HOW-TO GUIDE

Measuring Pulse-Width Modulated Sources

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Introduction to PWM

Pulse-width modulation (PWM) is a method of reducing the average power delivered by an electrical signal by breaking up the voltage/current into discrete parts (see Figure 1). This technique is often used to control the apparent brightness (luminance) of LEDs by switching the signal between "on" (full power) and "off" states, resulting in a lower average power over a given time period. The ratio of the time spent in the on state to the total time period is referred to as the duty cycle. The larger the duty cycle, the brighter the LED. Another setting that influences brightness (luminance) is the refresh rate. The refresh rate is the number of times the display image is updated per second. For the purposes of this guide, we will refer to PWM and refresh rate analogously.

Typically, a pulse-width modulated signal takes a shape similar to the graph shown in Figure 1.

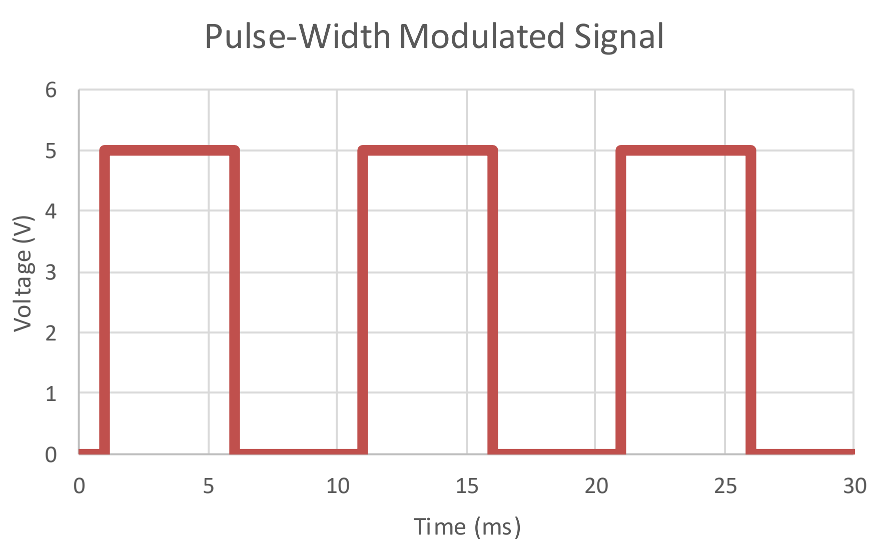

Figure 1 *– Example of a pulse-width modulated signal.*

Note in Figure 1 how the voltage switches between 5V ("on" state) and 0V ("off" state). The signal in this example has a pulse-width of 5 milliseconds (ms) because that is the amount of time it spends in its "on" state during each of its 10 ms periods. From this information we can calculate the duty cycle using the following equation:

$$Duty\ Cycle = \frac{Pulse\ Width}{Period}$$

Therefore, the duty cycle for this signal is 0.5 or 50% (it is typically expressed as a percent) meaning it spends half of its period in its "on" state. A duty cycle of 100% would mean that the signal is constantly in its "on" state, which means it is no longer being pulse-width modulated. A 100% duty cycle results in the average voltage being equal to the max voltage. Pulse-width modulation reduces the average voltage of the signal, as shown in the following equation. The average signal is:

$$\bar{V} = D * V_{max} + (1 - D) * V_{min}$$

Where D is the duty cycle and V is the voltage. For our example signal (Figure 1), the average voltage would be half as large as the non-pulse-width modulated signal. Changing the duty cycle also changes the average power because the power is the product of the current and the voltage.

In addition to its ability to control the average power delivered to a source, PWM is widely used for its efficiency benefits: very little power is lost in the PWM process. When the signal is off, there is almost zero current. When the signal is on, power is being transferred to the source (the LED) and there is nearly zero voltage drop across the power supply's switch. Because power is the product of current and voltage, the change in current is nearly zero when the signal is off and the change in voltage is nearly zero when the signal is on, therefore there is almost no change in power.

1.0 Considerations When Measuring PWM Devices

When taking measurements of displays and LEDs that are pulse-width modulated, the results can vary from measurement to measurement.

In Figure 2, notice that measurement 1 and measurement 2 have the same exposure time (~25 ms). In measurement 1, two pulses are measured but in measurement 2 only one pulse is measured. While this is an exaggerated example, it highlights a common challenge with measuring PWM sources. A measurement may record different luminance values at the same exposure time if the display pulses a different number of times.

