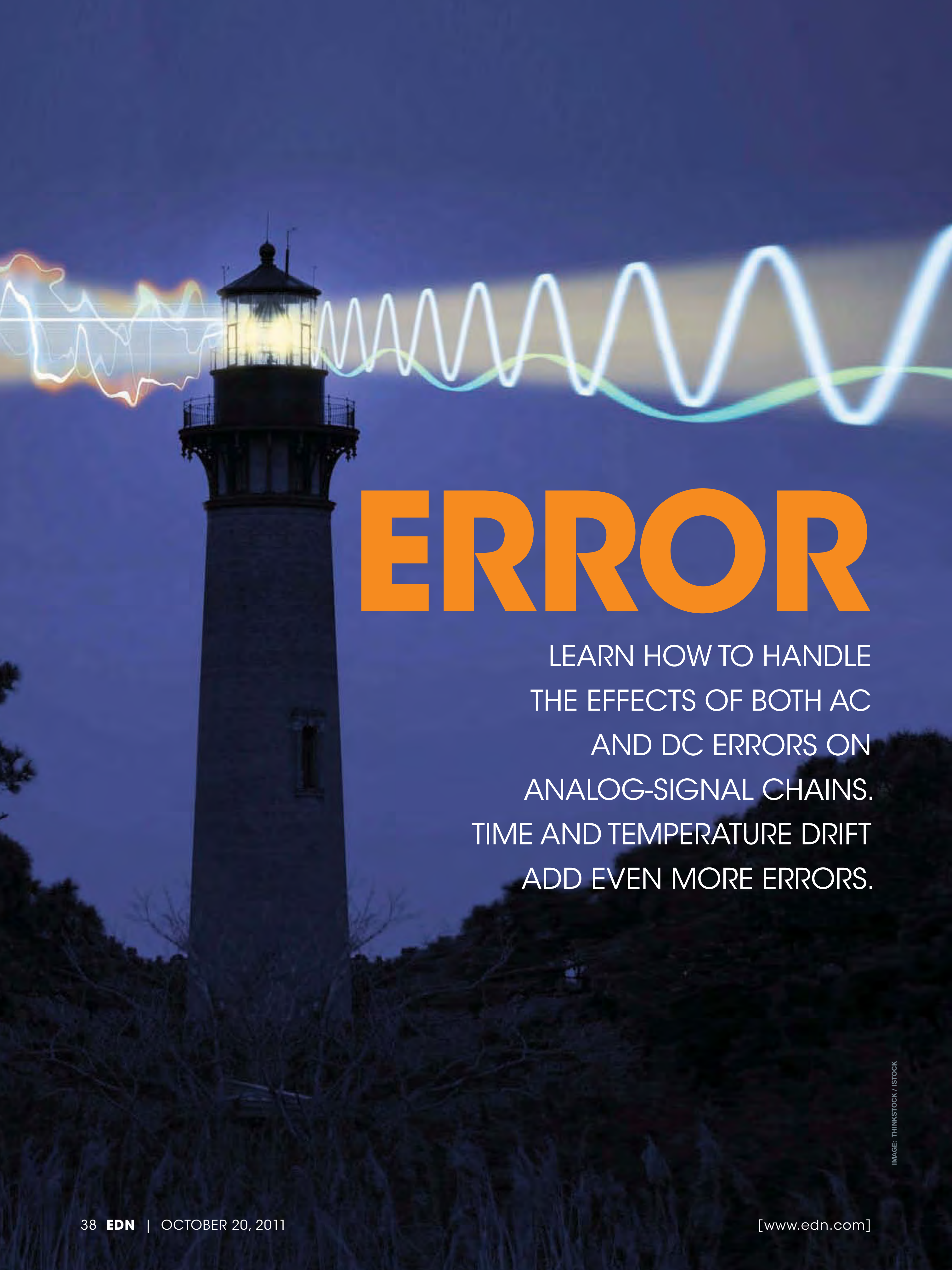


ERROR

LEARN HOW TO HANDLE THE EFFECTS OF BOTH AC AND DC ERRORS ON ANALOG-SIGNAL CHAINS. TIME AND TEMPERATURE DRIFT ADD EVEN MORE ERRORS.

IMAGE: THINKSTOCK / ISTOCK

BUDGETS KEEP YOUR ANALOG-SIGNAL PATH HONEST

BY PAUL RAKO • TECHNICAL EDITOR

To deal with errors in your design's analog-signal chain, you must understand their sources in attenuators, amplifiers, multiplexers, references, and ADCs. Although Monte Carlo Spice simulations can help you handle component tolerances, keep in mind that resistor tolerances can create dc errors and that capacitors and inductor tolerances can create ac errors. The stray capacitance and inductance on PCBs (printed-circuit boards) also create ac errors. Once you establish the dc and ac errors due to component tolerances, you can examine the dc and ac errors that the ICs in the signal path cause. You can then calculate and track all of the errors with a spreadsheet to ensure that your system will meet the required specifications (**tables 1** and **2**).

