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Low Noise Signal Conditioning for Sensor-Based Circuits

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IDEA IN BRIEF

Minimizing system noise in low power, cost conscious designs is critical. To attain the lowest noise floor and best performance from signal conditioning circuitry, designers must understand component level noise sources and account for them when calculating the overall noise of an analog front end—it is critical to read and understand beyond the limited data sheet noise specs in order to achieve high resolution with very small signals. Every sensor has its own noise, impedance, and response characteristics, so matching these to the analog front end is an important part of the design process. There are a number of ways to calculate the noise of a circuit—all of these should start with configuring the signal conditioning circuitry optimally before conducting the noise analysis and calculation. If there is a good SPICE model available for the op amp, using SPICE is the easiest approach.

Accurate signal conditioning and high resolution measurements are no longer limited to industrial or instrumentation applications. Designers of portable consumer electronic equipment also need to minimize system noise. This can be quite challenging due to the small signal voltages found in battery-powered devices. The accuracy of a system depends on its noise floor. To attain the lowest noise floor and best performance from signal conditioning circuitry, designers must understand component level noise sources and account for them when calculating the overall noise of an analog front end.

Some designers believe that choosing the lowest noise components can solve all of their signal conditioning noise issues. This is a good starting point, but data sheets for most IC amplifiers and voltage references used in signal conditioning applications specify noise at a limited number of frequencies. Thus, designers have limited information with which to select parts. They do not know where the component noise comes from and what influences it; whether or not noise changes with respect to time, temperature, and circuit configuration; or if it is necessary to know about the fabrication process before selecting the lowest noise part. With today's low power, cost conscious designs, many systems cannot afford the most expensive parts or those that trade low noise for higher power consumption. This article begins by exploring these topics and provides guidelines for selecting the best components for the design task at hand.

Low noise designs have become important in today's portable gadgets. Generally speaking, noise is any unwanted signal that affects the quality of the useful information. To understand why low noise design is critical, look at a typical signal chain, shown in Figure 1.

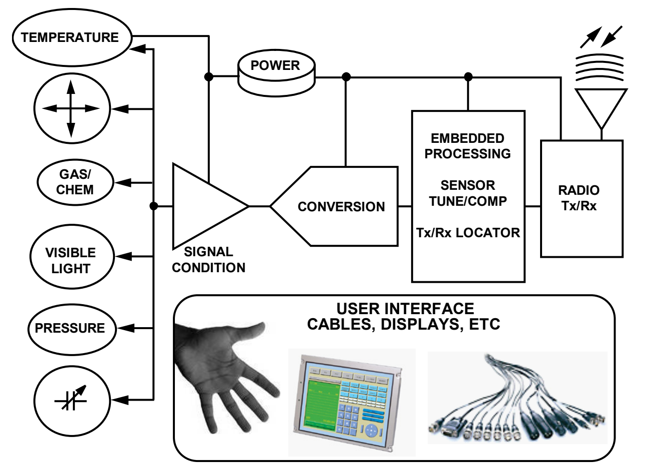


Figure 1. Typical Consumer Signal Chain.

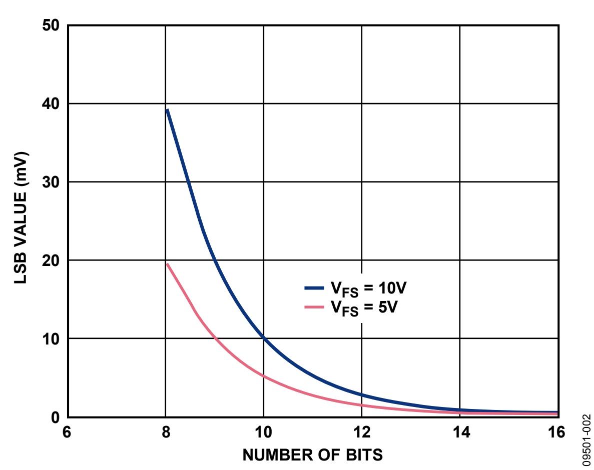


Figure 2. LSB Size Shrinks as Full-Scale Signals Are Reduced.

Popular sensor-based applications have moved toward lower operating supply voltages, (from ±22 V several years ago to ±0.9 V today), shrinking the LSB size while demanding higher precision and accuracy, Figure 2. As an example, the automotive industry has moved from 8-bit systems to 12 bits or higher. This trend has made measurement of the microvolts generated by sensors quite challenging. Imagine a real-world sensor that generates signals of 30 mV max (this is very common). In this case, 1/2 LSB in a 12-bit system is 3.5 μV, so 1 μV of input referred noise from the amplifier used as the analog front end would affect the quality of the measurement.

Signal-to-Noise Ratio

Equally important is keeping the analog front end noise down when driving an ADC. This is critical in order to avoid worsening the signal-to-noise ratio (SNR). The net SNR degradation (in dB) due to the amplifier will be:

$$SNR_{LOSS} = 20\log\left[\frac{N_{ADC}}{\sqrt{N_{ADC}{}^{2} + \frac{\pi}{2} f_{-3\text{dB}} \left(\frac{2.5Ne_n}{FSR}\right)^{2}}}\right] \quad (1)$$

where:

N_{ADC} is the rms noise of the ADC in microvolts (μV).

$f_{-3\,dB}$ is the –3 dB input bandwidth of the ADC in MHz (or the cutoff frequency of the ADC input filter, if used).

N is the noise gain of the amplifier (1 if in unity-gain buffer configuration).

e_n is the equivalent input noise voltage spectral density of the op amp in nV/√Hz.

FSR is the full-scale input span of the ADC (e.g., 5 V for a ±2.5 V range).

A poorly designed signal conditioning circuit degrades SNR and eliminates the benefits of the system's high resolution ADC. For example, Table 1 shows the SNR_{Loss} for an AD7671 16-bit analog-to-digital converter (28 μV rms noise, 9.6 MHz BW, 0 V–5 V input, G = 1) when driven with amplifiers having different noise specs.

Making accurate high resolution measurements depends on the system noise floor. The maximum achievable signal-to-noise ratio is

$$SNR = 10\log\frac{V_{signal\_rms}}{V_{noise\_rms}} \quad (2)$$

Table 1. Higher Amplifier Noise Causes More SNR_{LOSS} for ADC

Amp Noise (nV/√Hz) @ 1 kHz	SNR_{LOSS}
40	17
20	4.6
10	1.7
1	0.02

The system designer's goal is to process small signals generated by the sensor without distorting them. The following sections will address the noise generated by signal conditioning circuits and raise awareness for selecting appropriate parts.

Noise in Signal Conditioning Circuits

Noise can be separated into two distinct categories, extrinsic (interference) and intrinsic (inherent). Electrical and magnetic noise are forms of extrinsic noise. They can be periodic, intermittent, or random. System designers can reduce their effects in a number of ways.

Intrinsic noise can be defined as random processes due to quantum fluctuations inherent in all resistors and semiconductor devices (PN junctions) that create voltages and currents in any application. Noise cannot be completely eliminated. Thermal agitation of electrons and random generation and recombination of electron-hole pairs are examples of inherent noise that IC manufacturers try to reduce with better processes and design techniques.

Noise is usually specified as peak-to-peak (p-p) or rms, and is graphically shown as p-p or spectral noise density, Figure 3. Unlike ac signals, whose power is concentrated at just one frequency, noise power is spread over the entire frequency spectrum. Instantaneous values of noise are unpredictable, but it is possible to predict noise in terms of probabilities. Most noise has a Gaussian distribution.

It is very difficult to read values accurately and consistently from the p-p noise graphs. When noise power density is plotted versus frequency, it provides a visual indication of how power is distributed over frequency. The noise spectral density shows the noise energy at a given frequency, while the rms number gives the rms value over a given bandwidth or time interval. It is always good to know the p-p noise value. Because noise is random, there is always a probability that the voltage *could* exceed the peak-to-peak value. Multiplying the rms noise by 6.6 gives a 99.97% confidence

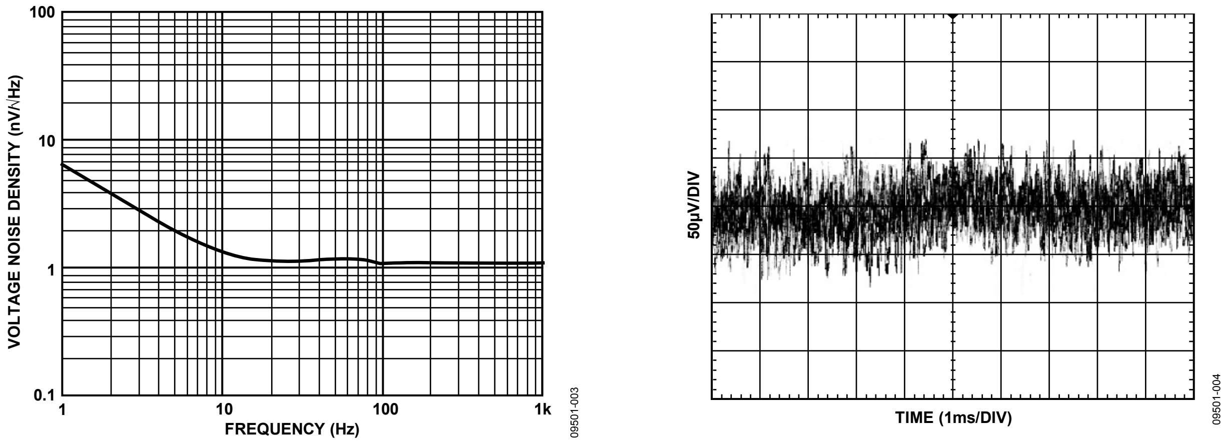


Figure 3. Typical Peak-to-Peak and Voltage Noise Density Graphs.

