Get The Most From High-Resolution ADCs

Voltage-reference accuracy and drift, nonlinearity, and a number of noise sources can wreak havoc on precision measurements.

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Today's analog-to-digital converters (ADCs) have unquestionably reached very high performance levels. But don't be fooled into thinking that you can merely put an ADC chip on a circuit board to achieve the performance implied by the data-sheet specifications. Indeed, several factors are key in determining the accuracy of an analog measurement and the precision with which the digital value represents the measured analog signal.

Some important considerations are voltage-reference accuracy and drift, linearity, quantization noise, and other noise sources. With the advent of 24-bit ADCs, quantization noise usually isn't the major error source. With delta-sigma converters, it's possible to get linearity under 2 ppm of full-scale.

Moreover, if the measurement can be set up as ratiometric, voltage-reference accuracy and drift can be removed as an error source. For a ratiometric measurement, the reference voltage is used for both sensor excitation and the ADC's reference voltage. Any changes in the reference are reflected in both the sensor results and the ADC. Therefore, changes in the reference are removed as a source of measurement error. Of course, not all measurements can be set up as ratiometric measurements.

The performance of an ADC will be specified by the parameters listed on the manufacturer's data sheet. These parameters are defined to adequately represent all parts over their specified operating range. Naturally, a single part will perform better than those specifications. Once an ADC is designed in, designers should factor in temperature considerations. The system can be tested at several temperatures to obtain a map of how the converter's performance changes with temperature. That calibration information can be used to periodically compensate for the drifts that occur with temperature variations.

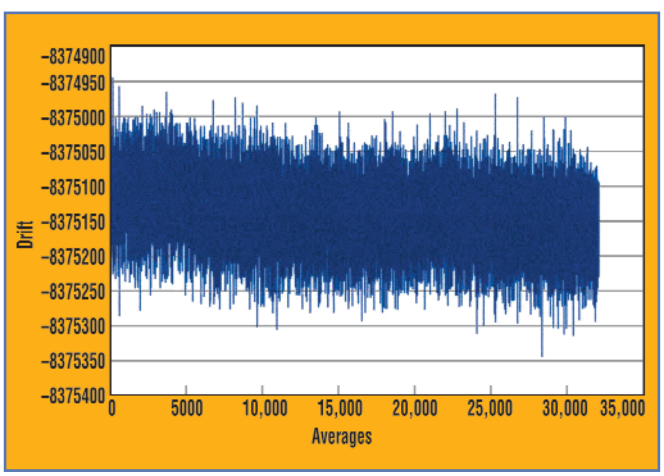
As far as raw performance is concerned, several factors have made it reasonable to talk about ADCs with 24 bits of precision. For example, the delta-sigma converter is essentially a single-bit conversion process. This assures that the system can be linear because there are only two voltages and one comparison.

During an analog-to-digital conversion process, the ADC's input is compared with either the maximum or minimum voltage to create a differential voltage, which is integrated and compared. The digital output is used to select the maximum or minimum voltage for comparison with the input voltage. This digital output produces a stream of ones and zeros that represents the input signal by the ratio of ones to zeros.

A combination of integration, oversampling, noise shaping, and digital filters helps weed out most noise to attain high resolution. Depending on the sampling speed and the number of samples averaged or filtered, the output can yield a result with high precision and low noise. To further reduce noise, additional averaging can be applied to the output results.

