Application Report
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Understanding Low-Amplitude Behavior of 11-bit ADCs

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ABSTRACT

In TI's line of high-speed analog-to-digital converters (ADCs) with SNRBoost technology, output amplitude tends to deviate from its expected value when the applied input amplitude is small. This application note explains this phenomenon and the reasons it occurs.

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1 Introduction

Traditionally, signal-to-noise ratio (SNR) in an ADC is limited by its thermal noise. The *N*-bit quantization error in an ADC is kept much lower compared to the thermal noise, so that overall SNR is not limited by quantization error.

However, in the case of ADCs with SNRBoost technology (such as the ADS62C15, ADS62C17, ADS58C28, ADS58C48, and ADS58C20), the thermal noise component is kept much better than the *N*-bit quantization error. For example, in the ADS62C17, the thermal noise component of SNR is approximately –76 dBFS, while its quantization error component is approximately –67.8 dBFS.

This noise partitioning results in one side effect: it is observed that at lower input signal amplitudes, the actual output amplitude includes a large degree of error (typically 10%). Refer to the two cases shown by Figure 1 through Figure 4.

In Figure 1 and Figure 2, the input signal amplitude is 1.78 V_{PP} (or –1 dBFS), and the output amplitude (reported by the FFT of the ADC output) is also quite close (–1.03 dBFS).

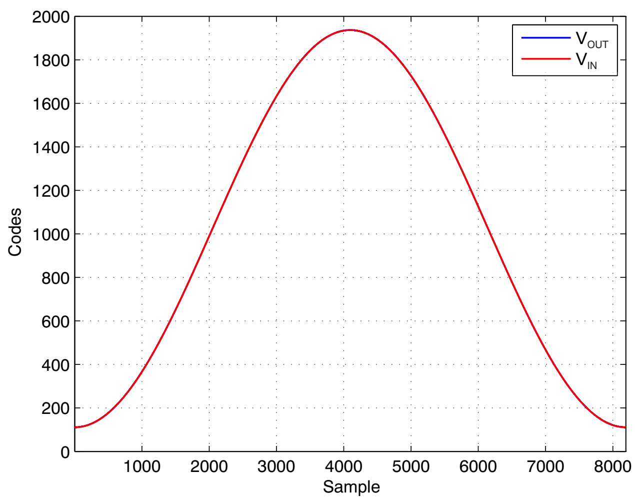

Figure 1. Time Domain Graph for V_{IN} = –1 dBFS

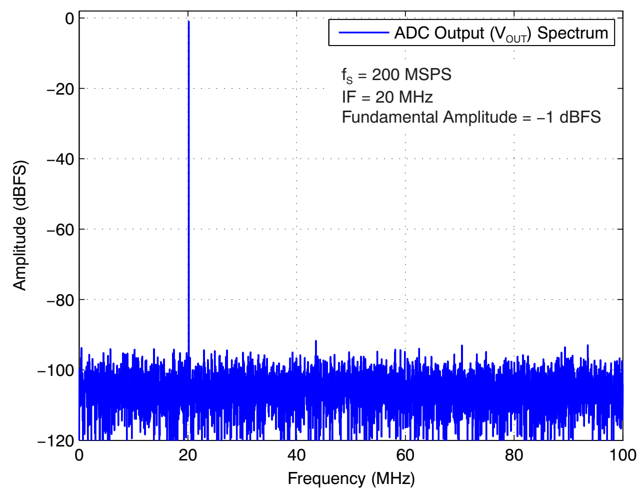

Figure 2. Spectrum Graph for V_{IN} = –1 dBFS

In this case, V_{OUT}, output amplitude is –1 dBFS and predicts input accurately.

In Figure 3 and Figure 4, the input signal amplitude is reduced by a factor 1000 to 1.78 mV_{PP} (or –61 dBFS). Now, the output amplitude from the FFT reports –59.8 dBFS, or an error of 1.2 dB (close to 10% error).

