Application Note

Seeing Is Believing!
ADC-AN-6

By Chuck Sabolis

Electronic image capture and digitization is the most subjective of all electronics disciplines. Its subjectivity is rooted in the unique interaction between the signal-processing capabilities of circuit hardware and the signal-processing capabilities of human physiology. Subtle, often insignificant, shortcomings or idiosyncrasies in signal-processing hardware can easily spawn image artifacts that are quickly detectable by the highly specific and extremely powerful skills of the human vision system. Understanding these interactions, especially in relation to an analog-to-digital converter (A/D or ADC), makes for a better image.

The Need Is Universal

Virtually every application in which electronic images are digitally captured, stored, transmitted, manipulated, etc., requires the use of an A/D to transform the analog output of the system's photodetector into its digital equivalent. High-end imaging applications including medical, commercial graphic, photo-CD workstations and many forms of scientific imaging continue their insatiable demand for higher-resolution (12 to 18 bits), higher-speed (1 to 20 MHz) A/Ds. In achieving image quality at this level, A/D converters have become second in importance only to the photodetectors themselves.

Improving the speed/resolution product of A/Ds requires performance trade-offs, and most A/D manufacturers are not making those trade-offs in favor of imaging. In response to the decreasing costs of digital computing power and the proliferation of digital signal processing (DSP) techniques, A/D manufacturers are often designing, testing and specifying new products with DSP applications in mind.

Total harmonic distortion (THD), for example, is a DSPbased specification many manufacturers seek to optimize. It is irrelevant to most imaging applications. Electronic image capture is not a DSP application. It is a traditional, time-domain, data-acquisition application.

Human Trade-Offs

The human visual system, impressive as it is, exhibits many trade-offs. While we are great at perceiving colors (due to an abundance of cones at the center of our retinas), our night vision is poor (not enough rods). The dynamic range of light intensities (brightness) we can detect is at least 100,000 to 1 (100 dB); however, the "accuracy" with which we perceive brightness is terrible.

We all know when a light is bright. Without the aid of scientific instruments, however, we can not determine exactly how bright it is. We are great at deciding which of two lights is brighter, especially in low-light conditions, but we can not tell how much brighter. Nor can we accurately determine when one light is twice or three times as bright as another. Our vision system lacks absolute accuracy and is very nonlinear.

Optimized for Edges

Along with perceiving color and detecting motion, the human visual system has been optimized for detecting edges; i.e., for detecting discontinuities. This ability is hardware-based and derives from the spatial density of visual receptors (rods and cones) on our retinas.

A/D converters, by their very nature, create discontinuities. They quantize or round off signals into predetermined levels. Improperly selected A/Ds in imaging applications can create discontinuities/edges where they do not otherwise exist or eliminate subtle edges that do exist. Because our eyes are optimized for detecting such things, we can spot these artifacts instantly.