AT A GLANCE

- Every component in the signal chain contributes ac errors, dc errors, or both.
- You must examine, analyze, and tabulate the errors in the signal chain so that the trade-offs you make ultimately yield a feasible design.
- Tiny signals and fast signals need special attention.
- You can use a spreadsheet to calculate errors.

Some programmers' claims that you can calibrate out all errors in software may lull you into a false sense of security regarding the errors in your design. However, dc analysis ensures that your ADC receives the required signal at its full dynamic range without clipping. A 10-bit converter has 1024 steps in its output code, so you might think it would be ideal for a 0.1%-accurate system because it has a range better than 1000-to-1. However, dc errors in the signal chain can put 100 counts of offset into the signal at the ADC, so you cannot achieve 0.1% accuracy no matter how much software correction you do. If the 100-count offset is positive, the ADC provides digital outputs only from 100 to 1024—not the full range of more than 1000 counts—so this system cannot achieve 0.1% accuracy. This situation is true even if software reduces the gain so that the ADC input does not saturate at its most positive level. Software can reduce the gain of the signal by 100 counts to compensate for the positive offset, but the signal still does not have a dynamic range of the full 10 bits.

Every component in the signal chain contributes ac errors, dc errors, or both (**Figure 1**). Other errors are due to drift, which most commonly refers to specification changes over temperature. Time drift, which contributes ac errors, refers to the changes in spec as a component ages, but the drift is so slow that engineers don't consider the errors to be normal ac errors. Electrical noise, which is inherent in the atomic vibrations due to temperature and can be a function of the quantum mechanics in a semiconductor device, also causes errors. As with so many other gray areas in analog design, you might think of time drift as low-frequency noise.

Errors, drift, and noise all conspire to make your analog-signal chain less accurate than you might hope. For this reason, experienced analog engineers would not start with a 10-bit ADC to make a 0.1%-accurate system; they would instead start with a 12- or even a 14-bit converter to leave margin for all of the analog components that contribute to the total system error. Some application engineers who work for ADC groups maintain that the analog components feeding the converter should be transparent, so that they have no effect on the converter. This scenario is at best optimistic and at worst

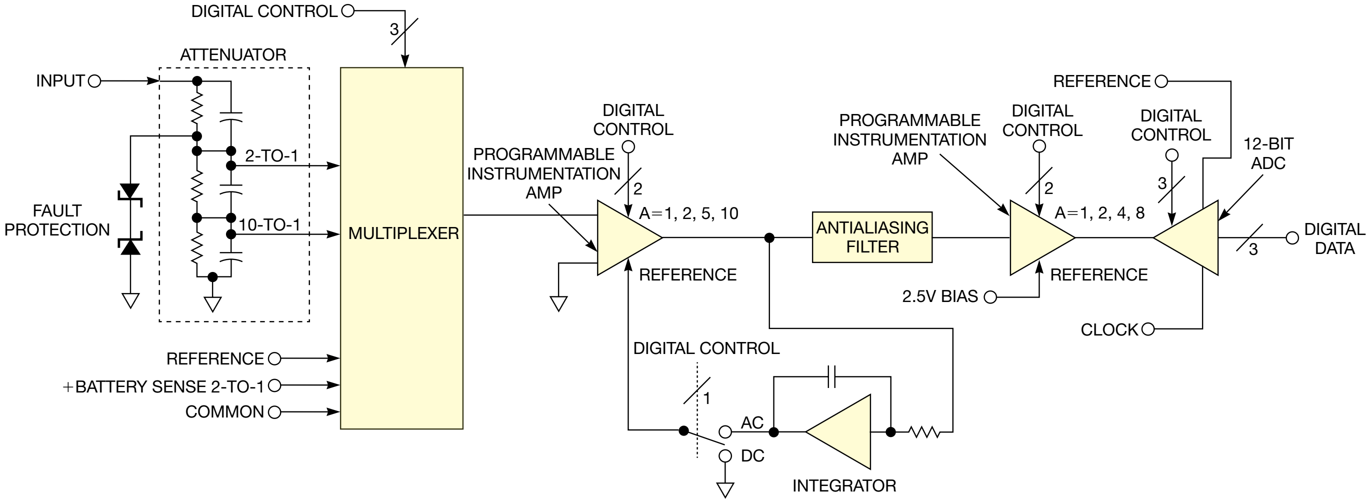
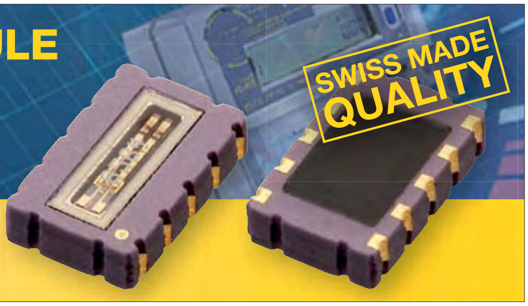


Figure 1 All of the parts in an analog-measurement signal path are subject to ac, dc, drift, and noise errors. Power-supply noise can also creep into the signal chain and ruin your measurements.



impossible. Like all things analog, it involves a trade-off. Perhaps you can use a cheaper ADC and better analog components to feed the converter. Then again, it may be better to use a more expensive converter and cheaper analog components. If you are lucky, you can use an inexpensive converter and inexpensive components and calibrate out all the errors with software. In any event, you must examine, analyze, and tabulate the errors in the signal chain so that the trade-offs you make ultimately yield a feasible design.

