Noise: 16-bit versus 12-bit

Background

All electronic devices generate thermal noise at the molecular level. Even simple passive resistive devices, including those from which sensors are made, generate this noise. Most of the apparent noise within in a data acquisition system comes from the combined effect of numerous thermal noise sources. Generally, the energy density of the complex noise waveform is fairly evenly distributed throughout the useful frequency range.

The total noise recorded by a data acquisition system includes the combined effect of several noise sources:

- Actual mechanical noise as read by the sensor (i.e. small movements due to local vibration in a crash or sled test),
- Thermal noise from passive or active sensor elements,
- Noise generated by the sensor cable and associated interconnections,
- Voltages induced into the sensor cabling by electromagnetic fields,
- Voltages induced into the sensor cabling caused by movement of the cable itself,
- Analog circuit noise within the data acquisition system,
- Noise or uncertainty inherent in the analog-to-digital (A/D) conversion devices.

A perfect 16-bit A/D converter has a theoretical maximum signal to full-scale noise ratio of ~90.3 dB. There are no perfect A/D converters, so actual values are lower. DTS uses a very low-noise, 16-bit A/D converter for TDAS PRO which has an actual shorted-input signal-to-noise (S/N) ratio between 86 and 88 dB. We have verified this experimentally.

We judge the maximum achievable data acquisition system S/N ratio by installing a 350 ohm bridge plug to simulate real-world use while eliminating the somewhat unpredictable effects of cabling and sensors. The total apparent noise then includes the effects of excitation noise, test bridge noise, analog signal processing circuit noise and A/D conversion noise.

With bridge plugs installed, S/N ratios in the 76-80 dB range are common. When you add sensors and cabling, typical values are in the 68-75 dB range at low to moderate gains (i.e., 1 to 250). At higher gains (>250), the maximum S/N ratio will decrease gradually with increasing gain. (Reality check—with a gain of 10 and a 70 dB S/N ratio, the equivalent sensor input noise is only about 30 μV.)

Perspective – 1000 g requested full scale with 1 g peak-to-peak noise

1000 g with a 1.8 headroom factor means that the actual full-scale range (based on rounding to the next lower gain) will be somewhere between 1800 and 2000. Let's say that it is exactly 1800 (best case).

If the apparent noise is 1 g peak-to-peak (+/-0.5 g), then the noise ratio is:

$$20\log(0.5/1800) = 71.1 \text{ dB}$$

That's very good! The TDAS PRO is performing at a level that is much better than a perfect 12-bit system. Remember that in a 12-bit system with the gain set the same way, each bit would be worth 0.88 g. With an uncertain least significant bit (LSB) in a 12-bit system, the best you can do is about 60 dB.

It is also important to remember that a 16-bit system will always have noise. That may seem silly because all electronic systems have noise, but the noise can actually look worse with a 16-bit system. This is because a really good 12-bit system may just produce flat-line data if the input voltage is centered on the LSB value. This clean data has only 1 g resolution, but it may look nice and clean. This will never happen in a 16-bit system because the equivalent voltage values of the LSBs in the 16-bit system are so small. The system in front of the 16-bit A/D converter can never be so quiet that that there will be any less than about 3-5 counts of noise (on a 16-bit scale of +/-32767 versus +/-2048 for a 12-bit system).

Unless the noise contains exaggerated energy levels in the data bandwidth (e.g., 60 Hz noise), the random noise will be averaged by the software filter. The software-filtered data has much greater resolution than a comparable 12-bit system. Data acquisition experts agree that some noise in a sampled system can be a good thing from a resolution standpoint. Engineers have devised creative schemes to ADD noise to certain 12-bit systems to improve the resolution.

Grounding and Shielding

When considering grounding and shielding issues, it is important to look these issues with a big picture, long-term view that understands everything that will be connected and map it out to make sure the entire test set-up is grounded in the best way.

The TDAS PRO design includes a number of grounding and shielding provisions and it is important to identify and implement the best path to success. Noise specifications and noise assessment are probably two of the most misunderstood parameters in electronic systems. Let’s start with some fundamental concepts.

Most of the noise we talk about in data acquisition systems is random thermal noise, with a spectral energy density that is relatively evenly distributed in the useful frequency range. If you look at a data sheet on a National Semiconductor Operational Amplifier, you will find an “Equivalent Input Noise Voltage” spectral distribution graph for the noise performance of the amplifier.

