BY **MIKE WOOD**

Rolling, rolling, rolling . . .

Camera light sensors react differently to images lit with PWM-dimmed LEDs

DID YOU KNOW that your cell phone and still cameras often use a completely different type of light sensor than the one in your video camera or camcorder? Most likely you knew that there were different types of optical sensors, but, unless you were a professional cameraman or photographer, you didn't really care too much. What might make you more interested, however, is the way these different types of sensors cope with light from LEDs, specifically LEDs dimmed using PWM (pulse width modulation).

> **" . . . none of these solutions really fix the core issue, they just mask it . . . "**

I don't want to get too far into the weeds with the technical details of the sensors themselves, but we need to at least cover the basics so we can understand the problem. The two main sensor types are commonly known as CCD (charge coupled device) and CMOS (complementary metal oxide semiconductor) sensors. Each technology has its own advantages and disadvantages that make them better suited for specific tasks. In very general terms, video cameras and camcorders typically use CCD sensors, while still cameras, DSLRs, webcams, and cell phones use CMOS sensors. Both sensor types do fundamentally the same job of turning light energy into an electrical signal representing an image, but they do it in different ways. The difference we are interested in is the timing of how the sensor is exposed to light, and whether that exposure uses a global or a rolling shutter.

As a broad statement, most CCD sensors use a global shutter while most CMOS sensors use a rolling shutter (*Note: this is not a hard and fast rule, it is possible for CMOS sensors to simulate a global shutter*). What is the difference between these two shutter types and why does it matter to us? Let's start with the global shutter. As the name suggests, a sensor using a global shutter exposes the entire image at one time. When the shutter opens, the sensor starts gathering and integrating light at every pixel across the whole frame at the same time. At the end of that light integration time (shutter time) the accumulated electrical charges on every pixel are simultaneously transferred to a non-light sensitive area of the chip and light collection stops. This simultaneity across the frame means that a global shutter effectively freezes a moment in time. **Figure 1** shows the process. Step **A** shows all pixels disabled, the shutter is closed; in **B**, the shutter is opened, all pixels are enabled and the sensor captures light everywhere; and finally, in step **C**, the pixels are disabled again.

Figure 1 – Global shutter

The rolling shutter in a CMOS sensor, on the other hand, behaves very differently. Take a look at **Figure 2**. The pixels in a CMOS sensor are not all exposed to light at the same time, instead each row of sensors (usually a horizontal row, but it can be vertical) is exposed to light one at a time. The top row is enabled to collect light first, and then, some short time later, the next row will be enabled and so on. After a row has been exposed for the selected integration or shutter time, light collection for that row is disabled. Each subsequent row will then be disabled, one after another, in sequence. Each row is enabled for the same selected shutter time, but every row is staggered as to its start and end times. The result is a band of enabled pixels that moves down the sensor with the width of that band defining the shutter speed. **Figure 2** shows the exposed band scanning down the image as the image is captured. This means that the bottom portion of the image (**C**) is exposed to light later in time than the top portion (**A**).

Figure 2 – Rolling shutter

This time shift from top to bottom of the image can cause some strange effects. Most familiar perhaps is the bending or skewing of the image if either the object or the camera is moving sideways as the image is taken. **Figure 3** shows a possible sequence.

Figure 3 – Image skew

In this example imagine that the camera is stationary, but we are taking a picture of the red vertical bar which is moving from right to left across our field of view. As we press the camera shutter, the red bar is on the right side of the field and so the top of our final image, **A**, records the bar in that position. However, as the rolling shutter scans down, so the red bar is moving to the left and thus each successive row of the

