Measuring Camera Shutter Speed

Peter D. Hiscocks
Royal Astronomical Society, Toronto Centre, Canada
Syscomp Electronic Design Limited
Email: phiscock@ee.ryerson.ca

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Introduction

This digital camera is a useful instrument for the measurement of light pollution. It can be used to simultaneously create a photographic record of a scene and perform the function of a light meter. If the camera is properly calibrated, the numerical value of a pixel in the image can be related to luminance (brightness) in the image. Then a digital camera becomes a low-cost measuring instrument, replacing specialized instruments of much higher cost.

The calibration is performed by photographing a source (such as an incandescent lamp) whose luminance is known. The photograph is taken at some specific shutter speed and aperture. In theory, this calibration value can be extrapolated to other values of shutter speed and aperture. For example, the exposure is directly proportional to the shutter interval. Unfortunately, there are several problems with this approach:

- The actual shutter speed is only approximately equal to its reported value.
- Depending on the camera,there may be some variation in shutter speed between exposures.
- At high shutter speeds, the opening and closing of the shutter is poorly defined, and so it is difficult to delineate the shutter interval with precision.

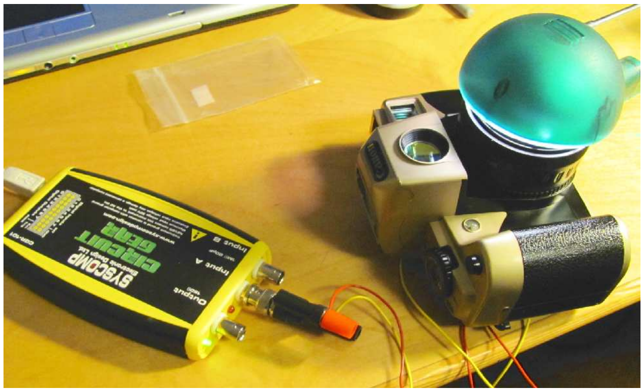
These variations are small enough that they have no visible imact on the exposure of images, but they do affect precision measurements of luminance. We needed to measure camera shutter speeds to determine whether it was feasible to extrapolate luminance measurement to different shutter speeds.

Mechanical Shutter

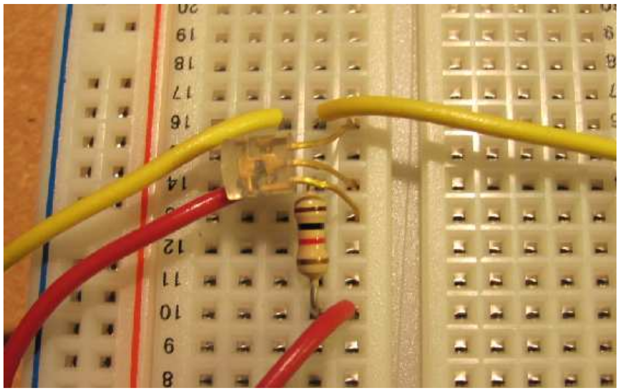
It's very straightforward to measure the interval of a mechanical shutter. A phototransistor is connected to a resistor and DC power supply. It is then placed in the body of the camera, behind the shutter. The camera is aimed at a source of light. The output of the phototransistor is connected to a digital oscilloscope, such as the Syscomp CGR-101. The shutter is triggered and the resultant pulse of light displayed on the oscilloscope. Compared to the speed of a mechanical shutter, the response of the phototransistor and oscilloscope are instantaneous. The oscilloscope captures the phototransistor pulse and display is an accurate rendition of the opening and closing of the shutter.

