Application Report
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PGA309 Noise Filtering

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ABSTRACT

The PGA309 programmable gain amplifier generates three primary types of noise: broadband noise, noise from the instrumentation amplifier auto-zero circuit, and noise from the Coarse Offset auto-zero circuit. Noise at the PGA309 output can be reduced by limiting the bandwidth with a simple filter. This application note describes how to select the filter components in order to get the desired bandwidth, and how to mathematically estimate the amount of output noise based on the circuit configuration. Components that improve RFI and EMI immunity are also described.

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1 Selecting Components for the Output Filter

The circuit shown in Figure 1 illustrates how the output amplifier can be used to create a simple single pole filter. The capacitor C_F in parallel with the internal feedback resistor RFO forms the filter. Table 1 lists the values of RFO for different gain settings. Table 1 also lists the nearest standard capacitor value for C_F to obtain bandwidths of 100Hz, 1kHz, and 10kHz. The C_F value required to obtain bandwidths not listed in Table 1 can be calculated as shown in Example 1. In addition, this configuration allows for a 10nF RFI/EMI capacitor, C_L, to be directly between the output and ground of a module.

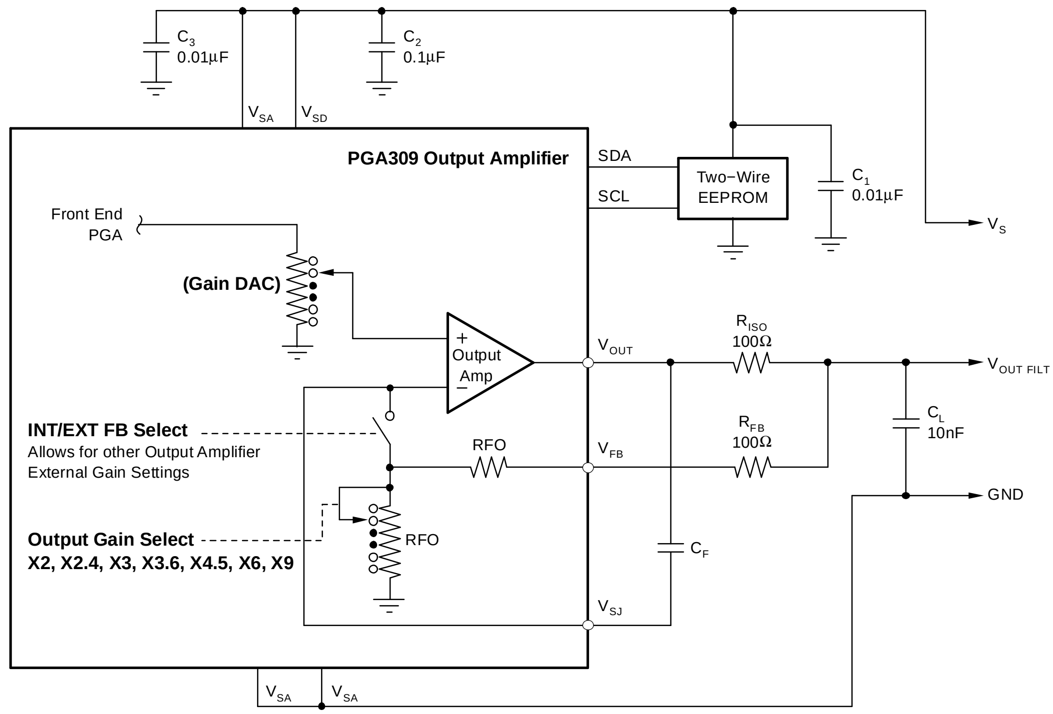

Figure 1. PGA309 with Simple Single Post Filter

Table 1. PGA309 Low Noise Filter Values at Different Gains

DESIRED BANDWIDTH	OUTPUT AMP GAIN	RFO (kΩ)	C_F COMPUTED (F)	C_F STANDARD
100Hz	2	18	8.842*E–08*	0.091μF
100Hz	2.4	21	7.579*E–08*	0.075μF
100Hz	3	24	6.631*E–08*	0.068μF
100Hz	3.6	26	6.121*E–08*	0.062μF
100Hz	4.5	28	5.684*E–08*	0.056μF
100Hz	6	30	5.305*E–08*	0.051μF
100Hz	9	32	4.974*E–08*	0.047μF
	.			
1kHz	2	18	8.842*E–09*	9100pF
1kHz	2.4	21	7.579*E–09*	7500pF
1kHz	3	24	6.631*E–09*	6800pF
1kHz	3.6	26	6.121*E–09*	6200pF
1kHz	4.5	28	5.684*E–09*	5600pF
1kHz	6	30	5.305*E–09*	5100pF
1kHz	9	32	4.974*E–09*	4700pF
10kHz	2	18	8.842*E–10*	910pF
10kHz	2.4	21	7.579*E–10*	750pF
10kHz	3	24	6.631*E–10*	680pF
10kHz	3.6	26	6.121*E–10*	620pF
10kHz	4.5	28	5.684*E–10*	560pF
10kHz	6	30	5.305*E–10*	510pF
10kHz	9	32	4.974*E–10*	470pF

Example 1. Calculation to Select C_F Value

For this example, we want to design a circuit with a gain of 4.5 and a bandwidth of 3kHz. When the gain is set to 4.5, the feedback resistor is equal to RFO = 28kΩ. The value of C_F is computed as shown:

$$C_F = \frac{1}{2\pi \cdot BW \cdot RFO} \tag{1}$$

$$C_F = \frac{1}{2\pi \cdot (3kHz) \cdot (28k\Omega)} = 1.895nF \tag{2}$$

Use a standard 2nF value resistor.

