Technology Close-Up

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Dynamic Range:

Buyers Need Comparable Specifications

by Albert J.P. Theuwissen

The dynamic range of a solid-state image sensor is one of the most significant characteristics if the device is used in high-end digital still photography or medical single-shot applications. In video applications, the monitor or the human eye averages the noise from picture to picture. In a single-shot application, however, the overall noise in the picture is frozen on the monitor or on the hard copy. To make digital still applications shot-noise-limited with an acceptable signal-to-noise ratio, the sensor must provide a large dynamic range.

Unfortunately, no one correct and uniform definition of dynamic range seems to exist. If a potential buyer compares the data sheets of various charge-coupled device (CCD) vendors, he or she will discover that every manufacturer seems to specify the dynamic range in a different way and under different conditions.

Most detector buyers already know that sensor manufacturers' dynamic range specifications are not comparable in a practical sense. Several CCD suppliers specify their devices without taking into account the effects of dark current and temperature. In fact, the dynamic range depends very much on various parameters related to the CCD's temperature and driving electronics.

A ratio of voltage swing to noise

A lot of misunderstanding exists (even for specialists in the field) when it comes to the definition of the dynamic range. The dynamic range should give the user an idea of the output voltage range that is available for the application, compared with the noise floor. Video processing circuitry that follows the CCD can affect the noise floor.

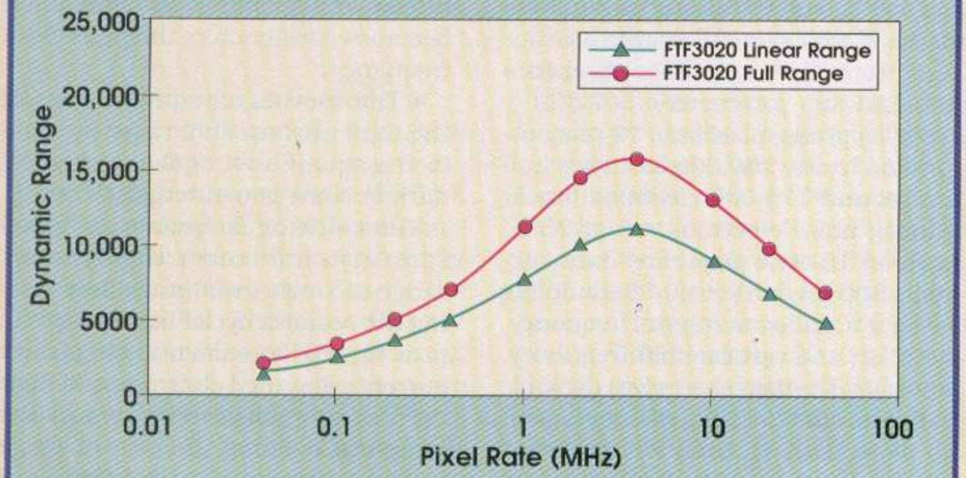

Figure 1. Dynamic range fluctuates with pixel readout rate, but optimizing the clocking speed minimizes its pixel rate effects.

Thus, we can define dynamic range as the ratio of the maximum available output voltage swing for the video signal to the noise level of the imager, measured after video preprocessing.

This definition contains two main components:

- The available output voltage swing is equal to the saturation level of the device minus the dark current generated in and by the device. The influence of dark current is becoming more important, especially with larger integration or storage times at elevated temperatures.
- The noise of the imager comprises two main components: the noise of the CCD output amplifier and the shot noise on the dark current.

As a formula, our definition can be written as:

$$DR = 20 \times \log [(N_{max} - N_{dark})/\sqrt{(n^2_{amp} + n^2_{dark})}]$$

where DR is the dynamic range in decibels; N_{max} is the number of electrons at saturation; N_{dark} is the number of dark current-generated electrons; n_{amp} is the number of electrons representing thermal output-stage noise; and n_{dark} is the number of electrons representing dark current shot noise, which also is equal to $\sqrt{N_{dark}}$. (The equation also is valid with parameters expressed in equivalent voltages, rather than electrons.) To convert DR to bits, 6 dB equals a bit.

