TEXAS INSTRUMENTS

Photodiode Selection and Placement Guide

Head-Up Display, DLP® Products

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1 Introduction

1.1 Purpose & Scope

The purpose of this document is to provide recommendations for photodiode placement in a DLP HUD and system level recommendations for handling various failures.

1.2 Terms & Abbreviations

Abbreviations	Description
HUD	Head Up Display
PGU	Picture Generation Unit (includes LEDs, DMD, optics, and screen)
DMD	Digital Micromirror Device
LED	Light Emitting Diode
SNR	Signal to Noise Ratio
FEA	Fly's Eye Array

1.3 References

1.	2511887	Piccolo DLP HUD LED Controller Application Note
2.	2511811	0.3" WVGA HUD Chipset Product Preview
3.	2512379	Piccolo software for the HUD DLPC120 ASIC – Getting Started Guide
4.	2512606	I2C Customer Guide for HUD DLPC120 ASIC
5.	2514427	Automotive Control Program Users Guide

1.4 Overview

The DLP HUD reference design uses an LED driver control loop with photo feedback. The photodiode is an essential component in this control loop. Carefully optimizing the placement and electrical response of the photodiode will yield the widest dynamic range for dimming.

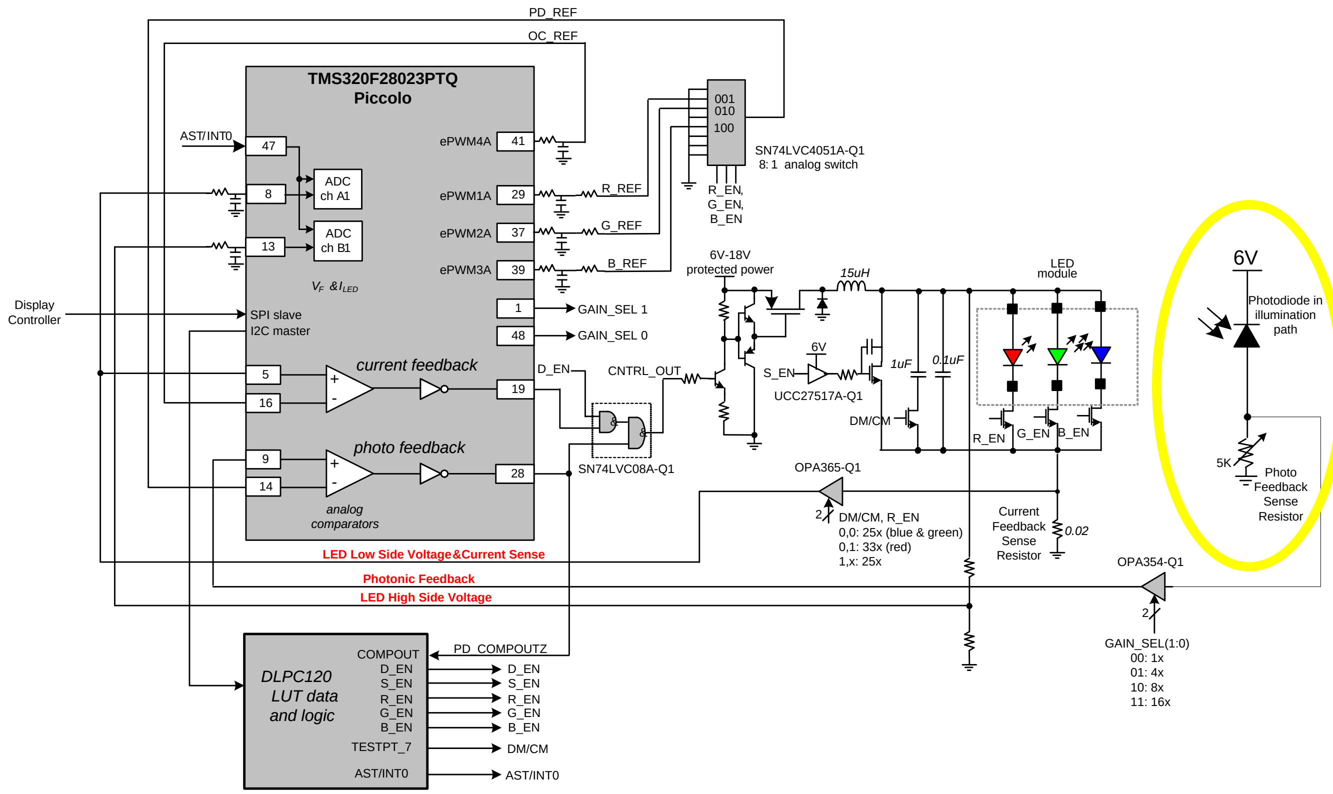

Figure 1: LED controller block diagram with photodiode

1.5 LED Driver as a Closed-Loop Control System

The photodiode acts as the sensor in a negative-feedback control loop. The current amplitude output by the photodiode directly influences the output LED brightness. The cleaner the signal on the photodiode and subsequent gain stages, the more flicker-free the image will be at the dimmest levels.

Note also that care must be taken in the system design to handle photodiode failures. In the case where the photodiode becomes disconnected—failing open circuit—the control loop will drive the LED to the max current limit set by hardware. Proper system level monitoring can detect this and protect the driver from potentially dangerous brightness settings. See section 4.1 for more information.

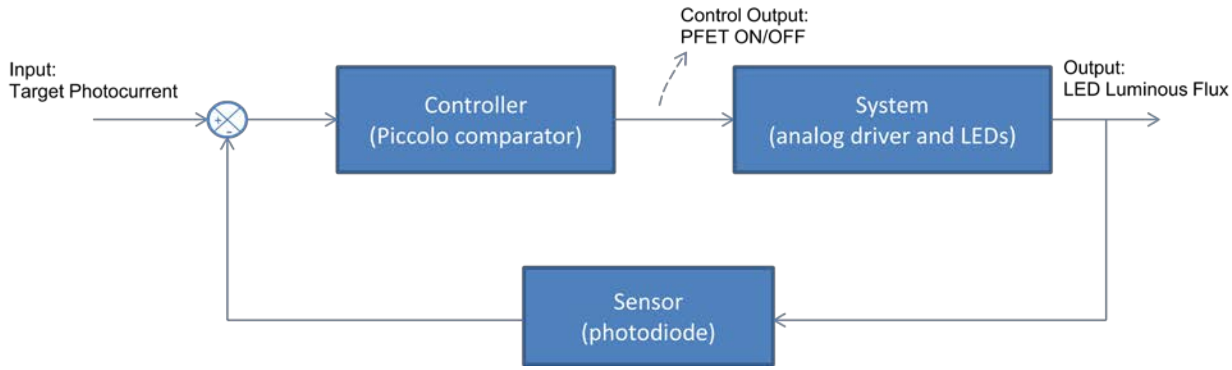

Figure 2: LED driver control loop

Taking care of the following points will maximize the performance of your system:

- Avoid back reflections and stray light on photodiode, to achieve maximum full-on-full-off contrast ratio (see section 3.1)
- Ensure illuminance on photodiode is within spec (not too much light) to maintain system linearity and color point accuracy (see section 3.2.1)
- Ensure enough light incident on the photodiode to minimize flicker at the dimmest achievable brightness level (see section 3.2.3)
- Ensure similar proportions of red, green, and blue light on photodiode

2 Electrical Design

2.1 Selecting a Photodiode

Specification	Recommended Value	Effect
Response/Rise time	<200ns	Shorter response times increase dynamic range of HUD at dimmest levels
Red-to-Blue Response Ratio	<5:1	Ratios closer to 1:1 maximizes dimming resolution for all colors and accuracy of the white point
Dark current at 105C	<1uA	The lower the dark current, the better the color point accuracy over temperature
Diode Capacitance	<50pF	Lower capacitance at the diode and interconnect will increase response time and increase dynamic range
Minimum Temperature Rating	-40C	Must be rated to operating range of system
Maximum Temperature Rating	>95C	Must be rated to operating range of system

The Signal to Noise Ratio (SNR) of the photodiode, cabling, and subsequent gain stage correlates to noise (flicker) on the output of the LED. Flicker due to low SNR is most visible at the minimum achievable brightness.

Ensuring the photodiode cable and PCB circuitry are well shielded will maximize the photodiode SNR and help minimize flicker.