Component tolerances are fundamental sources of errors. You must analyze and understand how component tolerances affect your input attenuator and other circuits (see **sidebar** "Component tolerances").

AN AMPLIFIER CAUSES DC ERRORS THAT COME FROM THE IMPERFECT NATURE OF REAL-WORLD OP AMPS.

FIRST ANALYZE DC ERRORS

Once you understand the dc and ac errors that the input attenuator contributes, you can look at the rest of the signal chain. The input multiplexer can contribute dc errors due to the small on-resistance of the internal semiconductor switches in the part. The on-resistance appears in series with the input resistor to the amplifier, creating an error term. The leakage from the multiplexer channels that are off also add a dc error. The multiplexer and the loading on the input attenuator cause errors, so you must tailor the input impedance of the first amplifier to minimize these errors. The resistor values of the first amplifier can cause issues that create more errors.

An amplifier causes dc errors that come from the imperfect nature of real-world op amps (**Figure 2**). The resistor values are used to set the closed-loop noise gain, which multiplies the op amp's offset-voltage error that appears at the output (**Reference 1**). For noninverting-amplifier configurations, the noise gain equals the closed-loop gain. For inverting configurations, the noise gain equals the closed-loop gain plus one.

The bias current that enters or exits the input pins also creates an error. When you analyze the input bias error, remember that the op amp is in the circuit and is working. As a result, the input bias current reacts to the source resistor, but the op amp servos the voltage that the current creates to keep the input pins of the amplifier at the same voltage. The op amp maintains a constant voltage across the input resistor, so the output error due to input bias current is purely a function of the feedback resistance times the bias current. The resulting voltage error appears at the output in both inverting- and noninverting-amplifier configurations. Derivations for differential amplifiers are a bit more involved and are less apparent (**Reference 2**).

How accurately you scale a signal to your intended gain can also create a dc error. You can refer to published resources to see how a gain error occurs; the open-loop gain of any op amp is not infinite (**Reference 3**). The results of the analysis may also surprise you when you see how significantly large errors can creep into your design. You can derive the gain error as a function of the difference in the ratio, N, between the open- and the closed-loop gain, as the following **equation** shows:

$$\delta=1-\frac{N}{1+N}=\frac{1}{1+N}.$$

Thus, if only a 20-dB difference exists between the open- and the closed-loop gain, N equals 10, meaning that gain error is 9.1% (**Reference 4**). Your error spreadsheet should have a term for this error. Older parts, such as Texas Instrument's LM741 op amp, have minimum open-loop gains of only 10,000 over temperature. In this case, the IC designers provided some good specs at the expense of others. Your application's requirements determine which specs are most important.

Gain nonlinearity also causes measurement errors and is more difficult to characterize and incorporate in an error budget. If the manufacturer of the part you are using does not define gain nonlinearity, you may need to characterize a batch of parts (**Figure 3** and **Reference 5**).

Using op amps in a noninverting arrangement can cause common-mode errors. The common-mode voltage appears on both input pins in common relative to the power-supply rails. Op amps create the least error when

TABLE 1 SLOW- AND FAST-CHANNEL ERROR COUNTS

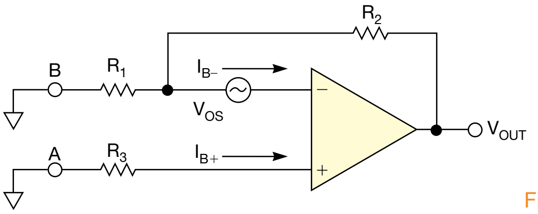
	Slow channel (counts)	**Fast channel** (counts)
Input attenuator	0	0
Buffer amplifiers	0	0
Multiplexer	0	0
First PGA	4	4
Filter	NA	NA
Second PGA	0.2	0.2
Level shift	4.1	0
ADC	NA	NA
Total	8.3	4.2
Maximum allowed	28	28
Margin	19.7	23.8

TABLE 2 OFFSET ERROR

Input voltage (V)	**Attenuator accuracy** (%)	**Attenuator common-mode voltage** (V)	**Buffer amplifiers** (%)	**Multiplexers** (%)	**First PGA** (%)
100	0.01	0.2	0	0	0.1
50	0.01	0.2	0	0	0.1
20	0.01	0.2	0	0	0.1
10	0.008	0.16	0	0	0.1
5	0.008	0.16	0	0	0.1
2	0.008	0.16	0	0	0.1
1	0.008	0.16	0	0	0.1
0.5	0.008	0.16	0	0	0.1
0.2	0.008	0.16	0	0	0.1
0.1	0.008	0.16	0	0	0.1

the input pins are in the center of the power rails. As the input pins approach either rail, an error occurs in the output (**Figure 4**). "Think of it as a worsening of the offset voltage as you sweep the input pins toward either rail," says Paul Grohe, an amplifier-application engineer at Texas Instruments. That offset acts just like the inherent offset voltage: The noise gain multiplies it, and it appears at the output.