An example measurement is shown in figure 1. Figure 1(a) shows the arrangement of the camera body, with a table lamp placed to shine into the lens. The photodetector circuit, shown in figure 1(b), is under the camera where the film would normally be located. The circuit is very simple: a 2N5777 phototransistor[1] with 1kΩ pullup

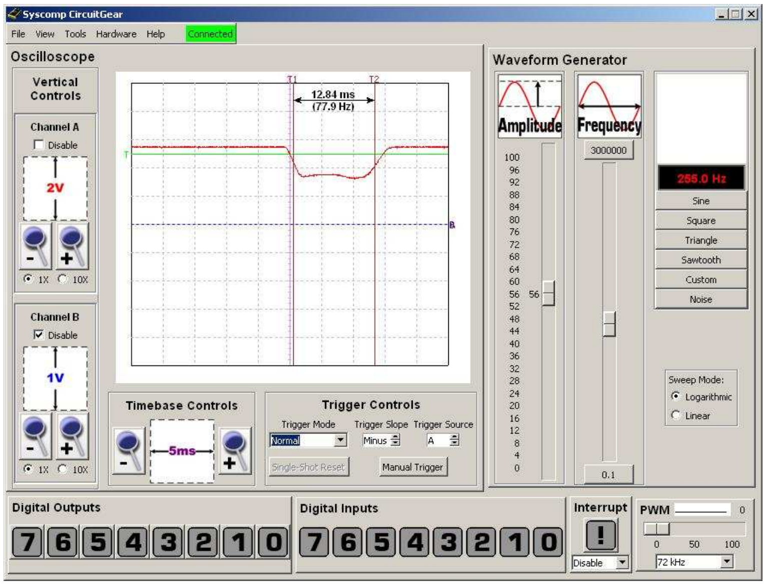
[1] The 2N5777 phototransistor may be difficult to find. However, it's not critical. Any darlington phototransistor will work in this circuit.



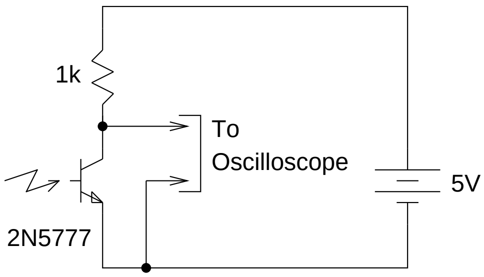
(a) Arrangement



(b) Circuit



(c) Measurement



(d) Schematic

Figure 1: Measurement of Mechanical Shutter

resistor to +5 volts. The output of the transistor collector goes to the oscilloscope channel A. When the shutter opens, light falls on the phototransistor, causing it to conduct. That causes a brief drop in the collector voltage, which is captured by the oscilloscope. Figure 1(c) shows the measurement result. The shutter is open for about 12.8 milliseconds, corresponding to a speed of 1/78 second.

This won't work with a digital camera. There is no way to insert a phototransistor behind the shutter in the position of the detector array. Furthermore, a digital camera may use a combination of mechanical and electronic shuttering.

Turntable Method

A record turntable rotates at a known speed: 33.3 rpm, 45 rpm or 78 rpm. If the turntable is black, place a white line between the centre and the edge. Photograph the turntable. In the photograph, the white line will sweep out a sector proportional to the shutter interval. Measure the angle and use the rotational speed to determine the shutter interval [2]. Figure 2 shows a typical image.

This method works after a fashion, but its range is very limited because of the limited choice of speeds of the turntable. We tested the Canon SX120IS over the shutter speed range 1 second to 1/6 second and measured shutter speed errors between 0.41% and 15%.

Figure 2: Turntable Calibration

VGA Computer Display Method

Rob Crocket [1] describes a shutter speed calibration technique using the scanning of a computer monitor display. A calibrated scale is overlaid on the display. The screen is photographed, with a result similar to figure 3.

For example, figure 3 shows the result of photographing the screen at 1/200 second.