This definition might look complicated and even conservative compared with what is used in the various commercial data sheets, but it is valid only if appropriate signal processing is used in the application.

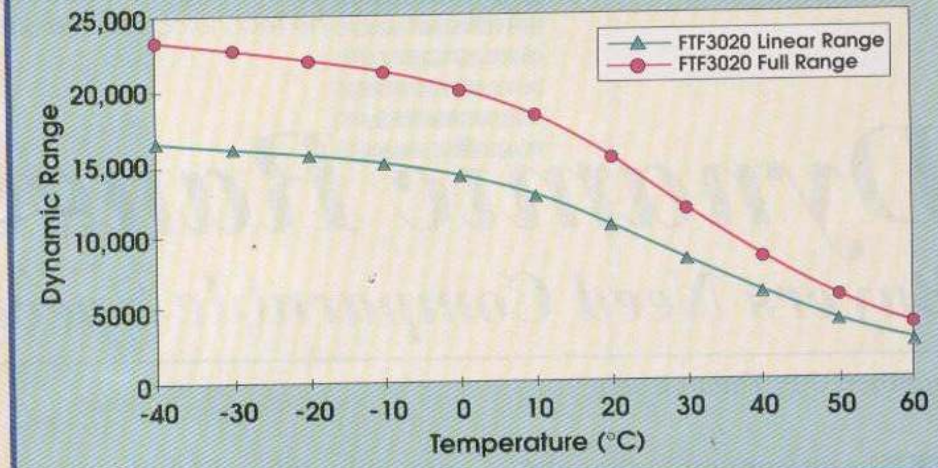

Figure 2. A CCD in an application at room temperature or above can have a dynamic range very different from a manufacturer's specification under cooler laboratory conditions.

This means that a video processing unit should remove at least the reset noise and 1/frequency noise. The processing unit can be based on a correlated double sampler or something similar. The equation also assumes the presence of an adapted low-pass filter that removes all of the high-frequency components of noise. If video preprocessing is not limiting the noise or is optimized for noise performance, the dynamic range figure will be lower.

Real-world examples

To study this equation more fully, we will calculate various parameters of the FTF3020, a full-frame CCD imager from Philips. Its data sheet lists the following parameters: 3072 (h) × 2048 (v) pixels; pixel size, 12 µm; saturation levels, 250,000 electrons (full range) and 175,000 electrons (linear range); noise electrons, 25 at 25 °C with an 18-MHz pixel rate; dark current, 300 pA/cm² at 60 °C, doubling every 8 °C; maximum pixel frequency, 40 MHz; and vertical shift frequency, <50 kHz. The data sheet gives dynamic range as 4200 (or 72.5 dB, equivalent to more than 12 bits) for the linear range, which is equivalent to slightly more than 12 bits even at 60 °C. (The device has a built-in antiblooming capability, which explains why its transfer curve is linear to only about 175,000 electrons. It then bends toward saturation and is not linear.)

We will use this device to investigate the four main components used in our definition of dynamic range:

- The saturation level of the imager is independent of any parameter considered in this study.
- The dark current is a strong function of temperature (for instance, doubling every 8 °C), and the amount of dark current collected in the imager's pixels is directly proportional to the integration time and the storage time.
- The noise level of the output amplifier is directly proportional to absolute temperature and is proportional to the square root of the bandwidth of the overall video amplifier. The latter has a relation to the pixel rate, so the optimized amplifier noise becomes a function of the pixel clock frequency.
- The root mean square value of the dark current shot noise is equal to the square root of the number of dark current-generated electrons.

The clocking frequency, or pixel rate, also influences the dynamic range through the storage time during the readout cycle. Increasing the pixel rate reduces the number of dark current-generated electrons and dark current shot noise and increases the temporal noise of the output stage by requiring more bandwidth in the output amplifier and video-processing electronics.