The TI Gen 1.0 PGU uses the Advanced Photonics, Inc. PDB-C156 photodiode. This does not meet the maximum operating temperature. As such, the TI Gen 1.5 PGU uses instead the Vishay TEMD5020 photodiode which meets all of the above requirements.

3 Optical Design

3.1 Placing Photodiode to Avoid Back Reflections

In an example PGU, the photodiode is placed such that it receives reflected light off the first surface of one of the lenses in the illumination path as shown in the figure below.

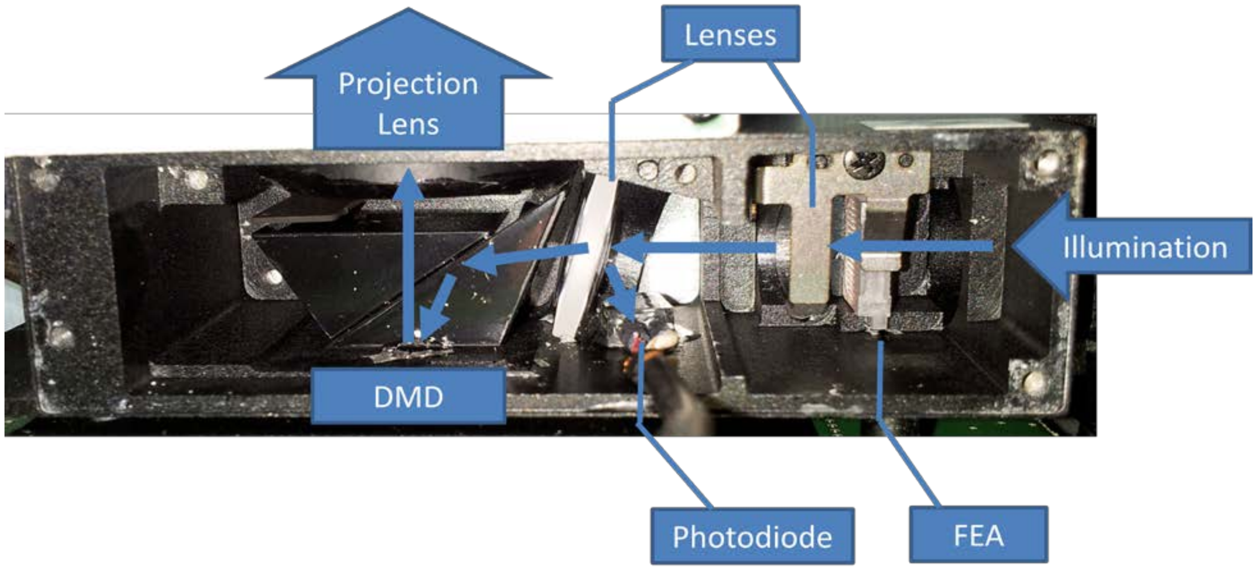

Figure 3: Example – Gen 1.0/Type A PGU with photodiode

3.1.1 Problem with back reflections on the photodiode

Full white brightness should not vary with image content. However, in this example placement, TI measured a difference in the peak brightness of a solid white field versus a coarse checkerboard pattern.

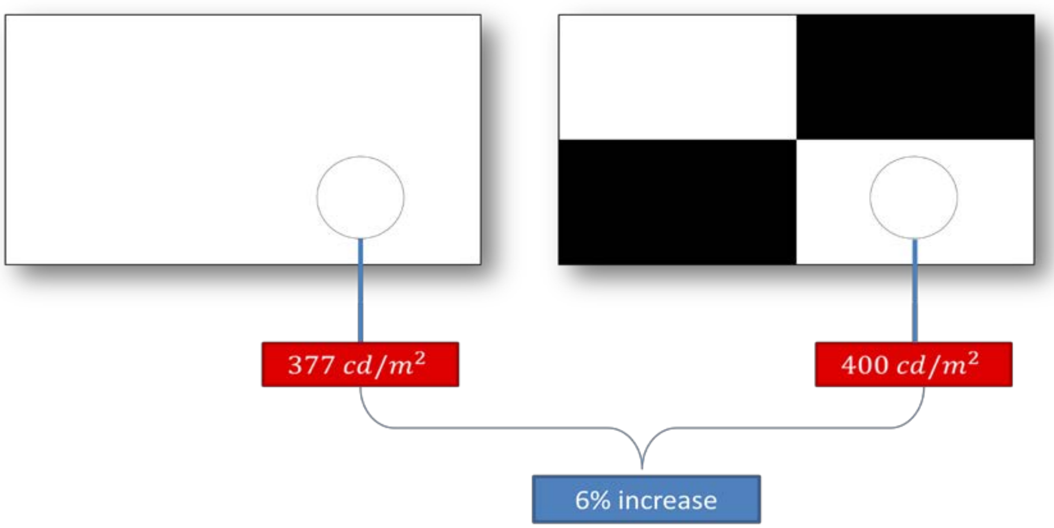

Figure 4: White solid field versus checkerboard

In the case of the white solid field, the LED driver electronics are driving less current to the LEDs than in the case where the black solid field is displayed.

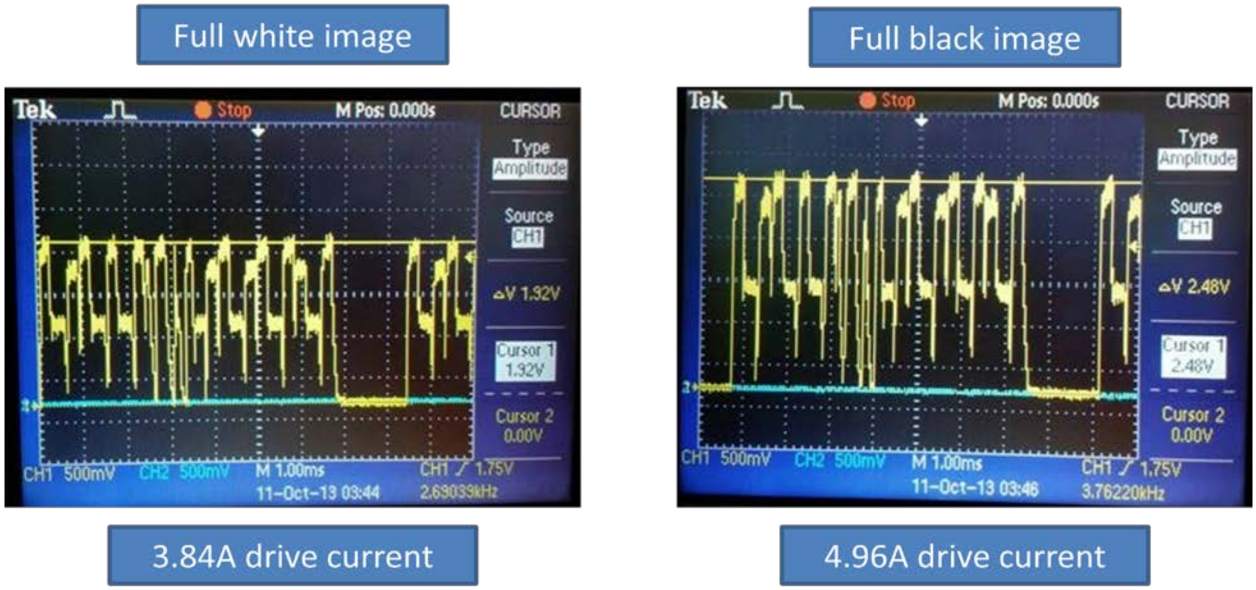

Figure 5: Measured LED current with back-reflected light

In this case, the percent difference between the LED currents is ideally equal to zero. Instead this example shows a percent difference of ~22.6%.

$$\%_{difference} = \frac{(i_{\max\_black} - i_{\max\_white})}{i_{\max\_black}} = \frac{4.96A - 3.84A}{4.96A} \cong 22.6\%$$

Equation 1

3.1.2 What is causing the difference in contrast?

Some DMD on-state light is reflecting off the first surface of the projection lens and back to the photodiode.