The screen refresh rate is known, something like 75.14Hz in this case. Then the time to refresh the screen is the inverse of that, 13.3 milliseconds. The image of figure 3 starts at 2.8 divisions and ends at 6.9 divisions. The total screen height, allowing for retrace, is 10.4 divisions. Then the shutter interval is:

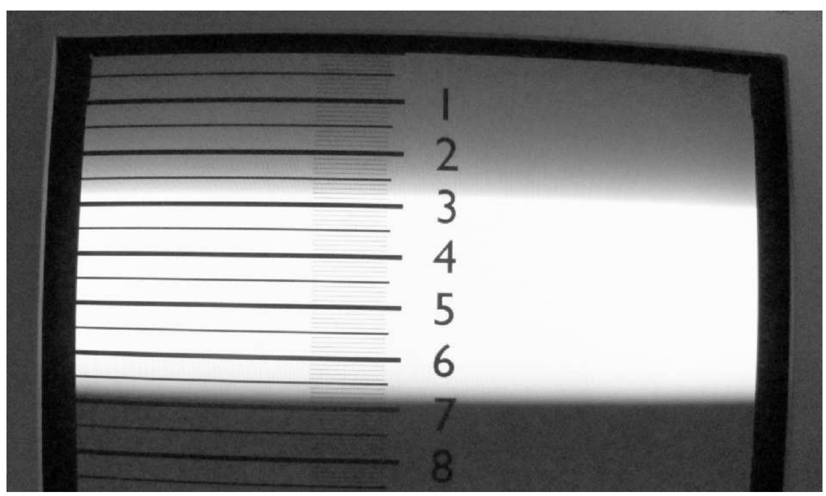


Figure 3: VGA Display Calibration

$$t_{shutter} = \frac{6.9 - 2.8}{10.4} \times 13.3 \quad (1)$$

$$= 5.24 \text{ milliseconds} \quad (2)$$

which corresponds to a speed of 1/190 second.

This technique was used to test the shutter calibration of the Canon SX120IS over the speed range 1/125 to 1/640 sec. The errors ranged from 0.83% to 6.47%. Shutter speeds greater than 1/640 gave extremely large errors, so the VGA technique is not useful above that speed.

Television Screen Method

The North American standard television screen originally used the NTSC scanning system. An electron beam scans the screen horizontally at a rate of 15750 lines per second [2]. Consequently, a photograph of such a screen will show a number of lines that is proportional to the shutter interval of the camera. Figure 4 shows part of an image taken at a shutter speed of $1/1000$ second. A careful count of the visible lines in the image reveals 15 visible scan lines. Then the exposure time is

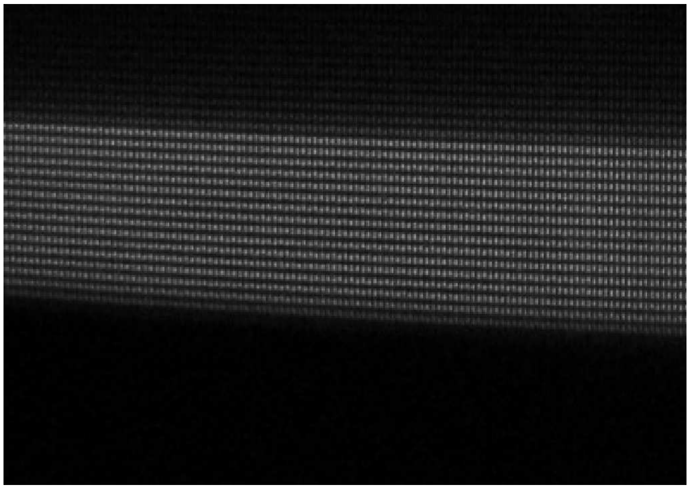


Figure 4: Television Screen

$$t_{shutter} = \frac{15}{17570} \quad (3)$$
$$= 0.853 \text{ milliseconds} \quad (4)$$
$$= 1/1171 \text{ seconds} \quad (5)$$

The images are somewhat difficult to interpret. When there are many scan lines in the image, counting is tedious and error prone. The opening and closing times of the shutter also make the beginning and end of the shutter interval somewhat ambiguous.

