Appendix A

INSTRUMENTATION AMPLIFIER SPECIFICATIONS

To successfully apply any electronic component, a full understanding of its specifications is required. That is to say, the numbers contained in a data sheet are of little value if the user does not have a clear picture of what each specification means.

In this section, a typical monolithic instrumentation amplifier data sheet is reviewed. Some of the more important specifications are discussed in terms of how they are measured and what errors they might contribute to the overall performance of the circuit.

Table A-1 shows a portion of the data sheet for the Analog Devices AD8221 instrumentation amplifier.

A **Table A-1. AD8221 Specifications[1]**

Parameter	Conditions	AR Grade			BR Grade			ARM Grade			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
B COMMON-MODE REJECTION RATIO (CMRR)											
CMRR DC to 60 Hz with 1 kΩ Source Imbalance	V_{CM} = –10 V to +10 V										
G = 1		80			90			80			dB
G = 10		100			110			100			dB
G = 100		120			130			120			dB
G = 1000		130			140			130			dB
C CMRR at 10 kHz	V_{CM} = –10 V to +10 V										
G = 1		80			80			80			dB
G = 10		90			100			90			dB
G = 100		100			110			100			dB
G = 1000		100			110			100			dB
NOISE	*RTI noise* = $\sqrt{e_{NI}^2 + (e_{NO}/G)^2}$										
Voltage Noise, 1 kHz											
Input Voltage Noise, e_{NI}	V_{IN+}, V_{IN-}, V_{REF} = 0			8			8			8	nV/√Hz
Output Voltage Noise, e_{NO}				75			75			75	nV/√Hz
RTI	f = 0.1 Hz to 10 Hz										
G = 1			2			2			2		μV p-p
G = 10			0.5			0.5			0.5		μV p-p
G = 100 to 1000			0.25			0.25			0.25		μV p-p
Current Noise	f = 1 kHz		40			40			40		fA/√Hz
	f = 0.1 Hz to 10 Hz		6			6			6		pA p-p
D VOLTAGE OFFSET[2]											
Input Offset, V_{OSI}	V_S = ±5 V to ±15 V			60			25			70	μV
Over Temperature	T = –40°C to +85°C			86			45			135	μV
Average TC				0.4			0.3			0.9	μV/°C
Output Offset, V_{OSO}	V_S = ±5 V to ±15 V			300			200			600	μV
Over Temperature	T = –40°C to +85°C			0.66			0.45			1.00	mV
Average TC				6			5			9	μV/°C
Offset RTI vs. Supply (PSR)	V_S = ±2.3 V to ±18 V										
G = 1		90	110		94	110		90	100		dB
G = 10		110	120		114	130		100	120		dB
G = 100		124	130		130	140		120	140		dB
G = 1000		130	140		140	150		120	140		dB
E INPUT CURRENT											
Input Bias Current			0.5	1.5		0.2	0.4		0.5	2	nA
Over Temperature	T = –40°C to +85°C			2.0			1			3	nA
Average TC			1			1			3		pA/°C
Input Offset Current			0.2	0.6		0.1	0.4		0.3	1	nA
Over Temperature	T = –40°C to +85°C			0.8			0.6			1.5	nA
Average TC			1			1			3		pA/°C