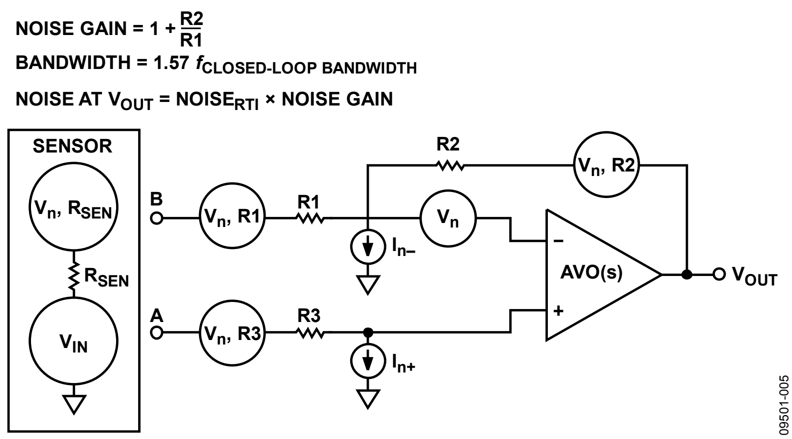


Figure 4. Signal Conditioning Circuit Showing All Noise Sources (Amplifier Is Assumed to Be Noiseless).

that the p-p value will not be exceeded. In ICs, the two most common forms of power density distributions are 1/f and white noise. The quantities of $e_n(f)$ and $i_n(f)$ are noise spectral densities and are expressed in nV/√Hz and pA/√Hz. It is important to specify the frequency band, since noise depends on the measurement bandwidth.

It is also difficult to mathematically characterize amplifier noise at low frequencies due to 1/f, temperature and aging effects, and possibly even popcorn noise (see Noise Types section), but repeated experiments have shown that noise rises at higher temperatures.

Aside from white noise and 1/f noise, other contributors to IC noise are popcorn noise, shot noise, and avalanche noise. In addition to ICs, other components such as the resistors, capacitors, and inductors commonly used in system designs each have their own noise.

Because noise is a probability function, designers need to add uncorrelated noise sources in root-sum-square fashion (rss). This means that adding two noise sources having the same energy only increases the overall noise by √2, or 3 dB. For correlated noise sources, an additional term made up of a correlation factor multiplied by the product of the noise sources will be added into the noise calculation equation.

Various amplifier noise sources, as well as sensor and external component noise sources, are shown in Figure 4. Amplifier noise is modeled by zero impedance voltage generators in series with the inputs and infinite impedance current sources in parallel with the input. Each of these terms varies with frequency and with amplifier type. Both input voltage noise (en) and input current noise (in) can be treated as uncorrelated noise sources added around an ideal "noiseless" amplifier.

$$Noise_{RTI} = \sqrt{BW}\sqrt{Vn^2 + 4KTR3 + 4KTR1[\frac{R2}{R2+R1}]^2 + In_+{}^2R3^2 + In_-{}^2[\frac{R1*R2}{R1+R2}]^2 + 4KTR_2[\frac{R1}{R1+R2}]^2} \quad (3)$$

Total output noise, referred to input (RTI), is comprised of resistor noise and op amp voltage and current noise as shown in Equation 3.

Note that in both inverting and noninverting configurations, noise gain (the amount that noise gets gained up by) is the same: 1 + R2/R1. Capacitors, not shown here but often used in circuits like this, do not generate noise themselves, but the amplifier current noise drops across a capacitor and creates a voltage noise error.

White noise is passed as if the filter were a brick wall type but with a cutoff frequency 1.57 times as large. The number 0.57 accounts for the transmitted noise above f0 (corner frequency of the filter). In amplifier applications, this gradual roll off is defined as f0 = β * ft, where β is the feedback factor and ft is the unity gain crossing. The amplifier passes white noise with a cutoff frequency of 1.57 f0.

As shown, amplifier voltage noise plays a big role in the output noise. Assume that the circuit above is configured for an inverting gain of 1000, using a variety of 10 MHz amplifiers with different noise specs and resistor values as shown. The result of this test is shown in Figure 5. But the amplifier with the lowest noise specified in its data sheet is not always the best for the application. There are other factors to consider when choosing an amplifier.

By knowing the sensor, the designer should be able to determine the operating frequency range (broadband, 1/f…). The designer should then pick an amplifier with the right characteristics. Today's amplifiers have broadband noise in the range of 0.9 nV/√Hz to 60 nV/√Hz.

Understanding the input architecture and the process technology on which the amplifier is manufactured will help in choosing the right amplifier for the job. In the early stages of system design, always think seriously about designing for best noise performance by choosing the right components and limiting the application's bandwidth. Users can then analyze for non-noise requirement such as input impedance, supply current, and gain. If noise requirements are not met, iterate this process. It is always wise to design for low noise rather than trying to reduce noise by shielding, layout, and other techniques.

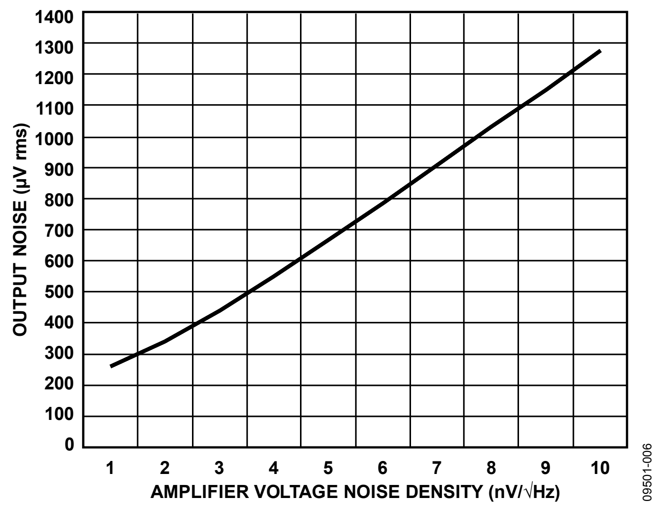


Figure 5. Amplifier Noise Contributes Greatly to the Output Noise of a Signal Conditioning Circuit.

It is important to know that trade-offs had to be made when the amplifier was designed. These might affect the application, so it is important to know how the part was designed and what process is used for fabricating the part. It is not enough to rely on a data sheet specification (x nV/√Hz, for example).

Bipolar op amp noise characteristic is dependent on its quiescent current. What works to minimize e_n (low rb and high Ic) is the opposite of what is good for low i_n. This represents a fundamental tradeoff in bipolar design. A number of parts include super beta or I_b cancellation circuits. These introduce correlated noise. During noise analysis, a correlation constant needs to be introduced to account for this correlated noise. Bias compensated op amps have higher noise current than can be predicted from their bias currents (Ib).

CMOS noise contributors are different in different regions of operation. Process dependencies or design tweaks can be used to get better noise specs, but each has its implications on the application. Flicker noise (1/f) is inversely proportional to the transistor width and length (W × L), so to reduce noise, designers use large geometry input stage transistors. This creates large input capacitances that might become a limiting factor in final applications. CMOS parts have much better current noise compared to bipolar. Current noise density (In) can often be neglected at room temperature, but can be a problem over temperature.

Compared to BJTs, JFETS have low gm, Therefore, FET op amps tend to have a higher voltage noise for similar operating condition. Their voltage noise (e_n) also contains flicker noise, but JFETs have much better current noise than BJTs. Their current noise (I_n) can be neglected at room but might become a problem over temperature, since it will double for every 20 degree temperature increase as the bias current (IB) doubles every 10 degrees. Many successful commercially available JFET op amps have traded voltage noise for input capacitance. Table 2 can be handy when selecting amplifiers. Table 3 shows some popular amplifiers on different processes.