Although some manufacturers publish charts that show CMRR (common-mode-rejection ratio) as a function of common-mode input voltage (**Figure 5**), Linear Technology provides graphs for bias current versus common-mode voltage, according to Tim Regan, an amplifier-application manager at the company. These graphs show the effects of common-mode limits versus temperature. Rail-to-rail parts have a guaranteed CMRR with common-mode voltage all the way to either power



$$\text{OFFSET (RTO)}=V_{OS}\left[1+\frac{R_2}{R_1}\right]+I_{B+}\times R_3\left[1+\frac{R_2}{R_1}\right]-I_{B-}\times R_2.$$

$$\text{OFFSET (RTI)}=V_{OS}+I_{B+}\times R_3-I_{B-}\left[\frac{R_1\times R_2}{R_1+R_2}\right].$$

Figure 2 You can calculate offset errors referred to the output or the input pins of the amplifier (courtesy Analog Devices).

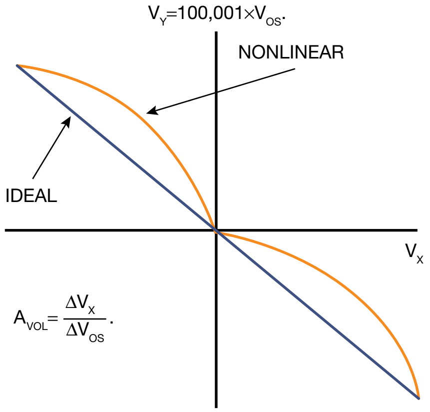


Figure 3 Gain nonlinearity shows up as an error between input V_Y and the amplifier's output, V_X (courtesy Analog Devices).

	Filter (%)	**Second PGA** (%)	**Level shifter** (%)	**Reference** (%)	**ADC** (%)	**Total** (%)	**Spec** (%)
	0.01	0.1	0	0.1	0.02	0.54	0.5
	0.01	0.1	0	0.1	0.02	0.54	0.5
	0.01	0.1	0	0.1	0.02	0.54	0.5
	0.01	0.1	0	0.1	0.02	0.498	0.5
	0.01	0.1	0	0.1	0.02	0.498	1
	0.01	0.1	0	0.1	0.02	0.498	1
	0.01	0.1	0	0.1	0.02	0.498	1
	0.01	0.1	0	0.1	0.02	0.498	1
	0.01	0.1	0	0.1	0.02	0.498	1
	0.01	0.1	0	0.1	0.02	0.498	1

AC ERRORS ARE MORE SUBTLE, MORE DIFFICULT TO UNDERSTAND, AND MORE SERIOUS, ESPECIALLY FOR SIGNAL CHAINS IN ’SCOPES.

rail. For the parts that operate over the rails, such as the LT1638 op amp, the company guarantees the common-mode voltage even above the positive supply. For purpose-built, high-side-current-sense amplifiers, such as the LTC6101, Linear doesn’t even spec CMRR, says Regan. Instead, the company provides a PSRR (power-supply-rejection-ratio) spec—the amount of change in the power-supply voltage—because the inputs connect to the positive supply, and they all move together.

Input offsets, bias currents, gain errors, PSRR, and common-mode errors are just a few of the specs that create dc error in your system. The antialiasing filter may cause similar errors if it uses op amps in active configurations. The level-shifting amplifier, which also serves as a buffer for the ADC, also has most of these error terms. Because the first amplifier in the signal chain amplifies the signal, the errors of the filter and the level-shifting amplifier tend to contribute less to total system error, but you still must account for them in your error budget.

When you finally get to the ADC, you can look at the dc specs, such as integral linearity and monotonicity. The ADC’s internal or external reference also has dc errors that must be included in your budget. It’s usually a good idea and worth the expense to use a high-quality reference because doing so eliminates the need for factory calibrations or any subsequent field adjustments. Potentiometers and trimmers have low reliability, so you may want to incorporate digital potentiometers or DACs to perform the trimming instead of using a mechanical part.

AC ERRORS COME NEXT

Understanding and tabulating all of the dc errors in the analog-signal path are complex tasks, but ac errors are even more subtle, more difficult to understand, and more serious, especially for signal chains such as those in oscilloscopes. Errors on the ac component of a signal occur at all points in the analog-signal chain. Your circuitry also has ac-error sources in the clock circuit that operates the ADC. Just as daunting, errors in the signal can result from the presence of ac