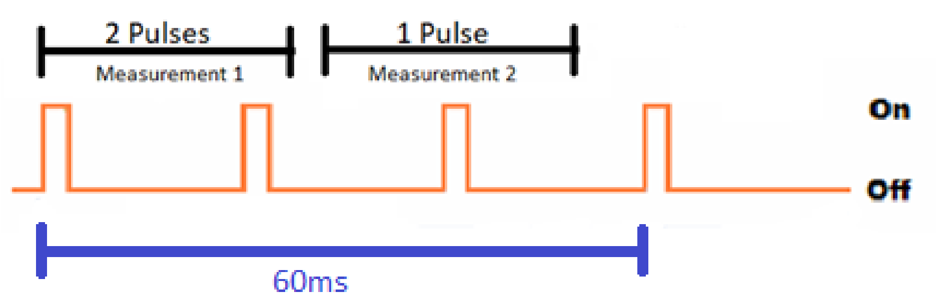

Figure 2 *– An exaggerated example of PWM effects on luminance measurements.*

2.0 Testing

Radiant recently performed testing of PWM LED sources in one of our labs to ascertain the best method for accurately measuring luminance/intensity of PWM sources. The tests were done using a Radiant ProMetric® I-16 Imaging Colorimeter with TrueTest™ Software. The impact of different test parameters on the sample measurements are detailed below.

2.1 LED Source

Sample measurements were made of a PWM LED source, as shown in Table 1. Radiant engineers took measurements at different exposure times and recorded the gray value. The LED source was driven with a current-controlled signal at a frequency of 0.1 kHz and a duty cycle of 25%.

***Table 1** – Gray values at different exposures.*

	Gray Level vs. Exposure Time						
Trial	**Cycles**	**Exposure Time (ms)**	**Minimum Gray**	**Maximum Gray**	**Range**	**Average Gray**	**Largest Percent Error (%)**
Auto-Adjusted	4.5	45	1515	1887	372	1741.23	12.99
1	2	20	748	755	7	752.00	0.53
2	2.5	25	753	1126	373	937.33	20.13
3	3	30	1126	1133	7	1129.00	0.35
4	3.5	35	1130	1501	371	1332.50	15.20
5	4	40	1501	1510	9	1505.46	0.30
6	4.5	45	1507	1883	376	1685.27	11.73
7	5	50	1879	1889	10	1883.00	0.32

Note that the percent difference for trial 2, 4, 6, and the auto-adjusted measurements. The percent differences are all above 10% which are well above most specifications. Relying on these measurements will lead to inaccurate and inconsistent luminance values.

Also note that trials 1, 3, 5, and 7 appear to provide accurate measurements. When the exposure time is an integer multiple of the period of the pulsing signal, the same number of pulses will be captured each time. In order to get accurate photometric data, a calibration would have to be made with the desired exposure time. For more information, contact Support@RadiantVS.com.

Figure 3 highlights the disparity between two measurements of the PWM LED with the same exposure time. The image shows a point of interest (POI) in the Focus Mode window within TrueTest™ Software. Despite having the same exposure time, the brightness output from the POI region varies by more than 370 gray. The instructions for setting up the Focus Mode window as shown in Figure 3 are detailed in section 3.0.