All electrical devices exhibit thermal noise, even passive resistors. Remember that the total noise you read at an A/D converter is a combination of sensor noise and equivalent input noise voltage multiplied by the selected gain, plus the noise inherent in the A/D process.

Units of Noise

A very common method of communicating noise performance is by trying to quantify the expected apparent noise voltage that seems to originate at the input to the system. This value is often expressed as some voltage level per root Hertz (Hz), referenced to input (RTI).

Expressing the expected noise in root Hz, RTI is a way of giving engineers enough information to help them make some estimates of the total noise over some frequency range. If you limit the bandwidth of a signal with either hardware or software filters, the total apparent noise level will be reduced.

Let’s say that you want to estimate the noise level that you would see over a useful frequency range of 0 to 2,000 Hz (SAE Class 1,000) with a noise spec of 0.1 µV per root Hz. You would estimate the total noise as an equivalent voltage at the input as:

$$(\sqrt{2000}) \times (0.1\ \text{uV}/\sqrt{\text{Hz}}) = 4.47\ \mu\text{V}$$

Let’s say that a sensor has a full-scale output of 15 mV and the thermal noise of the sensor is negligible. The S/N ratio of the system with that sensor would be approximately:

$$20 \log (15\ \text{mV} \div 4.47\ \mu\text{V}) = 70.5\ \text{dB}$$

Noise Floor

When discussing the noise performance of a particular system or that of a component, it is meaningful to consider the “noise floor.” Noise floor is generally the total noise over a given bandwidth as it relates to the full-scale range of a device, such as an amplifier or an A/D converter. Essentially, signals cannot be any quieter than the noise floor. The caveat to this is that post-filtering will often reduce “apparent” noise by effectively averaging the signal. (It is important to note that noise amplitude content at a given time may not be evenly distributed above and below the true mean. So, when averaged by a filter, noise content may appear as small DC off-sets.)

A/D converters typically have a noise floor no better than the least significant bit as compared to the full scale. Essentially, the last bit is always uncertain (no matter what the specs say).

This means that a typical 12-bit A/D converter has a best case noise floor of:

$$20 \log (1 \div 2e11),\ 20 \log (1 \div 2048) = -66\ \text{dB}$$

Good 16-bit A/D converters are typically specified as having a noise floor in the ball park of −86 to −88 dB. In TDAS PRO, our 16-bit A/D converter has a real-world shorted input noise floor of about −84 dB, which is about as good as it gets. When the signal routing circuitry is connected to the A/D converter, the noise floor falls between −80 and −82 dB.

Referenced to Output (RTO) and Referenced to Input (RTI)

A discussion of RTO and RTI as they relate to a data acquisition system brings up many points and issues to clarify. RTO is essentially the equivalent of RTI multiplied by gain.

A/D converters are essentially reading the output of all of the analog circuitry, including the connected sensor. It often makes sense to discuss system noise RTO to estimate how many bits of noise will be present at a particular gain.

On the other hand, analog signal processing devices are almost always specified in noise RTI, which is most convenient for calculating the noise floor of a particular input signal or sensor including at a particular gain.

In a well-designed A/D system, the noise floor of the analog electronics is lower than the noise floor of the A/D converter to as high a gain as possible. In TDAS PRO, the system noise floor at a gain of 1 is better than -80 dB, but at low gains the signal conditioning noise floor is well below that.

Using our noise spec of 0.1 μV/√Hz, you can estimate an RTO equivalent at a certain gain as follows:

$$((0.1\ \mu V/\sqrt{Hz}) \times (\sqrt{2000}) \times \text{Gain}), \text{ at a gain of 100, the total noise RTO} = 0.447\ mV$$

The full-scale range of the TDAS PRO A/D converter is 5 V, so the S/N ratio of the analog circuitry at gain of 100 is:

$$20 \log (5\ V \div 0.000447\ V) = 80.97\ dB$$

In fact, the apparent noise (RTO) exhibited by the TDAS PRO is essentially the same from gains of 0.8 to ~200. Above a point around 200 gain, the analog noise RTI multiplied by the gain grows slowly as the gain increases.

What does all of this mean to your specification and your test results? DTS has a detailed noise analysis procedure for the TDAS PRO which is based on a statistical analysis and a 12-bit equivalent scale. The table below shows typical noise performance of the TDAS PRO at various gains, and with the added effect of software filtering that must be applied to achieve SAE J211 Class 1000 response.

