Impact of voltage reference noise on ADC ENOB and noise-free resolution

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Introduction

Multiple systems ranging from thermostats to flight control employ an analog-to-digital converter (ADC) to capture real world analog signals which will be processed in the digital domain and take necessary actions based off of the digital results. Each ADC specifies a number of bits to represent the various digital levels it can produce. For a given constant ADC input, the output of the ADC is not a constant digital value due to various errors in a typical signal chain. Thus, it is important to consider the effective number of bits (ENOB) or the noise-free resolution of the signal chain for better comparison and to also extract maximum information from the captured data. Higher precision calls for higher ENOB and noise free resolution.

Typically, signal-to-noise ratio (SNR), total harmonic distortion (THD) and noise of the system play an important role in ENOB calculation. For multiple systems like field transmitters or test and measurement applications, DC input signal accuracy and precision is critical. Therefore, the noise specification becomes most critical. The voltage reference used with an ADC is a critical component in the signal chain that can impact the precision and accuracy.

The impact of the voltage reference on ADC noise

While it is possible to remove some noise by filtering, you cannot realistically filter out noise at low frequencies. In a voltage reference, it is also not possible to filter out flicker noise (which is noise from 0.1Hz to 10Hz) without having a major impact on signal chain performance because of the size of the resistor-capacitor filter components you'll need. Therefore, noise will almost always be present in your system.

In addition to the voltage reference noise, there will be noise from the ADC itself and the ADC driver. Each one of these components contributes noise to the circuit that generates a digital signal. Figure 1 is a simplified block diagram of this circuit.

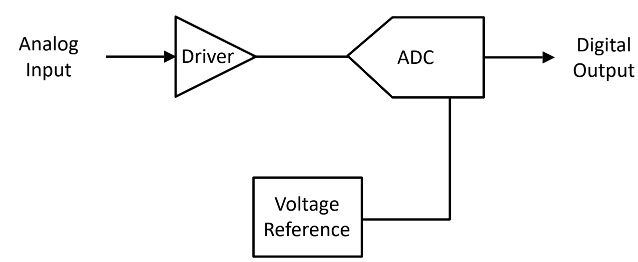

Figure 1. *Generic ADC circuit configuration with an external voltage reference.*

Equation 1 expresses the total noise of this circuit as:

$$\text{Total Noise} = \sqrt{\text{Noise}_{\text{Driver}}^2 + \text{Noise}_{\text{ADC}}^2 + \text{Noise}_{\text{VREF}}^2} \quad (1)$$

The amount of noise present in your circuit is important to know when determining your system's ENOB. In general, selecting low-noise devices is essential to a low-noise design.

In this article, I'll focus on not only voltage reference selection, but other data processing choices that can help you maximize ADC performance.

The impact of the voltage reference on THD

Repeated sampling of the voltage reference pin can cause current transients to appear that may only be separated by a few nanoseconds. However, for an ADC, the external reference must settle or recharge by the end of the sample phase in order to avoid a large gain error. Slowing the sampling speed could fix this issue, but that is not always an option. Typically, the more precise the ADC, the more current draw required on its reference input. If a voltage reference does not have high-enough bandwidth, or has too high of an output impedance, it will not be able to recharge the reference input of the ADC. This will cause a voltage droop, leading to gain error and lower ENOB.

For this reason, a high-bandwidth, low-output-impedance buffer external to the voltage reference is sometimes necessary to increase the THD of the ADC and meet the data-sheet specifications for distortion and ENOB. Some ADCs have an internal voltage reference buffer, but not all do. **Figure 2** shows where to add an external buffer to increase the THD of your circuit.

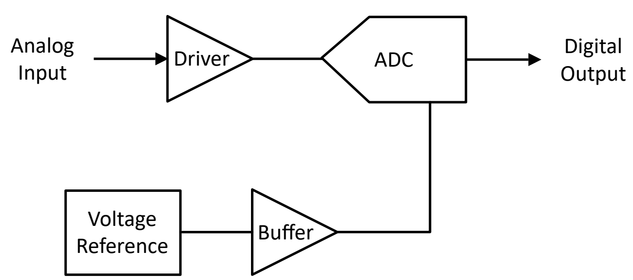

Figure 2. *Generic ADC circuit configuration with an external voltage reference and reference buffer.*

How voltage reference noise and THD affect the ENOB

ENOB measures how the AC characteristics of your circuit affect your ADC resolution. The noise and THD of your circuit are represented by a term known as signal-to-noise ratio and distortion (SINAD). SINAD represents these two AC characteristics in one number, as expressed by **Equation 2**:

$$\text{SINAD (dB)} = -20\log\sqrt{10^{-\text{SNR}/10} + 10^{\text{THD}/10}} \qquad (2)$$

From **Equation 2**, you can see that as the SNR increases, SINAD also increases. Thus, the less noise and distortion present, the better the SINAD. Using SINAD, you can use **Equation 3** to easily find the ENOB of your ADC - especially since:

$$\text{ENOB} = \frac{\text{SINAD} - 1.76\text{dB}}{6.02} \qquad (3)$$

Revisiting **Equation 1**, decreasing the total noise present in the voltage reference would decrease the total noise present in the circuit, leading to an increased SNR. With an increased SNR, the ENOB will also increase. Additionally, adding a high-bandwidth buffer on the output of the voltage reference would also lead to a decreased THD of the ADC, allowing the ENOB to increase.