2 Understanding the Noise Spectrum of Auto-Zero Amplifiers

When considering the noise generated by the PGA309, it is important to keep in mind that it uses auto-zero amplifiers in the programmable gain instrumentation amplifier (PGIA). The auto-zero technique has some interesting effects on the noise spectrum of an amplifier. One beneficial effect of the auto-zero architecture is that it eliminates 1/f noise (flicker noise). Typically, it accomplishes this at the cost of increasing the overall broadband noise. For applications where the bandwidth can be limited, the overall output noise will typically be lower for auto-zero topologies. Figure 2 illustrates the spectrum of the PGA309 (with no 1/f noise).

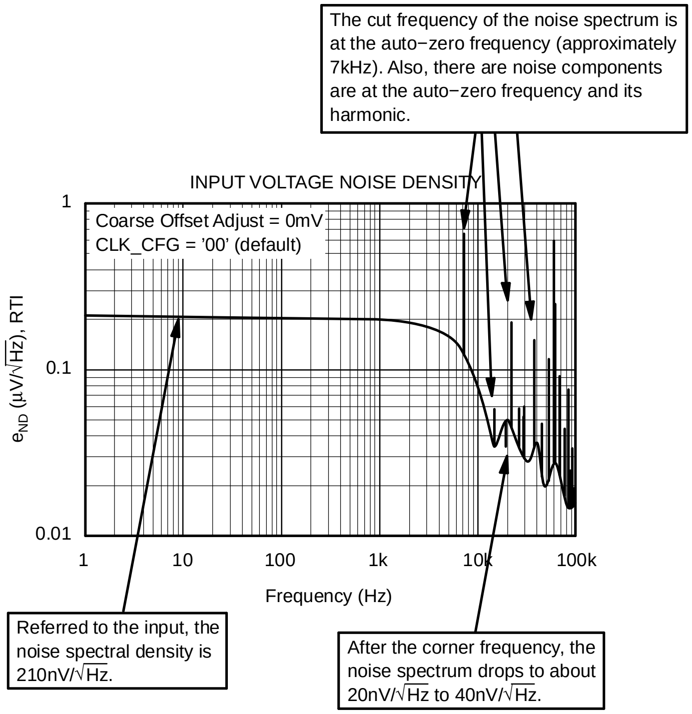

Figure 2. PGA309 Noise Spectrum

The auto-zero technique also shapes the noise spectrum in other ways. The noise spectrum for the PGA309 is a flat 210nV/√Hz from 0Hz to approximately 8kHz. The corner frequency of the noise spectrum is set by the auto-zero frequency. For the PGA309, the auto-zero frequency is between 7kHz and 8kHz. After the corner frequency, the noise spectrum drops to about 20nV/√Hz to 40nV/√Hz. Typically, there will be noise components at the auto-zero frequency and at harmonics of the auto-zero frequency. For an auto-zero frequency of 8kHz, you will see noise components at 8kHz, 16kHz, 24kHz, 40kHz, 56kHz, and at other harmonics in 8kHz multiples.

The PGA309 also has a Coarse Offset Digital-to-Analog Converter (DAC) that is used to compensate for the large initial offset of the sensor. When the Coarse Offset is not being used, the noise is dominated by the flat broadband (210nV/√Hz) noise, and the magnitude of the auto-zero clock harmonics is not a factor. The Coarse Offset DAC, however, has a different auto-zero scheme that has feed-through which may need to be considered. The Coarse Offset DAC has an auto-zero frequency that is half of the auto-zero frequency of the PGIA (typically, 3.5kHz to 4kHz). Figure 3 shows the noise spectrum of the PGA309 with the output of the Coarse Offset DAC set to maximum.

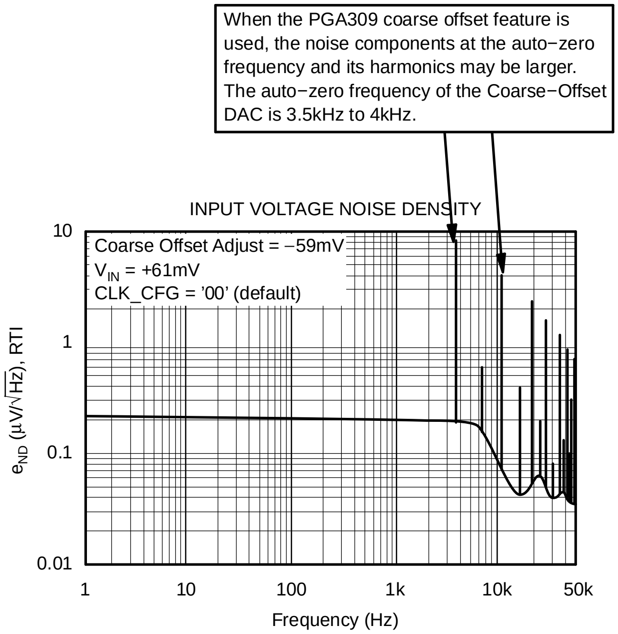

Figure 3. PGA309 Noise Spectrum with Maximum Coarse Offset (–59mV)