TDAS PRO Noise Performance[1]

Gain	Description	Chan 1	Chan 2	Chan 3	Chan 4	Chan 5	Chan 6	Chan 7	Chan 8	Avg (bits)	Avg (dB)
1	Raw data, 20k sps	0.40	0.40	0.46	0.42	0.48	0.40	0.42	0.40	***0.42***	***-79.7***
	Same data, SAE Class 1000	0.19	0.19	0.21	0.19	0.23	0.18	0.20	0.18	***0.20***	***-86.4***
128	Raw data, 20k sps	0.47	0.55	0.58	0.61	0.50	0.52	0.50	0.50	***0.53***	***-77.8***
	Same data, SAE Class 1000	0.25	0.30	0.31	0.33	0.26	0.28	0.27	0.27	***0.28***	***-83.2***
256	Raw data, 20k sps	0.74	0.74	0.81	0.77	0.72	0.77	0.72	0.73	***0.75***	***-74.7***
	Same data, SAE Class 1000	0.45	0.45	0.49	0.45	0.43	0.46	0.43	0.44	***0.45***	***-79.2***
512	Raw data, 20k sps	1.27	1.33	1.37	1.37	1.33	1.32	1.28	1.28	***1.32***	***-69.8***
	Same data, SAE Class 1000	0.81	0.86	0.89	0.89	0.85	0.83	0.80	0.82	***0.84***	***-73.7***
2000	Raw data, 20k sps	5.01	4.97	4.93	5.11	4.91	5.11	4.92	5.09	***5.01***	***-58.3***
	Same data, SAE Class 1000	3.25	3.27	3.20	3.44	3.19	3.41	3.22	3.43	***3.30***	***-61.9***

[1] Noise was evaluated by determining the min/max within ±3 sigma of the mean over 400 ms of data (50 ms pre-event and 350 ms post event). Each channel was connected to 350 Ω bridge plug at 10 V excitation for all data collection runs. Bit values are presented on a 12-bit scale to simplify comparison of the TDAS PRO 16-bit system to typical 12-bit systems.

Comparing Systems - A Word of Caution

The only way to compare noise specifications in a meaningful way is to include due consideration of the useful bandwidth and gains. This means that you have to consider the bandwidth limiting and averaging effects of the hardware response and any software filtering. For example, the raw data from a system with a hardware filter set to 4 kHz might not be directly compared one with the filter set to 2 kHz.

Accuracy and Resolution

Accuracy is, once again, a deeper subject than it appears on the surface. An accuracy assessment should combine the effects of issues such as LSB uncertainty, distortion, non-linearity, and thermal gain drift, to name a few.

There are no high-speed field data recorders that offer true "16-bit" accuracy. The manufacturers of the best A/D integrated circuits in the world (that meet the requirements of a crash test recorder) cannot do better than approximately 14-bit accuracy.

It is also true that specified accuracy for a 12-bit system versus a 16-bit system may be very similar. What a 16-bit system really buys is resolution. This resolution has accuracy benefits which may not be immediately apparent.

In a 12-bit system used at 50% of full scale, the best measurement resolution possible is about 0.1% (1 bit ÷ 1,024). Assuming that the analog electronics are of excellent quality, 0.1% is good resolution. If, however, multiple measurements are taken as part of a set-up or calibration routine, then the 0.1% may stack up two or more times.

With a 16-bit system such as that in the TDAS PRO, internal "each-use" calibration functions are performed by averaging many points during the calibration routine. When used in this way, we actually achieve resolutions to about 2 counts on a 16-bit scale, which is somewhere between 4 and 8 times better than can be achieved with a 12-bit A/D converter (depending upon how you look at 12-bit resolution).

Effect of Sampling Rate on Amplitude Accuracy

An important issue to consider when it comes to discussing the accuracy of a digital data acquisition system is what is called sampling error. Regardless of the DC accuracy of a data acquisition system, the ability to accurately recreate a changing signal decreases as the ratio between the frequency of the sampled data and the sampling rate decreases.

Let's take the example of a 1,000 Hz sine wave sampled at 10,000 samples per second. The worst case sampling related amplitude error can be as high as -4.89%. This is a real issue, and is being increasingly recognized as an issue which is at least as important as DC accuracy. Everyone has a different perspective when it comes to transient data acquisition. DTS decided that our systems must support higher sampling rates, because the future of accuracy improvements in the recording of crash-test-related transient events has to include increasing the sampling rate. At 25,000 samples per second, the sampling error of a 1 kHz sine wave is reduced to a worst case of -0.8% amplitude accuracy.