LED Array Method

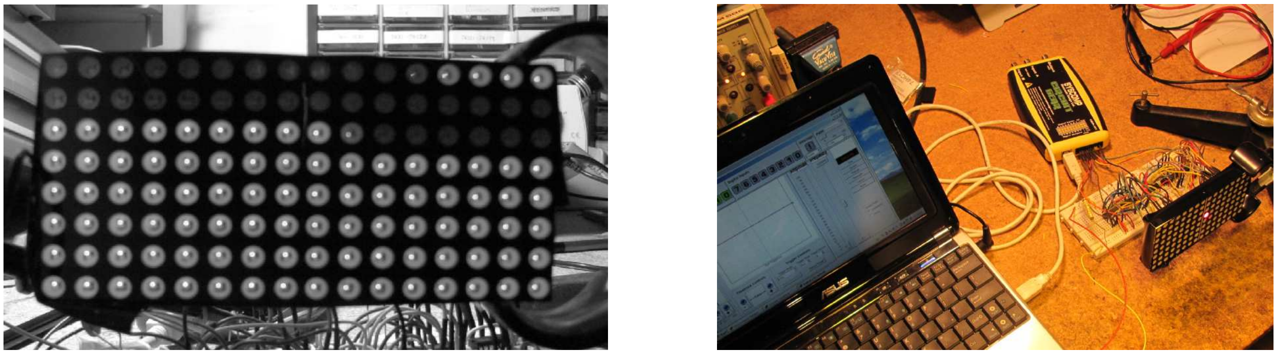
Gabele [3] shows a 10x10 matrix of LEDs that was used in calibrating camera shutter speed. A more sophisticated version is available from Image Engineering [4]. The list price is currently €699.

Realizing that the Syscomp CircuitGear CGR-101 and Waveform Generator WGM-201 could serve as the basis for such a device, we decide to construct our own version. We need a digital counter that drives an array of LEDs such that one LED is illuminated at a time, and every LED in the display illuminates in sequence.

The array is scanned starting in the upper right corner, line by line, finishing in the lower left corner. Figure 5(a) shows a typical display for the 8x16 LED array used in our version. In this image, the shutter opened in row 3. The shutter remained open until the 4th LED in row 1. Knowing the clock interval (the time each LED is illuminated) we can calculate the total shutter interval.

The LED method has the advantage that it can be operated at essentially any clock speed, so it can cover the entire range of camera shutter speeds. Furthermore, the turn-on and turn-off times of an LED are essentially instantaneous in this application, so the action of the shutter can be known quite precisely[2].

[2] At high clock rates (fast shutter speeds), the LED display is quite dim. However, histogram equalization of the image or simple brightening of the image brings the display up to a level where the LEDs can be counted easily.



(a) Typical Display (b) Arrangement

Figure 5: LED Array Calibration

Figure 5(b) shows the measuring setup. In this image, the CGR-101 CircuitGear digital outputs were used to exercise the digital logic for debugging purposes. One of the 128 LEDs is selected from a combination of the switches on the CircuitGear graphical user interface (figure 1(c)). In figure 5(b), you can see that one LED is illuminated on the LED matrix display (bottom right corner of the figure).