Exposure Time: 45 ms

Minimum: 1507 Gray | Maximum: 1883 Gray

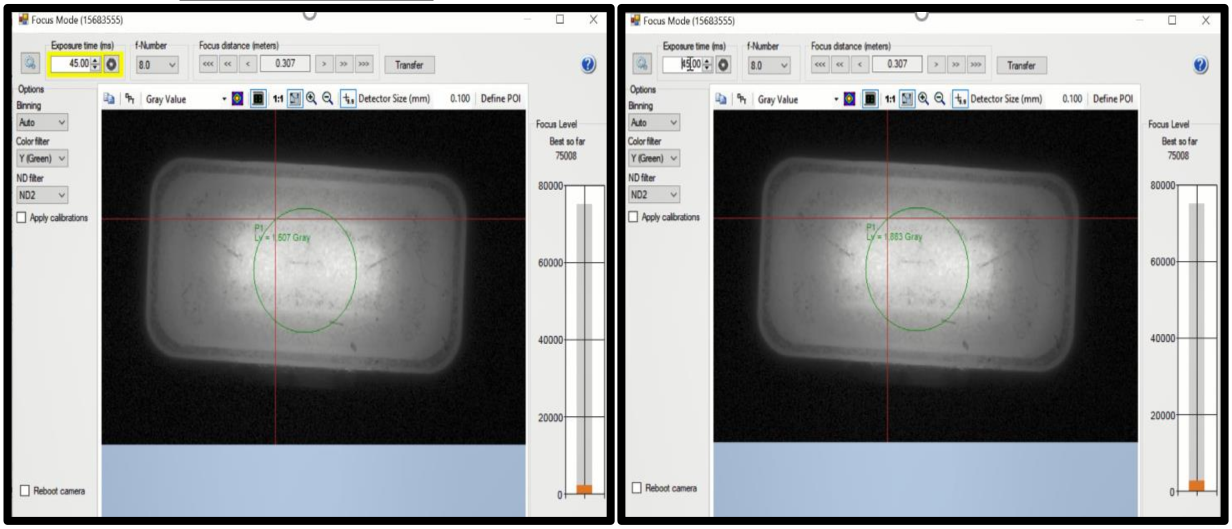

Figure 3 *– A comparison of two different gray values resulting from the same measurement setup due to the LED's PWM.*

2.2 LCD Monitor

Using an LCD monitor with a refresh rate of 50 Hz, the following results were obtained (see Table 2).

Table 2 *– Luminance values at different exposures.*

	Luminance vs. Exposure Time					
Trial	**Cycles**	**Exposure Time (ms)**	**Minimum Lv (nit)**	**Maximum Lv (nit)**	**Range (nit)**	**Average of 10 Lv Measurements (nit)**
A	1.25	25	92.6	105.4	12.8	98.9
B	2.75	55	95.8	102	6.2	98.51765
C	4.25	85	97.2	101	3.8	98.74211
D Auto-Adjusted Exposure	5.25	105	96.7	99.7	3	98.67143

From the data in Table 2, we see that the shorter the exposure time is (e.g., Trial A), the greater the range in luminance will be. This relationship stems from the low number of cycles captured in a single measurement at that short exposure time. The number of cycles tested was significantly shorter than our recommendation, but this example highlights the effects of pulse-width modulation. With an ND0 filter and an f/2.8 aperture, the auto-adjusted exposure (Trial D) provided results that were off by as much as 2 nits.

Lastly, note that the average luminance (Lv) does not change much at different exposure times. Averaging is a method of accounting for PWM/refresh rate; this is discussed in a later section. Figure 4 shows the POI within Focus Mode used to determine the luminance fluctuation of an LCD display. The luminance output from the POI region varies by more than 12 nits between two measurements with the same exposure time.