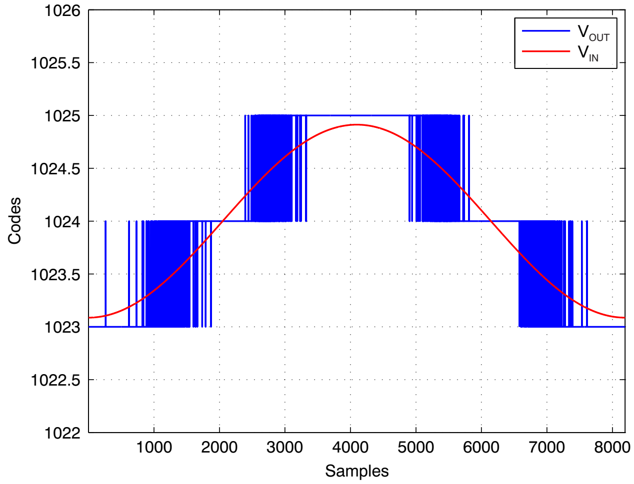

Figure 3. Time Domain Graph for Small Input Amplitude, V_{IN} = –61 dBFS

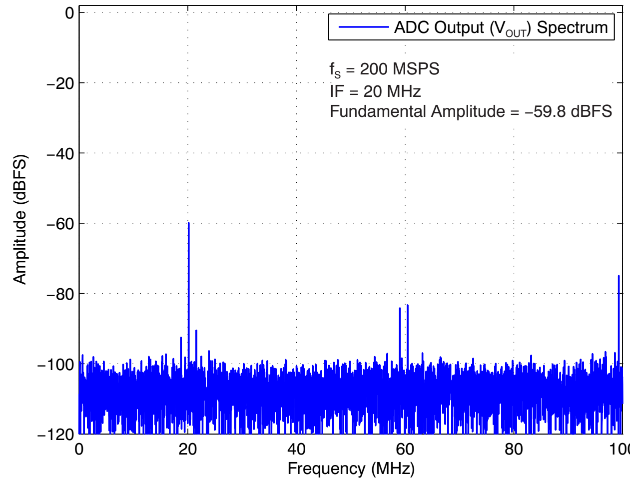

Figure 4. Spectrum Graph for Small Input Amplitude, V_{IN} = –61 dBFS

Here, V_{OUT}, output amplitude is –59.8 dBFS and overestimates the input by 1.2 dB.

To understand this effect better, let us sweep the input amplitude from full-scale down to very small amplitudes and note the output amplitude result (reported by the FFT). Figure 5 and Figure 6 show the summary of this experiment for an 11-bit ADC.

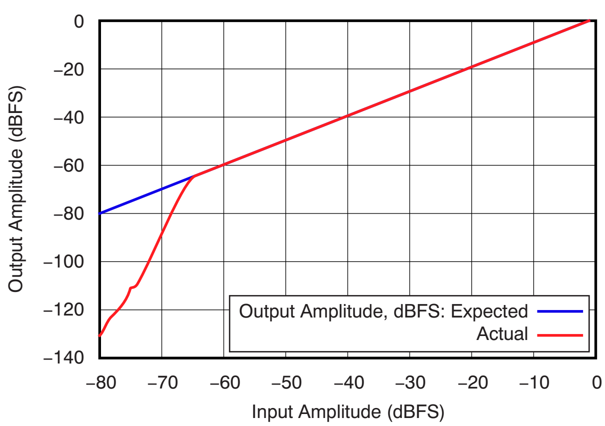

Figure 5. Input Amplitude Swept from 0 dBFS to –80 dBFS

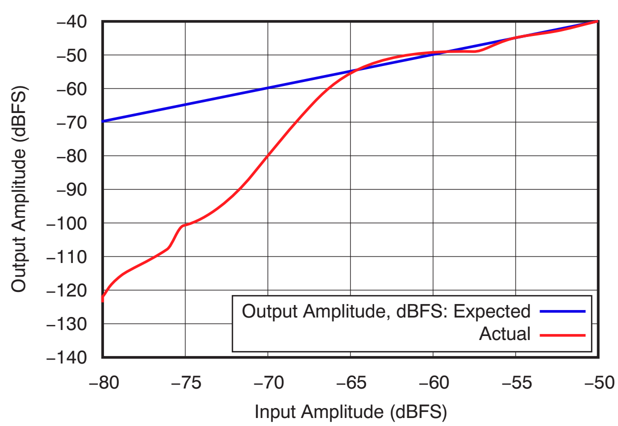

Figure 6. Input Amplitude Swept from 50 dBFS to –80 dBFS (Enlarged)

We can clearly see that at amplitudes less than approximately –50 dBFS, the error becomes significant.

1.1 Explanation of This Effect

To understand the cause of this behavior, it is helpful to start with a model of the ADC that includes the thermal noise and quantization error.