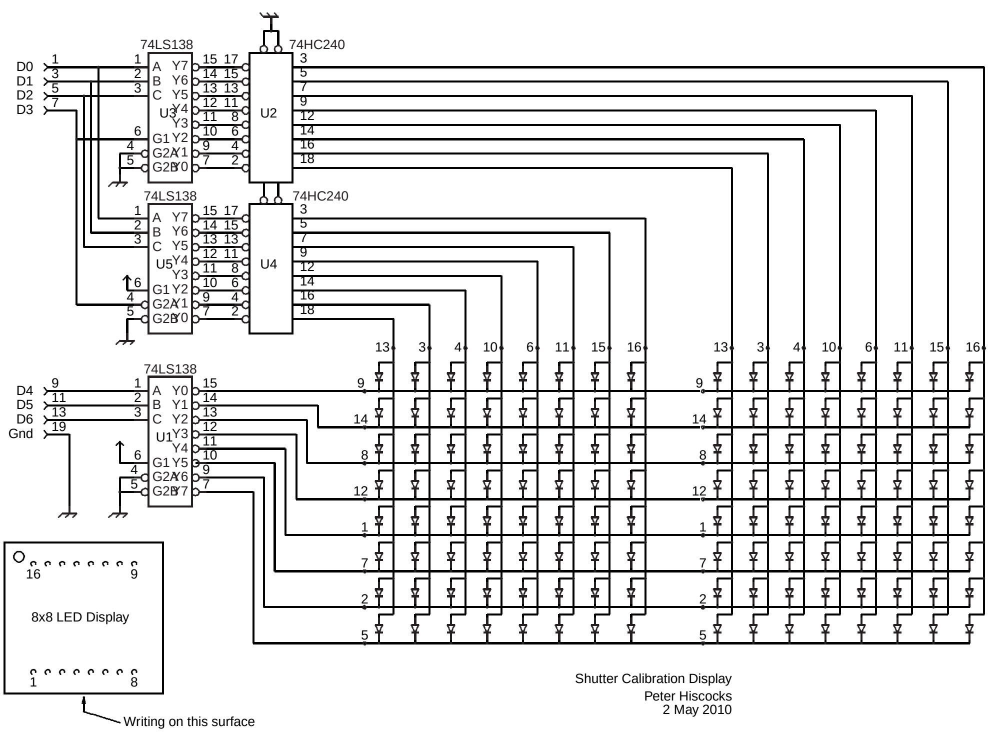


Figure 6: LED Calibrator Circuit

The circuit on the protoboard is shown in figure 6. The 8x8 LED matrix displays are of unknown type, obtained locally at Creatron [5]. The patch leads connecting the LED displays to the protoboard and the digital output of the CircuitGear to the protoboard, are also from Creatron[3]. Digital inputs D0 through D7 connect to the digital outputs of the CGR-101 CircuitGear for debugging, and the pattern generator outputs of the Waveform Generator WGM-201 for normal operation[4].

The circuit of figure 6 could be configured to be driven from a USB port, with a graphical user interface to control the settings. If there is interest in this, contact us.

The WGM-201 waveform generator hardware is a pod that plugs into the USB port of a host PC. The software is a program that runs on the host PC and creates a graphical user interface (GUI) for the hardware. The GUI of the waveform generator [5] is shown in figure 7.

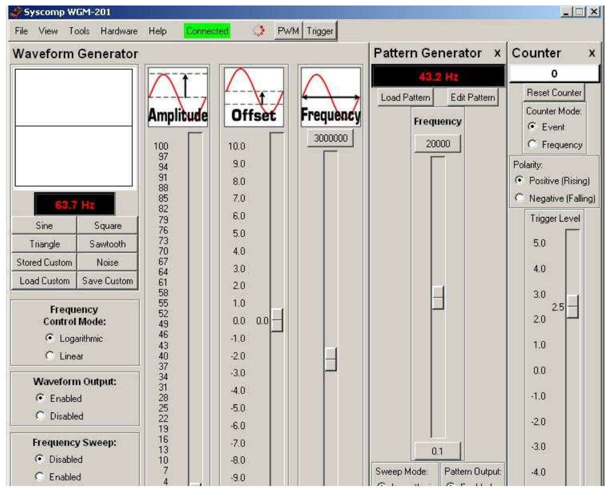


Figure 7: Waveform Generator User Interface

The generator was loaded with a 128 byte, 7 bit counter sequence. That pattern was created in a spreadsheet, saved as a `.csv` file, and then loaded into the generator. If for some reason we wished the scanning to proceed in a different order, we could have created another pattern file and loaded that into the generator.

The generator frequency such as 432.1 Hz can be specified directly through a text entry widget. For small variations around some particular frequency, the minimum and maximum frequencies (located at the bottom and top of the frequency control slider) can be specified by direct text entry. Then the slider control can be used to vary the frequency over that range. The frequency is based on a crystal-controlled timebase with a resolution of 0.1Hz, so the frequency can be specified with precision and accuracy.

Results: Canon SX120IS

The Canon SX120IS Point-and-Shoot camera is shown in figure 8. The SX120 has the option of fully manual control of aperture and shutter speed, and can produce monochrome images.