3 Estimating PGA309 Noise Output for a Given Design

The noise output on the PGA309 is a factor of gain, bandwidth, and amount of coarse offset used. To minimize output noise, you should set your bandwidth to the smallest level that will work for your specific application. Also, in many cases, it is possible to minimize the coarse offset by using the Zero DAC to compensate for the large initial offset of the sensor. A good way of understanding the trade-off between the Coarse Offset setting and Zero DAC is to use the PGA309 Gain Calculator software tool. This calculator can be downloaded via the PGA309 product folder on the TI web site, under *Software Tools*. It is described in detail in the PGA309EVM User's Guide.

The first step to determine the noise output of the PGA309 is to estimate the broadband noise of the PGA309. In order to perform this calculation, you need to know the gain and bandwidth requirement for the particular design. Then, you will calculate the output peak-to-peak noise. Section 3.1 reviews how to compute the output peak-to-peak noise based on the broadband spectrum noise.

3.1 Computing the Output Peak-to-Peak Noise Based on the Broadband Spectrum

In general, the total root mean squared (RMS) noise referred to the input of an amplifier can be computed by integrating the spectral noise density curve. In most cases, however, there are some simple formulas that can be used to simplify this computation. Figure 4 shows the PGA309 noise spectral density with a simple 1kHz filter superimposed on it. For this example, only the noise inside the 1kHz filter is integrated to get the total noise. There are two regions of the graph that affect the result. The region from 0Hz to 1kHz is rectangular; consequently, it lends itself well to a simple formula (*area = length x width*). The region beyond 1kHz depends on the type of filter used, and thus a table of correction factors K_n is developed based on the filter type. The correction factor effectively converts the filter to a *brick wall* filter so that the entire noise spectrum is rectangular (see Figure 5 and Table 2).

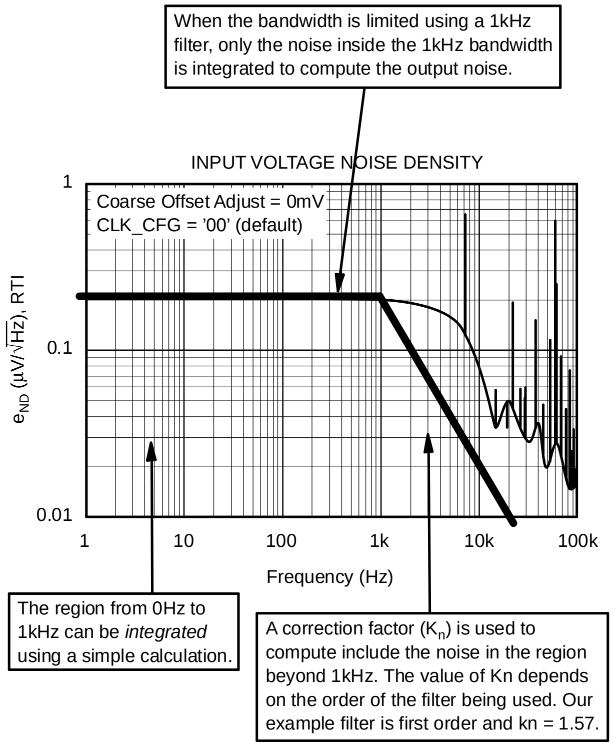

Figure 4. PGA309 Noise Density (1kHz Filter Superimposed)