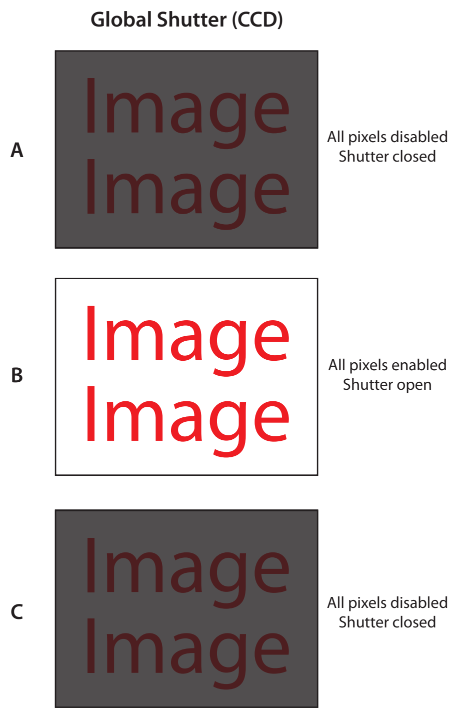

Figure 1 – Global shutter

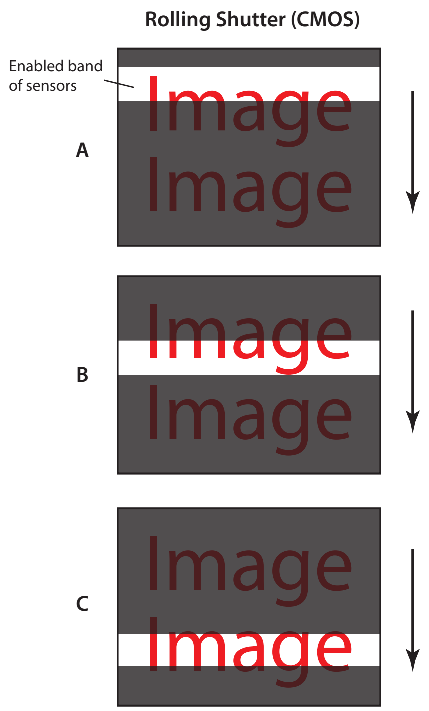

Figure 2 – Rolling shutter

image will see that bar further and further to the left. At point **B**, halfway through the scan, the bar is in the middle of the image, while finally, as we expose the last rows, **C**, the bar has made it all the way over to the left of the frame. The resultant final image shows a skewed diagonal bar from top right to bottom left. You can try this right now with your cell phone, which, I'm 99.9% sure, has a CMOS sensor. Try photographing from a moving car out of the side window (get someone else to drive), and you will see vertical light poles exhibiting this skew.

This skew distortion and sensitivity to movement is one reason why CMOS sensors are not that common in video cameras. Such cameras are very often moving and, of course, are used to capture images of moving objects.

Note: There are exceptions, some high end digital movie cameras such as those from RED and ARRI use CMOS sensors, but by running the scan at very high speed, and applying post-capture image processing, the skew can be removed from the captured image. Avatar was shot with CMOS based cameras, and Peter Jackson is shooting The Hobbit *with them right now.*

All very interesting Mike, you might be thinking, but what has this got to do with LEDs and lighting? Here's the problem: that time shift between the top and bottom of the frame can be a huge problem with light sources that don't emit continuous light, such as an LED source using PWM dimming. As a quick reminder, PWM dimming of an LED source is achieved by turning the LED on and off very rapidly and varying the ratio between the amount of time the light is on in relation to the time that it's off. When the light is on all the time, then the LED source is at full output. When it's off all the time, it's off, and when it's on for half the time and off for half the time our eyes see it as illuminating at 50% brightness. As long as the pulses are quick enough, our eyes convert that pulsing into an apparently constant brightness level. Most of the time cameras behave the same way as our eyes. In particular, a global shutter sensor will also convert the light pulses into an effective brightness level by integrating those pulses into each captured frame. You might get an aliasing problem with a global shutter if the PWM rate is very low and the frequency interferes with that of the frame rate, but, in general, you can usually resolve those issues by speeding up the PWM or by adjusting the shutter on the camera. *As a rule of thumb, PWM rates*