Figure 9 shows an example of an image photographed at high speed, $1/1600$ second shutter speed. The original jpeg image is underexposed, completely black. Histogram equalization using the `xv` image processing program results in the image of figure 9. This

Figure 8: Canon SX120IS Camera

[3] If you duplicate this circuit, check the polarity of the LEDs in the array. Some versions of this part are reversed, with the cathodes connected to the column lines.

[4] It would be possible to drive these digital output with a 7 bit digital counter, something like 2, 74HC161 four-bit counters, configured to reset at a count of 128. Then an oscillator signal, like the oscillator output of the CircuitGear, could be used to drive this circuit. I used the WGM-201 to save construction time.

[5] Several of the controls of the generator such as those for the the pulse width modulators, are hidden in this image because they are not used in this application. The bottom area of the GUI is also missing because this image was captured from a netbook, with limited screen resolution. For the complete GUI, see the data sheet on the Syscomp web site, [6].

image was counted as 99 illuminated LEDs, which is a $+0.84\%$ error in shutter speed. The shutter begins to close about half-way through the scan of the bottom line. There are an additional line (16 LEDs) that are partially illuminated as the scan returns to the first line of the display. We added half of those (8) add to the total of the fully illuminated LEDs.

Another image shot at the same speed yeilds a count of 101 LEDs, for an error of -1.16%.

In some cases, such as the result shown in figure 5(a) on page 5, the beginning and end of the shutter interval are quite clear. There are 103 fully illuminated LEDs. There are also two LEDs, exposed during the opening and closing of the shutter, that are partially illuminated. We might assign half a unit to them, giving the final illuminated LED count as 103.5.

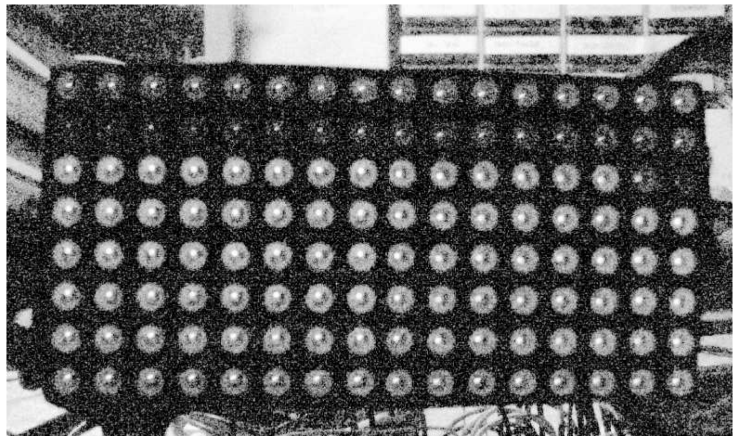


Figure 9: Histogram-Equalized Image, 1/1600 second

At higher shutter speeds, the opening and closing intervals affect more of the total, and there are more partially illuminated LEDs. How should this count toward the shutter interval? If we assume that the opening and closing transitions are approximately linear (and figure 1(c) on page 2 seems to suggest that is the case), then the effective beginning and end times occur at the half-way point through the transition. That's the assumption we've made in these measurements.

Clearly there is significant judgement required to determine which LEDs are partially illuminated, and there is still significant variation in the measurements.

The results of shutter speed measurements on the Canon SX120IS camera are shown on page 10. Each measurement was taken twice. The count of illuminated LEDs gives some idea of the consistency of results. As mentioned earlier, at high shutter speeds there is a certain amount of guesswork in deciding where the fadeout of LEDs begins, signalling the end of the shutter interval. An an overall result, the typical error is in the order of a few percent. The 6% error in for 1/30 second shutter speed is quite solid, so that may be taken as a worst-case benchmark for this range of speeds.