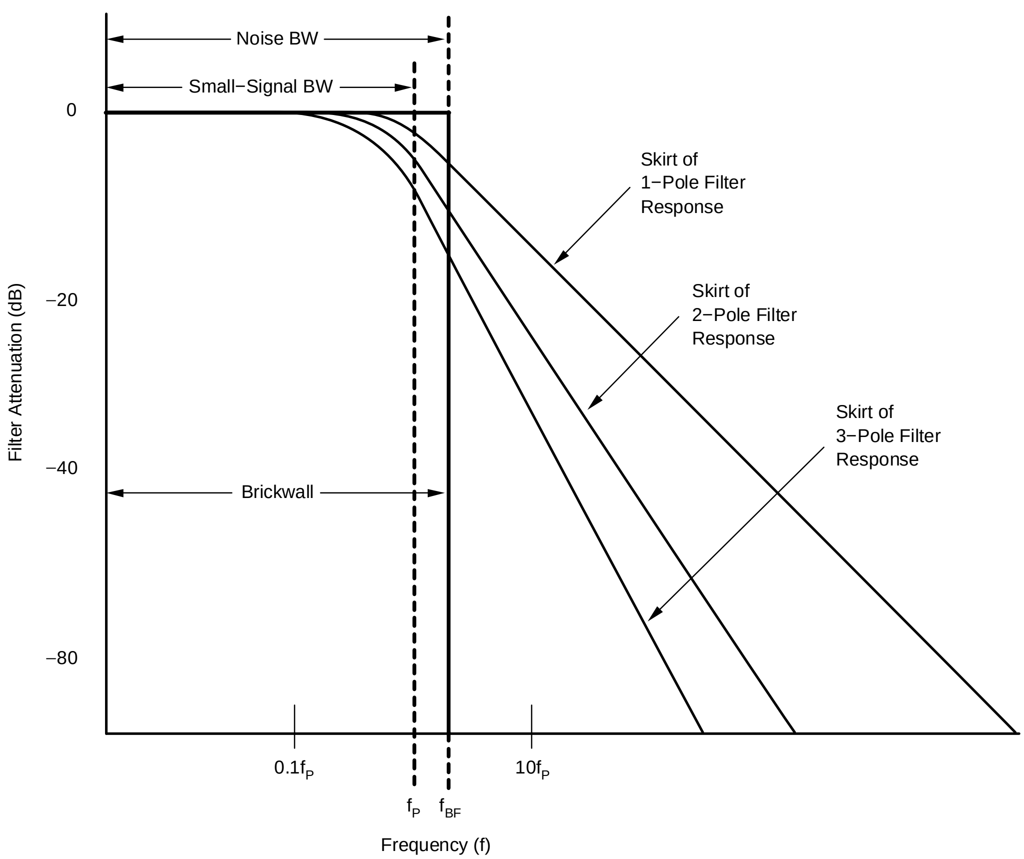

Figure 5. Low-Pass Filter *Brick Wall* Filter Equivalents

Table 2. Conversion From Standard Filter to *Brick Wall* Filter

NUMBER OF POLES IN FILTER	K_n AC NOISE BANDWIDTH RATIO
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

Example 2 in Section 3.2 illustrates how the noise calculation is performed. It should be emphasized, however, that the noise computed by integrating the spectral density curve is an RMS quantity. Most users are interested in the peak-to-peak noise. This noise has a normal distribution, and therefore, the peak-to-peak noise output can be estimated. Typically, the (RMS value x 6) is a good estimate of the peak-to-peak distribution. This practice is used because there is a probability of 0.3% that the peak-to-peak noise will exceed this level at a given instant in time. This factor is sometimes called the *crest factor*. Some engineers use different crest factors depending on whether they want to be more or less conservative with their estimates. Table 3 lists several crest factors and the associated probability that the signal will have a larger amplitude at a given instant in time.

Table 3. Crest Factors Used to Convert RMS Noise to Peak-to-Peak Noise

PEAK-TO-PEAK AMPLITUDE	CREST FACTOR	PROBABILITY OF HAVING A LARGER AMPLITUDE (%)
2 × RMS	2	32
3 × RMS	3	13
4 × RMS	4	4.6
5 × RMS	5	1.2
6 × RMS	6	0.3
7 × RMS	7	0.05

3.2 Example 2: General Formulas for Computing Noise from a Broadband Source

$$V_{noise\_broadband} = Gain \cdot Noise\_Density \cdot \sqrt{BW \cdot K_n} \quad (3)$$

$$V_{noise\_peak\_to\_peak} = 6 \cdot V_{noise\_broadband} \quad (4)$$

Where:

- **Gain** = Gain_of_PGIA × GAIN_DAC × Output_Amp_Gain
  Gain is the total gain of the PGA309
- **Noise Density** = 210nV/√Hz from 0Hz to 8kHz
- **BW** = PGA309 Bandwidth. The bandwidth can be adjusted by using the appropriate value of C_F as discussed in Section 1.
- **K_n** = the *brick wall* filter multiplier to include the skirt effects of a low-pass filter. This factor is selected from Table 2, based on the type of filter that is used in the particular application.

For our example design, we will choose:

$$Gain = (128) \cdot (1.0) \cdot (9) = 1152 \quad (5)$$

This is the maximum gain for the PGA309 (worst-case noise).

$$BW = 1.0kHz \;\; \text{Typical bandwidth} \quad (6)$$

$$K_n = 1.57 \;\; \text{This value is used because } C_F \text{ forms a first-order filter.} \quad (7)$$

The noise output is then calculated:

$$V_{noise\_broadband} = 1152 \cdot \left(210nV/\sqrt{Hz}\right) \cdot \sqrt{(1.0kHz) \cdot (1.57)} = 29mV_{RMS} \quad (8)$$

$$V_{noise\_peak\_to\_peak} = 6 \cdot (0.029V_{RMS}) = 174mV_{PP} \quad (9)$$

3.3 Computing the Output Peak-to-Peak Noise Using the Broadband Spectrum When Bandwidth is Greater than Auto-Zero Frequency

The method described in Section 3.1 works well when the filter bandwidth is less than the auto-zero frequency (7kHz and 8kHz). In cases where the bandwidth is greater than the auto-zero frequency, it becomes more difficult to estimate the noise because the spectral noise density of the PGA309 begins to roll off. (See Figure 6.) Table 4 lists measured results for several different configurations. These measured results provide an approximation of expected noise for wide bandwidth configurations.

