ADC “Accuracy” Vs “Resolution”: I am so confused. What does my application really require?

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Introduction

The way ADC makers specify the performance of the ADC in datasheets can be confusing and may often inferred incorrectly for an application development. One the biggest confusion can be “Resolution” and “Accuracy” which are two different parameters but often used interchangeability. The Article here presents and explains ADC “Resolution” and “Accuracy”, their relationship to dynamic range, noise floor and implication of these parameters on some of the applications like metering.

ADC Dynamic Range, Accuracy and Resolution

Dynamic Range is defined as ratio between the smallest and the largest signals that can be measured by the system.

Largest signal can be Peak to Peak value, Zero-to-Peak value or Root Mean Square(RMS) Full scale. Each of them is going to give different values. For example for a 1V Sine wave
Peak to Peak (Full Scale) Value = 2V
Zero to Peak Value = 1V
RMS Full Scale = 0.707x peak amplitude = 0.707 x 1 V = 0.707 V

Smallest signal is usually the RMS Noise which is the root-mean-square value of the signal measured with no applied signal. The measured RMS Noise level will depend on the bandwidth it is measured over. Each time bandwidth is doubled, recorded noise increases by 1.41 or 3dB.

Thus, it is important to note that dynamic range figure is always for a certain bandwidth that is often not specified, thus making the reported value meaningless.

The dynamic range and signal to noise ratio (SNR) of a device are most properly defined to be the same thing. That is:

Dynamic Range = SNR = RMS Full-scale/RMS Noise

and is usually quoted in dB.

Dynamic Range (dB) = SNR (dB) = 20*Log10 (RMS Full-scale/RMS Noise)

Instead of RMS Full Scale, some manufactures quote Zero-to-Peak or Peak to Peak which increases the final Dynamic range or SNR by 3dB or 9dB to make figures look better, so one need to be careful to check the specifications as it can be misleading.

Resolution and Accuracy are terms that are often interchanged when the performance of an ADC is discussed. It is important to note that Resolution does not imply Accuracy nor does Accuracy imply Resolution.

The resolution of ADC is determined by the number of bits it uses to digitize an input signal. For a 16-bit device the total voltage range is represented by 2^{16} (65536) discrete digital values or output codes. Therefore the absolute minimum level that a system can measure is represented by 1 bit or $1/65536^{th}$ of the ADC voltage range.

The accuracy of the A/D converter determines how close the actual digital output is to the theoretically expected digital output for a given analog input. In other words, the accuracy of the converter determines how many bits in the digital output code represent useful information about the input signal.

As explained earlier, for a 16-bit ADC resolution the actual accuracy may be much less than the resolution because of internal or external error sources. So for example a given 16-bit ADC may only provide 12 bits of accuracy. In this case, the 4 LSb's (Least Significant Bit) represent random noise produced in the ADC.

ADC Dynamic Range and ADC Accuracy are often same thing.

Figure 1 shows basic ADC measurement Circuit.

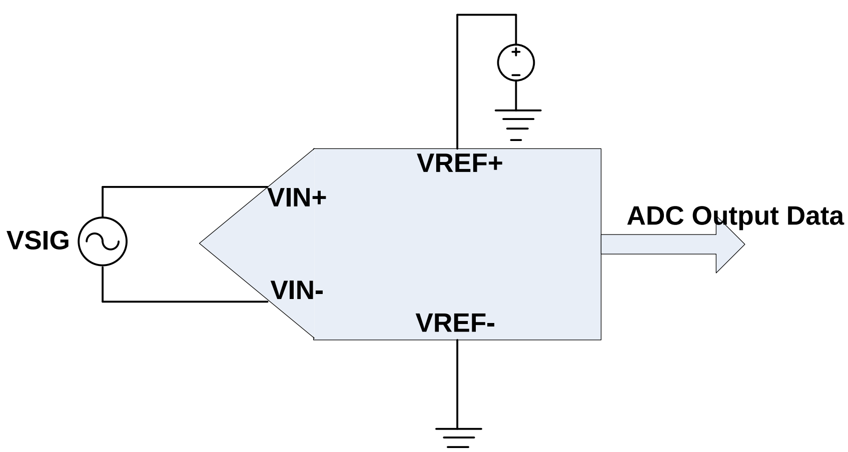

Figure 1: ADC Measurement Circuit

The ideal A/D converter produces a digital output code that is a function of the analog input voltage and the voltage reference input where

Output code = Full Scale Voltage x [VIN+ - VIN-] / [VREF+ - VREF-]
= Full Scale Voltage x [VIN /VREF]

Each digital output code represents a fractional value of the reference voltage.