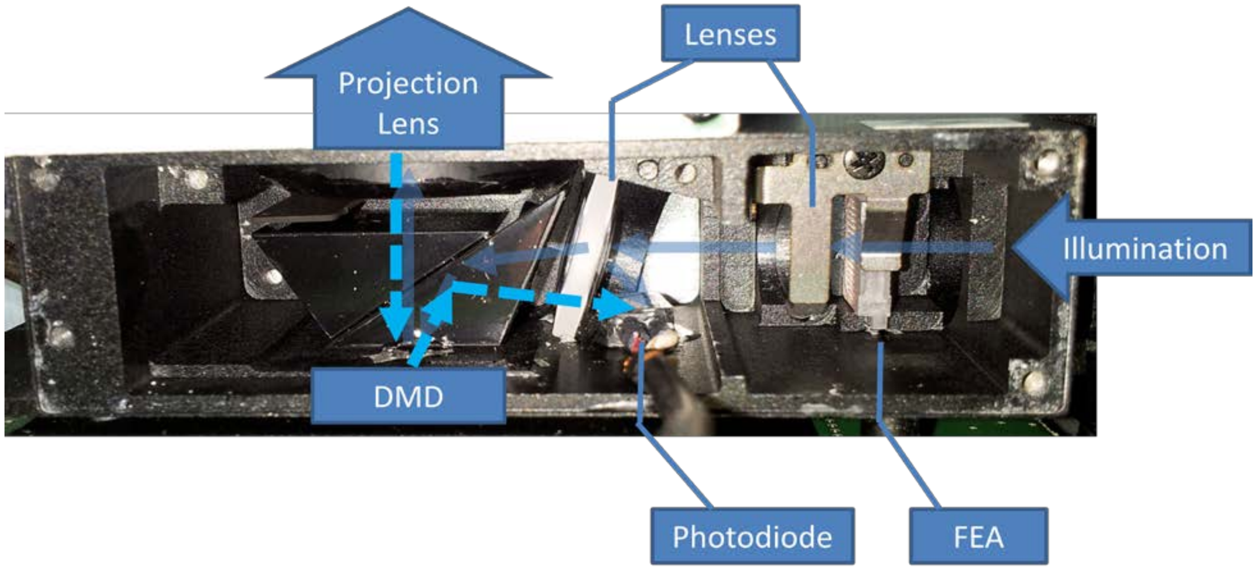

Figure 6: Back-reflected light

3.1.3 The Solution: Moving the photodiode to avoid back reflections

Moving the photodiode out of the back-reflected path improves contrast significantly.

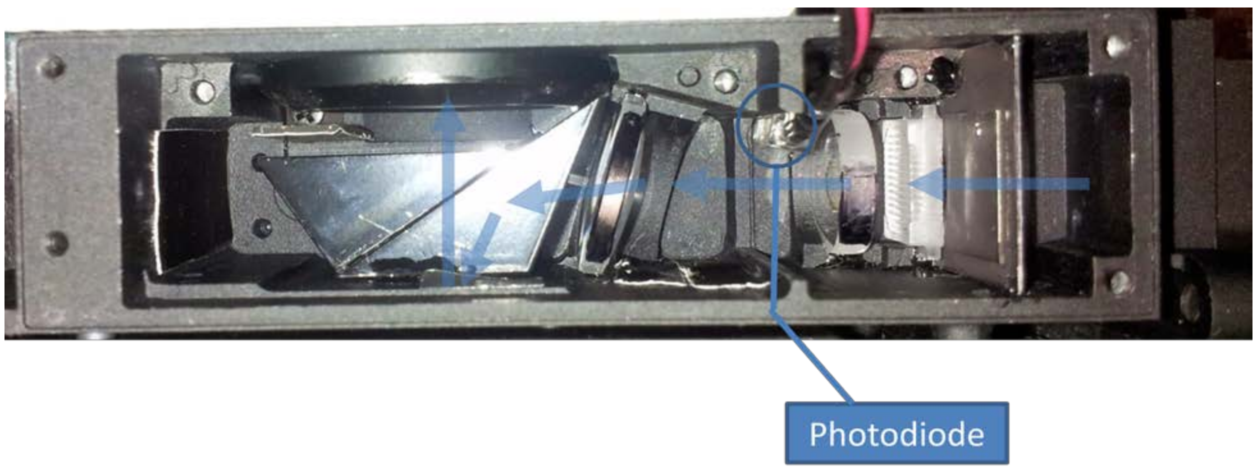

Figure 7: New photodiode placement avoiding back-reflected light

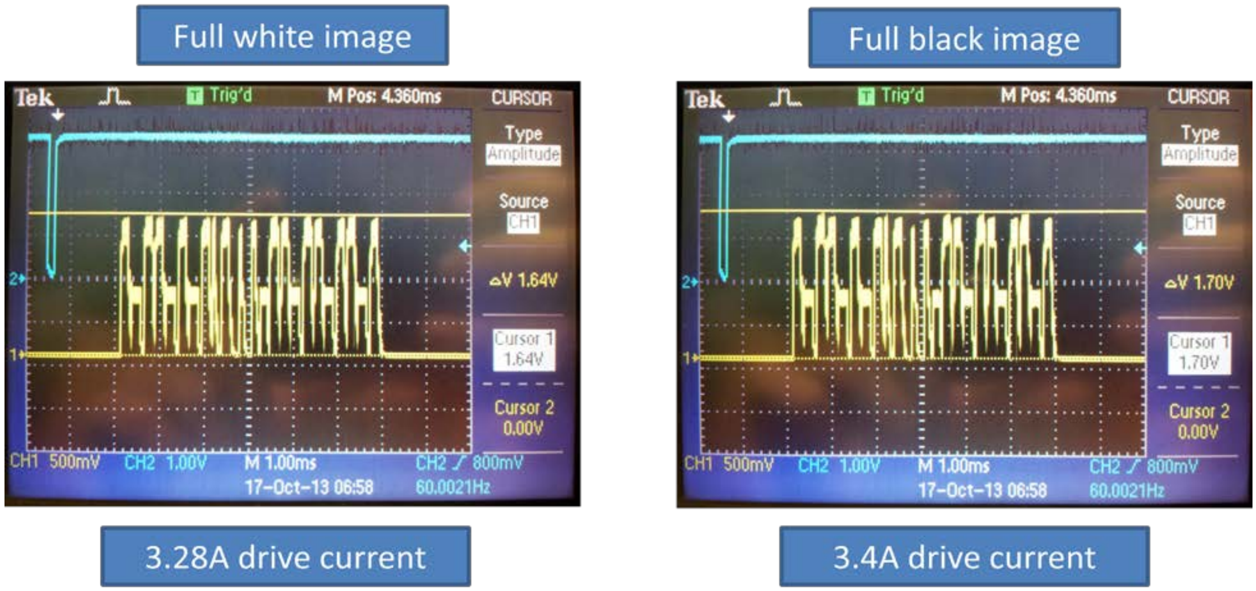

Figure 8: LED currents without back-reflected light

Taking new LED current measurements shows a much smaller dependence on image content.

$$\%_{difference} = \frac{(i_{\max\_black} - i_{\max\_white})}{i_{\max\_black}} = \frac{3.4A - 3.28A}{3.4A} \cong 3.5\% \quad \textit{Equation 2}$$

Compare the contrast, measured off the windshield, between the two cases. There is a large improvement.

Dimming	Original configuration full on/full off contrast	Modified configuration full on/full off contrast
65535	1080	1200

This shows approximately 11% increase in contrast.

In conclusion, it is clear that the photodiode placement is vital to full-on-full-off contrast. Therefore, care must be taken to understand stray light and avoid back reflections from the DMD.

3.2 Optimizing Photodiode Placement for Target Photocurrent

The right photodiode placement will maximize dynamic range, allowing the HUD to achieve the maximum brightness over the widest temperature range and the minimum dimming brightness across the entire temperature range.

The photo-feedback circuit and control loop are designed to a specific range of photocurrents to achieve maximum dimming range. The target peak photocurrent at maximum system brightness should approximately equal **600uA**, though values from 500uA to 1000uA are acceptable.

Regardless of PGU efficiency or brightness, the photodiode should be positioned such that it supplies the same peak photocurrent for all designs when at their maximum specified brightness.

For example:

Design	Max Specified Luminance	Peak Photocurrent at Max Specified Luminance, 50/50 seq, and 25°C
TI design 1	15,000 nits	500uA~1000uA
TI design 2	28,000 nits	500uA~1000uA
Customer design	20,000 nits	500uA~1000uA

3.2.1 Case Study: High photodiode illuminance affecting linearity

If too much light is incident on the photodiode surface, the photodiode may begin operating outside of its linear range. In this case, gray ramp linearity and dimming step linearity will suffer at the brightest dimming levels.