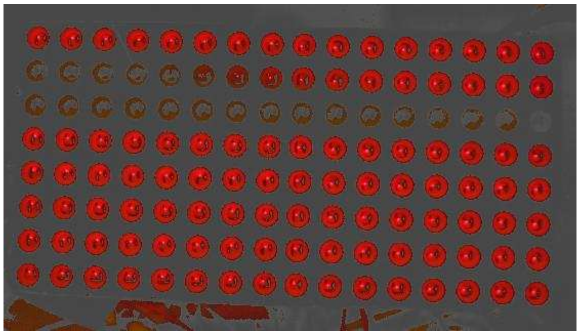
Results: Nikon D80

Figure 10: Nikon D80 Camera

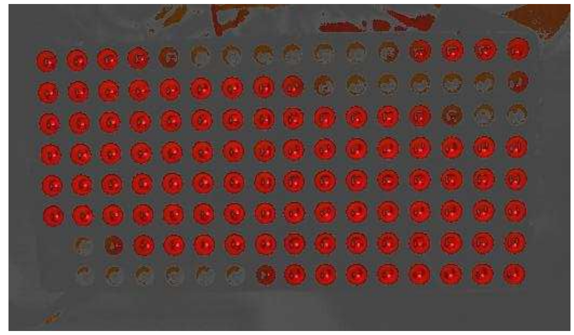
The Nikon D80 is a semi-professional digital SLR camera, with features like interchangeble lenses and through-the-lens viewing. The shutter calibration images were quite interesting – and somewhat unexpected, figure 11.

The shutter mechanism on the D80 is *Electronically controlled vertical-travel focal plane shutter*[6]. The mechanism is described it [7]. As Russ Macdonald explained, the shutter mechanism in the Nikon is effectively a rectangular opening (a slit) that moves from bottom to top. (Physically, the shutter moves from top to bottom. The optics invert the movement.)

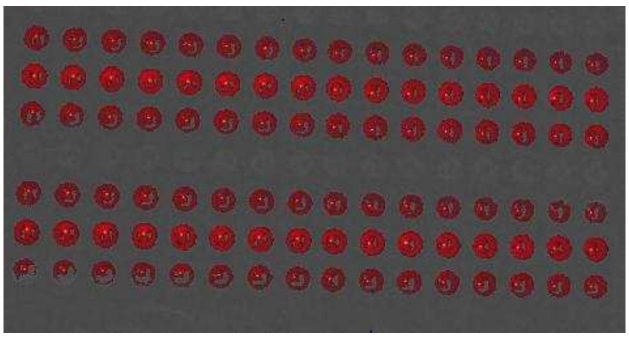
[6] `http://www.dpreview.com/reviews/nikond80/`



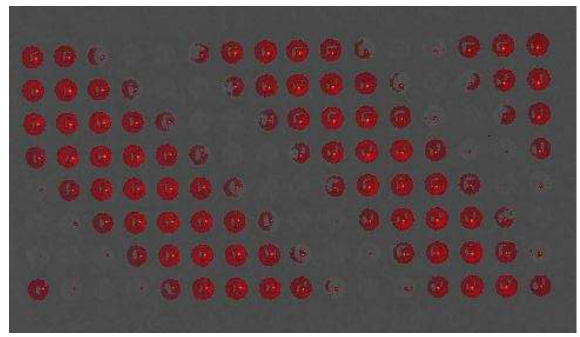
(a) 1/200 sec, landscape



(b) 1/200 sec, portrait



(c) 1/2000 sec, landscape



(d) 1/2000 sec, portrait

Figure 11: Nikon D80 Calibration Images (best viewed in colour)

Figure 11 shows typical results for the Nikon. The pattern of illuminated LEDs is very different, depending on the orientation of the camera. Clearly, there is an interaction between the moving shutter and the movement of the illuminated LED on the display.

Images obtained with the camera in its normal orientation (figures 11(a) and (c)) are not easy to interpret. Figures 11(b) and (d), taken with the camera on its side, are more useful.

Consider first figure 11(d), because it's the easiest to interpret. The shutter slit is moving from left to right at a relatively low speed. The LEDs are scanning from right to left at a much higher rate. The speed of the LED scanning is such that the shutter slit is scanned slightly over 2 complete times. (Put another way, the slit moved from the left edge of the image to the mid-point of the image during one complete scan of the LEDs.)