Table 2. Noise performance of different processes

	Bipolar	**CMOS**	**JFET**
Voltage Noise	Best	Good	Better
Current noise	Good	Best	Better
e_n Corner Frequency	Best	Good	Better
I_n Sensitivity to Temperature	Best	Better	Good

Table 3. Three popular amplifier noise specs on different processes

Part Number	**EN (nV/√Hz)**	**IN (pA/√Hz)**	**Fc (Hz)**	**Input**
AD8599	1	1.5	9	Bipolar
AD8655	2.7	0.007	2000	CMOS
AD8610	6	0.005	1000	JFET

Once the sensor and amplifier have been chosen based on the above guidelines, choose components that go around the amplifier. Small resistors are usually better, as they will reduce the effects of the amplifier's current noise. Resistors introduce their own noise that will raise the system's noise floor. Additionally, the resistor noise should not dominate the amplifier noise. In fact, op amp simulation models such as those recently released by Analog Devices do not allow large resistors to be used to set the gain of low noise amplifiers.

Narrowing the measurement bandwidth is another good practice when designing low noise signal conditioning circuits. This can be done using simple single-pole circuits or more complicated multi-pole active filter (see filter tool design on the ADI website).

With today's low power, cost conscious designs, many systems cannot afford the most expensive parts nor can they afford the higher power consumption of low noise parts. To attain the lowest noise floor and best performance from signal conditioning circuitry, designers must understand component level noise sources and account for them when calculating the overall noise of an analog front end. It is critical to read and understand beyond the limited data sheet noise specs in order to achieve high resolution with very small signals.

NOISE TYPES

White Noise (Also Called Broadband Noise)

Flat part of the noise graph, which is the noise floor of the part, Figure 6. It is defined over a frequency and is constant. Squaring both sides gives white noise power, which is proportional to bandwidth, regardless to band location. This is the noise floor of the systems and limiting factor for system resolution.

$$E_N = \sqrt{\int_{f_1}^{f_2} e_n{}^2 df} = e_n\sqrt{f_2 - f_1} = e_n\sqrt{\Delta f} \tag{4}$$

If $f_1 < 1.0f_2$, then it can be approximated as

$$E_N = e_n\sqrt{f_2} \tag{5}$$

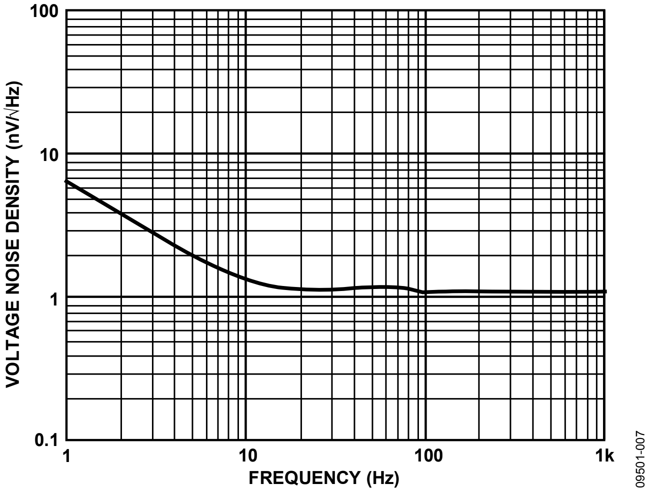


Figure 6. Amplifier White Noise Is the Flat Part of a Typical Noise Graph.

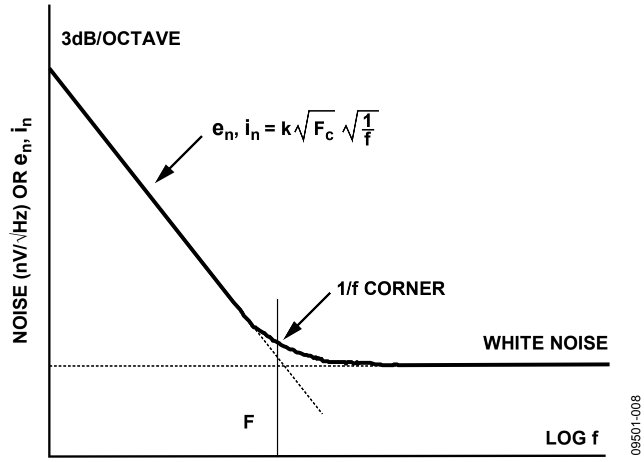


Figure 7. Typical Op Amp Noise Graph Highlighting the 1/f Noise.

1/f Noise (Also Called Pink Noise)

At low frequencies, noise goes up inversely proportional to frequency (1/f term), Figure 7. 1/f noise is always associated with current and is caused by traps, which when current flows, capture and release charge carriers randomly, therefore causing random fluctuation in the current. In BJTs, 1/f noise might be caused by contamination and imperfect surface conditions at the base-emitter junction of a transistor. In CMOS, it is associated with extra electron energy states at the boundary between silicon and silicon dioxide

The 1/f corner frequency (which is really a figure of merit) is a frequency above which the amplitude of noise is relatively flat and independent of frequency. Note that the corner frequency for a voltage noise is different than the corner frequency of a current noise density.

$$en = K\sqrt{f_c}\sqrt{\frac{1}{f}} \qquad (6)$$

$$E_N = en\sqrt{fce\ln\left(\frac{fH}{fL}\right)} \qquad (7)$$

$$I_N = in\sqrt{fci\ln\left(\frac{fH}{fL}\right)} \qquad (8)$$

One characteristic of 1/f is that power content in each decade is equal.

Popcorn Noise (Also Called Burst Noise)

In the early days of IC making, “popcorn noise” was a serious issue that resulted in random discrete offset shifts in a timescale of tens of milliseconds. Today, although popcorn noise can still occasionally occur during manufacturing, the phenomenon is well understood. Popcorn noise is part of 1/f noise and happens at very low frequency. Popcorn noise causes step function voltage changes at the output of an op amp and is mostly caused by transistors jumping erratically between two values of hfe (beta). It is purely a function of process, and badly processed parts have more popcorn noise.

Shot Noise

Occurs whenever current passes through a P-N junction and, of course, there are many junctions on today’s ICs. Barrier crossing is purely random and the dc current generated is the sum of many random elementary current pulses. Shot noise is constant over all frequencies. A current noise which has a uniform power density, it becomes part of white noise.

$$I_n = \sqrt{2qI\Delta f} \qquad (9)$$

Where:

q = Charge on an electron (1.6×10^{-19} coulombs)

I = Current through the junction (in pA)

Δf = Bandwidth in Hz

Schottky Noise

This noise is found in P-N junctions who are operated in reverse breakdown mode and occurs when electrons, under the influence of the strong electric field acquire enough kinetic energy to create additional electron-hole pairs by collision against the atoms of crystal lattice. These pairs can create other pairs in avalanche fashion. The resulting current consists of randomly distributed noise spikes flowing through the reverse biased junction. Schottky noise is similar to shot noise and requires current flow; but it is much more intense than shot noise, making Zener diodes famously noisy.

Resistor Noise

Found in all resistors and caused by thermal shakeup of electrons in resistors which cause movements of charge, causing a voltage to appear. Resistor noise becomes part of white noise and is constant over all frequencies. One can use the formula below to find the noise value of a resistor. As a rule of thumb, 1 kΩ has 4 nV/√Hz of noise. It is worth mentioning that doubling the resistance increases the noise by 3 dB (4× resistance = doubling the noise, i.e., 6 dB). Carbon composition and thick film resistors have excess noise over and above calculated thermal noise.

$$E_N = \sqrt{4kTRB} \qquad (10)$$

Where:

k = Boltzmann's constant (1.374×10^{-23} J/°K)

T = Absolute temperature (°K), T = °C + 273°

R = Resistance (W)

B = Bandwidth (Hz)

$4kT = 1.65 \times 10^{-20}$ W/Hz

There are three ways to reduce this noise: 1) pick small resistors, which increases power consumption; 2) control the temperature (cool the temp); 3) reduce measurement bandwidth.

DESIGN PROCESS

As analog-to-digital and digital-to-analog converter resolutions increase and power supply voltages decrease, the size of a least significant bit becomes smaller. This makes signal conditioning tasks more difficult. As the signal size gets closer to the noise floor, both external and internal noise sources, including Johnson, shot, broadband, flicker, and EMI, must be addressed.