TI has seen this in its PGU with peak illuminance greater than 70mW/cm^2 and photocurrent greater than 1.3 mA on the TEMD5020.

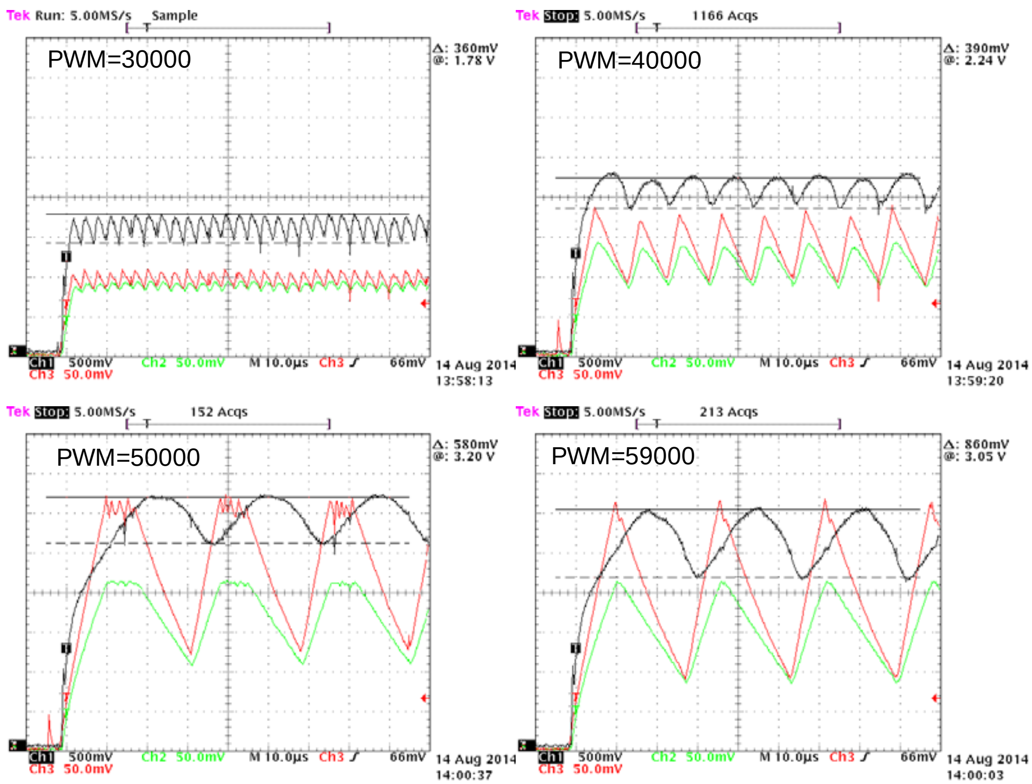

Figure 9: Photodiode saturation

CH1	Photo feedback
CH2	External photosensor
CH3	Current feedback

At the higher brightness levels, the frequency response of the photodiode decreases considerably, affecting maximum achievable brightness and linearity. The photodiode had a bias of 3.3V and a series resistance of 1490 ohms.

3.2.1.1 The Solution

1) Reduce the amount of light on the photodiode
2) Increase the voltage bias above 3.3V (see reference schematic)

For more detailed information on the theory behind this non-linear operation, please see the Hamamatsu Optosemiconductor Handbook, Chapter 2 – Si photodiodes.

3.2.2 Case Study: High Photodiode Illuminance Limiting Maximum Brightness

If too much light is incident on the photodiode and the series resistance is not decreased proportionately, the photo-feedback signal may saturate at 3.3V before the LEDs reach their desired brightness or maximum current.

If the photodiode is operating outside of its linear range as above, decrease the amount of light on the photodiode. If the photodiode is operating in the linear range, decrease the series resistance so that the peak photocurrent at maximum brightness does not saturate the photodiode.

3.2.3 Case Study: Photodiode illuminance too low

If too little light is incident on the photodiode surface, the SNR of the photodiode output may be too low at the dimmest levels and cause noticeable flicker, typically at photocurrents below 1uA. Targeting the right amount of light will maximize the dynamic range at the dimmest levels.

The following figure shows a single Discontinuous Mode pulse at a very low PWM compare level (~34mV versus black level). At very low PWM compare levels, the ratio of pulse amplitude to PWM level is very non-linear. Higher photocurrents set the operating point at PWM levels where the ratio is more linear.

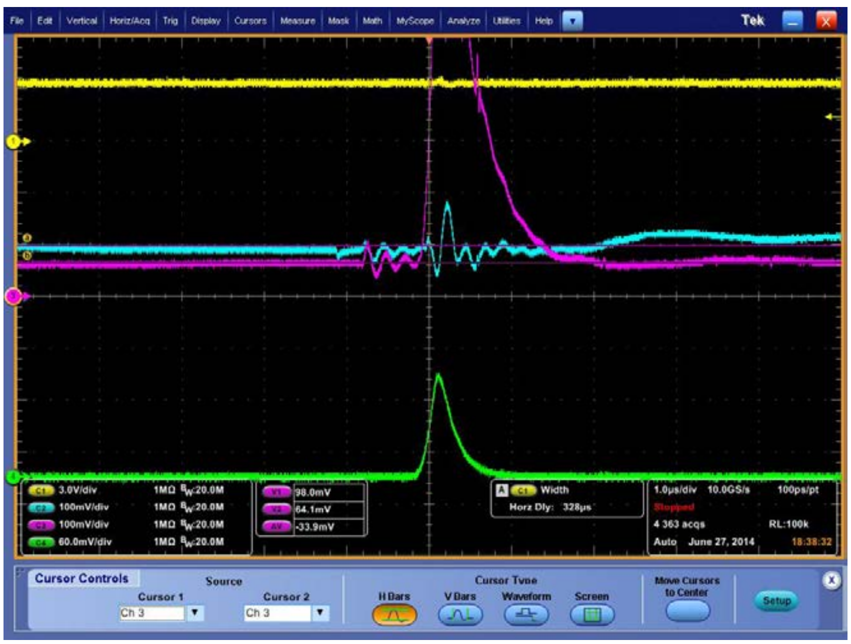

Figure 10: Single pulse at lowest dimming level in Discontinuous Mode

CH1	DEN
CH2	PWM_OUT
CH3	Photo feedback
CH4	External Photosensor

3.2.4 The Solution: Targeting optimal placement during optical design

Assume the operating requirements for a given HUD are as follows:

Requirement	Condition	Value	
Brightness at eyebox	max dimming level	15,000	nits
	min dimming level	3	nits
Lumens on diffuser	max dimming level	40.0	L
	min dimming level	0.008	L
Peak photocurrent	max dimming level	600	uA
	min dimming level	0.12	uA

Define the amount of light on the photodiode relative to the total luminous flux incident on the diffuser screen as:

$$Y = K \times X$$ ***Equation 3***

Where:

Y = units of light on the photodiode for 1 unit of light input
X = units of light output from the PGU for 1 unit of light input
K = ratio of light output from the PGU to light incident on the photodiode

In TI's system:

$$K \cong 0.01$$ ***Equation 4***

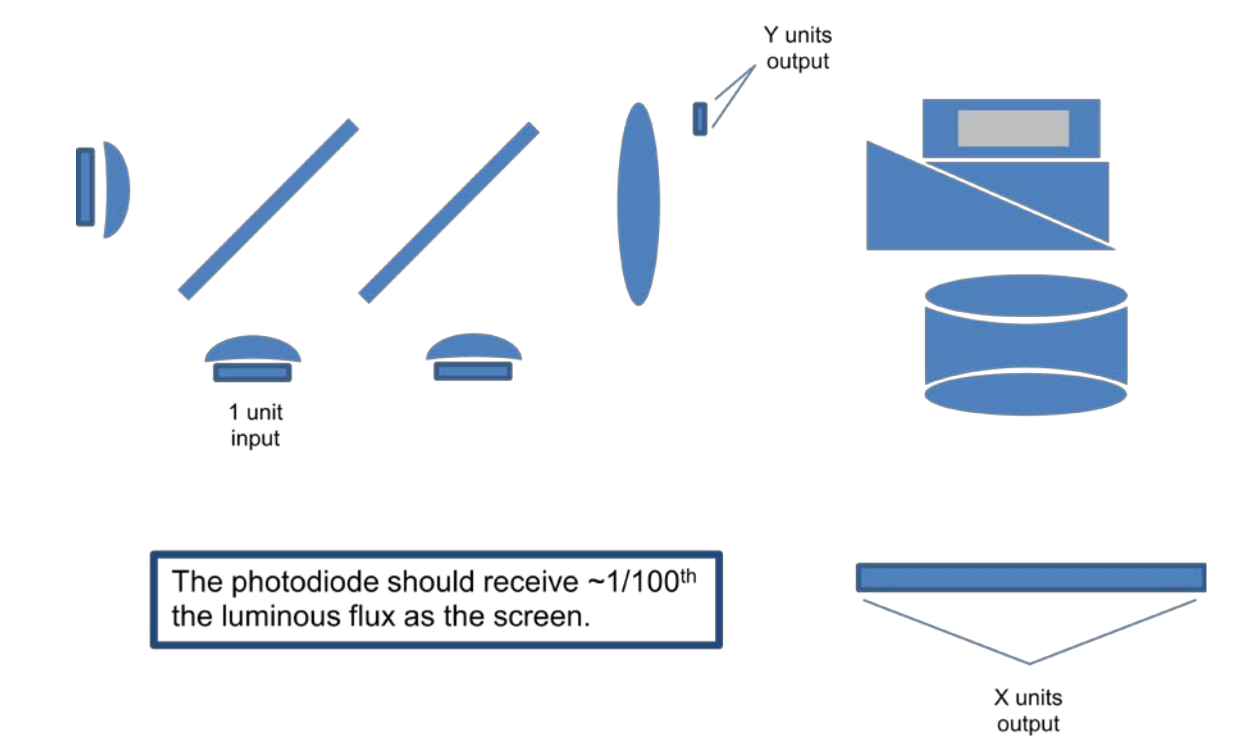

Figure 11: Photodiode and diffuser screen

3.2.5 Calculating K for your system

The primary goal is to keep the peak photocurrent between 500uA and 1000uA when the HUD dimming level is set to maximum brightness. To turn this into a meaningful requirement for the optical designers, this must be translated into luminous flux incident on the photodiode.

By calculating the ratio K, the system engineer can provide the optical designer a clear requirement for placing the photodiode in the geometric model of the PGU.

Most designs similar to TI's EVM can use **K=0.01**. However, several parameters affect the K value and it may be necessary for a system engineer to calculate a new K value.

Parameters affecting the value of K include:

- Lumens required onto diffuser screen for maximum brightness
- LED emission spectrum
- Photodiode responsivity
- Red, green, blue duty cycle at maximum brightness
- On/off duty cycle at maximum brightness

3.2.5.1 Deriving the general equation for K

Assume the following:

$$\boldsymbol{X = \phi_X/\phi_{LED}}$$ **Equation 5**

$$\boldsymbol{Y = \phi_Y/\phi_{LED}}$$ **Equation 6**

$$Y = K \times X$$ **Equation 7**

Where:

- ϕ_X is the luminous flux incident on the diffuser screen
- ϕ_Y is the luminous flux incident on the photodiode
- ϕ_{LED} is the luminous flux output from the LED
- X is the PGU efficiency with respect to the diffuser screen
- Y is the PGU efficiency with respect to the photodiode
- K is the ratio of Y to X; this section shows how to solve for K

These three equations allow the optical designer to calculate Y based on X and K.

The system engineer now needs to calculate how much luminous flux on the photodiode ϕ_Y is needed to generate 600uA of photocurrent i_{PD}. The luminous flux on the photodiode can be defined as:

$$\boldsymbol{\phi_Y = \int_\lambda \left(P_{pk} \times J(\lambda) \times \eta(\lambda)\right) d\lambda}$$ **Equation 8**

Where:

- P_{pk} is the peak output power per wavelength of an LED (a scalar)
- $J(\lambda)$ is the normalized emission spectrum of the LED at the location of the photodiode (Figure 11)
- $\eta(\lambda)$ is the CIE luminous efficacy curve that converts radiant flux (watts) to luminous flux (lumens) (Figure 12)

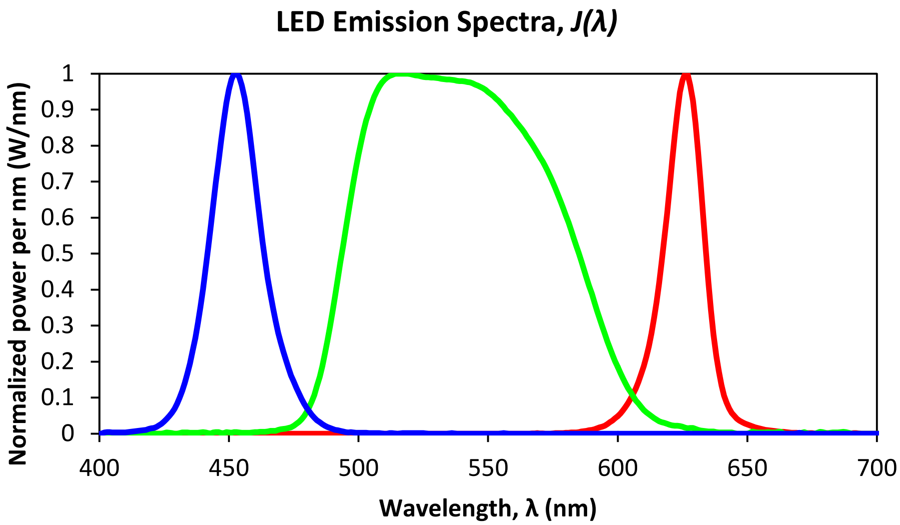

Figure 12: $J(\lambda)$ = Red, Green, and Blue LED emission spectra after dichroic filters

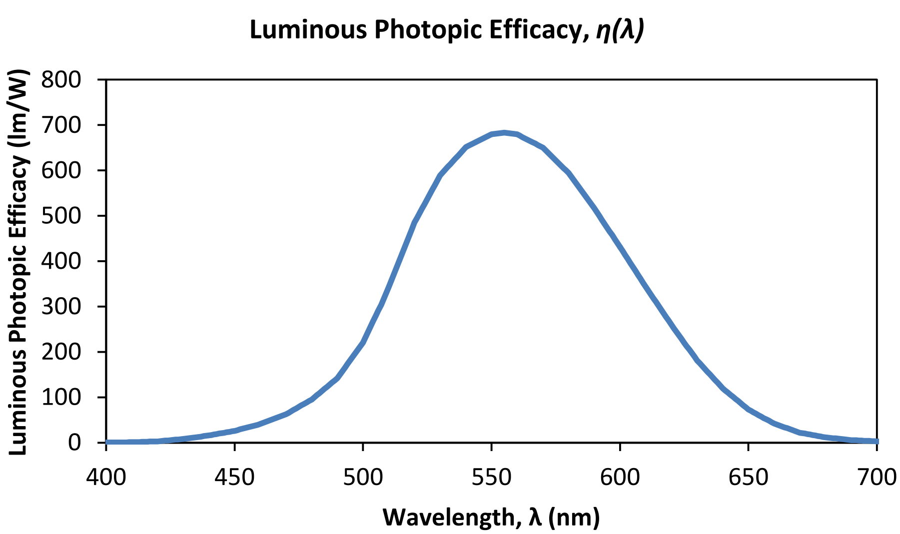

Figure 13: $\eta(\lambda)$ = CIE Luminous Efficacy Curve

Next define photocurrent i_{PD} as:

$$\boldsymbol{i_{PD}} = \int_{\lambda}\left(\boldsymbol{P_{pk}} \times \boldsymbol{J}(\boldsymbol{\lambda}) \times \boldsymbol{R_{rad}}(\boldsymbol{\lambda})\right) \boldsymbol{d\lambda}$$

Equation 9

Where:

- P_{pk} is the peak output power per wavelength of an LED (a scalar)
- $J(\lambda)$ is the normalized emission spectrum of the LED at the location of the photodiode (Figure 11)
- $R_{rad}(\lambda)$ is the spectral response of the photodiode (Figure 13)