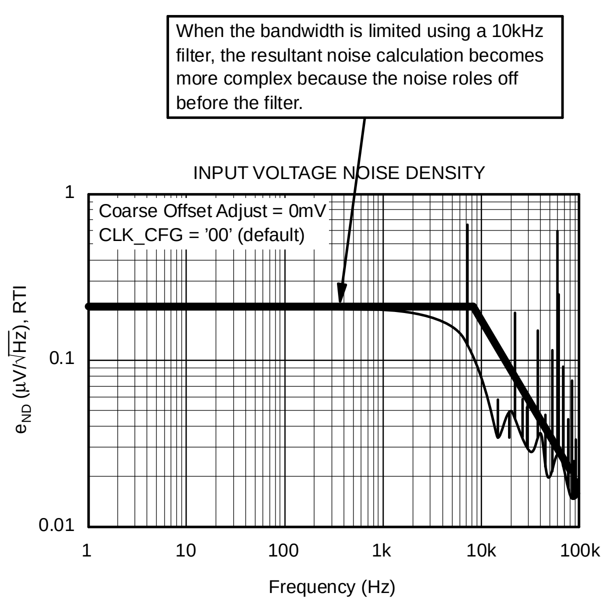

Figure 6. PGA309 Noise Density (10kHz Filter Superimposed)

Table 4. Summary of Measured Results[(1)]

FILTER	COARSE OFFSET	OUTPUT NOISE RMS	OUTPUT NOISE CALCULATED (Example 1)	OUTPUT NOISE PEAK-TO-PEAK (CALCULATED FROM RMS SCOPE)[(2)]
100Hz	None	$3.7mV_{RMS}$	$2.88mV_{RMS}$	$22mV_{PP}$
100Hz	Max (–48mV)	$8.7mV_{RMS}$		$52mV_{PP}$
1kHz	None	$9mV_{RMS}$	$9.12mV_{RMS}$	$54mV_{PP}$
1kHz	Max (–48mV)	$12.5mV_{RMS}$		$75mV_{PP}$
10kHz	None	$17.8mV_{RMS}$	$29mV_{RMS}$[(3)]	$106mV_{PP}$
10kHz	Max (–48mV)	$42.1mV_{RMS}$		$252mV_{PP}$
None	None	$26.3mV_{RMS}$		$157mV_{PP}$
None	Max (–48mV)	$65.3mV_{RMS}$		$391mV_{PP}$

(1) All measurements made with Gain = 1125, V_{REF} = 3.4V. For other gains, compute the output noise using this equation: V_{NOISE} = (Gain)(Measured_Output_Noise)/1125
(2) Crest factor = 6.
(3) Not accurate because of noise roll-off.

3.4 Effect on PGA309 Coarse Offset Auto-Zero Feed through on Noise

The PGA309 can compensate for the initial large offset of a sensor by using its Coarse Offset DAC. The Coarse Offset DAC uses the auto-zero technique (its auto-zero frequency is 3.5kHz to 4kHz). For large values of coarse offset, the auto-zero clock feed-through can be the dominant noise source. Since the noise generated by the auto-zero feed-through is not broadband noise, there is no simple formula to estimate this noise. The easiest way to get an approximate noise output for this effect is to examine the measured results. (See Table 4.) Keep in mind that the measured results will include both the broadband noise and the auto-zero feed-through. As a rule of thumb, the effects of auto-zero feed-through from coarse offset can double the noise from the PGA309 when coarse offset is set to maximum.

3.5 What to Expect on an Oscilloscope

When the coarse offset is not used or set to a small level, broadband noise will dominate. This noise appears to be a random signal (or white noise) on the oscilloscope. (See Figure 7.) When coarse offset is set to a larger level, the auto-zero clock feed-through dominates. This signal looks like a noisy square wave with a frequency of 3.5kHz to 4kHz; see Figure 8.