Noise sources, which are generally uncorrelated, are combined in a root-sum-square (RSS) fashion:

$$E_{N\_total} = \sqrt{{E_{N1}}^2 + {E_{N2}}^2} \qquad (11)$$

Correlated noise sources such as input bias current cancellation, on the other hand, must be combined in an RSS fashion with an added correlation factor:

$$E_{N\_total} = \sqrt{{E_{N1}}^2 + {E_{N2}}^2 + 2CE_{N1}E_{N2}} \qquad (12)$$

Figure 8 illustrates all of the noise sources found in a typical signal conditioning circuit, along with a general equation that can be used for inverting, noninverting, difference, and other common configurations.

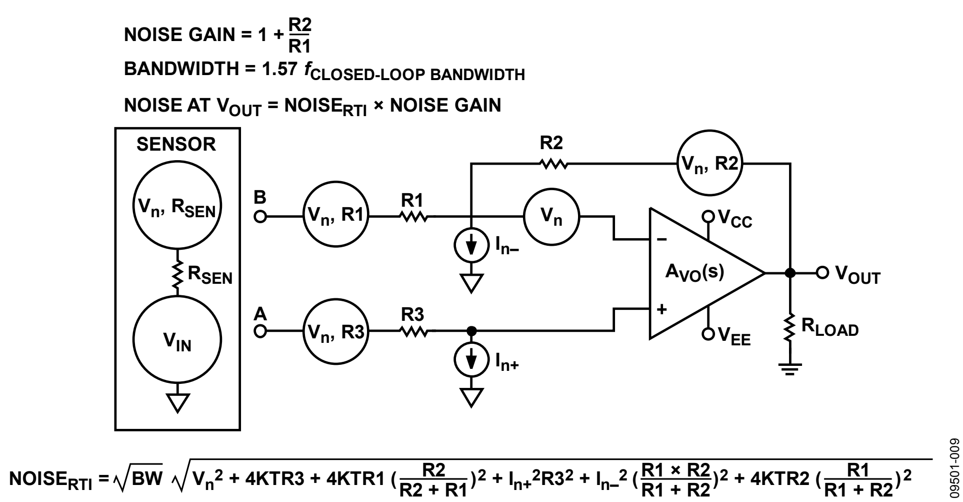
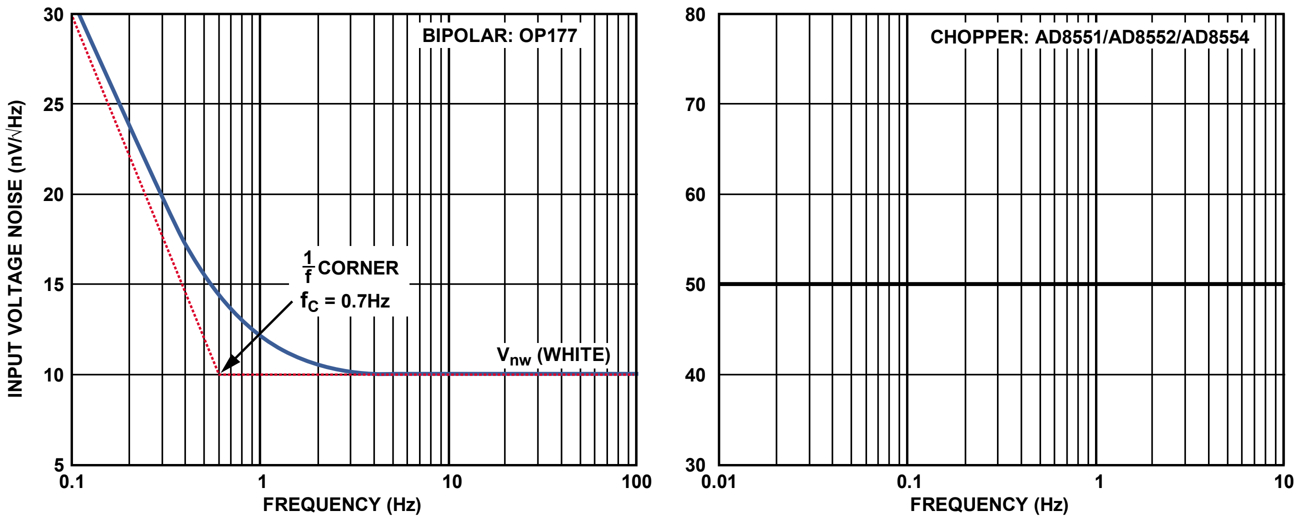


Figure 8. Noise Sources Include the Op Amp's Input Voltage Noise and Input Current Noise, Plus Johnson Noise from the External Resistors.



NOISE BANDWIDTH	BIPOLAR (OP177)	CHOPPER (AD8551/AD8552/AD8554)
0.1Hz TO 10Hz	0.238µV p-p	1.04µV p-p
0.01Hz TO 1Hz	0.135µV p-p	0.33µV p-p
0.001Hz TO 0.1Hz	0.120µV p-p	0.104µV p-p
0.0001Hz TO 0.01Hz	0.118µV p-p	0.033µV p-p

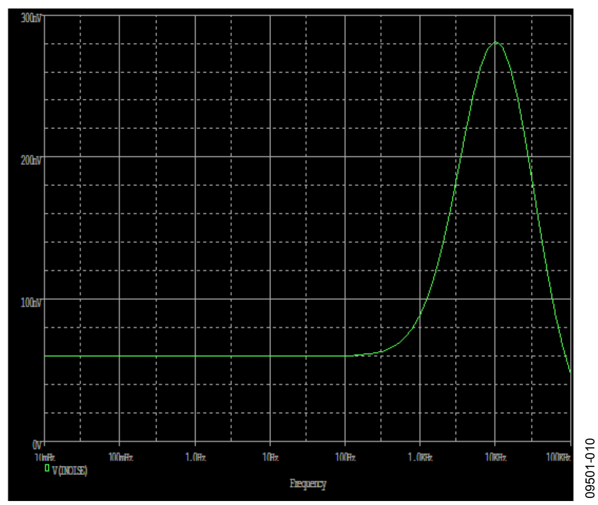


Figure 9. Standard Amplifiers, such as Analog Devices' OP177, Exhibit 1/f Noise at Low Frequencies (Top Left). Auto-Zero (Chopper) Amplifiers, such as Analog Devices' AD8551/AD8552/AD8554, Have No 1/f Noise (Top Right). PSpice Correctly Models the Behavior of the AD8638 Auto-Zero Amplifier (Bottom Right).

The Right Design Approach

Starting with a sensor and its characteristic noise, impedance, response, and signal level, achieving the lowest referred-to-input (RTI) noise will optimize the signal-to-noise ratio (SNR).

Instead of solving gain and power requirements first, and then struggling with noise issues, it is more effective to approach the problem with a low noise focus. This is an iterative process. Start by considering the region of operation for the amplifier: broadband or 1/f. Next, design for the best noise performance by selecting appropriate active components. Surround the amplifier with the passive components and limit the bandwidth. Then analyze the non-noise requirements, such as input impedance, supply current and open-loop gain. If the noise spec is not met, continue this process until you have an acceptable solution.

Op Amp Selection

In some cases, an op amp with 22 nV/√Hz broadband noise may be better than one that specifies 10 nV/√Hz. If the sensor operates at very low frequencies, an amplifier with low 1/f noise might be best. Standard amplifiers, such as the OP177 from Analog Devices, have a noise spectral density that looks like the graph shown top left in Figure 9. Auto-zero amplifiers, on the other hand, continuously correct any errors that appear at their inputs over time and temperature. Since 1/f noise approaches dc asymptotically, the amplifier also corrects this error. The graph shown top right in Figure 9 shows how first-generation auto-zero amplifiers do not exhibit 1/f noise, making them useful for low frequency sensor signal conditioning. Second generation auto-zero amplifiers, shown bottom right of Figure 9, feature lower wideband noise (22 nV/√Hz). The unusual PSpice macro-model correctly simulates the amplifier's voltage noise, showing the elimination of 1/f noise.

Rail-to-Rail Inputs

For low voltage designs, a rail-to-rail (RR) output and input may be appropriate. As the common-mode input goes from one rail to the other, one differential input pair takes over as the other differential pair stops working. Offset voltages and input bias currents can change suddenly, causing distortion as shown in Figure 10. For low noise design, question the need for the RR input feature.

To address this problem, op amps such as Analog Devices' AD8506, use an internal charge pump to eliminate input voltage crossover distortion. If not designed correctly, the charge pump will produce noise that will appear at the output potentially causing a problem if the noise falls in the frequency band of interest. Use a spectrum analyzer on the output pin to make sure that the amplitude of the clock is much lower than that of the signal.