To calculate the influence of pixel rate on dynamic range (Figure 1), some other parameters are set to fixed values: The vertical clocking speed is chosen to be 50 kHz, temperature is fixed at 20 °C and integration time is set at 20 ms.

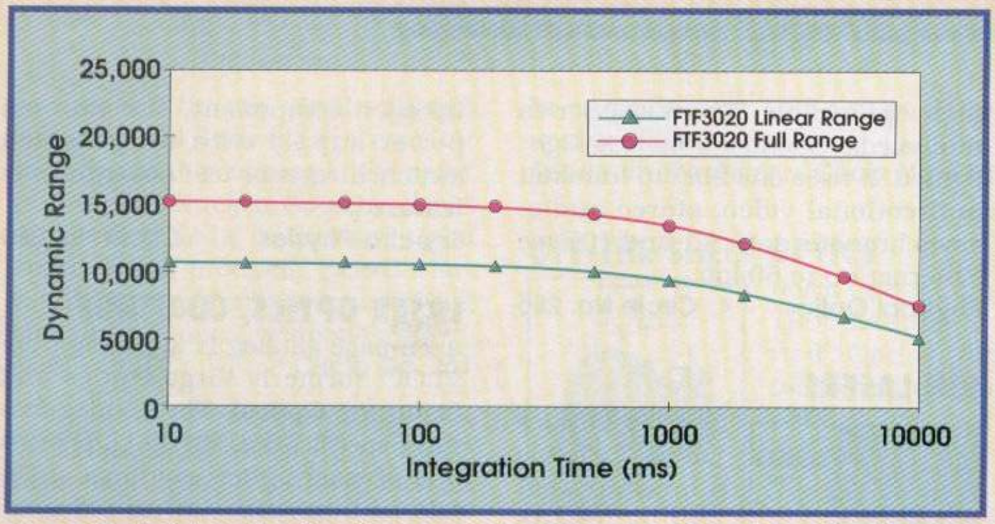

Figure 3. As integration time increases, dynamic range drops. The effect is strongest when integration times are longer.

There seems to be an optimum clocking speed for maximum dynamic range. This can be explained by the trade-off between increasing output amplifier noise and decreasing dark current and dark current shot noise. For the device in our example, this optimum is at a 4-MHz pixel rate.

The temperature will influence the dynamic range through dark current, shot noise on the dark current and temporal noise of the output amplifier. To calculate the dynamic range as a function of the temperature (Figure 2), the following parameters were fixed: integration time at 10 ms, vertical clocking frequency at 50 kHz and pixel rate at the optimal clocking frequency.

Temperature, integration effects

The dependence of the dynamic range on temperature is easy to explain: At higher temperature, the dark current is dominant; at lower temperatures the dynamic range is mainly determined by the noise floor of the output amplifier. The latter does not change very much with temperature. For that reason, the curves become relatively flat. Reducing the CCD temperature (e.g., by means of active cooling) improves its dynamic range.

The last parameter that influences dynamic range is integration time, which relates directly to dark current. The dynamic range (Figure 3) is calculated at different values of the integration time, keeping the temperature constant at 20 °C, the vertical clocking speed constant at 50 kHz and the pixel rate constant at the optimal value.

Increasing the integration time automatically increases the dark current. This effect is of only minor importance for the shorter integration times because for these values the integration is relatively short compared with the storage time, which is set by the readout speed of the device.

Realistic assumptions

Thus far the dynamic range of the devices is considered on a more or less theoretical base. For instance, the devices were driven at their optimum speed, etc. In a realistic application, the operating frequency is not defined by the CCD, but by the surrounding electronics, such as the analog-to-digital converter.

On the other hand, the temperature at which the imager operates is usually higher than room temperature because of heat dissipation in the camera. A realistic proposal to operate the imager can be 35 °C sensor temperature and 5-MHz pixel frequency, integration time of 10 ms and vertical clocks of 50 kHz.

With these operating conditions, the dynamic range of the FTF3020 can be calculated as 7960 or 78 dB, 13 bits (linear range) and 11,370 or 81 dB, 13.5 bits (full range). □

Meet the author

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