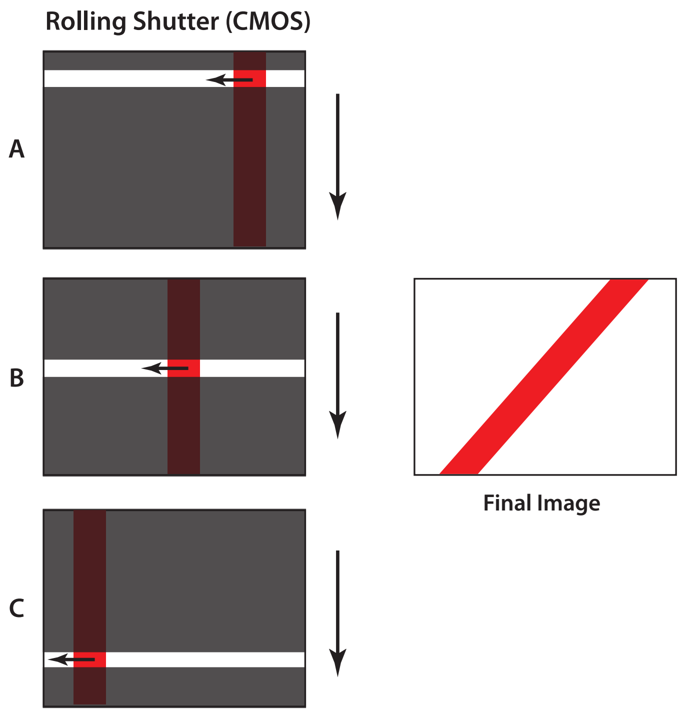

Figure 3 – Image skew

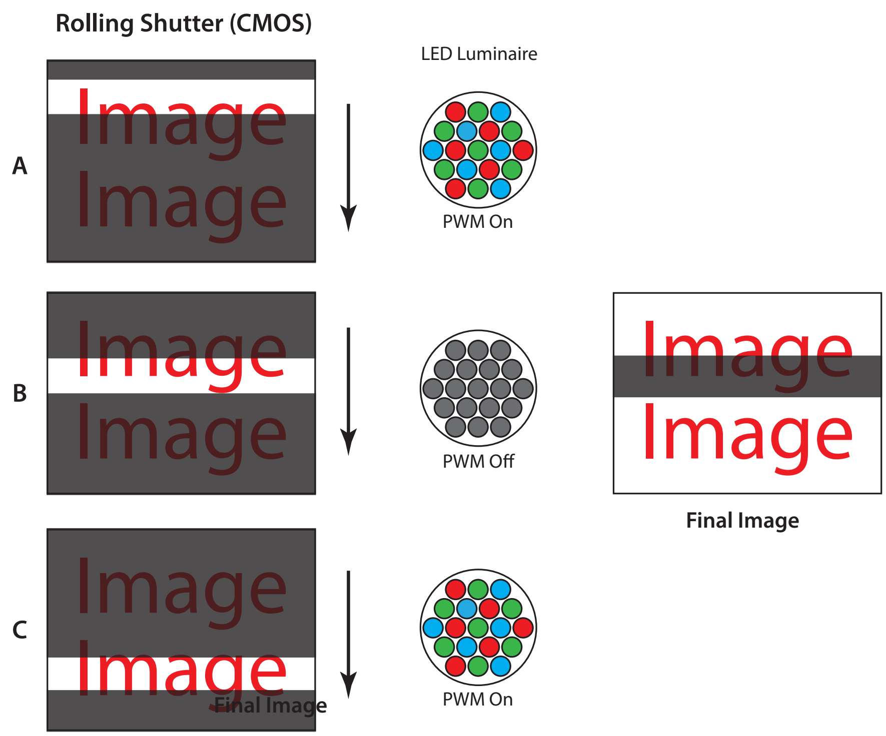

Figure 4 – PWM banding

of more than 400Hz seem to work with CCD based video cameras.

Unfortunately rolling shutter sensors present a very different and more intractable problem than the simple aliasing you get with global shutters! **Figure 4** shows our same image as **Figure 2**, but this time using an LED luminaire with PWM dimming to illuminate the scene.

Figure 4 – PWM banding

At point **A** in the exposure process all is well, the LED PWM timing is such that the LEDs are energized and the rows of pixels currently enabled are receiving light. However, at point **B** we have a problem. Now the LED PWM cycle has turned the LEDs off so that particular strip of pixels will receive no light. By the time we get to **C**, the LEDs have turned back on again and the bottom of the image is exposed to light again.

The end result is an image with two problems. Firstly, and most obviously, there is a band of the image that received no light when the PWM cycle was off, so it shows up as a dark stripe across the picture. Secondly, and more subtly annoying, the areas of the image that did receive light are actually overexposed! Those areas see the LEDs on at full power, no matter what the dim level is actually set to. A rolling scan shutter doesn't integrate the light across the whole PWM cycle as both our eyes and a global scan shutter do. Instead each pixel sees the light as either off, or on at full power. Black or white, no shades of grey.

In practice you rarely see a stationary black stripe across an overexposed image. Instead, in a CMOS sensor based video camera the band will be moving up or down the image at a speed dependent on the ratio between the CMOS scan frequency and the PWM frequency. Similarly with a still camera, such as a DSLR that uses a rolling shutter, you will usually see an underexposed band rather than a fully black one. Either way it's annoying and usually unacceptable. This phenomenon can be very hard to get rid of. The scan speed on many CMOS cameras is quite high, so PWM frequencies in excess of 1 kHz, which are normally thought of as camera-safe, may still exhibit problems. Sometimes opening up the camera shutter angle, or finding a shutter speed and PWM angle that don't match too closely, will help reduce the problem. Sometimes changing the LED dimmer level, or using multiple LED units where the PWM frequencies are out of phase with each other will also help. However, none of these solutions really fix the core issue, they just mask it. If all else fails, switching to a global shutter camera will usually solve it.

If you haven't seen this problem yet, let me assure you that you have been lucky so far and you will! As LEDs are used increasingly for key lights and as lights for TV, film, and still photography the problem will appear more and more often. There's nothing really new here, none of this is a new problem to the film community. It's a problem that film DPs have long learned to live with and address with arc and fluorescent lamps which also have intermittent light output. Nor is it very different from the problems with using electronic flash with mechanical SLR cameras, which also used a form of rolling shutter called a focal-plane shutter. If you recall, the solution for that particular problem was to set the shutter speed to 1/60 of a second or slower so that the mechanical rolling shutter behaved as if it were a global one. However LEDs present a more difficult problem than the older light sources. The contrast range of light intensity in an LED PWM cycle can be larger than with prior technologies, and the transitions from on to off are more abrupt. An LED goes from full output to zero output in essentially zero time, so there is no chance to blur the edges. You can run your LEDs at full power, or dim them linearly to bypass the problem, as some manufactures are already doing, but that technique has its own problems and

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isn't a universal panacea. *LED wavelength can shift with current when they are linearly dimmed. It's fine for white LEDs, not so good for colored ones.*

I encourage you to experiment. Take your cell phone camera or your webcam (both of which use inexpensive CMOS sensors with low scan rates that exaggerate the problem) and look at some images lit with PWM dimmed LEDs. You may be surprised at what you see. ■

Mike Wood runs Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on product design, technology strategy, R&D, standards, and Intellectual Property. A 30-year veteran of the entertainment technology industry, Mike is the current chair of the PLASA Governing Body and Treasurer of PLASA North American Regional Board. Mike can be reached at mike@mikewoodconsulting.com.