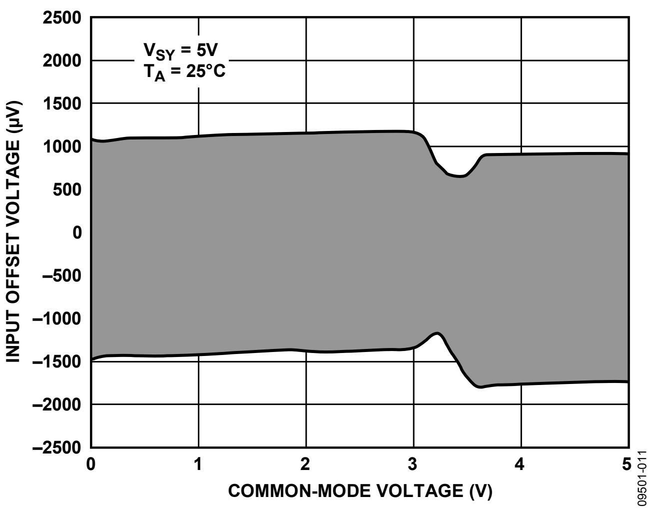


Figure 10. The Input Offset Voltage of a Rail-to-Rail Amplifier Can Change Dramatically as the Common-Mode Input Voltage Changes.

Bias Current Cancellation

Newer bipolar op amps use a technique to partially cancel the input bias current. This technique can add uncorrelated or correlated current noise. For some amplifiers, the correlated noise can be larger than the uncorrelated component. With Analog Devices' OP07, for example, adding an impedance-balancing resistor can improve the overall noise. Table 4 compares two widely used Analog Devices' op amps the OP07 that trades higher voltage noise for lower current noise, vs. the OP27.

Choose three to four parts from the available low noise devices. Consider the process technology. Look for special design techniques such as auto-zeroing, chopping, and bias current cancellation. Look at die size photos for input transistor area, remembering that large input transistors produce low noise, but large input capacitance. CMOS and JFET amplifiers have much lower current noise than bipolar devices. Low noise designs use low valued resistors, so the amplifier output drive must be large enough to drive heavy loads.

Table 4. OP07 and OP27 Voltage and Current Noise

Parameter	Conditions	OP07E	OP27E	Units
Input Offset Current		0.5	7	nA
Input Bias Current		±1.2	±10	nA
Input Noise Voltage	0.1 Hz to 10 Hz	0.35	0.08	µV p-p
Input Noise Voltage Density	f = 1 kHz	9.6	3	nV/√Hz
Input Noise Current Density	f = 1 kHz	0.12	0.4	pA/√Hz

Passive Component Selection

After selecting the amplifier, surround it with the appropriate resistors and capacitors. These, too, have noise. Figure 11 shows the effect of using the wrong resistor values. The output noise goes up as the resistors, used for setting the gain, go up. In all three situations, the gain is 1000.

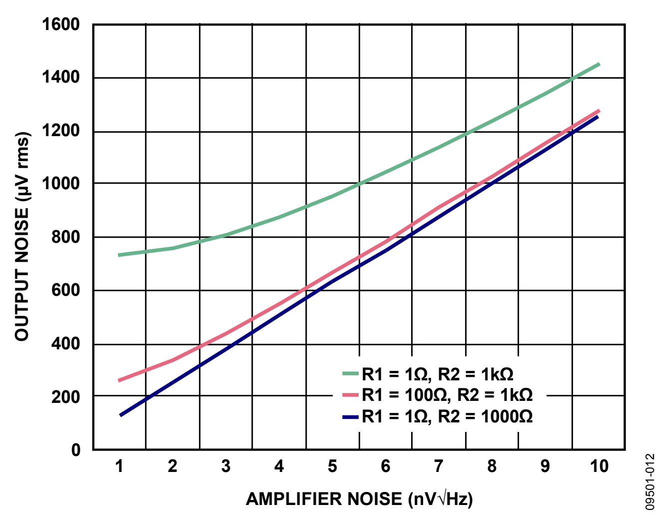
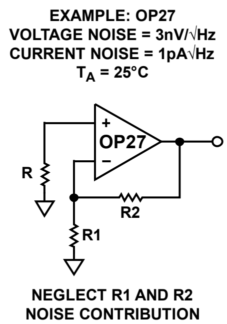


Figure 11. Use Low Value Resistors to Maintain Low Output Noise.



RTI NOISE (nV/√Hz)
DOMINANT SOURCE IS HIGHLIGHTED

CONTRIBUTION FROM	VALUES OF R		
	0	3kΩ	300kΩ
AMPLIFIER VOLTAGE NOISE	3	3	3
AMPLIFIER CURRENT NOISE FLOWING IN R	0	3	300
JOHNSON NOISE OF R	0	7	700

09501-013

Figure 12. Voltage Noise Dominates with Small Resistors; Johnson Noise Dominates with Medium Values; Current Noise Dominates with Large Resistors.

Understanding the sensor's characteristics is important. Neglecting the noise contribution of R1 and R2 and focusing on the noise of the source impedance, R, Figure 12 shows that the voltage noise dominates with small values of R, the Johnson noise dominates with medium values, and the current noise dominates with large values. Therefore, sensors with low output impedance should use small resistors and op amps with low voltage noise.

In addition to resistors, capacitors are also used for compensation and noise reduction. Reactive components do not add any noise, but noise current flowing through them will develop noise voltages that enter your calculations. In summary, it is important to use low impedances around the amplifier to minimize the effects of current noise, thermal noise, and stray pickup of EMI.

Bandwidth Selection

After choosing an amplifier and the associated resistors and capacitors, the next step is to design for best bandwidth (BW). Be careful not to overdesign for a wide bandwidth. The bandwidth should be wide enough to pass the fundamental frequencies and important harmonics, but no wider. Select an amplifier that has enough BW and follow it by an RC filter. The amplifier itself is also a single pole filter. Amplifiers and resistors have noise over each Hertz of BW so the greater the BW, the greater the output noise and the lower the SNR.

Figure 13 shows the effects of the amplifier's BW vs. noise for the same circuit configuration as before, but using amplifiers with different BW. To limit the added noise, the BW should be narrowed as much as possible.

To narrow the bandwidth, use an RC filter after the sensor. This can create loading problems that can be overcome by using a buffer as shown in Figure 14.

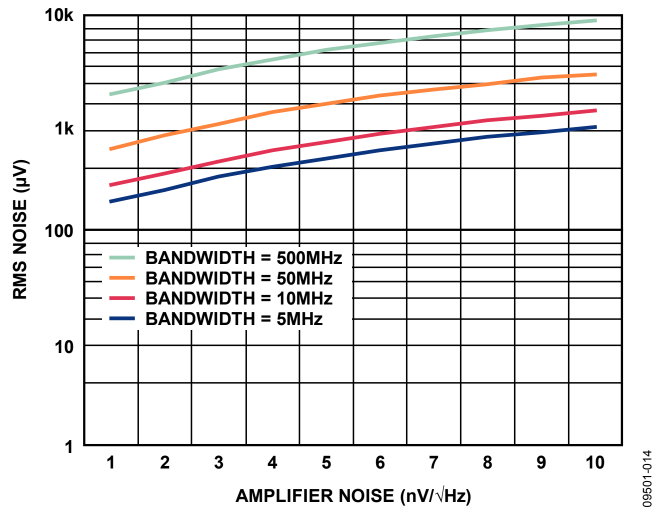


Figure 13. Output Voltage Noise Increases with Increasing Amplifier Bandwidth.

An amplifier and ADC having the specs and configuration shown (amplifier BW 350 MHZ) will have 166 µV rms noise. Adding an RC filter after the op amp, creating an effective BW of 50 MHz, reduces the noise to 56 µV rms.

Narrowing the BW by using the correct RC will greatly improve the SNR as shown, but the resistor itself can add noise. A better way to reduce the BW is by using the circuit shown top right of Figure 15. This places the resistor inside the op amp's feedback loop, reducing its effect by 1 + loop gain. Don't forget to reduce power supply noise from the signal path by using adequate decoupling caps at the supply pins.

After going through these steps, review the other system requirements. Below are some examples:

Do the selected components meet the other target specs?

Does the amplifier require dual supplies?

Is there a positive supply?

Does the amplifier consume too much power?

Are the components too expensive?

If necessary, return to Step 1 and repeat the process.

Every sensor has its own noise, impedance, and response characteristics, so matching these to the analog front end is critical. A well-defined low noise design process is needed to overcome many challenges in today's applications and to get the best SNR. This iterative process will produce a signal conditioning solution that is most suitable for today's challenging applications.