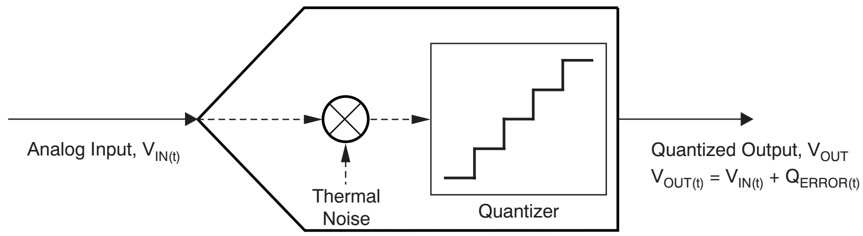

Figure 7. ADC Model

The model shows that the ADC output data are a quantized representation of the analog input that includes the quantization error. Using this model, we can explain the behavior with large and small input signals.

First, we will consider an analysis with a single-tone input signal before moving to a scenario with multi-tone or wideband input signals.

2 Single-Tone Input Signal

2.1 Single-Tone Large Input Signal Amplitude

The time domain waveforms of Figure 8 and Figure 9 show the ADC output and quantization error (or *Q-error*) signals for large input amplitude (–1 dBFS measured as an example). Note that the Q-error waveform appears random and does not show any component of the input signal. The quantization error is presumed to have a uniform probability distribution; this condition is also the basis for the classic, quantization error-limited SNR formula given by Equation 1.

$$\text{SNR} = 6 \bullet n + 1.76 \ (n = \text{number of bits}) \quad (1)$$

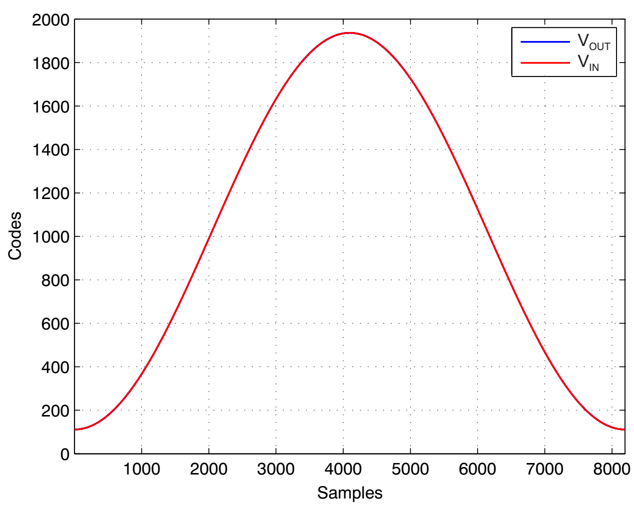

Figure 8. Analog Input V_{IN} and ADC Output V_{OUT} for –1-dBFS Input Amplitude

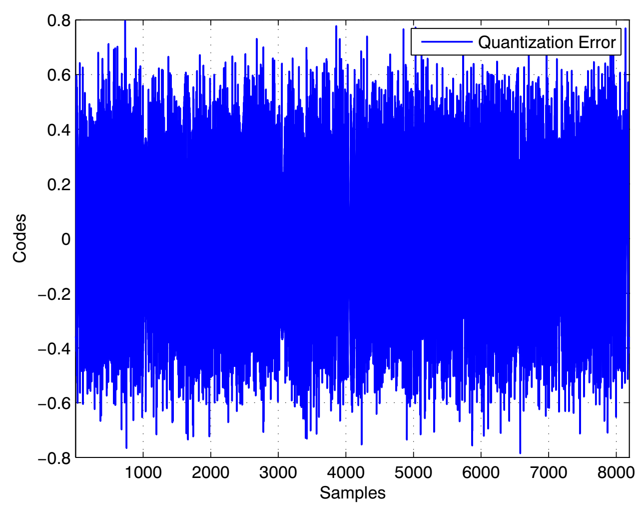

Figure 9. Quantization Error for –1-dBFS Input Amplitude

Figure 10 and Figure 11 show the spectrum of the ADC output and the Q-error, respectively. As expected from the time domain waveforms, the spectrum of the quantization error does not have any tones related to the input signal frequency; in other words, the energy of the Q-error is spread over the entire spectrum.