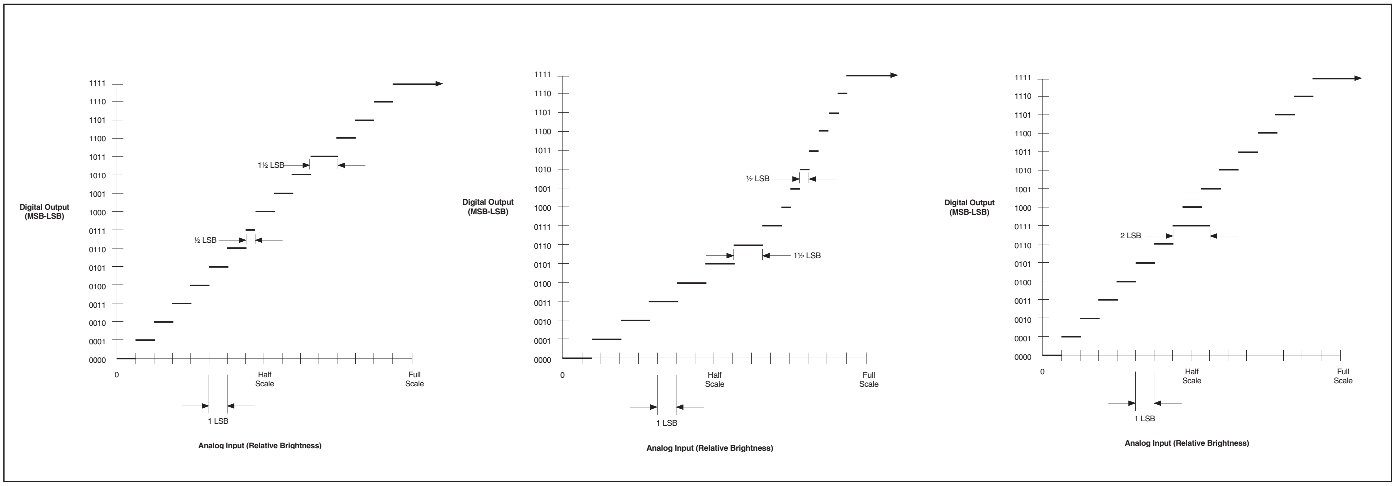

Figure 1. Input/output transfer functons for a linear photodetector configured with a 4-bit A/D; a) demonstrates ±½ LSB DNL errors; b)demonstrates how moderate DNL errors can accumulate to cause a significant INL error; c) demonstrates how a DNL error more negative than-1 results in a missing code.

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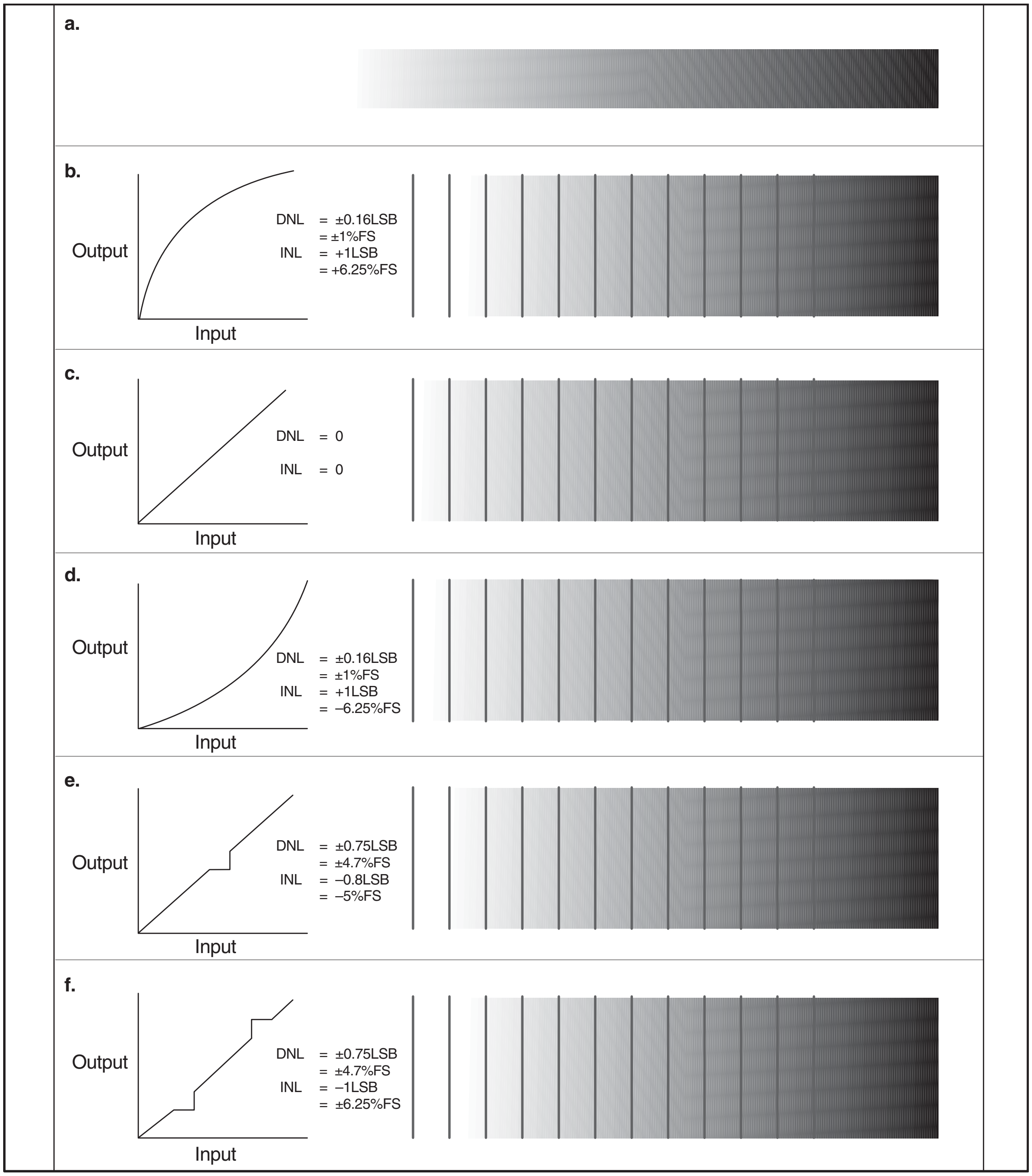


Figure 2. Demonstration of how INL and DNL errors in a 4-bit A/D affect the digitizing of the continuous tone wedge of a); b) small DNL errors accumulate to create a large positive INL; c) ideal A/D results step wedge; d) small DNL errors accumulate to create a large negative INL; e) a moderate DNL error at mid scale is quickly detectable though INL is hardly affected; f) DNL errors at ¼ and ¾ scale are also easily detectable.