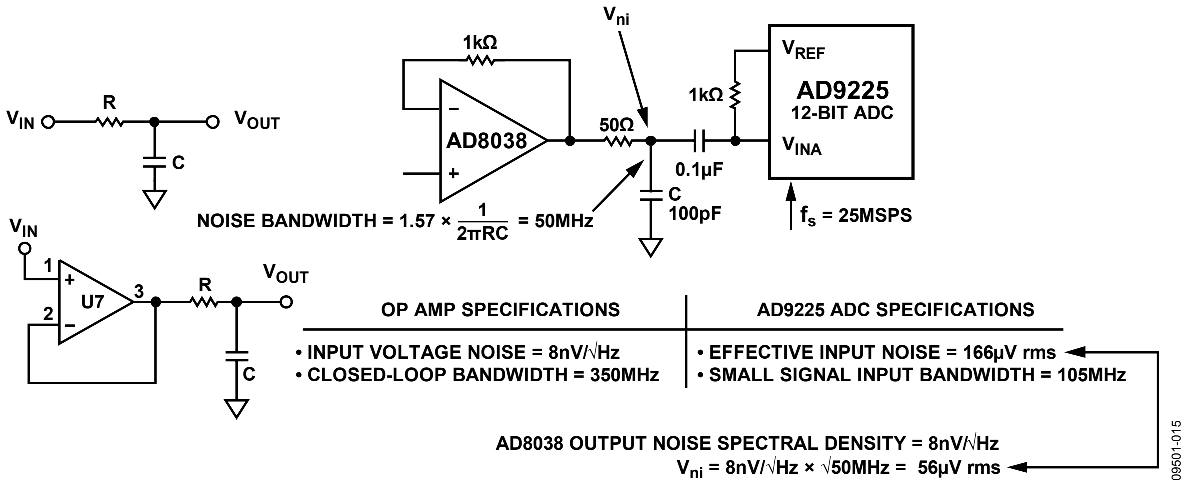


Figure 14. Add a Buffer Between the Sensor and Filter to Avoid Loading Problems.

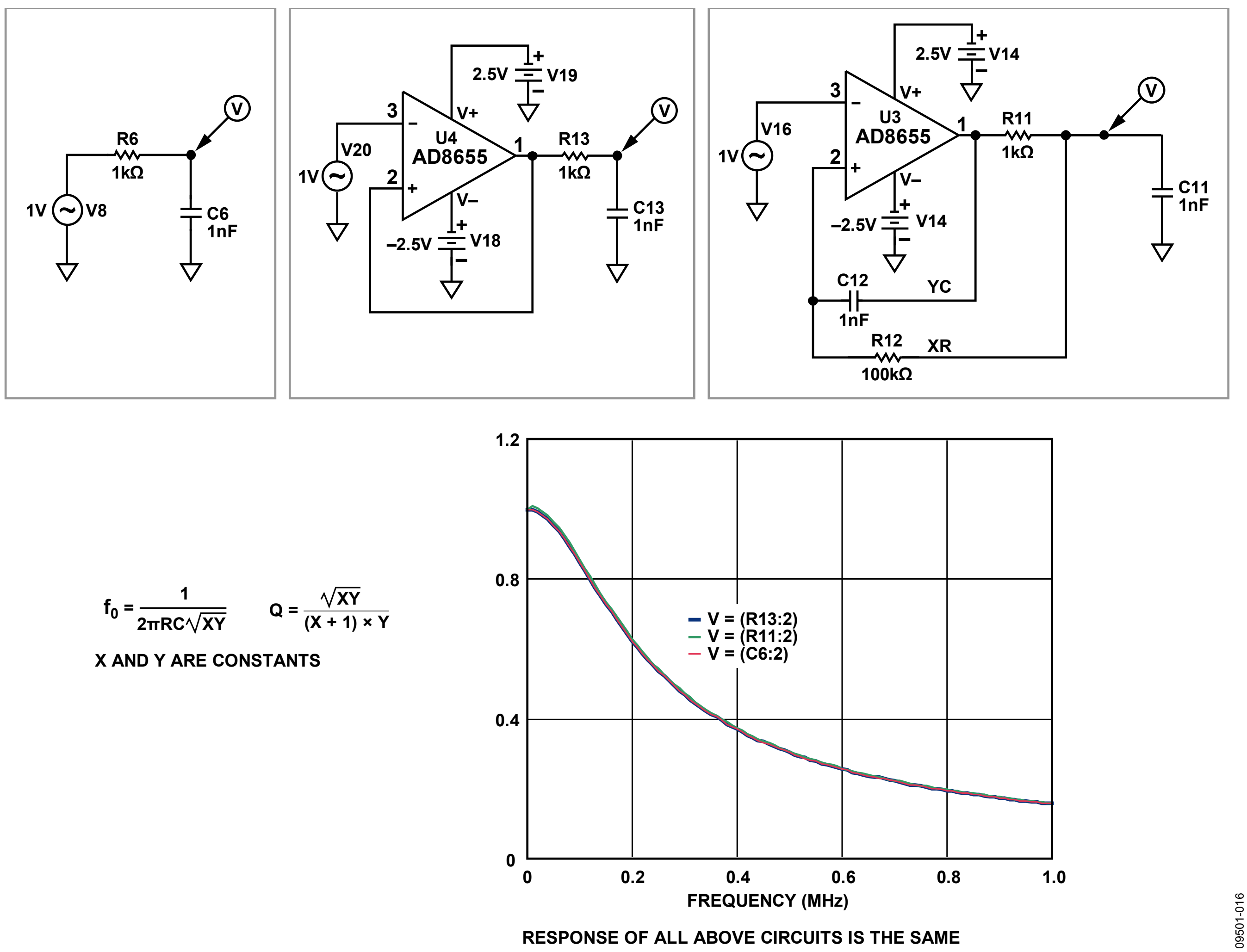


Figure 15. Simple RC Filter (a). Buffer Reduces Loading (b). Putting Resistor Inside Feedback Loop Minimizes Noise (c).

NOISE CALCULATION

The word "noise" suggests a range of electrical disturbances. The source of some of these disturbances is inherent to analog circuit components such as amplifiers and converters. To know the lowest signal level a circuit can reliably process, a designer has to calculate the circuit noise. This can be complex, as it involves deriving and solving many equations. Before writing equations, one has to identify and account for uncorrelated and correlated noise sources. We will examine a special situation where both correlated and uncorrelated noise exist, and offer optimization suggestions for the circuit. In this way, a designer can build circuits that function effectively with optimum noise performance.

To obtain the best noise performance, one has to limit the bandwidth and calculate noise over the noise effective bandwidth (NEB). One bandwidth limiting scheme uses a simple low-pass filter in or after the signal conditioning stage. Noise bandwidth is wider than the signal bandwidth regardless of filter order of the system. A signal has fallen to 0.707 times of its original value at its –3 dB frequency (f0), but noise bandwidth for a first-order filter extends to 1.57 f0. This means that white noise is passed as if the filter were a brick wall type with a cutoff freq 1.57 times as large. Multiplication factor for higher order (N) low-pass filters are shown in Table 5.

Table 5. Multiplication factors give noise equivalent bandwidth for filters of order N.

N	NEB
1	1.57 f0
2	1.11 f0
3	1.05 f0
4	1.025 f0

$$NEB = \frac{1}{A^2_{v\_\max}} \int_0^\infty |A_v(f)|^2\, df \qquad (13)$$

To calculate the noise equivalent bandwidth of an arbitrary circuit, such as the band-pass filter shown in Figure 16, a designer could use Equation 13, which integrates the magnitude of the signal gain over frequency, and divides it by maximum signal gain.

An easier way to calculate the circuit noise is to use simulation software such as PSpice. This band-pass filter has cut-off frequencies of (1/2 π × R3*C1) and (1/2π × R1 ×C21). It is important to have an accurate op amp model that models the voltage and current noise densities. The process of noise calculation is the same as hand calculation, but the software does the data crunching.

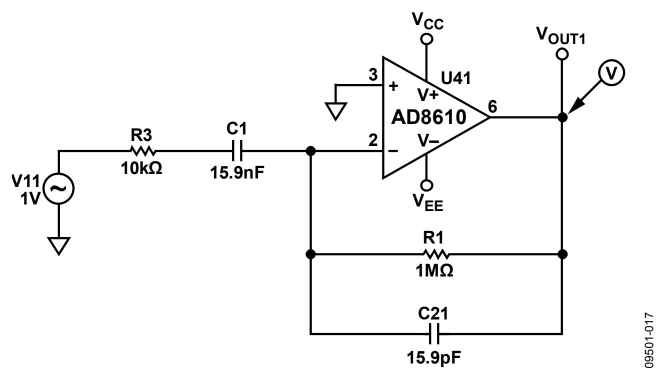


Figure 16. Band-Pass Filter.