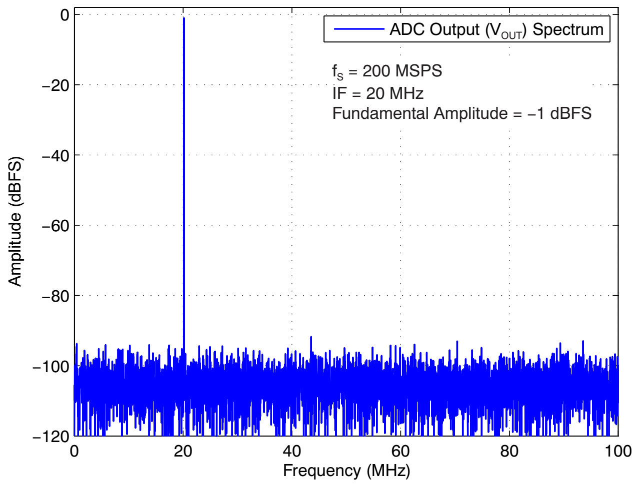

Figure 10. Spectrum Graph: ADC Output for –1-dBFS Input Amplitude

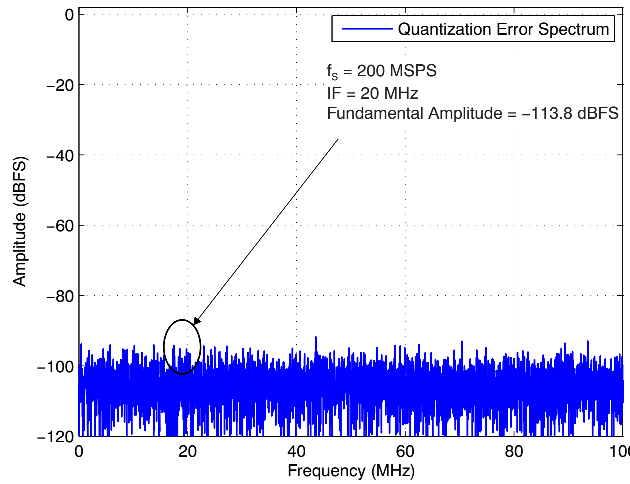

Figure 11. Spectrum Graph: Quantization Error for –1-dBFS Input Amplitude

In the spectrum of the output signal (Figure 10), the input signal frequency component can be seen well above the noise floor. Therefore, the amplitude of the input signal (as reported by the height of the tone in the spectrum) is largely unaffected by the Q-error.

In the frequency domain, Equation 2 is valid:

$$V_{OUT}(f) = V_{IN}(f) + Q_{ERROR}(f) \tag{2}$$

Where:

- $V_{OUT}(f)$ represents the power of the tone at frequency *f* in the spectrum
- $V_{IN}(f)$ represents the ideal (or expected) power of the tone at frequency *f* in the spectrum
- $Q_{ERROR}(f)$ represents the power of the quantization error at frequency *f* in the spectrum

As | $Q_{ERROR}(f)$ | << $V_{IN}(f)$, then, $V_{OUT}(f)$ becomes nearly equivalent to $V_{IN}(f)$.

2.2 *Single-Tone Small Input Signal Amplitude*

Figure 12 and Figure 13 show the time domain waveforms of the ADC output and Q-error for small input signal amplitudes. Compared to the previous case, the error no longer appears random and shows a strong dependence on the input signal.

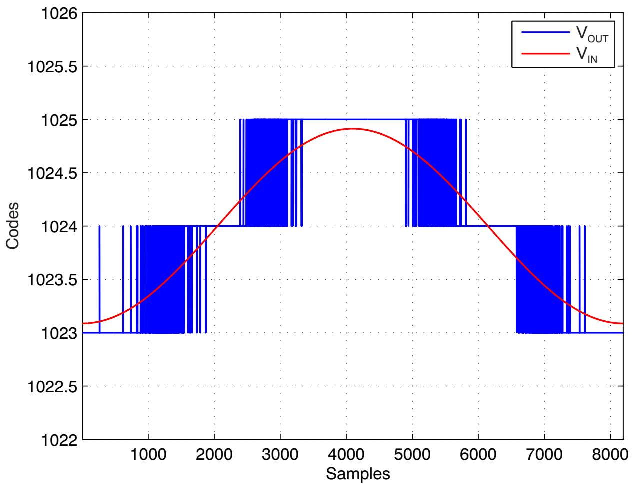

Figure 12. Analog Input and Quantized Output for –61-dBFS Input Amplitude

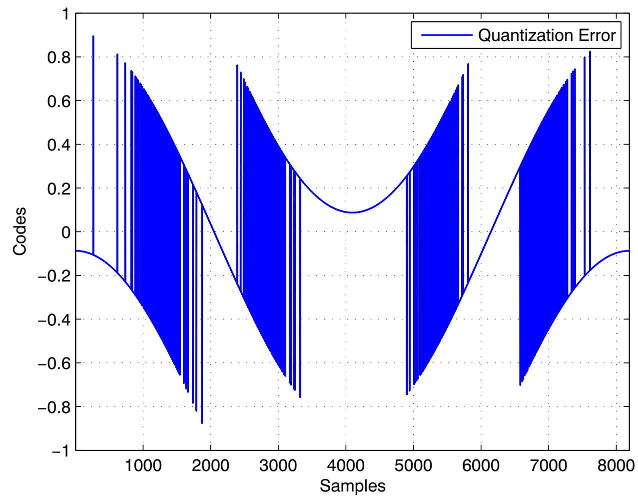

Figure 13. Quantization Error for –61-dBFS Input Amplitude

In this case, the spectrum of the Q-error (Figure 15) clearly shows the fundamental as well harmonics of the input signal.