Exposure Time: 25 ms

Minimum Lv: 92.6 nit — Maximum Lv: 105.4 nit

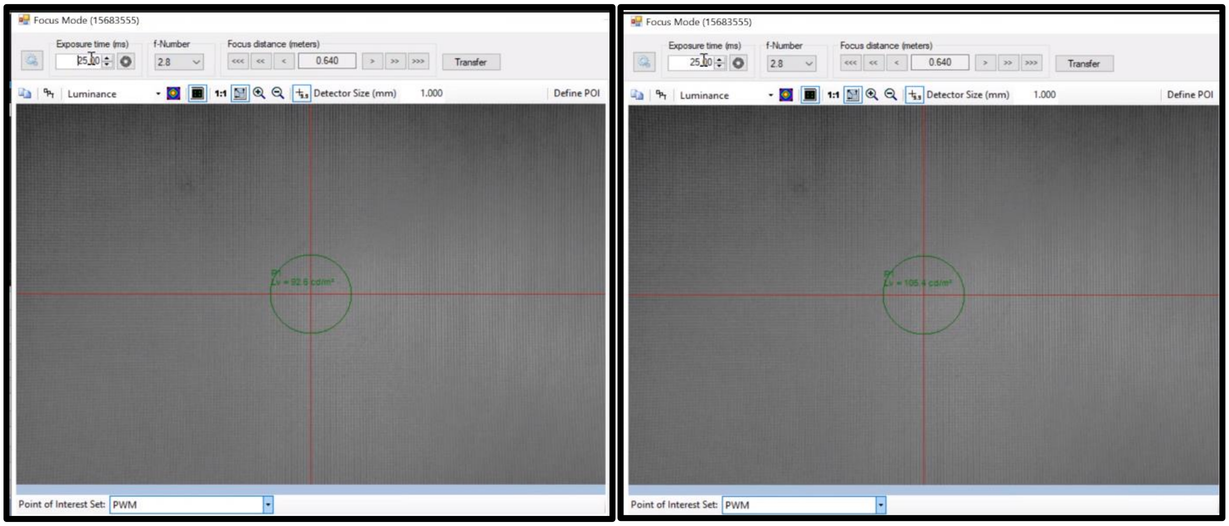

***Figure 4** – A comparison of two different luminance values resulting from the same measurement setup because of the display's refresh rate.*

3.0 How to Check

The first step in accounting for pulse-width modulation when taking a measurement is to check how large of an effect PWM has on the measurement. This can be checked by doing the following:

1. Open the Radiant Vision Systems software for the system in use (i.e., ProMetric, TrueTest, etc.) and make sure the camera is connected.
2. Set up the camera and source in the way measurements will be made. This includes making sure the source is at the correct brightness.
3. In the software, right-click on a measurement and select **Define Points of Interest** (shown in Figure 5).

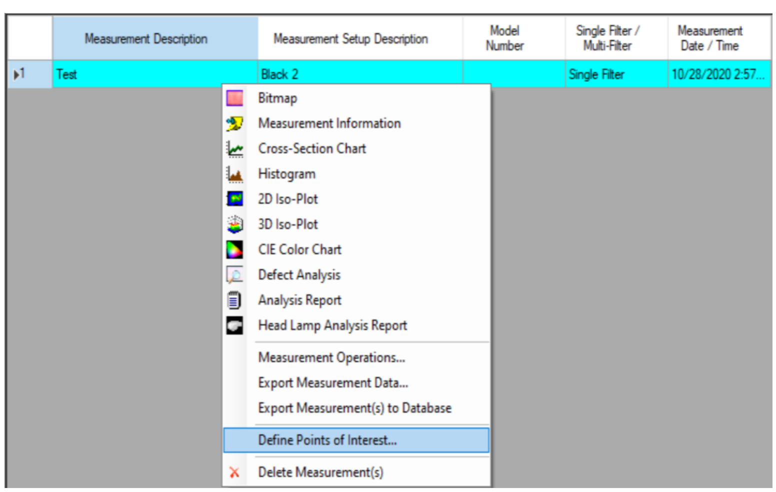

***Figure 5** – Define Points of Interest.*

4. Create a new Point of Interest (POI) called PWM. Draw a circular POI and place it at the center. Set the Evaluation Type to **Lv** (luminance), as shown in Figure 6. Then save, , and close out of the Define Points of Interest window. Please see the help file, , if you have any questions.

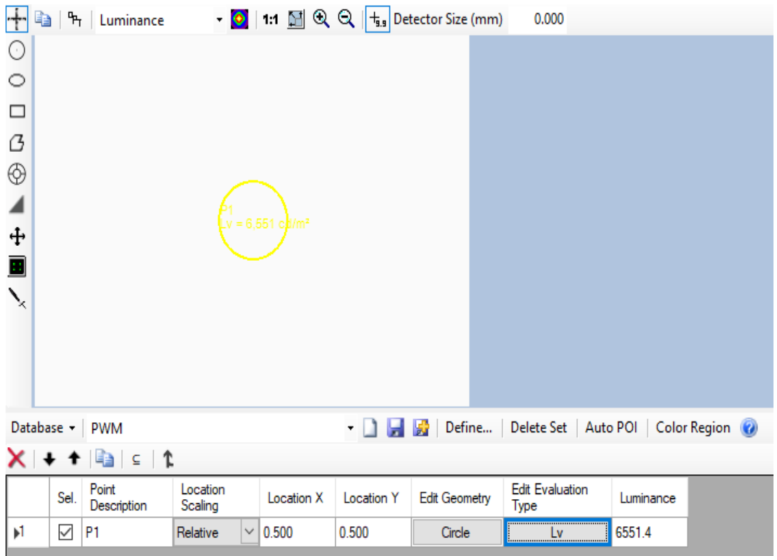

***Figure 6** – Create a new PWM POI.*

5. Open Focus Mode. In the Focus Mode window, select the **Turn on/off Points of Interest** button, , then navigate to the bottom of the window and select the **PWM POI** (shown in Figure 7).