Consider the leftmost diagonal group of LEDs, which represents one complete scan of the LED display. The LEDs we see illuminated were the ones under the shutter slit. Pick any one vertical line, which in this case is 4 illuminated LEDs. The exposure time for these LEDs should be the same as any other area of the image. If we know the scan rate, then we can determine the exposure time for the image. Here's the calculation:

The clock rate (the time each LED is illuminated) is 7.8μSec. Then time T_e to expose 4 adjacent vertical lines of 16 LEDs each is

$$T_e = 4 \times 16 \times 7.8 \times 10^{-6} = 500\mu\text{Sec}$$

The exposure speed S_e is the inverse of this:

$$T_s = \frac{1}{T_e} = \frac{1}{500 \times 10{-}6} = 2000$$

So the exposure speed was $1/2000$ second, as expected.

Repeating this for figure 11(b), using an LED clock rate of 51.3mSec and a vertical LED count of 6, results in $1/208$ second for the shutter speed.

Images 11(b) and (d) contain additional information about the behaviour of the shutter. If the shutter speed is changing, then the diagonals will be curved. If the shutter slit width changes during the exposure, the number of horizontal LEDs in each group will change over the exposure.

Conclusions

- For a film camera, a phototransistor detector with digital oscilloscope works well. For a digital camera, the LED scanner approach is most suitable.
- The technique works on a both the leaf shutter mechanism and on a moving blind shutter. The moving blind shutter must be oriented correctly relative to the LED scanner. The LED scan image shows shutter speed and verifies that the shutter is operating consistently across the image field.
- The Syscomp CGR-101 digital oscilloscope and WGM-201 waveform generator were useful instruments in this investigation.

Further Explorations

The image analysis program `ImageJ` can plot a profile of brightness in a defined area of the image. It's possible that this technique could be used to measure more precisely the brightness of the LEDs when they are partially illuminated during the shutter transition.

Mainly, the object of this exercise was to characterize the Canon SX120IS camera for shutter speed. The results of section are suggestive of the kind of accuracy one can expect.

Acknowledgements

I am pleased to acknowledge the help of my colleagues Alan Hooper and Gabriel Guillen, who participated in discussions and loaned equipment for the measurements. Russ MacDonald kindly explained some mysteries concerning the operation of the Nikon shutter mechanism.

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[5] Creatron
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[6] Syscomp Electronic Design Limited
http://www.syscompdesign.com

[7] Shutter (photography)
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Canon SX120IS Shutter Speed Measurements

Shutter Speed	Shutter Interval mSec	LEDs Run 1	LEDs Run 2	Shutter Interval mSec	Shutter Interval mSec	Error, %	Error, %
30	33.33	93	93.50	31.05	31.22	6.85	6.35
40	25.00	101	101	25.29	25.29	-1.16	-1.16
50	20.00	98	99	19.63	19.83	1.84	0.84
60	16.67	95	94	15.86	15.69	4.85	5.85
80	12.50	102	102	12.77	12.77	-2.16	-2.16
100	10.00	100	100	10.02	10.02	-0.16	-0.16
125	8.00	99	98	7.93	7.85	0.84	1.84
160	6.25	102	101	6.39	6.32	-2.16	-1.16
200	5.00	100	99	5.01	4.96	-0.16	0.84
250	4.00	99	97	3.97	3.89	0.84	2.84
320	3.12	99	94	3.10	2.94	0.84	5.85
400	2.50	98	96	2.45	2.40	1.84	3.85
500	2.00	102	96	2.04	1.92	-2.16	3.85
640	1.56	105	95	1.64	1.49	-5.17	4.85
800	1.25	104	102	1.30	1.28	-4.17	-2.16
1000	1.00	105	101	1.05	1.01	-5.17	-1.16
1250	0.80	104	100	0.83	0.80	-4.17	-0.16
1600	0.62	101	99	0.63	0.62	-1.16	0.84