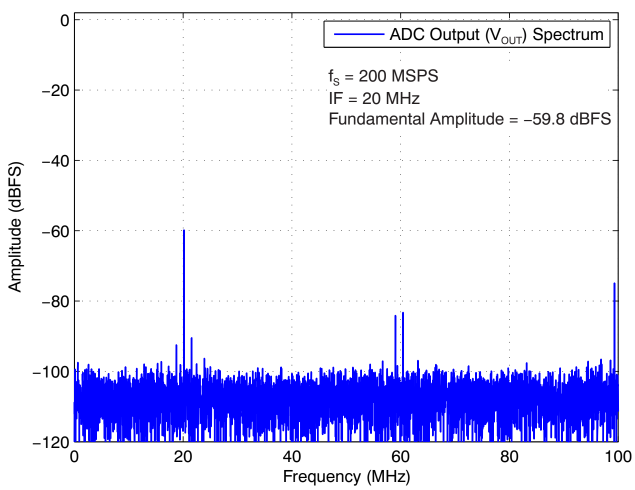

Figure 14. Spectrum Graph: ADC Output for –61-dBFS Input Amplitude

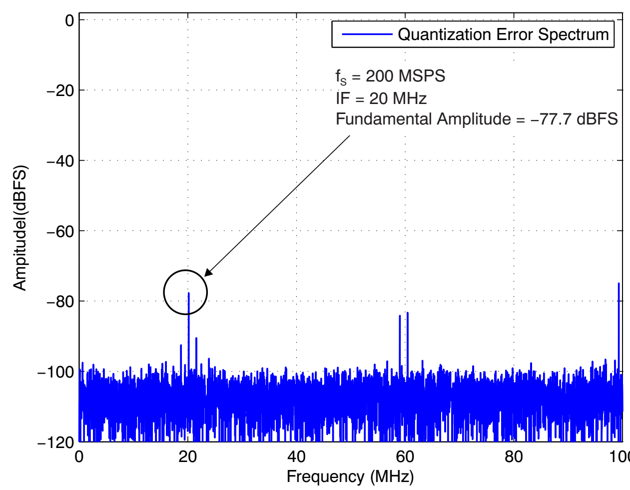

Figure 15. Spectrum Graph: Quantization Error for –61-dBFS Input Amplitude

We find that the Q-error component at the fundamental frequency is significant (–77.7 dBFS) and can alter the ADC output from its expected value of –61 dBFS.

Using Equation 2 and noting that the power of the output signal is a vector sum of the input signal and Q-error, we can see that the output signal power depends on the magnitude and phase of the quantization error as well.

Using a simple MATLAB® model, we then plot the amplitude and phase of the Q-error at the fundamental frequency. Figure 16 shows the ideal (or expected) output signal power (dashed black trace) and the actual ADC output power (red trace).

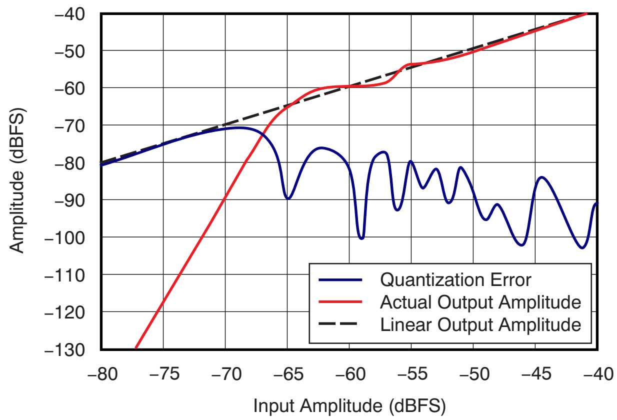

Figure 16. Amplitude Plot of Quantization Error

We can now see that (depending on the phase of the Q-error as shown in Figure 17), the output power is either under- or overestimated. This miscalculation explains the reason for inaccuracy of the output amplitude for small input signals.