Parameter	Conditions	AR Grade Min	AR Grade Typ	AR Grade Max	BR Grade Min	BR Grade Typ	BR Grade Max	ARM Grade Min	ARM Grade Typ	ARM Grade Max	Unit
REFERENCE INPUT											
R_{IN}			20			20			20		kΩ
I_{IN}	$V_{IN+}, V_{IN-}, V_{REF} = 0$		50	60		50	60		50	60	µA
Voltage Range		$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	V
Gain to Output			1 ± 0.0001			1 ± 0.0001			1 ± 0.0001		V/V
POWER SUPPLY											
F Operating Range	$V_S = \pm 2.3$ V to ± 18 V	±2.3		±18	±2.3		±18	±2.3		±18	V
G Quiescent Current			0.9	1		0.9	1		0.9	1	mA
Over Temperature	T = –40°C to +85°C		1	1.2		1	1.2		1	1.2	mA
DYNAMIC RESPONSE											
Small Signal, –3 dB Bandwidth											
G = 1			825			825			825		kHz
G = 10			562			562			562		kHz
G = 100			100			100			100		kHz
G = 1000			14.7			14.7			14.7		kHz
H Settling Time 0.01%	10 V step										
G = 1 to 100			10			10			10		µs
G = 1000			80			80			80		µs
H Settling Time 0.001%	10 V step										
G = 1 to 100			13			13			13		µs
G = 1000			110			110			110		µs
Slew Rate	G = 1	1.5	1.7		1.5	1.7		1.5	1.7		V/µs
	G = 5 to 100	2	2.5		2	2.5		2	2.5		V/µs
I GAIN	G = 1 + (49.4 kΩ/R_G)										
J Gain Range		1		1000	1		1000	1		1000	V/V
K Gain Error	V_{OUT} ±10 V										
G = 1				0.03			0.02			0.1	%
G = 10				0.3			0.15			0.3	%
G = 100				0.3			0.15			0.3	%
G = 1000				0.3			0.15			0.3	%
L Gain Nonlinearity	V_{OUT} = –10 V to +10 V										
G = 1 to 10	R_L = 10 kΩ		3	10		3	10		5	15	ppm
G = 100	R_L = 10 kΩ		5	15		5	15		7	20	ppm
G = 1000	R_L = 10 kΩ		10	40		10	40		10	50	ppm
G = 1 to 100	R_L = 2 kΩ		10	95		10	95		15	100	ppm
M Gain vs. Temperature											
G = 1			3	10		2	5		3	10	ppm/°C
G > 1[3]				–50			–50			–50	ppm/°C
INPUT											
Input Impedance											
Differential			100 ∥ 2			100 ∥ 2			100 ∥ 2		GΩ ∥ pF
Common Mode			100 ∥ 2			100 ∥ 2			100 ∥ 2		GΩ ∥ pF
Input Operating Voltage Range[4]	$V_S = \pm 2.3$ V to ± 5 V	$-V_S + 1.9$		$+V_S - 1.1$	$-V_S + 1.9$		$+V_S - 1.1$	$-V_S + 1.9$		$+V_S - 1.1$	V
Over Temperature	T = –40°C to +85°C	$-V_S + 2.0$		$+V_S - 1.2$	$-V_S + 2.0$		$+V_S - 1.2$	$-V_S + 2.0$		$+V_S - 1.2$	V
Input Operating Voltage Range	$V_S = \pm 5$ V to ± 18 V	$-V_S + 1.9$		$+V_S - 1.2$	$-V_S + 1.9$		$+V_S - 1.2$	$-V_S + 1.9$		$+V_S - 1.2$	V
Over Temperature	T = –40°C to +85°C	$-V_S + 2.0$		$+V_S - 1.2$	$-V_S + 2.0$		$+V_S - 1.2$	$-V_S + 2.0$		$+V_S - 1.2$	V
OUTPUT	R_L = 10 kΩ										
Output Swing	$V_S = \pm 2.3$ V to ± 5 V	$-V_S + 1.1$		$+V_S - 1.2$	$-V_S + 1.1$		$+V_S - 1.2$	$-V_S + 1.1$		$+V_S - 1.2$	V
Over Temperature	T = –40°C to +85°C	$-V_S + 1.4$		$+V_S - 1.3$	$-V_S + 1.4$		$+V_S - 1.3$	$-V_S + 1.4$		$+V_S - 1.3$	V
N Output Swing	$V_S = \pm 5$ V to ± 18 V	$-V_S + 1.2$		$+V_S - 1.4$	$-V_S + 1.2$		$+V_S - 1.4$	$-V_S + 1.2$		$+V_S - 1.4$	V
Over Temperature	T = –40°C to +85°C	$-V_S + 1.6$		$+V_S - 1.5$	$-V_S + 1.6$		$+V_S - 1.5$	$-V_S + 1.6$		$+V_S - 1.5$	V
Short-Circuit Current			18			18			18		mA
TEMPERATURE RANGE											
Specified Performance		–40		+85	–40		+85	–40		+85	°C
Operational[4]		–40		+125	–40		+125	–40		+125	°C

NOTES
[1] $V_S = \pm 15$ V, V_{REF} = 0 V, T_A = +25°C, G = 1, R_L = 2 kΩ, unless otherwise noted.
[2] Total RTI V_{OS} = (V_{OSI}) + (V_{OSO}/G).
[3] Does not include the effects of external resistor R_G.
[4] One input grounded. G = 1.