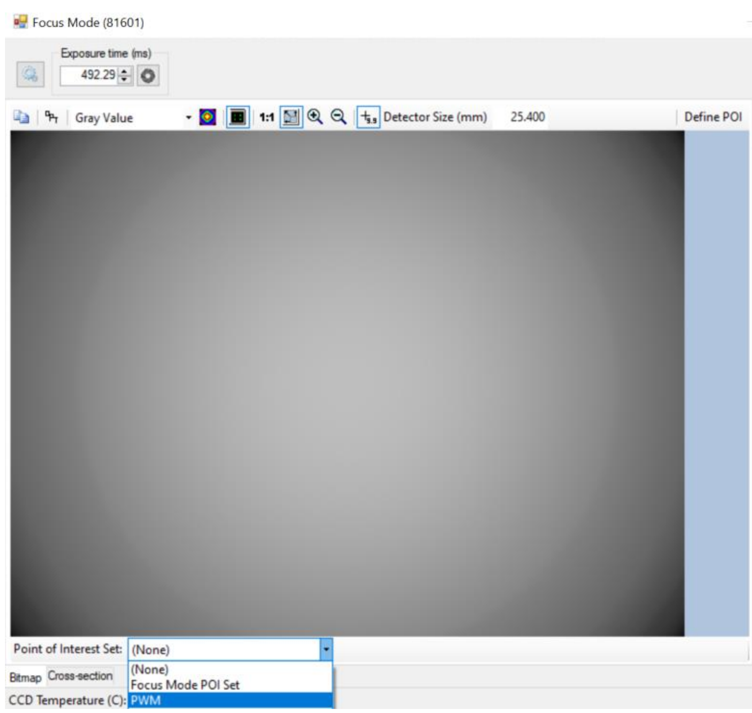

***Figure 7** – Focus Mode Window.*

6. Select **auto-adjust**. Deselect it once the software has determined an exposure.

7. Observe how the luminance value changes with each focus mode measurement. If the luminance changes drastically (more than 3% of the expected luminance) from measurement-to-measurement, then PWM might affect individual measurements.

4.0 Possible Fixes

Fortunately, it is possible to remove the effects PWM has on luminance measurements. Ultimately, a measurement needs to capture enough pulses to minimize the effects of slight differences in the total number of pulses measured. For example, if measurement A captures one pulse and measurement B captures two pulses, then measurement B has captured 100% more pulses. However, if measurement A captures one-hundred pulses and measurement two captures one-hundred and one pulses, measurement B has captured 1% more pulses. Accordingly, measurements using a larger number of pulses will have more accurate calibrated luminance values.

Referring to Table 1, dividing the average gray value for a trial by the number of cycles yields the approximate gray value for a single pulse. This value was determined to be roughly 378 gray for the example LED source.

Note that the range is roughly 375 gray for trials 2, 4, 6, and the auto-adjusted measurements. When the exposure time is a half integer of a cycle, it can vary by an entire pulse of the LED. If the goal was to minimize the percent error down to a more reasonable number, such as 3%, an average gray value of approximately 6,250 gray (33 LED pulses) would need to be captured (see explanation below).

$$Percent\ Error\ = \left|\frac{Experimental\ Value - \ Average\ Value}{Average\ Value}\right|\ =\ .03\ *\ 100\%\ =\ 3\%$$

Note that the maximum difference between the experimental value and the average value can be approximated by half of the range. Therefore,

$$Average\ Value\ = \left|\frac{Experimental\ Value - \ Average\ Value}{Percent\ Error}\right|\ = \left|\frac{\frac{1}{2}\ (375)}{.03}\right|\ = 6{,}250\ gray$$

However, there is also the consideration of measuring a gray value that large without overexposing the sensor.

Radiant recommends trying the one or more of the options below when measuring a PWM source:

1. The simplest way to measure a PWM source is to set the duty cycle to 100% so the source has a constant luminance value.
2. Increase the f/# so the exposure time must increase. This is because a larger f/# corresponds to a smaller aperture resulting in less light reaching the camera sensor (and consequently, longer exposure times are needed). Changing the aperture from the larger aperture to the smaller aperture will increase the exposure time by a factor of about $(f/large \div f/small)^2$. For example, changing from f/3.3 to f/8 we calculate the following factor, "k":

$$k\ =\ (8/3.3)^2\ \approx\ 5.877$$

While this factor is not going to be exact, it will provide an estimate of what the exposure time will be. In the example in Table 3, switching from f/3.3 to f/8 with an ND1 filter changed the exposure time from 24.9 ms to 136.9 ms. This corresponds to a factor of ~5.5 which is close to the estimated factor.