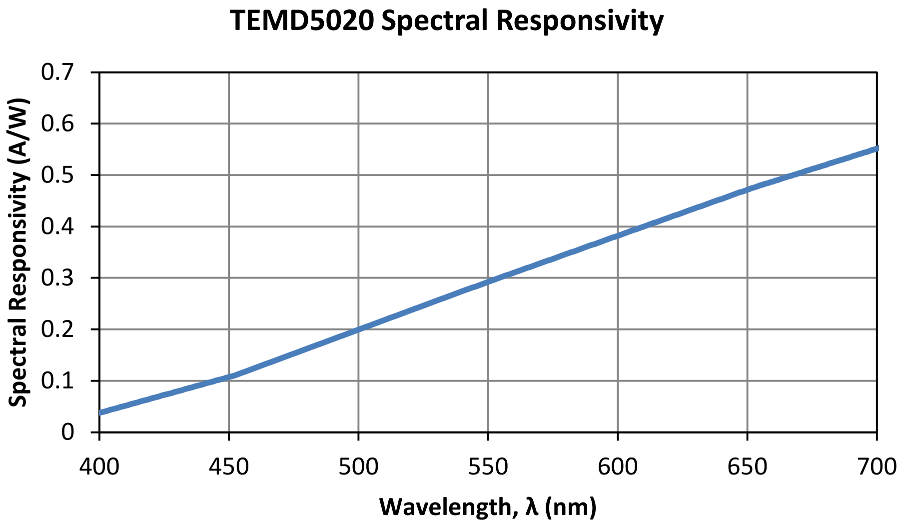

Figure 14: $R_{rad}(\lambda)$ = TEMD5020 Photodiode spectral response

Now calculate a conversion factor CF for the luminous flux per amp of photocurrent:

$$CF = \frac{\phi_Y}{i_{PD}} = \frac{\int_\lambda \left(P_{pk} \times J(\lambda) \times \eta(\lambda)\right) d\lambda}{\int_\lambda \left(P_{pk} \times J(\lambda) \times R_{rad}(\lambda)\right) d\lambda}$$

$$= \frac{P_{pk} \times \int_\lambda \left(J(\lambda) \times \eta(\lambda)\right) d\lambda}{P_{pk} \times \int_\lambda \left(J(\lambda) \times R_{rad}(\lambda)\right) d\lambda}$$

$$= \frac{\int_\lambda \left(\boldsymbol{J}(\boldsymbol{\lambda}) \times \boldsymbol{\eta}(\boldsymbol{\lambda})\right) \boldsymbol{d\lambda}}{\int_\lambda \left(\boldsymbol{J}(\boldsymbol{\lambda}) \times \boldsymbol{R_{rad}}(\boldsymbol{\lambda})\right) \boldsymbol{d\lambda}}$$

Equation 10

Finally, since each color will have a slightly different response, calculate the peak luminous flux for each color:

$$\boldsymbol{\phi_{Xpeak}} = \frac{\bar{\boldsymbol{\phi}}_{\boldsymbol{X}}}{\boldsymbol{DC_{color}} \times \boldsymbol{DC_{on/off}}}$$

Equation 11

Where:

- $\bar{\phi}_X$ is the average flux incident on the diffuser screen needed for maximum brightness
- DC_{color} is the duty cycle for the color (i.e. DC_{red}=0.375, DC_{green}=0.425, DC_{blue}=0.20)
- $DC_{on/off}$ is the shortest On duty cycle for maximum brightness, DC=0.5 for 50/50 mode

Now solve for K in terms of peak photocurrent, peak PGU luminous flux out, LED emission spectra, and photodiode responsivity:

$$K = \frac{Y}{X} = \frac{\phi_Y/\phi_{LED}}{\phi_X/\phi_{LED}} = \frac{\phi_Y}{\phi_X} = \frac{i_{PDpeak} \times CF}{\phi_{Xpeak}}$$

$$\boldsymbol{K} = \boldsymbol{600uA} \times \frac{\int_\lambda \left(\boldsymbol{J}(\boldsymbol{\lambda}) \times \boldsymbol{\eta}(\boldsymbol{\lambda})\right) \boldsymbol{d\lambda}}{\int_\lambda \left(\boldsymbol{J}(\boldsymbol{\lambda}) \times \boldsymbol{R_{rad}}(\boldsymbol{\lambda})\right) \boldsymbol{d\lambda}} \times \frac{\boldsymbol{1}}{\boldsymbol{\phi_{Xpeak}}}$$

Equation 12

3.2.5.2 Calculating K on TI's system

TI first measured the emission spectrum $J(\lambda)$ for each LED at the position of the photodiode, as shown in Figure 11. The spectra were captured using a BTS256e spectrometer. Note that these spectra are normalized.

$R_{rad}(\lambda)$ (Figure 13) was digitized from the TEMD5020 datasheet.

Using equation 11, the following CF values were calculated:

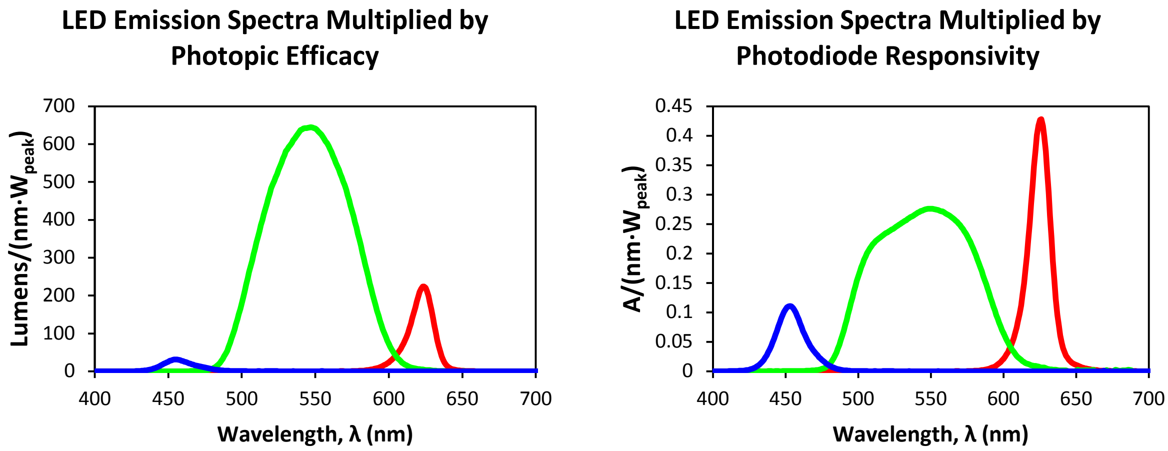

Figure 15: LED spectra after multiplication

$$\int_\lambda \left(J_{Red}(\lambda) \times \eta(\lambda)\right) d\lambda = \mathbf{4606\ lm/W_{peak}}$$
$$\int_\lambda \left(J_{Green}(\lambda) \times \eta(\lambda)\right) d\lambda = \mathbf{46298\ lm/W_{peak}}$$
$$\int_\lambda \left(J_{Blue}(\lambda) \times \eta(\lambda)\right) d\lambda = \mathbf{843\ lm/W_{peak}}$$

$$\int_\lambda \left(J_{Red}(\lambda) \times R_{rad}(\lambda)\right) d\lambda = \mathbf{8.33\ A/W_{peak}}$$
$$\int_\lambda \left(J_{Green}(\lambda) \times R_{rad}(\lambda)\right) d\lambda = \mathbf{24.55\ A/W_{peak}}$$
$$\int_\lambda \left(J_{Blue}(\lambda) \times R_{rad}(\lambda)\right) d\lambda = \mathbf{2.85\ A/W_{peak}}$$

$$CF_{Red} = 553\ lm/A$$
$$CF_{Green} = 1886\ lm/A$$
$$CF_{Blue} = 296\ lm/A$$

In this example, it is assumed that the PGU must output 40 lumens to yield 15,000 nits in the eyebox. Using the color points for the red, green, and blue LEDs as measured at the PGU output, the lumens required for each color to achieve a 6500K white point may be calculated using CIE xyY and CIE XYZ tristimulus values. The calculation is not shown in this document as several online tools and tutorials exist describing the process step by step. The resulting lumens required for each color in this example is shown in the following table.