(A) Specifications (Conditions)
A statement at the top of the data sheet explains that the listed specifications are typically @ T_A = 25°C, V_S = ±15 V, and R_L = 10 kΩ, unless otherwise noted. This tells the user that these are the normal operating conditions under which the device is tested. Deviations from these conditions might degrade (or improve) performance. For situations where deviations from the normal conditions (such as a change in temperature) are likely, the significant effects are usually indicated within the specs. The statement at the top of the specifications table also tells us what all numbers are unless noted; typical is used to state that the manufacturer's characterization process has shown a number to be average; however, individual devices may vary.

Instrumentation amplifiers designed for true rail-to-rail operation have a few critical specifications that need to be considered. Their input voltage range should allow the in-amp to accept input signal levels that are close to the power supply or ground. Their output swing should be within 0.1 V of the supply line or ground. In contrast, a typical dual-supply in-amp can swing only within 2 V or more of the supply or ground. In 5 V single-supply data acquisition systems, an extended output swing is vital because it allows the full input range of the ADC to be used, providing high resolution.

(B) Common-Mode Rejection
Common-mode rejection is a measure of the change in output voltage when the same voltage is applied to both inputs. CMR is normally specified as input, which allows for in-amp gain. As the gain is increased, there will be a higher output voltage for the same common-mode input voltage. These specifications may be given for either a full range input voltage change or for a specified source imbalance in ohms.

Common-mode rejection ratio is a ratio expression, while common-mode rejection is the logarithm of that ratio. Both specifications are normally referred to output (RTO).

That is,

$$CMRR = \frac{Change\ in\ Output\ Voltage}{Change\ in\ Common\text{-}Mode\ Input\ Voltage}$$

While

$$CMR = 20\ Log10\ CMRR$$

For example, a CMRR of 10,000 corresponds to a CMR of 80 dB. For most in-amps, the CMR increases with gain because most designs have a front-end configuration that rejects common-mode signals while amplifying differential (i.e., signal) voltages.

Common-mode rejection is usually specified for a full range common-mode voltage change at a given frequency, and a specified imbalance of source impedance (e.g., 1 kΩ source unbalance, at 60 Hz).

(C) AC Common-Mode Rejection
As might be expected, an in-amp's common-mode rejection *does* vary with frequency. Usually, CMR is specified at dc or at very low input frequencies. At higher gains, an in-amp's bandwidth does decrease, lowering its gain and introducing additional phase shift in its input stage.

Since any imbalance in phase shift in the differential input stage will show up as a common-mode error, ac CMRR will usually decrease with frequency. Figure A-1 shows the CMR vs. frequency of the AD8221.

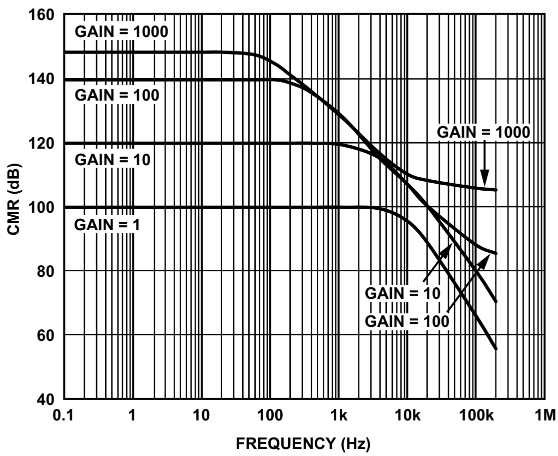

Figure A-1. AD8221 CMR vs. frequency.