To find NEB, select "AC sweep" from the "analysis setup" popup menu and click on the "noise enabled" button. The first step is to find the maximum gain, as shown Figure 17.

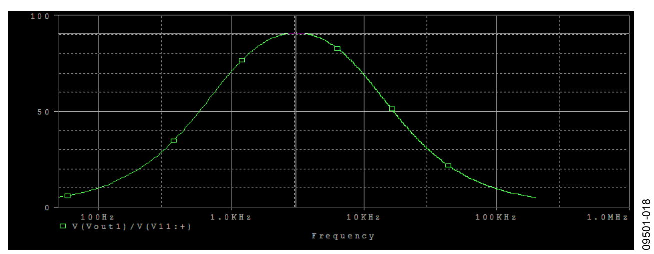


Figure 17. Maximum Gain of Circuit Shown in Figure 16.

Next, the summation operators can be used to find NEB as shown in Figure 18. The NEB is where the upper part of the graph flattens out, roughly 170 kHz in this example.

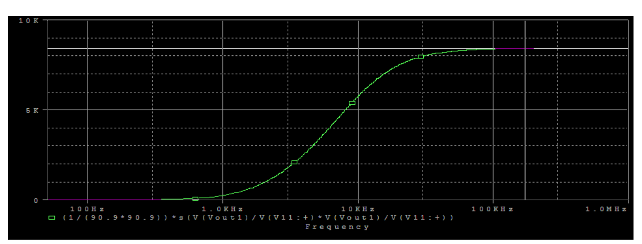


Figure 18. Noise Equivalent Bandwidth (NEB) of Circuit Shown in Figure 16.

PSpice also calculates other pieces of information that a designer needs to study. For example, it has already gathered the necessary data to display the input and output noise graphs for the circuit shown in Figure 16. This is done by selecting "enable noise" in the setup menu. The output noise result is shown in Figure 19.

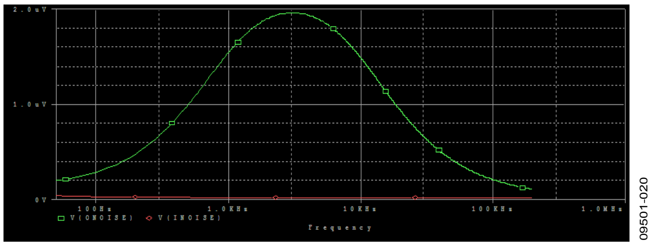


Figure 19. Output Noise of Circuit Shown in Figure 16.

Knowing the noise bandwidth allows a designer to find the noise over this bandwidth by using probe and the s operator, as shown in Figure 20. Place one cursor at low frequency (e.g., 1 Hz). Right click and place a second cursor at 170 kHz (circuit's noise bandwidth). The noise over this bandwidth can be read from "dif" in probe cursor.

Figure 20. Total Output Noise of Circuit Shown in Figure 16 Integrated Over NEB.

The above approach assumes that all of the circuit's noise sources are correctly identified and are configured for optimum noise performance. PSpice does not know the correct configuration and component values, which must be optimized by the circuit designer. Is the above circuit optimized for noise? Are all noise sources identified and accounted for? The op amp's process technology and design techniques affect its noise performance. Analog IC designers use internal circuit tricks to reduce the bias current of bipolar transistors using bias current cancellation. These tricks can introduce a correlated component to the current noise density specification. Table 6 shows the noise specification for an ultralow noise, low distortion op amp, such as the AD8599 from Analog Devices.

Table 6. AD8599 noise specification.

Noise Performance	Conditions	Typ	Max	Unit
Peak-to-Peak Noise (e_n p-p)	0.1 Hz to 10 Hz	76		nV p-p
Voltage Noise Density (e_n)	f = 1 kHz	1.07	1.15	nV/√Hz
	f = 10 Hz		1.5	nV/√Hz
Correlated Current Noise	f = 1 kHz	2.0		pA/√Hz
	f = 10 Hz	4.2		pA/√Hz
Uncorrelated Current Noise	f = 1 kHz	2.4		pA/√Hz
	f = 10 Hz	5.2		pA/√Hz
Total Harmonic Distortion + Noise (THD + N)	G = 1, $R_L \geq 1$ kΩ, f = 1 kHz, V_{RMS} = 1 V	−120		dB
Channel Separation (CS)	f = 10 kHz	−120		dB

Users of these ICs can improve the ac and dc performance of their circuits if they configure them correctly. As shown in Figure 21, balancing the amplifier inputs allows noise performance to be optimized. For example, dc performance can be optimized by placing resistor R5—equal to the parallel combination of R1 and R4—from the noninverting input to ground. This commonly used technique will cancel the input bias current of the op amp and reduce the overall dc error.

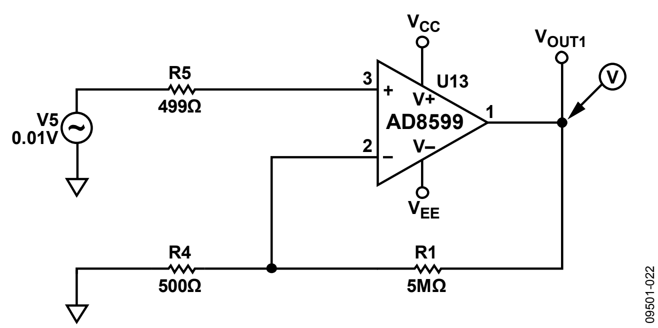


Figure 21. DC Optimized Circuit.

The above circuit is not optimized for noise, however. In order to do this, one has to identify all noise sources and write noise equations as explained above. Figure 22 identifies the noise sources; Equation 14 is the noise equation.

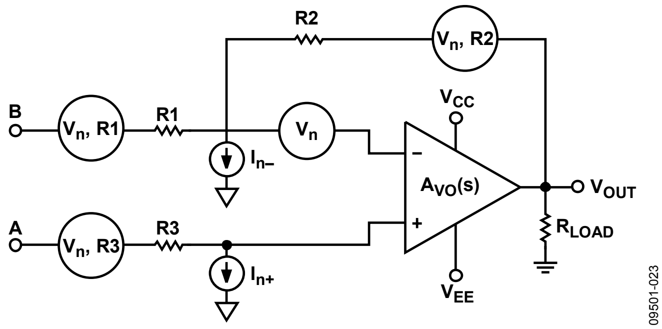


Figure 22. Noise Sources of Circuit in Figure 21.

$$NOISE_{RTI} = \sqrt{BW}\sqrt{Vn^2 + 4KTR3 + 4KTR1\left(\frac{R2}{R2+R1}\right)^2 + In_+{}^2R3^2 + In_-{}^2\left(\frac{R1\times R2}{R1+R2}\right)^2 + 4KTR2\left(\frac{R2}{R1+R2}\right)^2} \quad (14)$$

PSpice can be used to calculate the total noise of the circuit after NEB is found. Noise from 1 Hz to 15 kHz is shown in Figure 23.

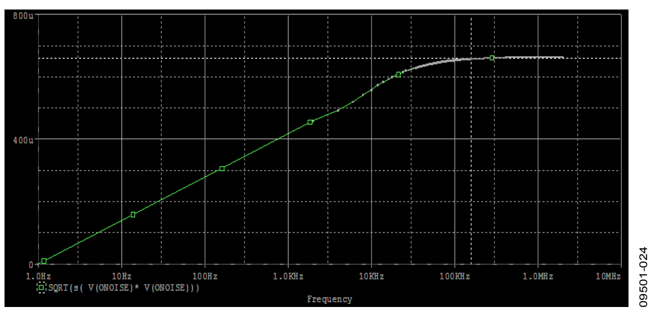


Figure 23. Output Noise of Circuit in Figure 21.

How do we balance the op amp's inputs to get the best noise performance? This is shown in Figure 24 where the inputs are balanced for both ac and dc parameters. Note that the resistor values have changed, although the noise gain is the same (1001) and current noise density sees equivalent resistance when flowing out of the amplifier input pins.

How is this circuit improved over the previous solution for noise? In order to answer this question, once again all noise sources are identified, and the appropriate equation is written to calculate the total noise at the output. This is shown in Figure 25; note that the contribution of balancing resistor Rb is captured in Equation 15.