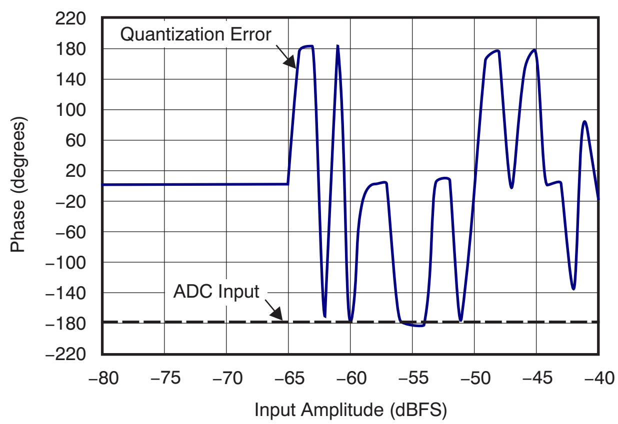

Figure 17. Phase Plot of Quantization Error

3 Multi-Tone Input Signal

Most real-world systems employ some form of multi-tone or a band of signals rather than a single tone. A single-tone signal is frequently employed during lab testing of ADCs because it is easy to understand and analyze ADC non-ideality effects with this type of signal.

It can be observed that in the case of a multi-tone signal applied to an ADC, the accuracy problem at low input signal amplitude is not seen. In fact, the output amplitude (from the FFT) closely matches the input signal amplitude.

In our model, we applied a signal with 16 tones equally spaced by 200 kHz (to mimic a multi-carrier GSM signal) with a total input power of –61 dBFS to the ADC (spectrum graph shown in Figure 18).

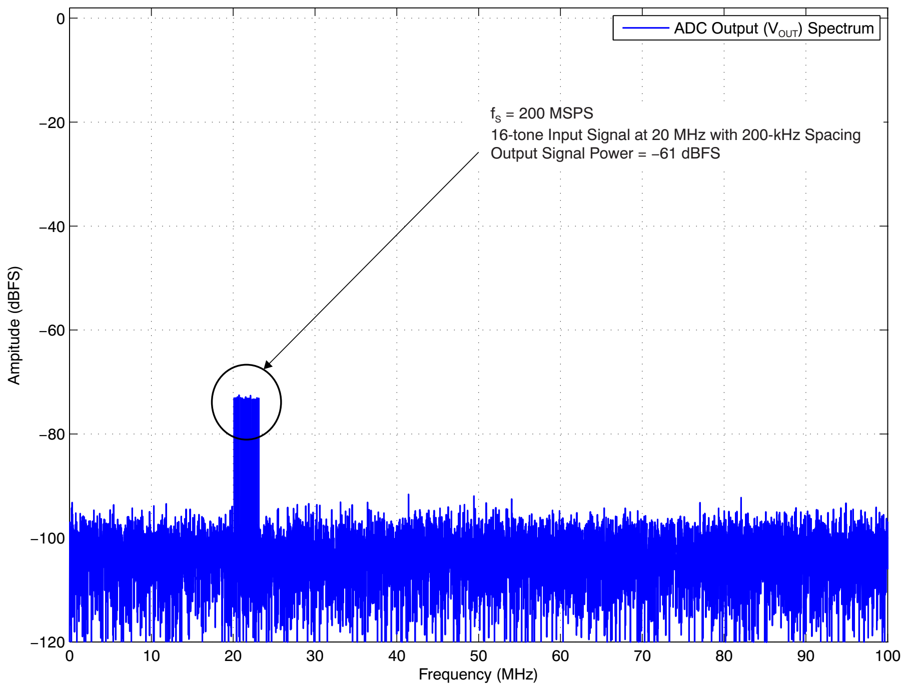

Figure 18. ADC Output Spectrum for 16-Tone Input Signal with –61 dBFS Total Power

As a result of the multi-tone nature of the signal, the energy of the quantization error is spread across the entire spectrum, and no specific tones are observed (Figure 19).