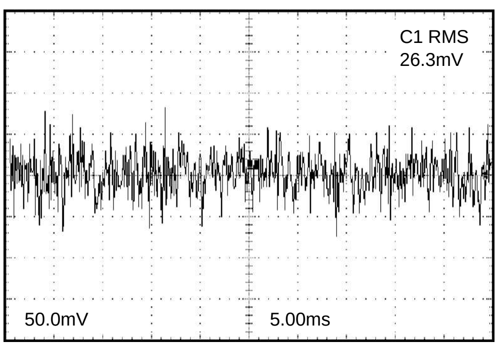

Figure 7. Broadband (White) Noise, Coarse Offset = 0V

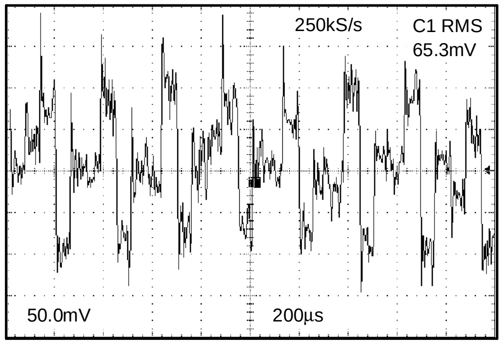

Figure 8. Noise with Maximum Coarse Offset

4 RFI and EMI

C_L, R_{FB} and R_{ISO} are used to prevent emission and reception RFI and EMI from the PGA309. These components are especially important if the PGA309 is being connected via cable to a measurement system. R_{FB} and R_{ISO} also protect against incorrect wiring faults. C1, C2 and C3 are decoupling capacitors that keep the digital signals used to communicate to the EEPROM out of the analog. Figure 9 illustrates noise that you can see if you have not properly decoupled the PGA309; the noise glitches correspond to the edges of the SCL signal.