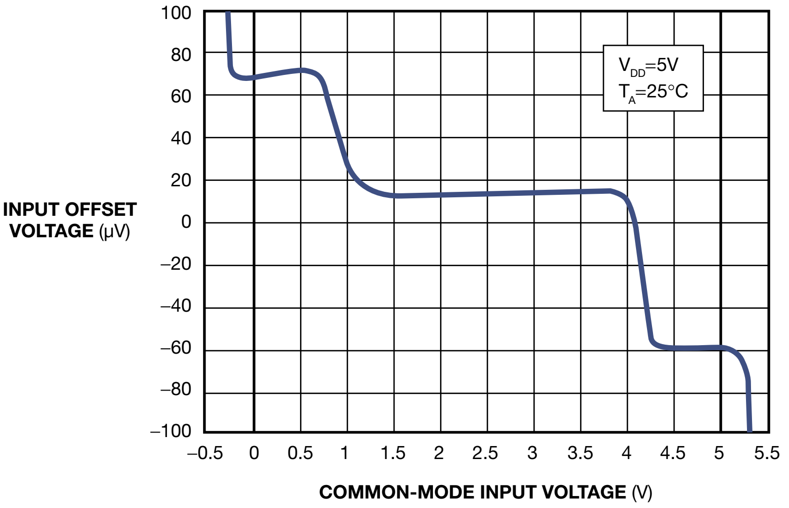


Figure 4 Like most other rail-to-rail-input parts, the TLV2450 amplifier has a dual differential-pair front end, causing the offset voltage and the offset current to change with common-mode input voltage (courtesy Texas Instruments).

noise on the power-supply circuits that feed analog chips.

It helps to look at the error sources from the outputs to the circuit's input. The last analog IC in the signal path is usually an ADC. Examine its ac specs to see whether it can meet your application's needs as it operates as an ac-sampling system on the ac signal.

One key spec is the ADC's ENOB (effective number of bits) at a given sampling frequency. For accurate 10-bit measurements, start with a converter that has an ENOB greater than 10. Otherwise, the rest of the signal chain will further degrade the 10-bit accuracy. Ensure that the converter's bandwidth is as high as the highest frequencies you need to accurately measure. ENOB is a simple way for manufacturers to express the ADC's SNR (signal-to-noise ratio) during operation. You may want to look at pin-compatible converters that come in 12-, 14-, and 16-bit versions so that your board's layout remains the same even if you have to increase the number of bits in the converter.

A buffer and a level-shifting circuit

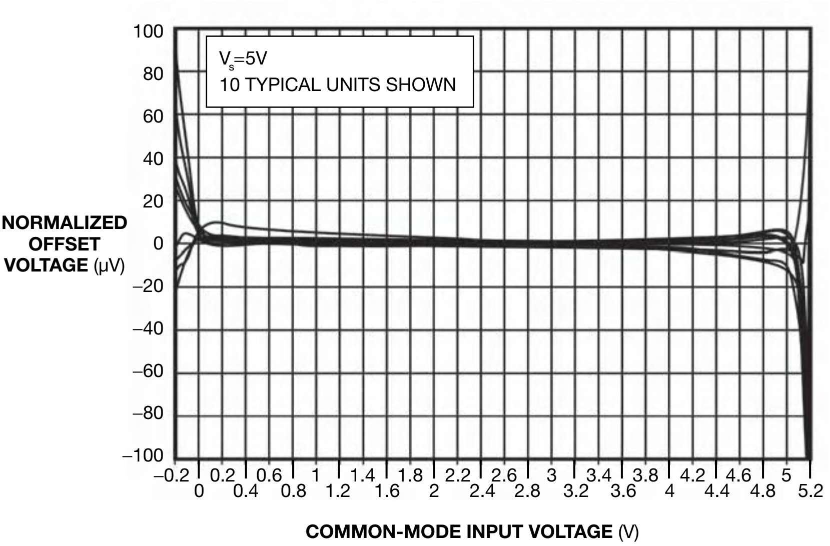


Figure 5 The OPA369 amplifier uses a charge-pump front end, reducing the offset-voltage change over the common-mode input voltage (courtesy Texas Instruments).

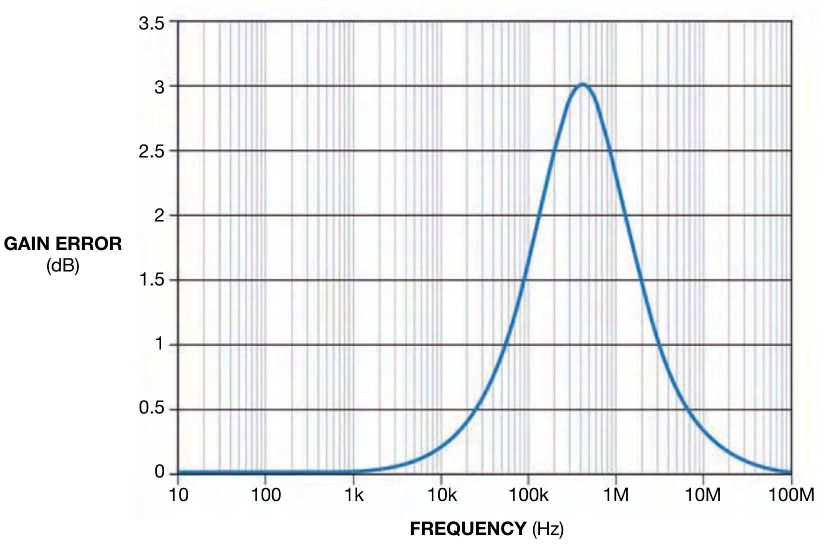


Figure 6 A significant gain error occurs over frequency because an amplifier's open-loop gain rolls off at higher frequencies (courtesy Texas Instruments).