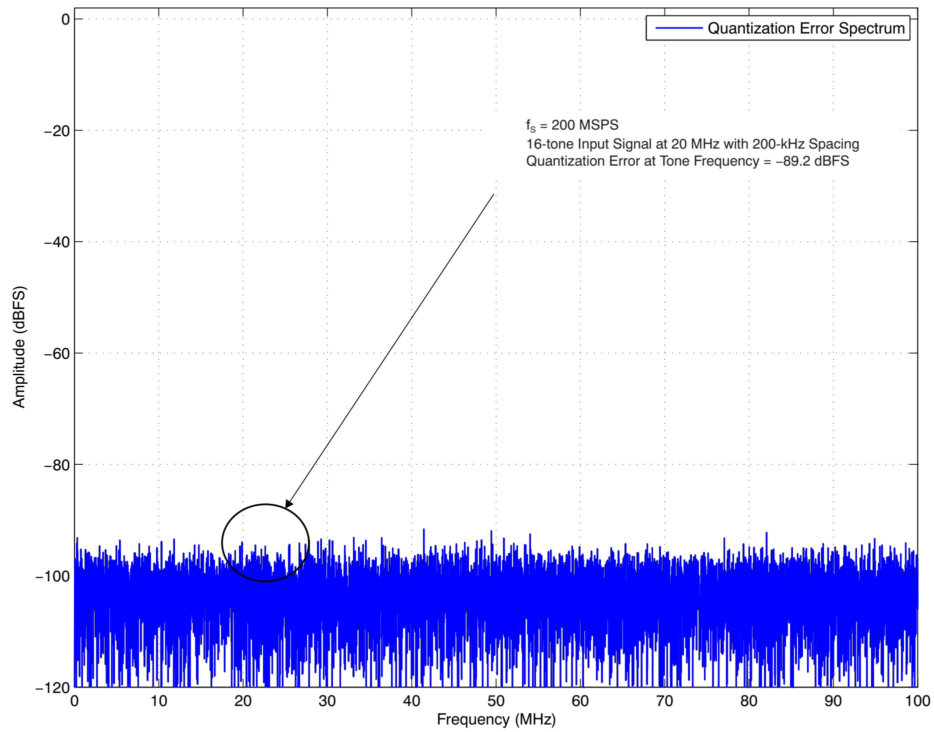

Figure 19. Quantization Error Spectrum for 16-Tone Input Signal with –61 dBFS Total Power

Figure 20 shows the result of sweeping the input signal amplitude and the expected versus actual values of the output power. It clearly shows that the output power tracks the input signal even down to very small power levels.

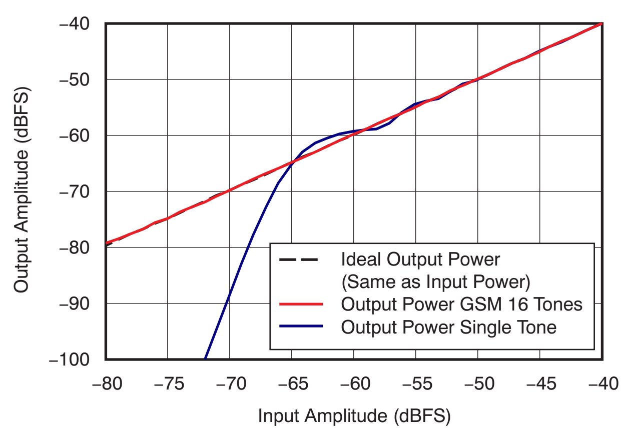

Figure 20. Output Amplitude for Single-Tone and Multi-Tone Input Signals

In summary, then, real-world systems that employ wideband signals do not face any limitations because of this effect.

4 Example: When Thermal Noise Dominates the Quantization Error

What happens in the case of traditional ADCs where the thermal noise is the dominant source compared to the quantization error?

Consider an 11-bit ADC with thermal noise of –64 dBFS as an example. Figure 21 through Figure 24 show how Q-error appears in the time domain in this case.

Compared to Figure 12 and Figure 13, the Q-error seems to be more random and shows less dependence on the input signal frequency. This effect is also shown by the spectrum of the Q-error in Figure 23; the energy is spread over the entire spectrum and no tones are seen. Therefore, in this case, the output amplitude (from the FFT) is quite close to the input amplitude.

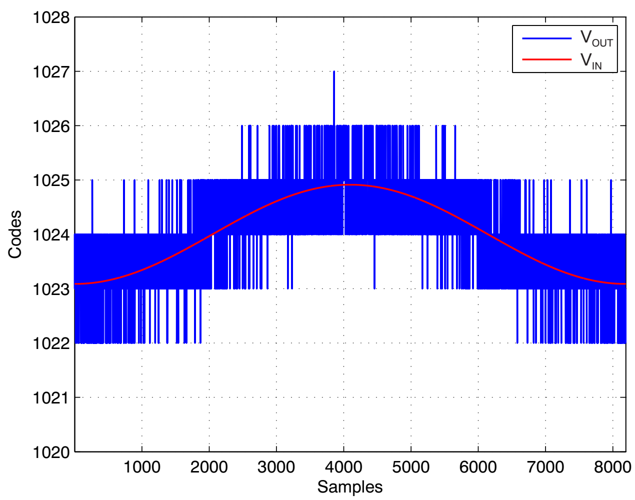

Figure 21. Time Domain Waveform: Analog Input and Quantized Output for –61-dBFS Input Amplitude