It is very important to note that ADC dynamic range should match the maximum amplitude of the signal to be converted to have the maximum ADC conversion precision.

Let us assume that the signal to be converted varies between 0 V to 2.5 V and that VREF is equal to 3.3 V as shown in Figure 2.

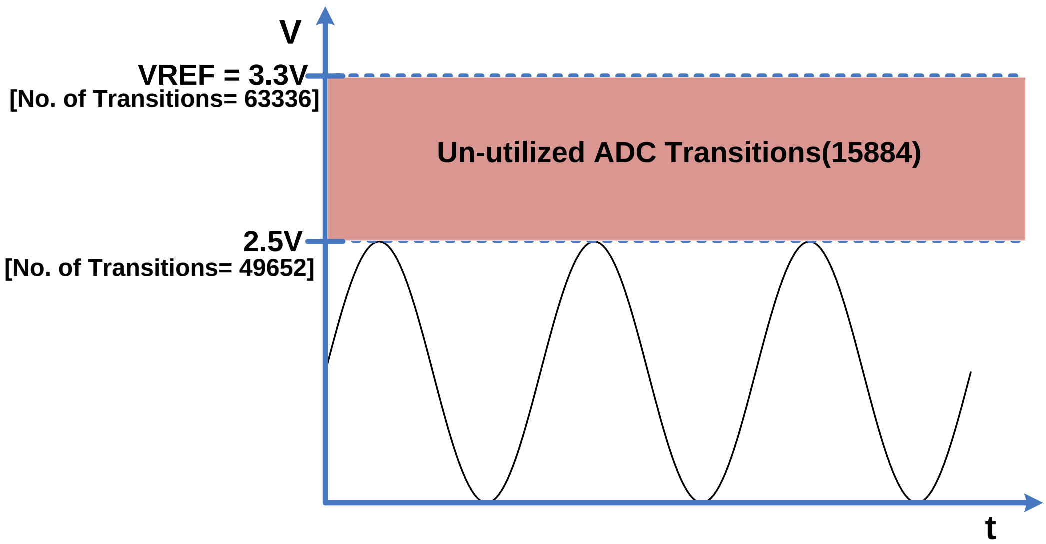

Figure 2: Input Signal Amplitude vs ADC dynamic range

A 16 bit ADC would have 2^{16} = 65536 Steps or transitions with Least Significant Bit(LSB) = VREF/65536 = 3.3V/65536 = 50.35 uV. For an ideal ADC, all code will have equal width of 1 LSB.
Now if the maximum signal value to the ADC is 2.5V, would mean total 49652 transitions (2.5V/1 LSB). In this case, there are 15884 unused transitions (65536 – 49652 = 15884). This implies a loss in the converted signal accuracy or loss in ENOB (by 0.4 bits).

The loss in ENOB or accuracy goes worse if the difference between the ADC Reference (VREF) and maximum signal level to the ADC increases. For example if maximum signal level to the ADC is 1.2V with VREF = 3.3V, the loss in ENOB becomes 1.5bits. So it is important to match the ADC Dynamic range to the maximum signal amplitude for best accuracy.

Next section explains some of the examples to show implications of these parameters on some of the typical applications.