The Big Spec

The single most important A/D spec for imaging applications is differential linearity error (also called differential nonlinearity or DNL). Figure 1 shows the analog-input/digital-output transfer function of a 4-bit A/D with associated photodetector. The horizontal axis is relative light intensity or brightness. The vertical axis is the A/D's digital output. There are 16 output codes and 15 transitions at which the output increments from each code to the next.

The I/0 function visibly demonstrates the A/D's quantizing function. For the ideal A/D, every tread in its staircase is exactly one least significant bit (LSB) wide. Each time the analog input increases an amount equal to 1 LSB (full scale range divided by 2n where n = number of bits), the digital output counts up to the next code.

An A/D exhibits a DNL error when it requires greater or less than the ideal increment in input signal to affect an increment in output code. In the staircase analogy, the treads are either wider or narrower than expected.

Approximately halfway through the I/0 function of Figure la, the output increments after the input has increased only ½ LSB. At this point, the device exhibits a negative 1½ LSB DNL error. Later in the function, a 1½ LSB input increment is required to affect an output increment. At this point, the device exhibits a positive ½ LSB DNL error. There is a limit on negative DNL errors. If they increase to – 1 LSB, the code disappears (Figure 1c).

While the DNL spec focuses on each individual step in an A/D's transfer function, integral linearity error (INL) relates to the overall linearity of the device's I/0 function over its full range.

In certain situations, sequential, relatively benign DNL errors can accumulate to produce significant INL errors. In Figure 1b, the first seven codes have + ½ LSB DNL errors, the eighth code is normal, and the next seven codes exhibit – ½ LSB DNL errors. Though the subsequent bowing is dramatic, it is comparatively smooth and would not be disastrous in an imaging application. That's because human vision is not very linear. Our visual linearity is less than ±1 percent. This is a level of performance normally associated with 6 to 7-bit A/Ds.

Conversely, small numbers of moderately large DNL errors, because they result in sharp discontinuities, can have little effect on the overall INL of a converter yet cause havoc in imaging applications, as is demonstrated below.

Figure 2a, commonly referred to as a continuous tone wedge, is a gradual linear excursion of gray tones from white to black. Precise, continuous tone wedges are often used to test or calibrate electronic imaging equipment.

Sixteen Distinct Levels

If the tone wedge is digitized by a linear photodetector married to a perfect 4-bit A/D and then reconstructed on a good CRT or photographic paper, the result will be the step wedge of Figure 2c. There are 16 distinct levels in this gray scale, corresponding to the 16 different output codes of the 4- bit A/D. Because our ideal A/D has perfect DNL, the incremental brightness in 2c is the same from step to step.

If the A/D has a series of cumulative negative DNL errors followed by a series of positive DNL errors, the result, as discussed, can be a rather severe positive INL bowing. Using this A/D, the reconstructed step wedge becomes that of Figure 2b. The opposite condition results in negative bowing and the step wedge of Figure 2d. In both examples, the calculated INL (using the endpoint definition) is equal to 1 LSB (6.6 percent of full scale). While this magnitude of INL error is detectable by the human vision system, neither of the two nonlinear step wedges is particularly offensive.

A moderately large positive DNL error at mid-scale, immediately followed by an equally large negative DNL error, results in respectable overall INL but yields the step wedge of Figure 2e. Our ability to detect edges makes the discontinuities in 2e stand out ... though the overall transfer function of 2e has better INL than either 2b or 2d. Figure 2f has DNL errors at ¼ and ¾ scale, and the results are similar to 2e.

A/Ds for imaging applications must have excellent DNL. As a minimum, the specified maximum DNL error should not exceed +½ LSB. Many contemporary A/Ds list ±1 LSB as a maximum DNL error; others list only typicals and rely more heavily on their FFT specifications. Recently introduced imaging-specific devices from DATEL Inc. guarantee ±¼ LSB maximum DNL errors.