COMPONENT TOLERANCES

Resistor tolerances in input attenuators create dc errors, and capacitors in the attenuators create a significant amount of ac errors (Figure A). For this reason, you must use discrete capacitors in the input attenuator to swamp out all the stray capacitance in the PCB (printed-circuit board) and in the multiplexer's input pins. Placing three capacitors in parallel with the resistors makes an ac-voltage divider alongside the dc-voltage divider that the resistors create. The capacitor ladder lowers the input impedance at higher frequencies. You must evaluate whether that lower impedance will cause a problem in your measurement system. If so, you must design a different input-attenuator structure. No matter what input structure you use, you must calibrate out the stray-capacitance-induced ac errors. For this reason, it is difficult to achieve both high-impedance inputs and high ac accuracy.

A Monte Carlo Spice simulation of the input attenuator shows serious ac errors in the attenuator at low frequencies (Figure B). You might think that picofarads of capacitance would not make much difference, but they make a big difference at megahertz frequencies. This high-impedance input structure has nominal 1-MΩ input impedance. It takes little capacitor tolerance to create significant errors, and those errors double the nominal dc-error terms at frequencies as low as 2 kHz (Figure C).

Other results of using an input attenuator are less intuitive. You don't necessarily need to use 0.1%-tolerant resistors to achieve a 0.1%-accurate output. A large difference in resistor values means that the tolerance of the larger-value resistor will dominate the output accuracy. Think of a voltage divider with a 100,000-to-1 difference. You could fashion this voltage ladder with a 10Ω resistor and a 999,990Ω resistor. You could use a 0.1%-tolerant resistor for the 999,990Ω resistor and a 1%-accurate resistor for the 10Ω resistor. Nevertheless, the output accuracy remains so close to 0.1% that you can round it to 0.1%. A 50%-accurate voltage ladder with equal-value resistors does require 0.1%-tolerant resistors to ensure a 0.1%-tolerant output voltage.

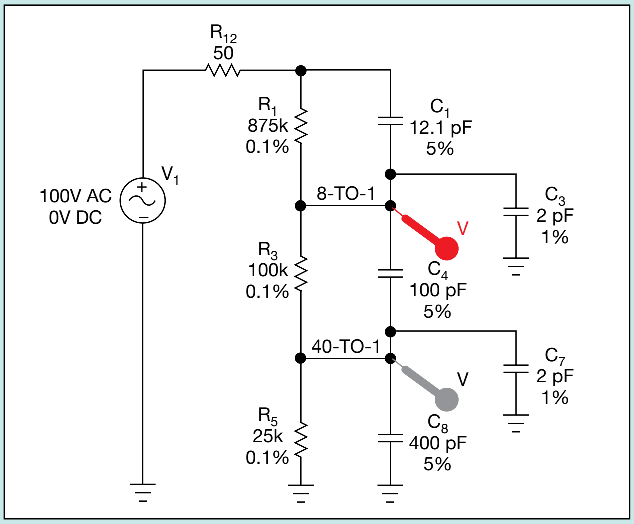


Figure A You can model your input attenuator network in Cadence's Orcad Capture for a Spice simulation. R$_{12}$ is the source resistance of your signal. Discrete capacitors C$_1$, C$_4$, and C$_8$ comprise an ac divider. C$_3$ and C$_7$ represent the PCB's and ICs' stray capacitance.

Vendors make resistors with laser trimming for tight tolerances; 1%-tolerant resistors are commonplace, and 0.1%-tolerant resistors are available. To get tighter tolerances, you can use custom resistors on ceramic substrates, such as those from Vishay and BI Technologies. This approach allows you to put multiple thin-film resistors on one substrate; the resistors then track each other over temperature. You can specify thin-film resistors on a single ceramic substrate that track each other to within 0.02%. The absolute-value tolerance of the resistors is 0.05%. This tolerance figure should not pose a problem because you should design your measurement channel so that the ratio of resistors determines a measurement attenuation or gain.

Thin-film ceramic resistors can achieve tighter ratiometric tolerances, such as 0.01%, but cost becomes a factor. Instead, you might investigate using an IC that has built-in resistors, such as those from Linear Technology, Maxim, and Analog Devices. Bear in mind, however, that you cannot just blindly accept the tolerance ranges on the data sheet. You must solder a statistically significant batch of parts onto your PCB and determine whether your soldering process degrades resistor tolerance. If assembling the PCB into an enclosure causes stress or warping, these problems also affect the tolerances of all of the resistors on your PCB, even those inside an IC.