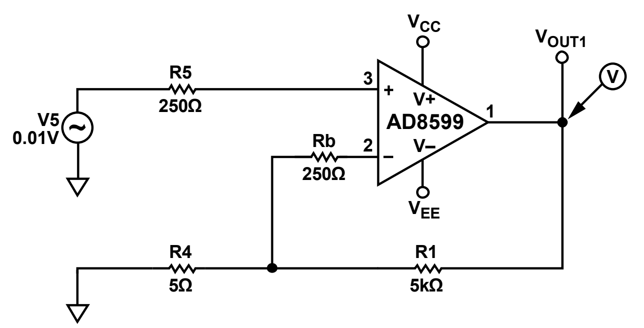


Figure 24. AC and DC Optimized Circuit.

$$(NOISE_{RTO})^2 = \left(1+\frac{R2}{R1}\right)^2 \times \left(Vn^2 + (4KTR3)^2 + In_+{}^2R_3{}^2 + (4KTRb)^2\right) + \left(\frac{R2}{R1}\right)^2 \left((4KTR1)^2\,In_-{}^2Rb^2\right) + In_-{}^2R2^2 + (4KTR2)^2 \quad (15)$$

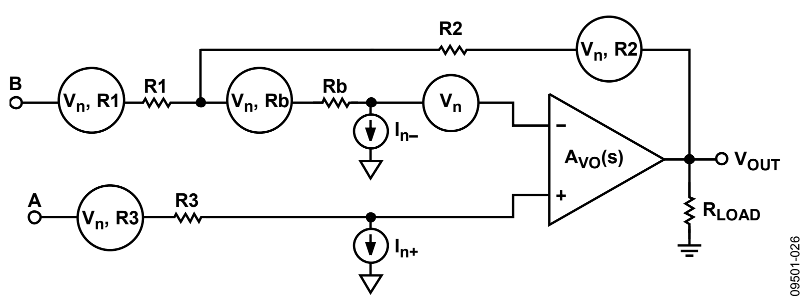


Figure 25. Noise Sources of Circuit in Figure 24 Identified.

A side by side comparison of the results from Figure 21 and Figure 24 is shown in Table 7. The total output noise difference between the two configurations may not seem that large, as small resistors were used for balancing, but the difference becomes much more of a problem if larger resistors are used for R5 in Figure 21.

Table 7. Side by side comparison of Figure 21 and Figure 24

Component	Unbalanced	Balanced
Vn^2	1.14^{-18}	1.14^{-18}
$(4KTR3)^2$	7.99^{-18}	3.99^{-18}
$(4KTR2)^2$	8.00^{-15}	8.00^{-15}
$(4KTRb)^2$	0.00^{00}	3.99^{-18}
$(4KTR1)^2$	8.00^{-18}	4.00^{-18}
$In_-{}^2 Rb^2$	0.00^{00}	2.49^{-19}
$In_-{}^2 R2^2$	1.43^{-18}	$5.61E^{-19}$
$In_+{}^2 R3^2$	1.44^{-12}	1.00^{-12}
NEB	15.7 kHz	15.7 kHz
Total Noise(RTO) µV	560	484

Are there other easy ways to calculate the noise of a circuit aside from the two approaches presented so far? Another approach in noise calculation of a given circuit is given in an example of a popular application circuit, namely an op amp configured as buffer driving an ADC.

Using the voltage noise density graph of the Analog Devices' AD8675 (broadband noise = 2.8 nV/rt-Hz) as an example, Figure 26, breakup the NEB into two regions (low frequency and high frequency). Note that the NEB for AD8675 configured as a noninverting unity gain buffer is the op amp's unity gain bandwidth (10 MHz).

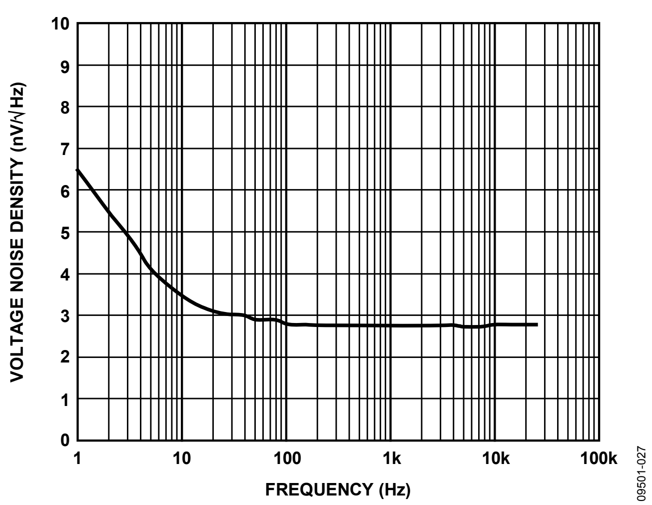


Figure 26. AD8675 Noise Density vs. Frequency.

All op amp data sheets have a voltage noise density graph that can be used to find the low-frequency noise (p-p noise) and the corner frequency. This information and Equation 16 can be used for noise calculation at low frequencies:

$$V_{n,rms}(F_L, F_H) = noise_{Broadband}\sqrt{F_c \ln\frac{f_H}{f_L} + (F_H - F_C)} \quad (16)$$

Using Equation 16 with values for F_L = 0.1 Hz, F_H = 70 Hz, corner frequency F_C = 25 Hz results in the low frequency noise contribution of 40.45 nV rms, shown in Equation 17.

$$\begin{aligned} &V_{n,rms}(F_L, F_H) \\ &= noise_{Broadband}\sqrt{25\ \text{Hz} \ln\frac{70\ \text{Hz}}{0.1\ \text{Hz}} + (70\ \text{Hz} - 25\ \text{Hz})} \\ &= 40.45\ \text{nV} \end{aligned} \quad (17)$$

Calculation of the noise over the high frequency region (over the flat region of the noise or white noise area) is shown in Equation 18.

$$\begin{aligned} V_{white\_noise} &= V_{noise\,@\,70Hz-10MHz} \\ &= V_{noise\_density\,@\,1KHz} * \sqrt{BW} \\ &= 2.8\ \text{nV} * \sqrt{10000000 - 70} \\ &= 8.854\ \text{uV}_{\text{RMS}} \end{aligned} \quad (18)$$

Add the noise values for the two regions in an rms fashion, shown in Equation 19, to obtain a total noise of 8.86 µV rms.

$$\begin{aligned} &V_{noise\_RTO} \\ &= \sqrt{(V_{\frac{1}{f}noise})^2 + (V_{white\_noise})^2} \\ &= 8.86\ \text{uV}_{\text{RMS}} \end{aligned} \quad (19)$$

How effective is this solution? How accurate is the approximation? How low a signal level can this circuit reliably process? This is possible to test by looking at the SNR, shown in Equation 20.

$$SNR_{opamp} = 20 * \log(\frac{Vout_{rms}}{V_{noise\_RTO}})$$
$$= 20\log(\frac{Vfs_{rms}}{V_{noise\_RTO}}) \quad (20)$$
$$= 20\log(\frac{\frac{20\ V}{2\sqrt{2}}}{8.86\ \text{uV}}) = 122\ \text{dB}$$

The low frequency noise of the amplifier is negligible (the AD8675 has a very low corner frequency), so the total SNR of this solution can be calculated using only the white noise contribution. This solution is good for up to 20 bits. This amplifier degrades the SNR of a 16-bit ADC such as Analog Devices AD7671 (SNR = 90 dB) by very little, as shown in Equation 21.

$$SNR_{total}$$
$$= -20\log\sqrt{10^{-SNR_{opamp}/10} + 10^{-SNR_{ADC}/10}} \quad (21)$$
$$= -20\log\sqrt{10^{-122/10} + 10^{-90/10}} = -89.99\ \text{dB}$$

There are a number of ways to calculate the noise of a circuit; a few were shown in this article. But all of these methods should start with configuring the signal-conditioning circuitry optimally before conducting the noise analysis and noise calculation. If there is a good PSpice model available for the op amp, using SPICE is the easiest approach. If not, then one of the other two approaches, using noise density graph approach or pen and paper calculation approach using Equation 13, are the alternatives.

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10. Seminar: Noise Optimization in Sensor Signal Conditioning Circuits, Part 1.
11. Seminar: Noise Optimization in Sensor Signal Conditioning Circuits, Part 2.

RESOURCES

For online seminars on this and related subjects, visit www.analog.com/seminars.

Products Mentioned in This Article

Product	Description
AD7671	16-Bit 1 MSPS Bipolar PulSAR® ADC
AD8506	Dual, 20 µA Maximum, Rail-to-Rail I/O, Zero Input Crossover Distortion Amplifier
AD8599	Dual, Ultralow Distortion, Ultralow Noise Op Amp
AD8675	36 V Precision, 2.8 nV/√Hz Rail-to-Rail Output Op Amp
OP07	Ultralow Offset Voltage Operational Amplifier
OP177	Ultraprecision Operational Amplifier
OP27	Low Noise, Precision Operational Amplifier

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