Photo Noise

Most imaging systems seek to have overall system noise limited by the photodetector and not the signal-processing electronics. In the context of this article, A/D noise can be thought of as instantaneous DNL errors that are random in both space and time. If given incident light conditions are expected to yield a given digital output code, A/D noise can easily result in the next higher or lower code.

Although a full explanation of noise in A/Ds requires another article, a straightforward manner in which to narrow the selection of A/Ds is to apply a DC input signal to a continuously converting device and observe the number of different output codes appearing. Practitioners of this approach commonly describe devices as having two codes of noise or three codes of noise, etc.

Most people use a grounded input for this test. Virtually all of today's high-resolution A/Ds exploit the so-called subranging architecture, and for these devices, the noisiest code transitions do not occur around zero. A good test setup must be able to vary the A/D input throughout its full range.

Additional Critical Capabilities

Full-scale step response and overvoltage recovery time are two relevant A/D specs that are easily understood in the context of multiple-ment, scanned imaging systems employing CCDs. In these systems, it is possible to encounter a full-scale change (from empty well to full well) between adjacent pixels. A good imaging A/D must be able to sequentially acquire and accurately convert both signal extremes.

Because most of today's sampling A/Ds do not bring the output of their sampling front-end to a device pin, listed specifications for large-signal bandwidth, small-signal bandwidth, S/H slew rate and S/H acquisition time are difficult to verify and can be misleading. A/Ds that do not specify how they will perform under the above conditions need to be carefully evaluated.

The test for full-scale step response is straightforward. Immediately after the S/H front-end goes into hold, the A/Dconverter section begins converting. This event is usually controlled by a timing signal brought out to a device pin. Once the conversion has begun, the input can be changed without affecting its results. In the step test, the A/D first converts a static signal at one extreme of its input range. When the S/H goes into hold, the input is driven to its other extreme. When the S/H is released back into signal-acquisition mode, it sees the new input and is forced to slew its full range and settle in order to accurately acquire the new input (see Figure 3).

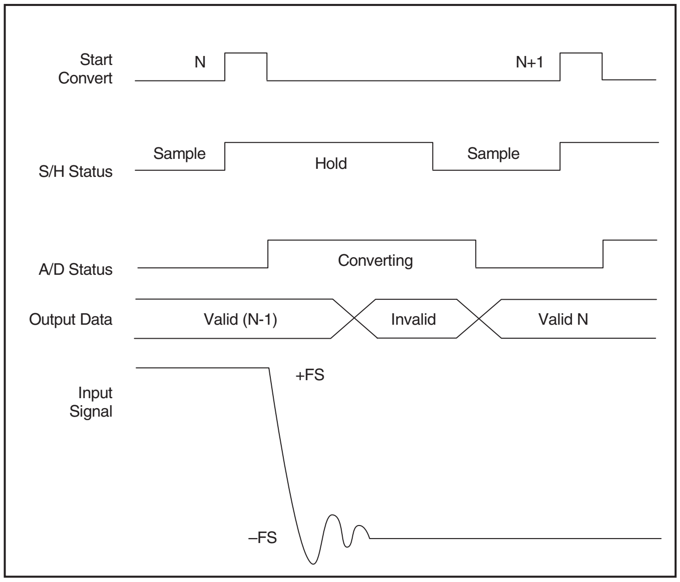
Overvoltage Recovery Time

Whether caused by greater-than-expected light intensities or longer-than-appropriate exposure/integration times, imaging photodetectors can quickly saturate and become nonlinear. Saturation conditions can ripple through subsequent analog-signal-processing circuitry, and it is not uncommon for A/D converters to experience input voltages exceeding their nominal ranges.

Though most A/Ds will saturate under these conditions (driving their output to all 1s or all 0s), the important question is how quickly devices recover from an overvoltaged input. Manufacturers frequently specify an overvoltage recovery time (in nanoseconds) with the implication that users should wait before continuing to collect accurate data. This stop-and-wait approach is inappropriate for imaging. It's more appropriate to simply note how many conversions should be discarded, or at least flagged, before continuing with accurate data.

Overvoltage recovery times can vary widely with the magnitude and/or the duration of the infraction. A/D manufacturers typically specify an overvoltage recovery time for a 10 percent overvoltage. The same specs may not apply for a 20 percent overvoltage.

The best advice, as usual, is to test any A/Ds you may be considering under conditions appropriate to your application. Ideally, the A/D you select should be able to perform accurately on the very next conversion following the removal of the overvoltage condition. If it cannot, appropriate clamping, assuming it does not slow things down, is always a good idea.



When testing a sampling A/D for full-scale response, the input signal can begin to change as soon as the front-end S/H goes into "hold."

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03/20/09

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