3. Increase the exposure time by adding an ND filter. Adding an ND filter reduces the amount of light incident on the camera sensor therefore, longer exposure times are needed. These longer exposure times will enable you to capture more pulses and thus measure the luminance more accurately. Note, each added ND filter decreases the amount of light reaching the sensor by a factor of 10. This means the exposure time will increase by roughly a factor of 10. For example, ND1 filter increases the exposure time by a factor of ~10, having an ND2 increases the exposure time by a factor of ~100, etc.

Often, combining both options 1 and 2 is enough to mitigate the effect of PWM. The effects of changing the ND filter and F/# are shown in the example test shown in Table 3.

Table 3 *– The effects of changing the ND filter and f/# on PWM measurements.*

Trial	F/#	ND Filter	Exposure Time (ms)	Gray Level	Average Gray	Maximum Gray	Minimum Gray	Percent Error (%)
A	3.3	Clear	2.55	N/A	N/A	N/A	N/A	N/A
B	8	Clear	15.37	2190	1690	2190	1096	35.15
C	3.3	ND1	24.9	1332	1579.64	1999	1332	26.55
D	8	ND1	136.9	1637	1644.67	1690	1570	4.54
E	3.3	ND2	243.47	1699	1701.57	1732	1675	1.79
F	8	ND2	1330.72	1683	1684.83	1694	1682	.54

Starting with the lowest ND filter and largest aperture (Trial A), the exposure time was too small to take a measurement. Decreasing the aperture to f/8 (B) allowed us to take a measurement, however, the percent error is 35.15%. Switching back to f/3.3 and adding an ND1 filter (C) yielded similar results with a percent error of 26.55%. Once f/8 and an ND1 filter were used simultaneously (D), the data became more reasonable with a percent error of 4.54%. Depending on your specifications, these test parameters may yield sufficient accuracy.

Lastly, the results for both apertures with an ND2 filter (Trials E and F) were much better. To determine the best setup to use for your application, consider whether your priority is precision (Trial F in this example, ND2 + f/8) or takt time (Trial D in this example, ND1 + f/8). In this example case, ND2 + f/3.3 (Trial E) is a solid intermediate option providing both a 243.47 ms exposure time and only a 1.7% error.

4. Another option that can be used to mitigate PWM is to calculate the average of multiple measurements. Table 2 demonstrates the effects of this approach. To use this option, change the relevant test parameters found under **Settings/Advanced Options** (shown in Figure 8).

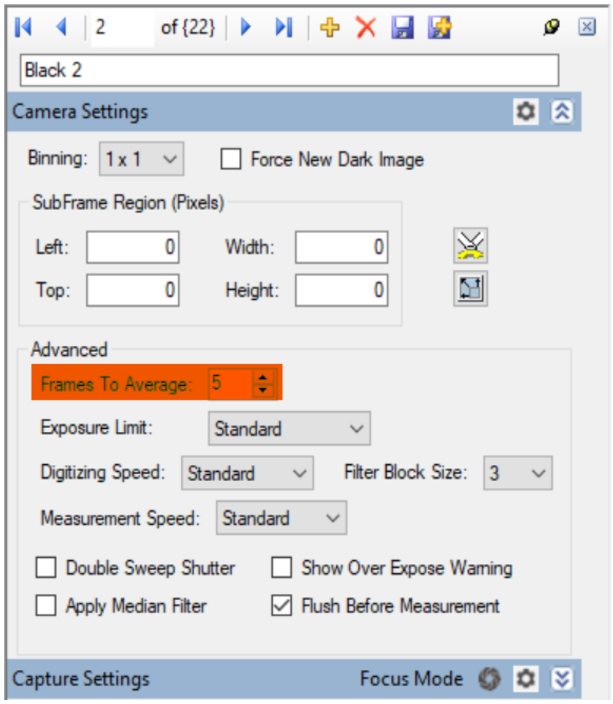

***Figure 8** – Advanced camera settings.*

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