Effective Averaging: Several conditions determine the effectiveness of averaging:

- The noise has to be high enough so that the ADC result changes. A result that always remains the same doesn't provide any statistical information about the actual signal level. It could be almost high enough to output the next code, but no amount of averaging will increase the resolution and give you that information—unless you occasionally get that next code output. For this reason, it's sometimes useful to add noise to the input. If the noise is evenly distributed, it won't have an overall effect. But it will supply additional code outputs, which can be averaged to achieve a higher resolution.
- For a random distribution



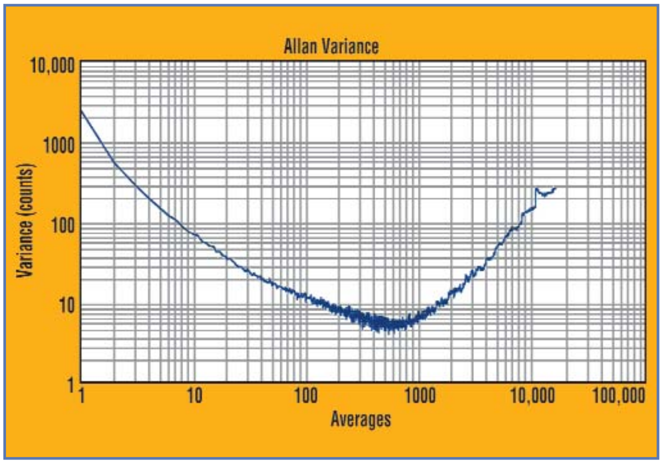
1. Shown here is an example of data that has a small drift in average value.

of noise, the signal-to-noise ratio (SNR) will be improved by the square root of the number of points averaged. For example, averaging four samples doubles SNR—so you effectively gain another bit of resolution. In other words, 4N averages can give you N bits of additional resolution.

• If there's a pattern to the noise, averaging might actually decrease the overall SNR. Drift is one such pattern that can seriously affect averaging. Drift can't be distinguished from changes in the input signal. It's easy to visualize that averaging more samples from a ramp doesn't lead to a higher resolution or more stable result.

• Semiconductor circuits have many types of noise sources. For high-precision, low-speed measurements, a predominant noise source can be flicker noise, also known as 1/f noise. The source of this noise is one of the longstanding unsolved problems in physics. But it's prevalent in active devices—and many passive ones. The 1/f name comes from the fact that the noise level increases for lower frequencies. It will appear as drift for measurements close to dc.

So if you're trying to achieve results close to the specified performance for high-resolution ADCs, all sources of noise must be carefully examined. The process of averaging can reduce random noise, but it has a limitation. As the number of averages is increased, more time samples are used to compute the average.



2. The results of this Allan Variance show a steady improvement in SNR up to about 800 averages. Using a larger number of averages actually degrades the results.

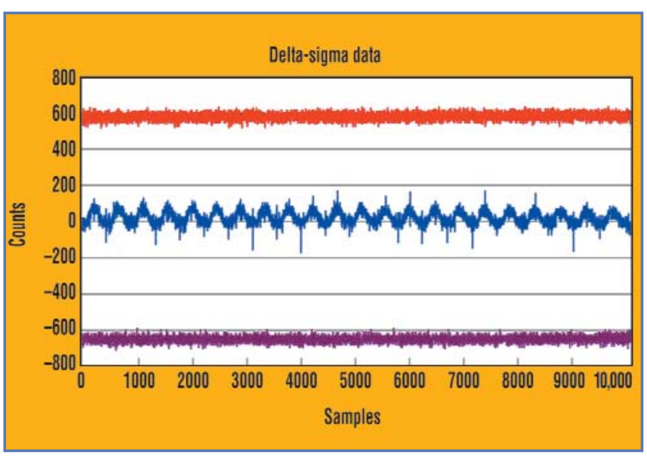
Obviously, if that signal is stable, then the larger number of samples will give a more precise measurement of the mean voltage. But if the signal has a slope, then additional samples increase the total range of values and shift the result. Consequently, 1/f noise limits the maximum number of useful averages. This can be shown graphically with a technique called Allan Variance.

Allan Variance: A way to determine the limitations of averaging large sets of data is known as Allan Variance. It basically breaks up the data into smaller subsets, then calculates the variance achieved for each different number of averages. The technique also shows that averaging can actually make the noise worse for some groups of data.