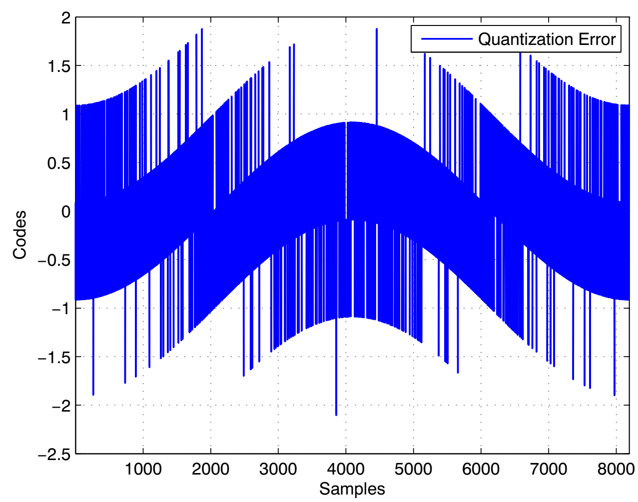

Figure 22. Time Domain Waveform: Quantization Error for –61-dBFS Input Amplitude

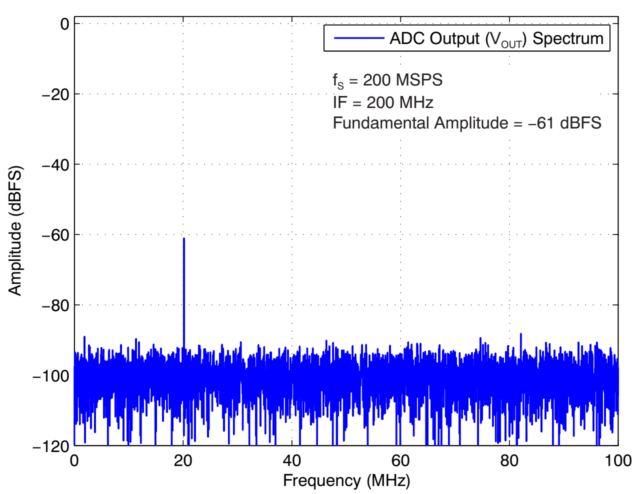

Figure 23. Spectrum Graph: ADC Output for –61-dBFS Input Amplitude

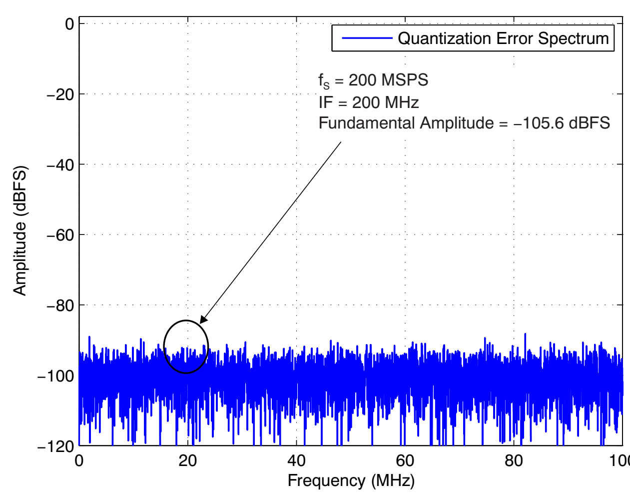

Figure 24. Spectrum Graph: Quantization Error for –61-dBFS Input Amplitude

5 Conclusion

In this application note, we have explained the behavior of an ADC when its thermal noise is much better compared to its quantization error; at small input signal levels of a single-tone input, the output amplitude as reported by a FFT analysis has a large error component.

Using a simple model, we then explained the cause of this error in output amplitude for low input signal levels. We noted that the quantization error is very different at large and small signal levels. At large signal levels, the error signal is random (that is, no tones are seen in the spectrum), whereas at small signal levels, the error spectrum clearly shows tones at the fundamental frequency of the input signal and its harmonics.

Next, we showed that in the case of a multi-tone input (or a band of signals), the issue is not seen: the output amplitude matches the input amplitude even at very low input power.

We conclude that although this behavior is characteristic of single-tone input signals (and is important for designers and application engineers to understand), most real-world systems that use a band of signals are not limited by this effect.