An error-budget spreadsheet is just a nominal starting point to add up all the inaccuracy in your signal path. If the worst-case resistor tolerance goes from 0.2 to 0.3% after soldering, then you must use the 0.3% value in your spreadsheet.

Manufacturers can trim carbon and metal-film resistors—but not carbon-composition or wire-wound devices—during manufacturing. They can measure carbon and wire-wound types only after manufacturing; they then separate the resistors into tolerance bins (Reference A), creating an unusual situation (Figure D). With 10 or 20 carbon-composition resistors in a signal chain, you might think that the entire signal path will have a gaussian distribution of accuracy. Unless you use the most accurate grade a manufacturer offers, however, this scenario is unrealistic because the vendor makes all the resistors in a batch, measures them, puts all of the 1%-tolerant resistors into a bin, and sells them for a higher price. As a result, you cannot count on any resistors in the 5%- or 10%-tolerant line to be the exact value that you want. The vendor removes all of the close-tolerance resistors to sell as 1%-tolerant parts.

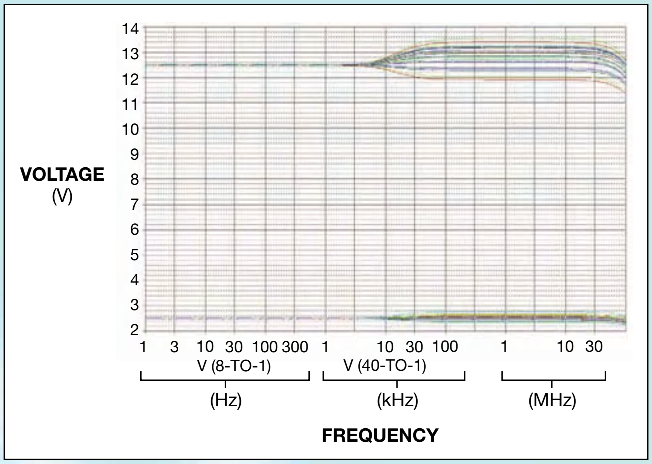


Figure B The PSpice Monte Carlo simulation of the input attenuator shows significant ac errors as low as 10 kHz.

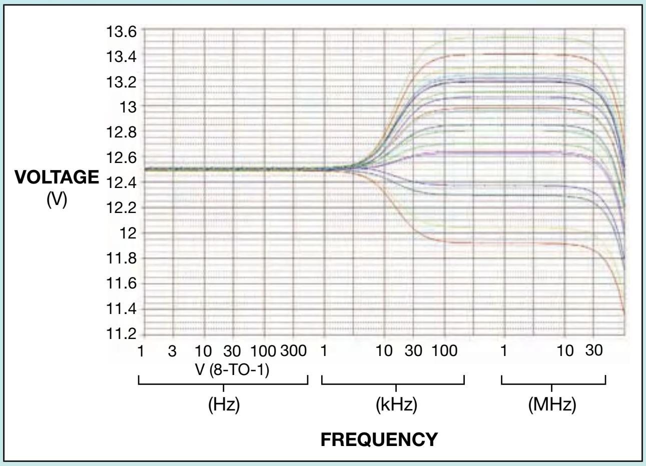


Figure C This expanded view of the simulation demonstrates the difficulty of high-impedance measurement inputs. Even the capacitors' small tolerance changes greatly affect the accuracy at frequencies as low as 3 kHz. Attenuator capacitances react with the source impedance to corrupt measurements at frequencies higher than 30 MHz.

Figure D Manufacturers bin components and ICs in tolerance levels, removing the low-tolerance parts and selling them at higher grades (courtesy Howard Johnson, PhD).

Hence, the distribution of resistor values in the 10% line is not gaussian; it is more like a bathtub distribution with parts that are greater than 5% at a high level and those lower than 5% at a low level. All of the parts are within 10%, but this skewed distribution means that the measurement chain almost never averages out to a tolerance nearing 0%.

If you only rarely use carbon-composition or wire-wound resistors, this problem may seem unimportant, but it occurs in almost all factory-binned parts. Manufacturers select the close-tolerance parts and sell them for higher prices. This scenario can apply to op amps and other active parts.

Capacitor vendors specify looser tolerances on their parts than those of resistors because the vendors cannot automatically trim capacitors during production. They make film capacitors by winding a roll of film into a cylindrical shape. They can precisely control the area of the film, but the thickness of the film varies slightly due to the exigencies and vicissitudes of manufacturing. Film-capacitor vendors just roll up the capacitors and measure them so that they can place them into 10%-, 5%-, and 1%-tolerant bins. Manufacturers of carbon-composition and wire-wound resistors face a similar problem.

Ceramic capacitors have similar manufacturing variability. Ceramic-capacitor vendors can control the area and layers of the parts but not the distance between the plates of the capacitor after sintering in a high-temperature oven.

Semiconductor junctions form capacitors in a signal chain and behave as varactors. Their capacitance changes depending on the amplitude of the applied voltage, much like a tuning capacitor in a radio. The varying capacitance changes the ac error in your system depending on the signal that is passing through. It can be difficult to minimize these errors and may require you to add compensation components or remove the errors in software.