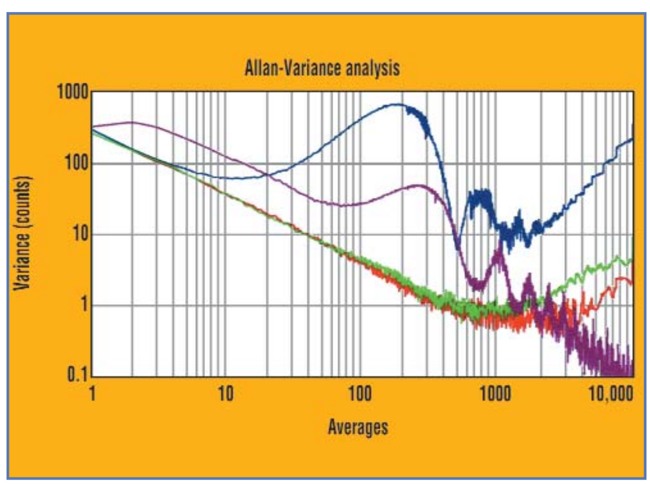
As shown in Figure 1, some regions of the data are fairly flat. Averages that include those areas should achieve the expected improvement in SNR. But we would expect that longer averages, which start to include shifting or drifting data, will cause the average to shift as well.

Note that there's a steady improvement as you increase the number of averages, until you attain a certain number of averages *(Fig. 2)*. In general, the SNR improves with an increasing number of averages. But after about 800 averages, no further benefit comes with a larger number of averages. In fact, the variance or the standard deviation squared actually starts to increase. With this set of data, the noise isn't reduced if you use more than 800 points to compute the average value.

Early delta-sigma converts exhibited a problem called idle tones. With a stable dc voltage applied to the input, the data results had the appearance of a low-frequency "tone," which usually occurred at 0 V. However, some manufacturers shifted the location of the tone voltage away from zero. They still had a tone, but it wasn't easy to locate the problem voltage.



3. These waveforms represent the output of a delta-sigma converter at three different dc voltage levels. Note the presence of an "idle tone" at 0 V.



4. When idle tones are present (upper two plots), the benefits of averaging are reduced.

There are a couple of reasons for this tone frequency. The nature of the delta-sigma process is one source of the tones. At certain voltages, the data bits out of the modulator would form into a low-frequency pattern. But this tone frequency was of a very low amplitude. Another source of tone frequencies was leakage of the sample clocks into the analog input. This would also create a low-frequency tone that couldn't be removed by the digital filters because it was within the passband. Figure 3 shows an example of this large form of tone frequency.

As might be expected, the Allan Variance reveals a rather interesting pattern when averaging data that includes this tone pattern. As mentioned earlier, this tone frequency was usually most pronounced at an input of 0 V. With these types of tones, the Allan Variance proves that a much smaller benefit results from averaging the data. Figure 4 clearly illustrates this where the two upper curves represent data containing idle tones. So consider using the Allan Variance if you want to gain a good understanding of your system's resolution limits.

System Design: Even after you have found the best delta-sigma ADC and designed the system to reduce the various error sources, a great deal of care must still be taken to ensure that the design can be realized in hardware. Consideration must be given to factors such as grounding and ground-return currents, power distribution, shielding, circuit-board construction, bypassing, signal paths and returns, lead inductance, parasitics, and thermocouple effects.

Aside from the electrical characteristics, other factors can affect the performance of a high-resolution system. These include component stresses, air flow, device orientation, and temperature distribution. In short, getting the full performance inherent in a given ADC takes a great deal of engineering focus and management over all associated details.

The online version of this article *(www.elecdesign.com)* includes a subroutine for computing the Allan Variance. Sometimes we assume that if we want lower noise, and we have plenty of time, we just need to average the noise data. It's useful to take an example of your data and pass it to this subroutine. Next, take the output and plot it on a log-log plot. You might be surprised that there's a consistent limit to how many averages you can use. The author will gladly send you a copy of the main program if requested by e-mail. Also, feel free to write if you have any other questions about this article.

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