(D) Voltage Offset
Voltage offset specifications are often considered a figure of merit for instrumentation amplifiers. While any initial offset may be adjusted to zero through the use of hardware or software, shifts in offset voltage due to temperature variations are more difficult to correct. Intelligent systems using a microprocessor can use a temperature reference and calibration data to correct for this, but there are many small signal, high gain applications that do not have this capability.

Voltage offset and drift comprise four separate error definitions: room temperature (25°C), input and output, offset, and offset drift over temperature referred to both input and output.

An in-amp should be regarded as a 2-stage amplifier with both an input and an output section. Each section has its own error sources. Because the errors of the output section are multiplied by a fixed gain (usually 2), this section is often the principal error source at low circuit gains. When the in-amp is operating at higher gains, the gain of the input stage is increased. As the gain is raised, errors contributed by the input section are multiplied, while output errors are reduced. Thus, at high gains, the input stage errors dominate.

Input errors are those contributed by the input stage alone; output errors are those due to the output section. Input-related specifications are often combined and classified together as referred to input (RTI) errors, while all output-related specifications are considered referred to output (RTO) errors. It is important to understand that although these two specifications often provide numbers that are not the same, either error term is correct because each defines the total error in a different way.

For a given gain, an in-amp's input and output errors can be calculated using the following formulas:

Total Error, RTI = Input Error + (Output Error/Gain)

Total Error, RTO = (Gain × Input Error) + Output Error

Sometimes the specification page will list an error term as RTI or RTO for a specified gain. In other cases, it is up to the user to calculate the error for the desired gain.

As an example, the total voltage offset error of the AD620A in-amp when it is operating at a gain of 10 can be calculated using the individual errors listed on its specifications page. The (typical) input offset of the AD620 (V_{OSI}) is listed as 30 μV. Its output offset (V_{OSO}) is listed as 400 μV. The total voltage offset referred to input (RTI) is equal to

$$\text{Total RTI Error} = V_{OSI} + (V_{OSO}/G) = 30\ \mu V + (400\ \mu V/10) = 30\ \mu V + 40\ \mu V = 70\ \mu V$$

The total voltage offset referred to the output (RTO) is equal to

$$\text{Total Offset Error RTO} = (G\,(V_{OSI})) + V_{OSO} = (10\,(30\ \mu V)) + 400\ \mu V = 700\ \mu V.$$

Note that the RTO error is 10 times greater in value than the RTI error. Logically, it should be, because at a gain of 10, the error at the output of the in-amp should be 10 times the error at the input.

(E) Input Bias and Offset Currents

Input bias currents are those currents flowing into or out of the input terminals of the in-amp. In-amps using FET input stages have lower room temperature bias currents than their bipolar cousins, but FET input currents double approximately every 11°C. Input bias currents can be considered a source of voltage offset error (i.e., input current flowing through a source resistance causes a voltage offset). Any change in bias current is usually of more concern than the magnitude of the bias current.

Input offset current is the difference between the two input bias currents. It leads to offset errors in in-amps when source resistances in the two input terminals are unequal.

Although instrumentation amplifiers have differential inputs, there must be a return path for their bias currents to flow to common (ground).

If this return path is not provided, the bases (or gates) of the input devices are left floating (unconnected), and the in-amp's output will rapidly drift either to common or to the supply.

Therefore, when amplifying floating input sources such as transformers (those without a center tap ground connection), ungrounded thermocouples, or any ac-coupled input sources, there must still be a dc path from each input to ground. A high value resistor of 1 MΩ to 10 MΩ connected between each input and ground will normally be all that is needed to correct this condition.

(F) Operating Voltage Range

A single-supply in-amp should have the same overall operating voltage range whether it is using single or dual supplies. That is, a single-supply in-amp, which is specified to operate with dual-supply voltages from ±1 V to ±18 V, should also operate over a 2 V to 36 V range with a single supply, but this may not always be the case. In fact, some in-amps, such as the AD623, will operate to even lower equivalent voltage levels in single-supply mode than with a dual-supply mode. For this reason, it is always best to check the data sheet specifications.