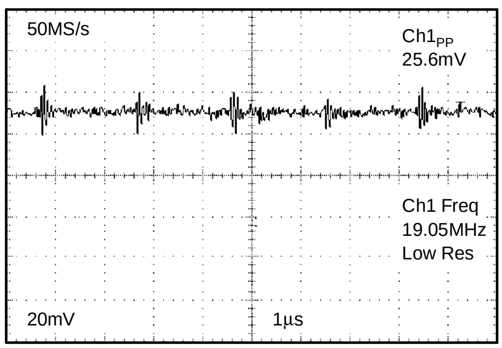

Figure 9. Noise Generated with Improperly Decoupled Digital Source

Appendix A Measurement Results

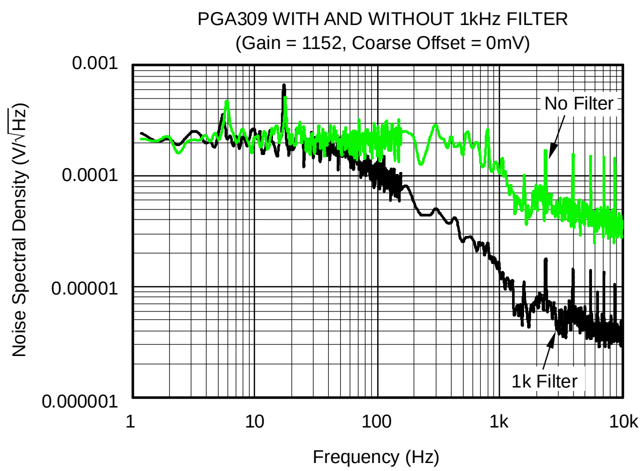

Figure A-1. Noise with 100Hz Filter, No Coarse Offset

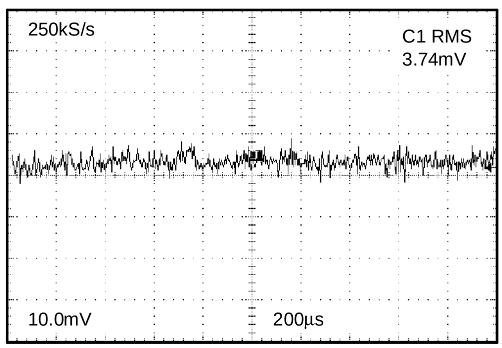

Figure A-2. Noise Measurement

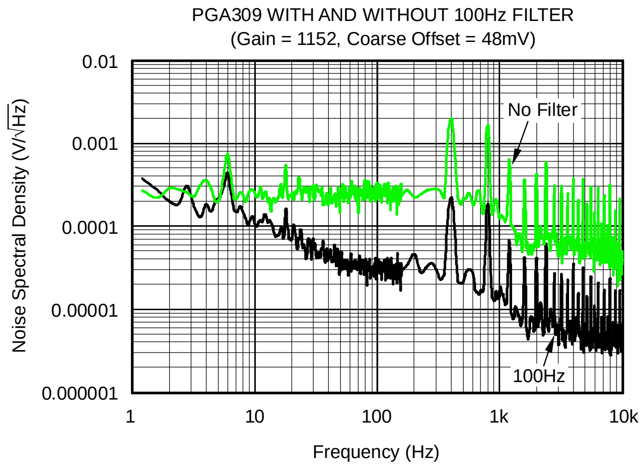

Figure A-3. Noise with 100Hz Filter, Maximum Coarse Offset

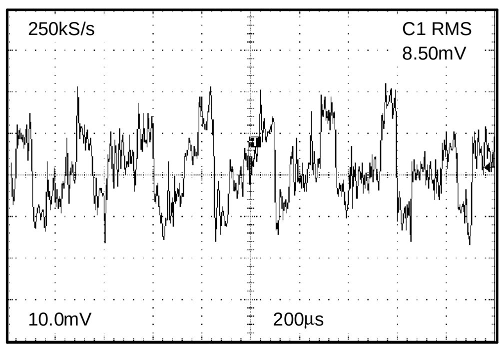

Figure A-4. Noise Measurement

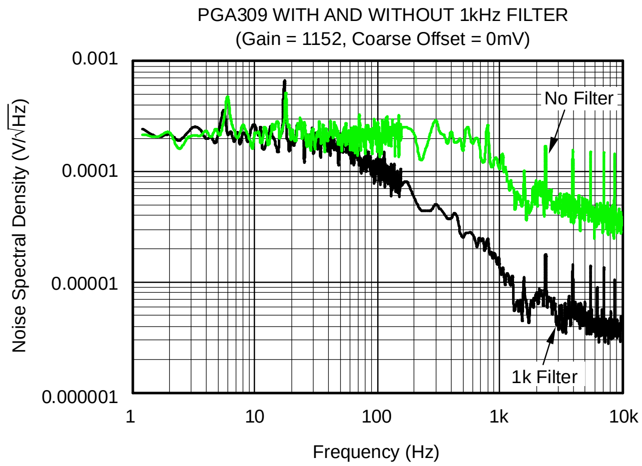

Figure A-5. Noise with 1kHz Filter, No Coarse Offset

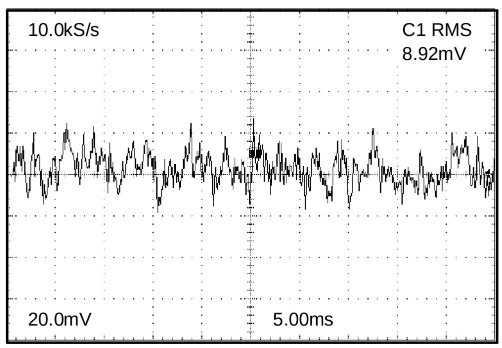

Figure A-6. Noise Measurement

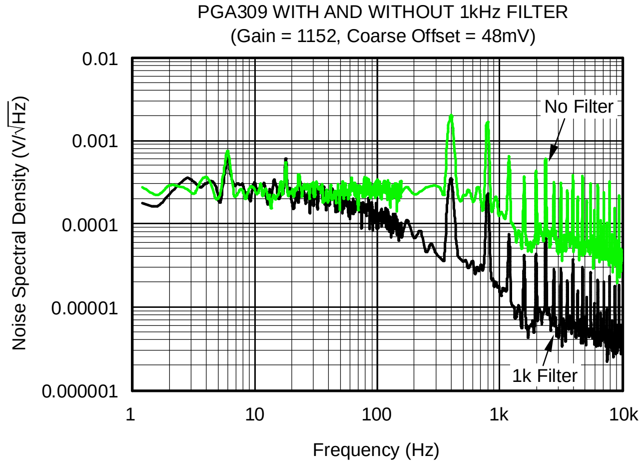

Figure A-7. Noise with 1kHz Filter, Maximum Coarse Offset