	Red	Green	Blue	White point	
x	0.6878	0.2967	0.1518	0.3127	
y	0.3104	0.6287	0.0262	0.329	
Y	7.1	31.6	1.3	40	lumens

At maximum brightness, TI's standard sequence uses an on/off duty cycle of 70% and red, green, blue duty cycles of 37.5%, 42.5%, and 20% respectively. This translates to:

$$\phi_{XpeakRed} = \frac{7.1\ lm}{70\% \times 37.5\%} = 27.1\ lm$$

$$\phi_{XpeakGreen} = \frac{31.6\ lm}{70\% \times 42.5\%} = 106.3\ lm$$

$$\phi_{XpeakBlue} = \frac{1.3\ lm}{70\% \times 20\%} = 9.1\ lm$$

This yields K values of:

$$K_{Red} = \frac{600uA \times 553lm/A}{27.1\ lm} = 0.012$$

$$K_{Green} = \frac{600uA \times 1886lm/A}{106.3\ lm} = 0.011$$

$$K_{Blue} = \frac{600uA \times 296lm/A}{9.1\ lm} = 0.020$$

A different K value for each color may be given to the optical designers, but this may add complexity to the optical design. To simplify, a single K value may be used. A value of **K=0.01** was selected as the TI baseline through experimentation. This yields peak photocurrents of 490uA, 564uA, and 306uA for red, green, and blue respectively in this example. Peak photocurrents of 300uA to 1000uA have been shown to be acceptable experimentally.

3.2.5.3 Example: Adjusting K for a different photodiode

The photodiode used for the previous example was the TEMD5020. At λ=650nm, the TEMD5020 produces approximately 0.47 A/W.

Assuming the TEMD5080 is used instead, the photodiode responsivity is different. There are several important specifications in the datasheet:

TEMD5080 Specification	Value
Reverse light current (E_e=1mW/cm^2, λ=950nm)	60 uA (typ)
Relative spectral sensitivity (λ=650nm)	0.72
Relative spectral sensitivity (λ=950nm)	0.98
Radiant sensitive area	7.7 mm^2

Convert this information into A/W at λ=650nm.

$$\phi_e(950nm) = E_e \times Area = 1\ mW/cm^2 \ \times 7.7mm^2 \times \frac{1cm^2}{100mm^2} = 77\mu W$$

$$R_{rad}(950nm) = \frac{reverse\ light\ current}{\phi_e(950nm)} = \frac{60\mu A}{77\mu W} = 0.78\ A/W$$

$$R_{rad}(650nm) = R_{rad}(950nm) \times \frac{spectral\ sensitivity\ at\ 650}{spectral\ sensitivity\ at\ 950} = 0.78\frac{A}{W} \times \frac{0.72}{0.98} = 0.57\ A/W$$

Assume the responsivity ratio is the same across all colors and approximate K as:

$$\boldsymbol{Kcustomer = 0.01 \times \frac{0.47\ A/W}{Rrad(650nm)} = 0.01 \times \frac{0.47\ A/W}{0.57\ A/W} = 0.008}$$

Equation 13

3.2.5.4 Example: Adjusting K for different brightness requirements

Consider the case where the diffuser screen is replaced with a 100% more efficient diffuser. This results in a 50% decrease in the lumens requirement on the diffuser:

Requirement	Condition	Value	
Brightness at eyebox	max dimming level	**15,000**	nits
	min dimming level	3	nits
Lumens on diffuser	max dimming level	**20.0**	L
	min dimming level	0.006	L
Peak photocurrent	max dimming level	600	uA
	min dimming level	0.12	uA

Given that the lumens requirement is less, assume the customer decides to operate the DMD with an on/off duty cycle of 50/50 at all brightness levels.

Assume the same color temperature of 6500K and RGB duty cycles of 37.5%, 42.5%, and 20%.

	Red	Green	Blue	White point	
x	0.6878	0.2967	0.1518	0.3127	
y	0.3104	0.6287	0.0262	0.329	
Y	3.6	15.8	0.6	20	lumens

Redo the calculations for the new ϕ_{Xpeak}:

$$\phi_{XpeakRed} = \frac{3.6\ lm}{50\% \times 37.5\%} = 19.2\ lm$$

$$\phi_{XpeakGreen} = \frac{15.8\ lm}{50\% \times 42.5\%} = 74.4\ lm$$

$$\phi_{XpeakBlue} = \frac{0.6\ lm}{50\% \times 20\%} = 6.0\ lm$$

Keeping the CF values used in the previous example:

$$CF_{Red} = 553\ lm/A$$
$$CF_{Green} = 1886\ lm/A$$
$$CF_{Blue} = 296\ lm/A$$

Calculate the new K values:

$$K_{Red} = \frac{600uA \times 553lm/A}{19.2lm} = 0.017$$

$$K_{Green} = \frac{600uA \times 1886lm/A}{74.4lm} = 0.015$$

$$K_{Blue} = \frac{600uA \times 296lm/A}{6.0lm} = 0.030$$

$$\boldsymbol{K = min\{K_{Red}, K_{Green}, K_{Blue}\} = 0.015}$$ **Equation 14**

3.3 Tuning photodiode position and series resistance

After the PGU has been built, how does one verify if the photodiode is in the optimal position? What value should be used for the photodiode's series resistance? These questions will be answered in the following section.

Goals of photodiode placement:

- Must not saturate at peak brightness for each LED (see section 3.2.1)
- Maximum photocurrent approximately 600uA~1000uA

Goals of setting photodiode series resistance:

- Maximum photocurrent must not saturate the op amp input (V_{in} < 3.3V)
- Maximum photocurrent should use full range of op amp minus 10% (Vin = 3.0V)

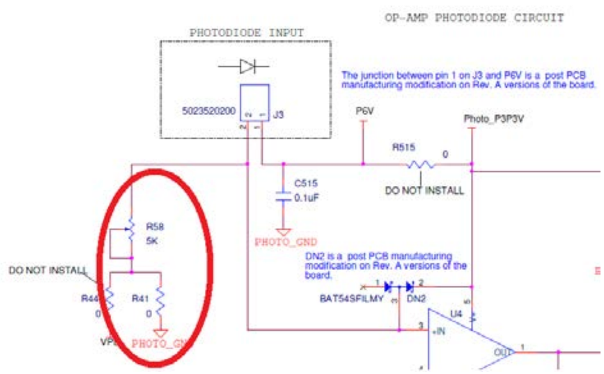

Figure 16: Photodiode series resistance

The following sections illustrate two methods of experimentally determining optimal position and series resistance after the PGU has been manufactured. Note that the TI reference design biases the photodiode with 6V.

3.3.1.1 Method 1: Optimize to LED current limit

The most straightforward method to set the photodiode series resistance is to ensure each LED is driven at its current limit when PWM = 59000 at room temperature. This ensures that the LED driver is not limiting the maximum brightness of any of the LEDs at room temperature.

With a complete system, follow these steps:

1) Set the photodiode series resistance to 3000 ohms
2) In the Automotive Control Program, set the backlight value to 65535
3) With the CA-210 connected, execute the LED Characteristics under Utilities (see the Automotive Control Program Guide for more information)
4) If any LED does not plateau by PWM=59000 (reached its current limit), reduce the photodiode series resistance and repeat step 3

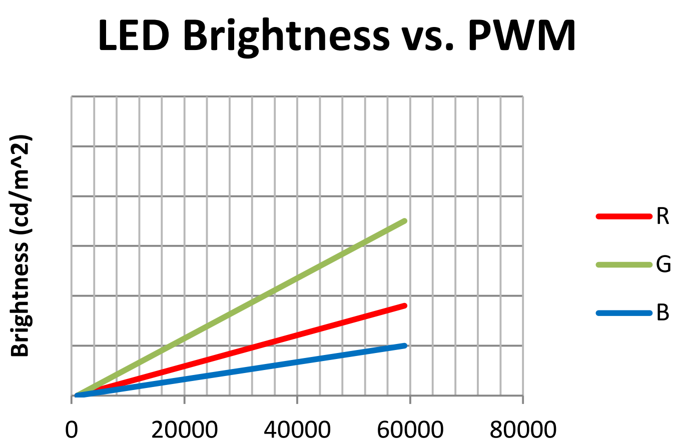

Figure 17: Photodiode series resistance too high

5) If any LED plateaus at PWM<16000, increase the photodiode series resistance and repeat step 3

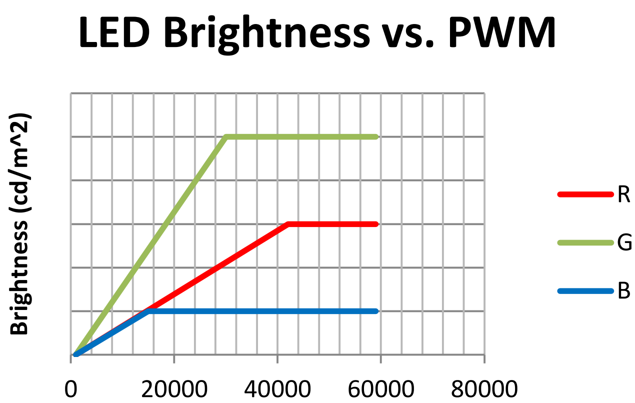

Figure 18: Photodiode series resistance too low

6) After the LED Characteristic Sweeps show each LED has reached its current limit, enter calibration mode and set the PWM=59000 for all three LEDs

7) Using an oscilloscope, probe the output of the photo feedback op amp

8) If the scope plot shows frequency roll off (see section 3.2.1), move the placement of the photodiode so that it receives less light and repeat steps 2 thru 8

9) If the final photodiode series resistance in steps 1 thru 5 is more than 5000 ohms, move the photodiode so that it receives more light and repeat steps 2 thru 9

*If the CA-210 is not available for steps 3 thru 5, the PWM values may be set manually while the operator measures the output of the current feedback op amp on an oscilloscope. This method will also show at what PWM value the current limit is reached.