(G) Quiescent Supply Current

This specifies the quiescent or nonsignal power supply current consumed by an in-amp within a specified operating voltage range.

With the increasing number of battery-powered applications, device power consumption becomes a critical design factor. Products such as the AD627 have a very low quiescent current consumption of only 60 μA, which at 5 V is only 0.3 mW. Compare this power level to that of an older, vintage dual-supply product, such as the AD526. That device draws 14 mA with a ±15 V supply

(30 V total) for a whopping 420 mW, 1400 times the power consumption of the AD627. The implications for battery life are dramatic.

With the introduction of products such as the AD627, very impressive overall performance is achieved while only microamps of supply current are consumed. Of course, some trade-offs are usually necessary, so micropower in-amps tend to have lower bandwidth and higher noise than full power devices. The ability to operate rail-to-rail from a single-supply voltage is an essential feature of any micropower in-amp.

(H) Settling Time

Settling time is defined as the length of time required for the output voltage to approach, and remain within, a certain tolerance of its final value. It is usually specified for a fast full-scale input step and includes output slewing time. Since several factors contribute to the overall settling time, fast settling to 0.1% does not necessarily mean proportionally fast settling to 0.01%. In addition, settling time is not necessarily a function of gain. Some of the contributing factors to long settling times include slew rate limiting, underdamping (ringing), and thermal gradients (long tails).

(I) Gain

These specifications relate to the transfer function of the device. The product's gain equation is normally listed at the beginning of the specifications page.

The gain equation of the AD8221 is

$$Gain = \frac{49{,}400\ \Omega}{R_G} + 1$$

To select an R_G for a given gain, solve the following equation for R_G:

$$R_G = \frac{49{,}400\ \Omega}{G - 1}$$

The following are samples of calculated resistance for some common gains:

G = 1: $R_G = \infty$ (open circuit)
G = 9.998: R_G = 5.49 kΩ
G = 100: R_G = 499 Ω
G = 991: R_G = 49.9 Ω

Note that there will be a gain error if the standard resistance values are different from those calculated. In addition, the tolerance of the resistors used (normally 1% metal film) will also affect accuracy. There also will be gain drift, typically 50 ppm/°C to 100 ppm/°C, if standard resistors are used. Of course, the user must provide a very clean (low leakage) circuit board to realize an accurate gain of 1, since even a 200 MΩ leakage resistance will cause a gain error of 0.2%.

Normal metal film resistors are within 1% of their stated value, which means that any two resistors could be as much as 2% different in value from one another. Thin film resistors in monolithic integrated circuits have an absolute tolerance of only 20%. The matching between resistors on the same chip, however, can be excellent —typically better than 0.1%—and resistors on the same chip will track each other thermally, so gain drift over temperature is greatly reduced.

(J) Gain Range

Often specified as having a gain range of 1 to 1000, many instrumentation amplifiers will often operate at higher gains than 1000, but the manufacturer will not promise a specific level of performance.

(K) Gain Error

In practice, as the gain resistor becomes increasingly smaller, any errors due to the resistance of the metal runs and bond wires inside the IC package become significant. These errors, along with an increase in noise and drift, may make higher gains impractical.

In 3-op amp and in-amp designs, both gain accuracy and gain drift may suffer because the external resistor does not exactly ratio match the IC's internal resistors. Moreover, the resistor chosen is usually the closest 1% metal film value commonly available, rather than the calculated resistance value; so this adds an additional gain error. Some in-amps, such as the AD8230, use two resistors to set gain. Assuming that gain is set solely by the ratio of these two resistors in the IC, this can provide potentially significant improvement in both gain accuracy and drift. The best possible performance is provided by monolithic in-amps that have all their resistors internal to the IC, such as the AD621.

The number provided for this specification describes maximum deviation from the gain equation. Monolithic in-amps, such as the AD8221, have very low factory-trimmed gain errors. Although externally connected gain networks allow the user to set the gain exactly, the temperature coefficients of these external resistors and the temperature differences between individual resistors within the network all contribute to the circuit's overall gain error.