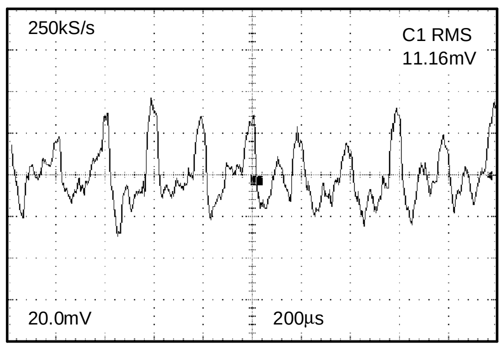

Figure A-8. Noise Measurement

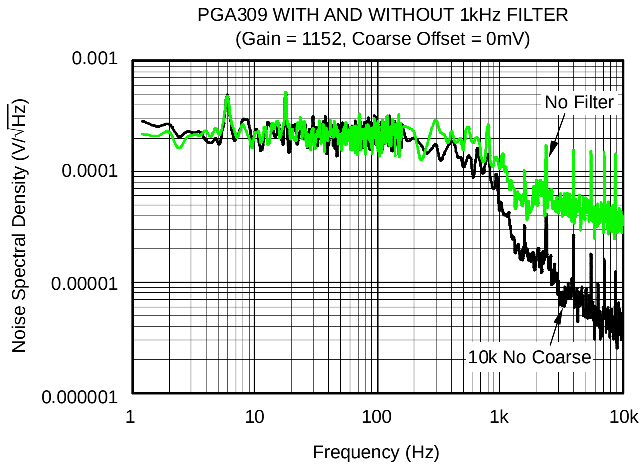

Figure A-9. Noise with 10kHz Filter, No Coarse Offset

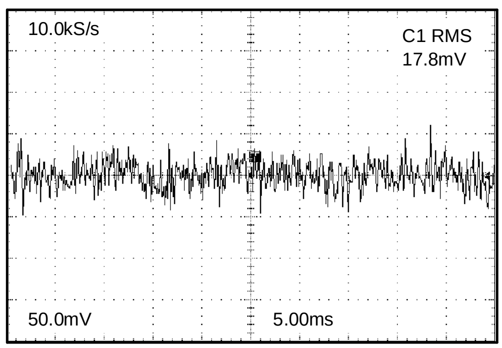

Figure A-10. Noise Measurement

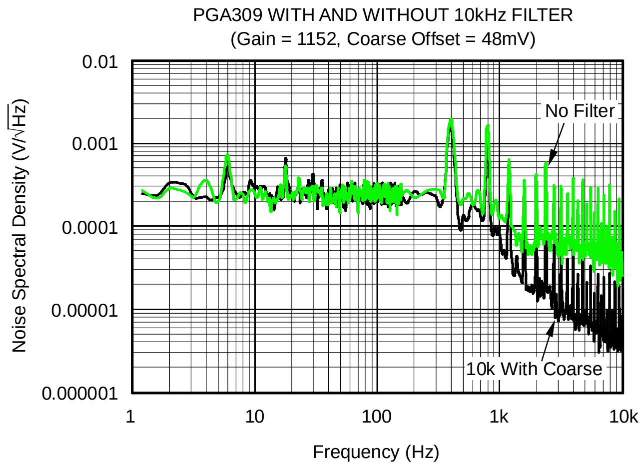

Figure A-11. Noise with 10kHz Filter, Maximum Coarse Offset

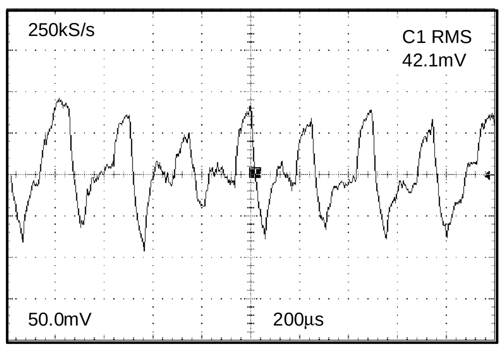

Figure A-12. Noise Measurement

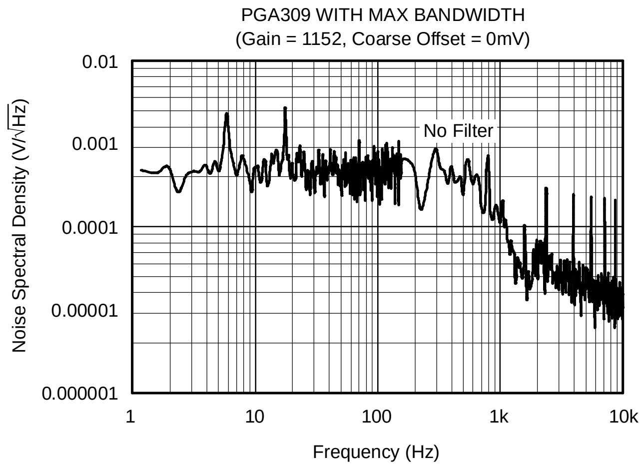

Figure A-13. Noise with Maximum Bandwidth, No Coarse Offset

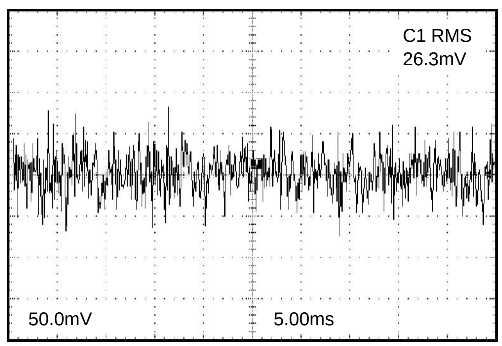

Figure A-14. Noise Measurement

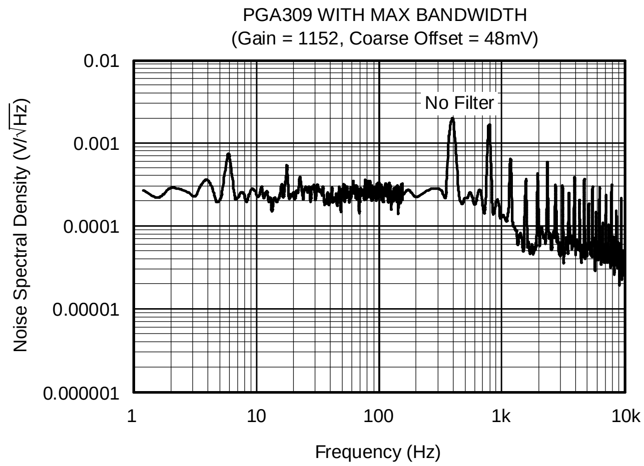

Figure A-15. Noise with Maximum Bandwidth, Maximum Coarse Offset

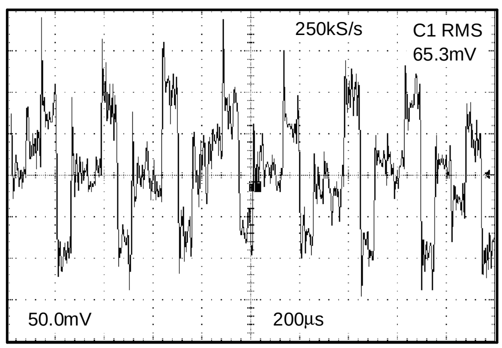

Figure A-16. Noise Measurement