Application Examples

a) Digital Camera

For a digital camera, simply said, dynamic range is the range of values from the lightest to darkest detectable, expressed in bits, generated within a pixel of image sensor. The minimum bit rate (resolution) of an ADC is determined by the dynamic range (accuracy) of the image sensor. If the dynamic range of the sensor is for instance 1000:1 (also quoted as 60dB) the ADC should be at least 10 bit (2^10 = 1,024 discrete levels) in order to avoid loss of information. However, in practice it makes sense to overspecify the ADC to 12 bits to allow for some margin of error on the ADC.

Claiming a camera has a 12-bit dynamic range simply because the camera has an ADC (Analog-to-Digital-Converter) of 12 or 16-bits is misleading because noise and the capacity of the pixel well to produce such a dynamic range has not been considered.

So from the above it is easy to understand that this is only true if the sensor itself has sufficient dynamic range. The tonal range and dynamic range can never be larger than the dynamic range of the sensor. Therefore it is important to know what your real dynamic range is on a camera. The example in this section have shown that the distention of having a camera with a dynamic range of 12-bits is not the same as having a camera with a 12-bit ADC.

b) Resistance Thermometer [RTD]

Let's take an example of Resistance thermometers [RTDs] based on temperature sensor that exploit the predictable change in electrical resistance of some materials with changing temperature. They are usually made using Platinum and have following characteristics:-
Sensor Resistance at 0^oC = 100 ohms
Change in Resistance/ ^oC = 0.385 ohms (European Fundamental Interval)
Sense current to excite Sensor= 1mA
Temperature range = 0 to 500 ^oC

Note that Resistance thermometers require a small current in the order of 1mA to be passed through in order to determine the resistance. A 1°C temperature change will cause a 0.385 ohm change in resistance, so even a small error in measurement of the resistance can cause a large error in the measurement of the temperature.

RTD is expected to detect change in temperature by 0.1 ^oC which becomes the system's LSB over 0 to 500 ^oC. The corresponding delta change in resistance over this range would be 192.5 ohms. With this delta change, voltage over the range would be 192.5mV.

Now Dynamic Range = Full Scale Voltage / LSB Size
= 192.5mV/38.5 uV
= 5000
To satisfy this requirement it seems that 13-bit ADC should be sufficient.

Note that since the voltage across the RTD sensor range from 100mV to 292.5mV with LSB size low enough for any SAR ADC to resolve, you would need a gain amplifier to push this range within what ADC can support practically. Lets say we take a gain

amplifier with fixed gain of 17. With that, voltage would be from 1.7V to 4.92V. As explained earlier [shown in Figure 2], with this output voltage range you are going to underuse your ADC and this will limit the dynamic range.
Since LSB size is what we care the most in this application [RTD sensor should be able to respond to with 0.1^{o}C of temperature change] and assume typical ADC with full scale voltage of 5V, you would need a converter with

ENOB[effective No of Bits] = 1.44ln [full scale range/LSB]
= 1.44ln[5V/38.5uV]
= 17 bit (approx)

A good Sigma delta ADC should be able to provide this performance.
Note that a 13-bit application may not always need a 13-bit converter.

c) Electricity Metering

Electricity meters are now becoming more sophisticated and required high accuracy often across a very wide dynamic range since any inaccuracies in measurement would result in severe losses to utility companies.

For a typical class 1 meter with 2000:1 dynamic range, smallest signal that must be measured would be around 0.5 mV, assuming ADC full scale voltage is 1V.

The maximum error specification for the metering device is typically 0.1% of the parameter being measured over the specified dynamic range.
Target Error = 0.1% of 0.5mV
= 500 nV.
Therefore the smallest signal to measure would be 500nV.
System needs to resolve 500nV out of 1V which would require ADC with 1V/500nV = 2 x 10^{6} output transitions. This would require ADC with 21 bit ENOB.

An important point to note is that a generic 21 bit ADC is not going to satisfy these requirements unless it has a good noise floor and is able to resolve voltages as low as 500nV.
This specific example only covers voltage measurement requirement for electricity meters. Just to mention, current measurement on electricity meters have more stringent requirements than voltage, the details for which are not covered in this example.

In summary, the ADC accuracy cannot depend on the ADC performance and features alone; it depends on the overall application design around the ADC. The system actually dictates the real dynamic range required

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