If the data eventually is digitized and fed to an intelligent system (such as a microprocessor), it may be possible to correct for gain errors by measuring a known reference voltage and then multiplying by a constant.

(L) Nonlinearity

Nonlinearity is defined as the deviation from a straight line on the plot of an in-amp's output voltage vs. input voltage. Figure A-2 shows the transfer function of a device with exaggerated nonlinearity.

The magnitude of this error is equal to

$$Nonlinearity = \frac{Actual\ Output - Calculated\ Output}{Rated\ Full\ \ Scale\ \ Output\ Range}$$

This deviation can be specified relative to any straight line or to a specific straight line. There are two commonly used methods of specifying this ideal straight line relative to the performance of the device.

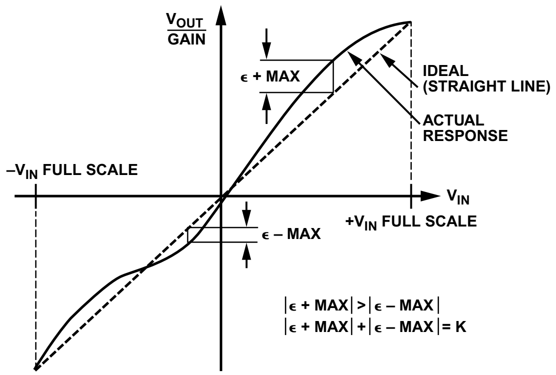

Figure A-2. Transfer function illustrating exaggerated nonlinearity.

The *best straight line* method of defining nonlinearity consists of measuring the peak positive and the peak negative deviation and then adjusting the gain and offset of the in-amp so that these maximum positive and negative errors are equal. For monolithic in-amps, this is usually accomplished by laser-trimming thin film resistors or by other means. The best straight line method provides impressive specifications, but it is much more difficult to perform. The entire output signal range needs to be examined before trimming to determine the maximum positive and negative deviations.

The endpoint method of specifying nonlinearity requires that any offset and/or gain calibrations are performed at the minimum and maximum extremes of the output range. Usually offset is trimmed at a very low output level, while scale factor is trimmed near the maximum output level. This makes trimming much easier to implement but may result in nonlinearity errors of up to twice those attained using the best straight line technique. This worst-case error will occur when the transfer function is bowed in one direction only.

Most linear devices, such as instrumentation amplifiers, are specified for best straight line linearity. This needs to be considered when evaluating the error budget for a particular application.

Regardless of the method used to specify nonlinearity, the errors thus created are irreducible. That is to say, these errors are neither fixed nor proportional to input or output voltage and, therefore, cannot be reduced by external adjustment.

(M) Gain vs. Temperature

These numbers provide both maximum and typical deviations from the gain equation as a function of temperature. As stated in the Gain Error section (K), the TC of an external gain resistor will never exactly match that of other resistors within the IC package. Therefore, the best performance over temperature is usually achieved by in-amps using all internal gain resistors. Gain drift error can be subtracted out in software by using a temperature reference and calibration data.

(N) Key Specifications for Single-Supply In-Amps

There are some specifications that apply to single-supply (i.e., rail-to-rail) in-amp products, which are of great importance to designers powering in-amps from low voltage, single-supply voltages.

Input and Output Voltage Swing

A single-supply in-amp needs to be able to handle input voltages that are very close to the supply and ground. In a typical dual-supply in-amp, the input (and output) voltage range is within about 2 V of the supply or ground. This becomes a real problem when the device is powered from a 5 V supply, or can be especially difficult when using the new 3.3 V standard. A standard in-amp operating from a 5 V single-supply line has only about 1 V of headroom remaining; with a 3.3 V supply, it has virtually none.

Fortunately, a decent single-supply in-amp, such as the AD627, will allow an output swing within 100 mV of the supply and ground. The input level is somewhat less, within 100 mV of ground and 1 V of the supply rail. In critical applications, the reference terminal of the in-amp can be moved off center to allow a symmetrical input voltage range.