Inductors are as problematic as capacitors. You must manually select any magnetic inductor to get 1% tolerance. If you are designing high-frequency circuits with air-core inductors, you might be able to ensure that the inductors you buy have tight tolerance, but these parts also cost more than 5%- or 10%-accurate parts.

The fact that precision resistors are much less expensive than precision capacitors and inductors will affect your design choices. Use tighter-value resistors if it allows you to loosen the spec on your capacitors and inductors. Accurate resistors often cost 10 times less than accurate inductors and capacitors. Avoid using mechanical potentiometers or trimming capacitors. After electrolytic and tantalum capacitors, these parts are the least reliable in electronic systems. AVX and Johanson Technology make capacitors you can laser-trim during manufacturing. Their reliability is similar to that of a conventional ceramic capacitor.

REFERENCE

A Johnson, Howard, "7% solution," *EDN*, June 10, 2010, pg 22, http://bit.ly/p14yVv.

sit just in front of the ADC. The nonideal op amp in this functional block creates ac errors. The dc-gain-error analysis shows that the ratio between open- and closed-loop gain creates substantial gain errors. These errors become worse at higher frequencies because of single-pole gain roll-off, in which the open-loop gain falls to one at the unity-gain-bandwidth point. So the faster you operate any operational amplifier, the less gain ratio there is between the open-loop and the closed-loop gain. You must factor this frequency-dependent error term into your error budget.

EVERY PIECE OF TEST EQUIPMENT IN YOUR LAB HAS A CALIBRATION SCHEDULE. YOU SHOULD ALSO PROVIDE YOUR OWN CALIBRATION.

Several published sources exist for ac analysis (**references 6** and **7**). If your application requires an accurate signal path, you must use op amps with significantly more bandwidth than your signals. Some designers dispense with amplifiers and instead couple and level-shift with a balun (balanced-unbalanced) transformer. Amplifiers exhibit significant amounts of closed-loop gain error when you feed them signals with frequency components near the unity-gain point (**Figure 6**).

THE JOYS OF CALIBRATION

All of the dc and ac error sources combine with spec drift over time to reduce the accuracy of your measurements. For that reason, every piece of test equipment in your lab has a calibration schedule from the manufacturer. You should also provide your own calibration for your designs. "Calibration absolves a lot of sins," says Texas Instruments' Grohe.

The first calibration takes place in the factory during manufacture. This calibration may involve hand-selecting components to meet tighter accuracy specs than the vendor guarantees in the data sheet. Another facet of ensuring accuracy in manufacturing is burning in key components for hundreds or even thousands of hours so that any initial drift occurs before you install the part in your system. Fluke, Agilent Technologies, and Tektronix all perform this task with voltage references that they use in their high-accuracy voltmeters. They solder their reference ICs onto carrier boards or into the main PCBs. They then apply power to the chip until the part's initial drift has settled to a final value. Determining an adequate time for this initial drift to run its course is a science unto itself. Test-equipment manufacturers keep long-term records of various reference ICs they sample from production. IC manufacturers cannot perform a die reduction or a process change without notifying the test-equipment manufacturer. Test companies also buy references from vendors they are not using in production to see whether their data sheets' drift claims are realistic.

Providing an accurate signal chain is difficult, especially in high-impedance systems. One way to handle the problem is to use an analog front end to interface with the sensors in your design. Texas Instruments' LMP91000 analog front end, for example, handles high-impedance inputs and performs signal conditioning and calibration. The company's LMP90xxx and Maxim's MAX1457 family handle resistive-bridge sensors and perform excitation and measurement. ZMDI's ZSI21013 analog front end, like Maxim's parts, performs linearization using an integrated EEPROM. For inductive sensors, you might consider Microchip's MCP2036. Maxim, Analog Devices, and Intersil offer analog front ends for image sensing, and Irvine Sensors' MS3110 capacitance-sensor IC can resolve to capacitances as low as attofarads and has an on-chip EEPROM to store trimming and program settings. The e2v CPIC2.0 for MEMS (microelectromechanical-system) transducers has 30-aF resolution, and austriamicrosystems' AS1716 capacitive-sensor front end senses

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Texas Instruments
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Vishay
www.vishay.com

ZMDI
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automotive-engine knock. Dozens of capacitive-sensor front ends target touch-sensing applications.

If an analog-front-end IC does not meet your needs, your design should provide for self-calibration wherever possible. Place a ground or a system common in the multiplexer and in the reference voltage and send the reference voltage into one of the multiplexer's channels. You may also want to send one or two key analog power-supply voltages into the multiplexer so that your product's software can apply known voltages and the system can measure its own power supply to calibrate out any errors. With an accurate voltage reference and clock, you know voltage and time. With accurate components for these two characteristics, you can derive other quantities, such as current, resistance, and slew rate. By carefully selecting your components, and using factory and field calibrations, you can keep your signal chain honest and trustworthy.**EDN**

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You can reach Technical Editor Paul Rako at 1-408-745-1994 and paul.rako@ubm.com.