How voltage reference noise affects noise-free resolution

While ENOB valuably represents the resolution of your ADC output, it does not account for DC performance. To understand the resolution implications of noise from a DC input to your ADC, consider finding the noise-free resolution of your circuit. Using **Equation 4** you can calculate the noise-free resolution by observing the code spread in number of least-significant bits (LSB) of an ADC's digital output while measuring a DC signal:

$$\text{Noise Free Resolution} = \text{N} - \log_2(\text{Code Spread}) \qquad (4)$$

To highlight the impact of reference noise on the system precision performance, my colleagues and I conducted DC code spread tests for a given signal chain using the REF70 (with 0.23ppm$_{p\text{-}p}$ flicker noise) and the REF50 (with 3ppm$_{p\text{-}p}$ flicker noise). Both the REF50 and REF70 are high-precision voltage references used with high-precision ADCs, and have differing DC characteristics. However, in this exercise, the goal was solely to compare the noise performance of these devices in a signal-chain circuit.

The design uses batteries for a stable DC source with a voltage level close to the full-scale range of the **ADS8900B** 20-bit SAR ADC, which captures data at 20kSPS. **OPA2320** is used with a gain = 1 to drive the **ADS8900B** inputs. This ADC integrates the reference buffer driver; therefore, an optional reference buffer is not required. Placing a simple resistor-capacitor low-pass filter on the output of the voltage reference further lowers the noise from the voltage reference. **Figure 3** shows the setup used for these tests.

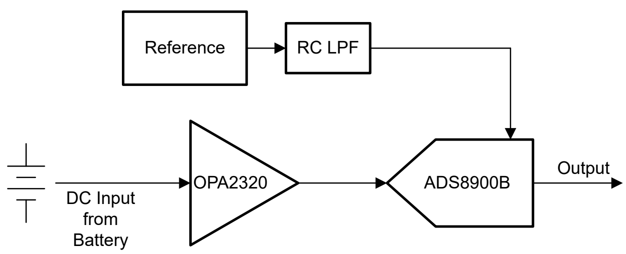

Figure 3. *The circuit used for the following noise-free resolution tests.*

The signal-chain components beside the voltage reference also have flicker noise, which will be part of the final code spread. Because the signal chain remains the same with different references only, the impact on performance numbers must be from the voltage reference noise only.

High-precision systems employ data-processing techniques to improve the precision and increase the overall resolution. In this experiment, we converted the 20-bit raw data from the **ADS8900B** to a 24-bit length by multiplying the output by 16. Different finite impulse response (FIR) filters processed the converted 24-bit data. FIR filters are easy to implement and settle faster if there's a change in the input values. The output data rate remains at 20kSPS, but with latency as defined by the filter characteristics.

At a 24-bit level, the noise (and thus the precision) of REF50 and REF70 are almost similar, with the overall noise dominated by the signal chain and its wide bandwidth noise. The difference in the average code value is because of the reference voltage difference – an accuracy specification that you can eliminate through calibration. These results can be seen in Figure 4 and Figure 5.

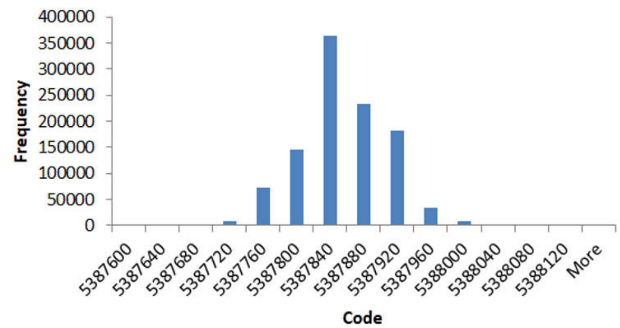

Figure 4. *Results with REF50 noise = 3ppm$_{p\text{-}p}$.*

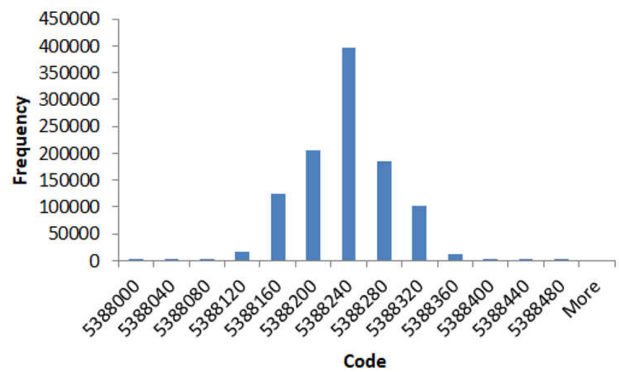

Figure 5. *Results with REF70 noise = 0.23ppm$_{p\text{-}p}$.*

We used the Octave tool to conduct post-processing of the raw data with three different digital filters:

- 1,024-tap moving average filter.
- 801-tap 17Hz low-pass filter.
- 455-tap 36Hz low-pass filter.

