential input actually allows both the HI and LO voltages to vary from signal return, but only as long as both potentials also remain within the common-mode range window.

You can usually find the common mode range of your input by referring to the specifications, or optionally the schematic. The outer boundaries of the differential input window are partly dependent on the voltage rails to the input amplifier as illustrated in Figure 4B (most amplifier inputs will allow the input voltage range to swing up to or close to the voltage rails). You could increase the effective common mode range by connecting your input voltage using a voltage divider, but it may still be limited by the part itself and input protection circuitry. If the input is an A/D converter, then the common-mode range will be limited by the magnitude of its voltage reference, or  $\pm$ reference for a bipolar A/D converter. You can refer to these voltages to ballpark your input common mode range, but always make sure the input potential at each input with respect to return does not go outside of this range.

### **DIFFERENTIAL APPLICATION TRAP #1 – High Common Mode Voltage Drives Measurement Failure**

Refer to Figure 4. It's very important to refer to the common-mode input range of a differential instrument and make sure your input signal stays within its window of possible measurement. It's very easy to exceed the common mode limit of many devices with modern applications, unless the differential input device has been specifically designed for high common mode voltage levels. This is partly because most modern instruments have trended to the use of lower voltage rails, like 3.3V or 2.5V, which limits their common mode input range. The reason some of these devices are still able to convert input voltages well above their voltage rails is because they typically employ voltage dividers at their front-end, followed by high gain amplifiers and/or high resolution converters (allowing them to divide inputs down to lower voltages). The voltage divider reduces the large input level to a lower level inside the smaller common-mode window present right at the input to the amplifier or A/D converter.

Instruments with differential current inputs can be problematic in this regard, because they do not employ voltage dividers in their front-end circuits like voltage inputs often do. Rather, they often use current shunt resistors, like 50 $\Omega$  or 100 $\Omega$ , to convert small DC currents to voltage at the input of their amplifier or A/D converter. If you do the math, then using 50 $\Omega$  shunts and a 20mA full-scale current ( $0.020 \times 50 + 0.020 \times 50 + 0.020 \times 50 = 3V$ ), you realize that you cannot connect more than 2 or 3 channels in series before the input common mode range window limit is reached for an instrument front-ended with a low voltage rail like 2.5V or 3.3V. If the input is really an A/D converter, perhaps with a 1.235V reference, then only one channel could be converted, as two in series would force one input potential outside the 1.235V full-scale limit of conversion. A possible high common mode differential current input could mate lower value shunt resistors to high resolution converters having higher voltage references and/or rail voltages to expand their common-mode signal range window.

## **DIFFERENTIAL APPLICATION TRAP #2 – Floating Signal Ground Drives Measurement Failure**

Earlier we discussed that no measurement can be made if an input is floating. By nature, single-ended voltage measurements do not generally float, because one point of measurement is signal return and its presence tends to keep the signal from floating (adding earth ground to return will help ensure it never does). But for differential inputs, the A/D or amplifier of the input circuit requires a third connection that is used to reference its  $\pm$ input potentials to its own signal return before it can measure anything meaningful. Failure to make this connection is as if the differential  $\pm$ inputs are connected between two random points in space with no path to return, or even an indirect path to return (you must complete a circuit to return to make the measurement). Always look for this third connection and make sure it is wired (either directly when provided or indirectly when hidden). For example, you may connect channels in series to return, or the circuit components may connect in series to return. Other times the internal measurement circuit will make this return connection for you and you will not be able to identify a separate wire point for Return. If you are measuring a differential output, wire its Return/Common third terminal to the input Return when provided. If you only have two output connections (a single-ended source) and three input connections (a differential input), you either connect differential IN- to Return or to another voltage that is referenced to Return (that could be an adjacent channel, or another circuit referenced to Return). In this way, you “anchor” IN- to another signal within the common mode range window that itself has a path to I/O Return (input signal return). For example, if I have multiple differential inputs on the same instrument, I could connect the first IN1- to RTN, then connect the second channel’s IN2- to the first IN1+ (i.e. IN2- has an indirect path to the A/D signal ground through  $\pm$ IN1). Adjacent channels could be alternately stacked upon each other like this and each would still convert correctly because all differential potentials have a series reference path to the amplifier or A/D signal return (but you must additionally respect the potential limits of the common mode range window as you connect channels in series in this manner). But even after referencing your signal to return which allows you to make a meaningful measurement, you must connect earth ground to return at one point to ensure that the signal never floats.

## **DON'T FORGET TO CONNECT EARTH GROUND TO DIFFERENTIAL RETURN**

*The connection of earth ground to the I/O is sometimes a source of confusion, because a valid measurement can usually be made without connection to earth ground.*

Instrument instructions generally recommend that your input signal be additionally tied to earth ground if the signal is not otherwise earth grounded (this is usually made at RTN or COM for differential input circuits). But in most case, the circuit will continue to measure properly with or without adding this earth ground connection. This leads some technicians to ignore this recommendation which could lead to measurement error or even equipment damage. High impedance inputs like those of instrumentation amplifiers can be made to float in the presence of high levels of EMI, and inputs could be driven to levels outside their common-mode range (they have very low bias currents as a result of their high input impedance). This is why it is recommended that a connection to earth ground be made at the input Return lead. Connecting Return to earth ground helps to ensure the input will not float outside of its input range in the presence of high EMI. But equally important, adding earth ground gives the input circuit a low impedance path for shunting transient energy or fault voltages safely to earth ground away from the sensitive input components.

## **CONCLUSION**

After reviewing Parts 1 and 2, you should realize that correctly applying single-ended or differential measurement techniques, using shielded cable, and properly wiring return and earth ground are very important to the integrity of your measurement system. Sometimes your equipment will determine which measurement method must be used, three-wire differential or two-wire single-ended, and you will not have a choice. Single-ended I/O makes only two connections and its measurement already includes its signal return or common in one lead. Differential I/O separates return from its signal leads and requires a minimum of three connections. Some differential circuits will not break out return to a third connection and will instead make it for you internally. Single-ended measurement takes one potential with respect to signal return, differential measurement takes one potential with respect to the opposite potential, and each may be offset from signal return. Use differential measurement for differential outputs, or where the distance between the output signal source and the input device is greater than 3 meters. In practice, differential measurement is most often applied to single-ended and floating output signals with only two connections for the benefit of its high common-mode noise rejection, ideal for small signal conversion. Because it rejects common mode noise so well, differential measurement is preferred for operation in the presence of strong electric fields, high levels of EMI and RFI noise, and where signal levels are lower level (full-scale spans less than 1V). It's also favored for rejecting 50-60Hz AC power line noise widely present in industry. While differential potentials may be offset from return and channel pairs from each other, they must remain within the common mode

range window of an input. Differential inputs are not normally isolated unless specified as such, nor do differential inputs ever “float” relative to one another. In general, you use single-ended measurement when there are only two leads and one lead is already connected to a shared reference point, where signal levels are higher level (where full-scale spans are 1V or greater), or where outputs and inputs are closely coupled (less than 3 meters apart). Single-ended measurement is mostly acceptable in relatively noise-free environments, when used with shielded cable over shorter distances, and favored where the emphasis is on greater channel density, simplicity, and low cost (less wiring).

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### **The Essentials of Single-Ended and Differential Voltage Measurement: Part 1**

Part 1 of this paper ([8501-035](#)) reviews single-ended voltage measurement and should be reviewed first.

*Bruce Cyburt, Senior Design Engineer, Acromag, Inc., February 16, 2016*