Figure 6 shows the filter response for these filters.

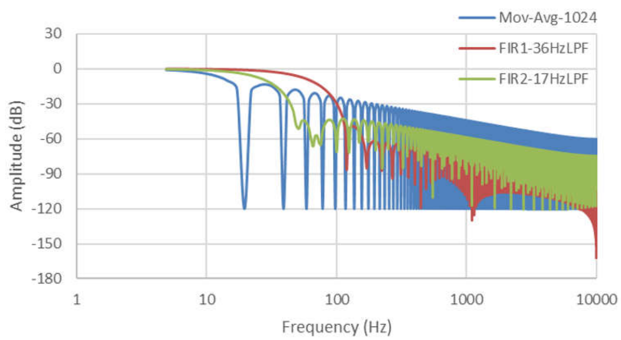

Figure 6. *Digital filter response.*

Figure 7, **Figure 8** and **Figure 9** illustrate the impact of the digital filter on the code spreads.

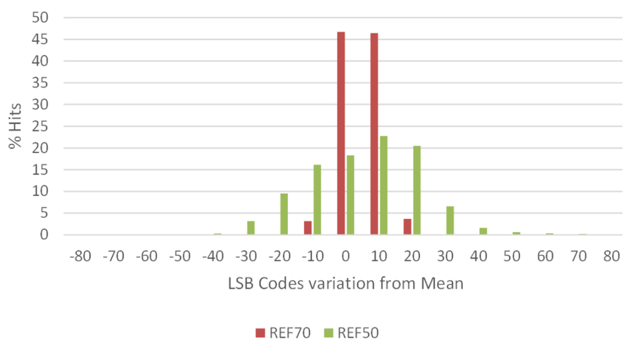

Figure 7. *1,024-tap filter histogram.*

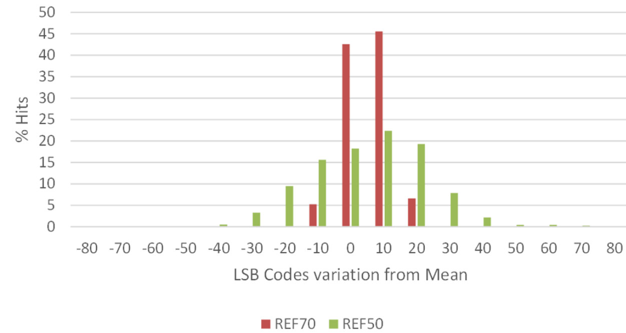

Figure 8. *455-tap filter histogram.*

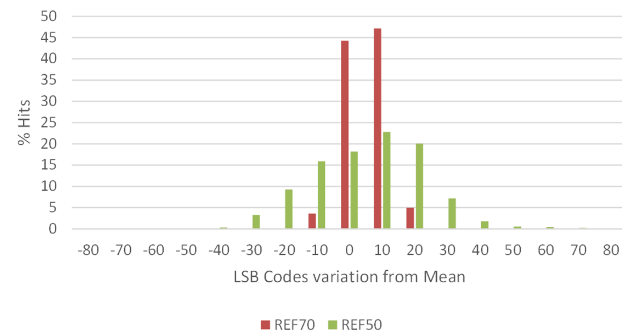

Figure 9. *801-tap filter histogram.*

Using **Equation 4**,you can easily compare the impact of the REF50 and REF70 with each filter profile on the ADC resolution. The results from these tests are summarized in **Table 1**.

Digital filter type	Corner frequency (Hz)	Number of taps	DC code spread (LSB)	Noise-free resolution (bits)	DC code spread least significant bit	Noise-free resolution (bits)
			REF70 at 24 bits		REF50 at 24 bits	
No filter	N/A	0	448	15.1	496	15.0
1,024 tap moving average	8	1,024	35	18.8	118	17.1
FIR No. 1	17	801	38	18.7	121	17.0
FIR No. 2	36	455	49	18.3	135	16.9

Table 1. *Comparison of DC code spread using different filter profiles and reference devices.*

This comparison shows that in the highest precision applications, the REF70 performs better than the REF50 when calculating noise-free resolution, mostly because of the devices' difference in flicker noise levels. The reduced code spread when using the REF70 shows that its ultra-low noise can offer nearly a 2-bit resolution advantage in high-precision applications. Additionally, we can see that using a low noise reference allows using a fast 455 tap filter while still being able to maintain a high noise free resolution. Low voltage reference flicker noise will lead to lower code spread, thus enabling higher noise-free resolution. Like the ENOB, noise is an important consideration when designing your signal chain for low noise-free resolution.

Conclusion

As ADCs are used in thousands of applications and technologies, there will always be a need to obtain better accuracy and higher precision. Whether you are designing a highly advanced x-ray system, an exceptionally precise battery test circuit, or any other world-leading innovation, careful voltage reference selection and implementation are essential to improve the precision and accuracy of your ADC signal chain. You will increase the ENOB and noise-free resolution of your ADC, enabling more advanced and diverse signal-chain implementations.

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