To ensure all systems can reach the maximum brightness of the LEDs, this should be done with the most efficient (brightest) corner LEDs.

3.3.1.2 Method 2: Optimize for brightness target

To optimize the system for more dimming resolution and low-end dimming range, the photodiode series resistance can be set based on the target maximum brightness level for each color in the system.

The photodiode placement guidelines above are designed for a series resistance of 3000 ohms at the target maximum brightness. However, due to variation in the optical, mechanical, and electrical design, this will likely need to be varied.

With a complete system, follow these steps:

1) Set the photodiode series resistance to 3000 ohms
2) In the Automotive Control Program, set the backlight value to 65535
3) With the CA-210 connected, execute the LED Characteristics under Utilities (see the Automotive Control Program Guide for more information)
4) If the brightness at PWM=50000 is less than the target maximum brightness for any LED, decrease the photodiode series resistance and repeat step 3
5) If the brightness at PWM=16000 is greater than the target maximum brightness for any of the LEDs, increase the photodiode series resistance and repeat step 3
6) After the LED Characteristic Sweeps show each LED has reached its target maximum brightness between PWM=16000 and PWM=59000, enter Calibration Mode and set the PWMs to the value corresponding to the target maximum brightness
7) Using an oscilloscope, probe the output of the photo feedback op amp
8) If the scope plot shows frequency roll off (see section 3.2.1), move the placement of the photodiode so that it receives less light and repeat steps 2 thru 8
9) If the final photodiode series resistance in steps 1 thru 5 is more than 5000 ohms, move the photodiode so that it receives more light and repeat steps 2 thru 9

4 Software Design

4.1 Protecting Against Photodiode Failures

The photodiode is typically connected to the LED driver electronics by a cable rather than being located on the same electronics board (see Figure 16). This connection presents a possible point of failure that the system must anticipate and appropriately respond to avoid driving an image many times brighter than intended. In a negative feedback system such as this, if the photodiode fails open (photocurrent is stuck at zero), the LEDs will be driven to the maximum brightness set by the current limit.

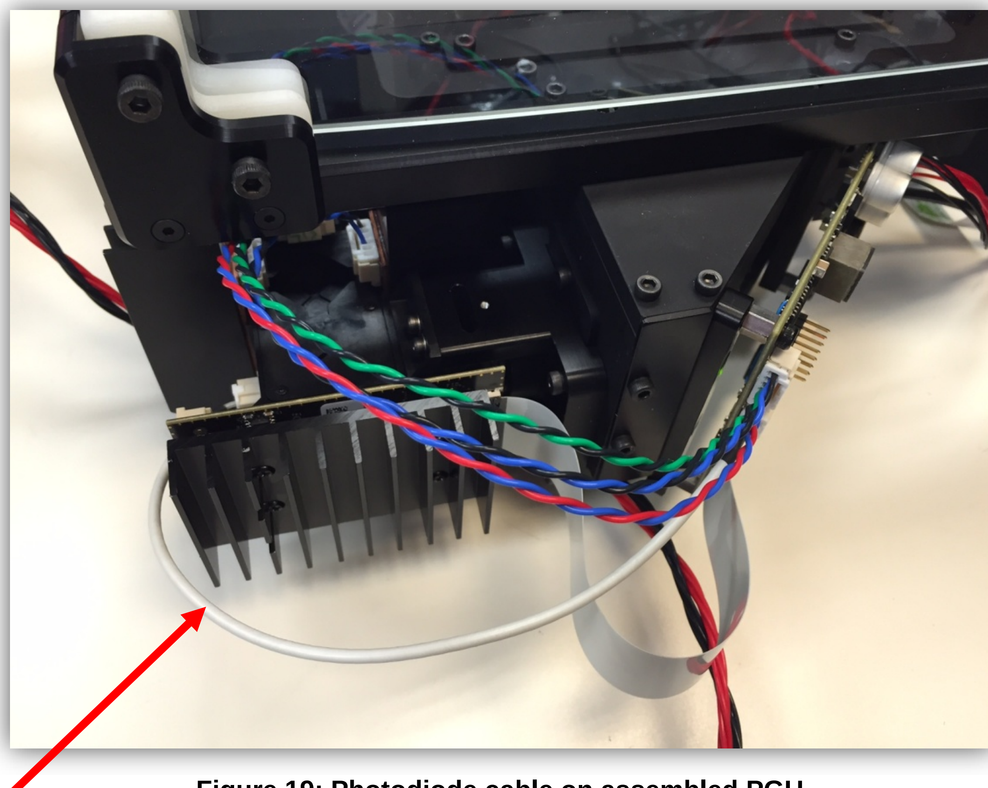

Figure 19: Photodiode cable on assembled PGU

4.1.1 What happens in Continuous Mode if the photodiode fails?

The following two scope captures illustrate what can happen if the photodiode fails open.

Figure 20: Continuous Mode: Normal operation in LDC2 with low PWM

Figure 21: Continuous Mode: LDC2 photodiode fails open

CH1	DEN
CH2	SEN
CH3	PWM_OUT
CH4	External Photosensor

4.1.2 The Solution: Protecting against over bright conditions in Continuous Mode

The microcontroller (Piccolo in TI's system) should monitor the LED driver for any indication that the photodiode might have failed. A few possible methods are:

1) Sample **current feedback** voltage with Piccolo ADC
    a. Configure DLPC120 AST function to trigger during the green pulse (see section 4.2)
    b. Configure Piccolo ADC to trigger off AST function and sample current feedback voltage (see reference code)
    c. Store ADC value after conversion is complete
    d. On subsequent frames, set AST function to sample red, then blue LEDs
    e. If all three LEDs are hitting the current limit, the photodiode might have failed open

2) Sample **photo feedback** voltage with Piccolo ADC
    a. Configure DLPC120 AST function to sample during the green pulse (see section 4.2)
    b. Configure Piccolo ADC to trigger off AST function and sample photo feedback voltage (see reference code)
    c. Store ADC value after conversion is complete
    d. On subsequent frames, set AST function to sample red, then blue LEDs
    e. If all three samples show ~0V on the photo feedback when the PWM>2000, the photodiode might have failed open
    f. If all three samples show ~3.3V on the photo feedback, the photodiode might have shorted

3) Auxiliary photodiode
    a. Design an auxiliary photo feedback circuit that integrates across the total frame time (16.67ms)
    b. Configure the microcontroller to sample the value each frame and reset the integrator
    c. If sampled frame brightness exceeds the expected maximum for a given backlight, this could indicate the primary photodiode has failed open

To prevent driving the display too bright after a failure is detected, possible options are:

1) Set all LED PWM compare levels equal to 0 (shut off the display)

2) Set current limit to predetermined safe level
    a. White point will not be preserved, but display will still operate

4.1.3 What happens in Discontinuous Mode if the photodiode fails or the PWM is set too high?

The following scope captures illustrate what happens when the PWM value is set to a brighter value than the LED is capable of emitting at its current limit. This situation could happen if:

- An LED light output dims abnormally with age, temperature, or voltage
- PWM values set too aggressively during calibration for a given LDC table
- Amount of light hitting the photodiode decreases unexpectedly due to shifts in the mechanics or optics
- Photodiode fails open

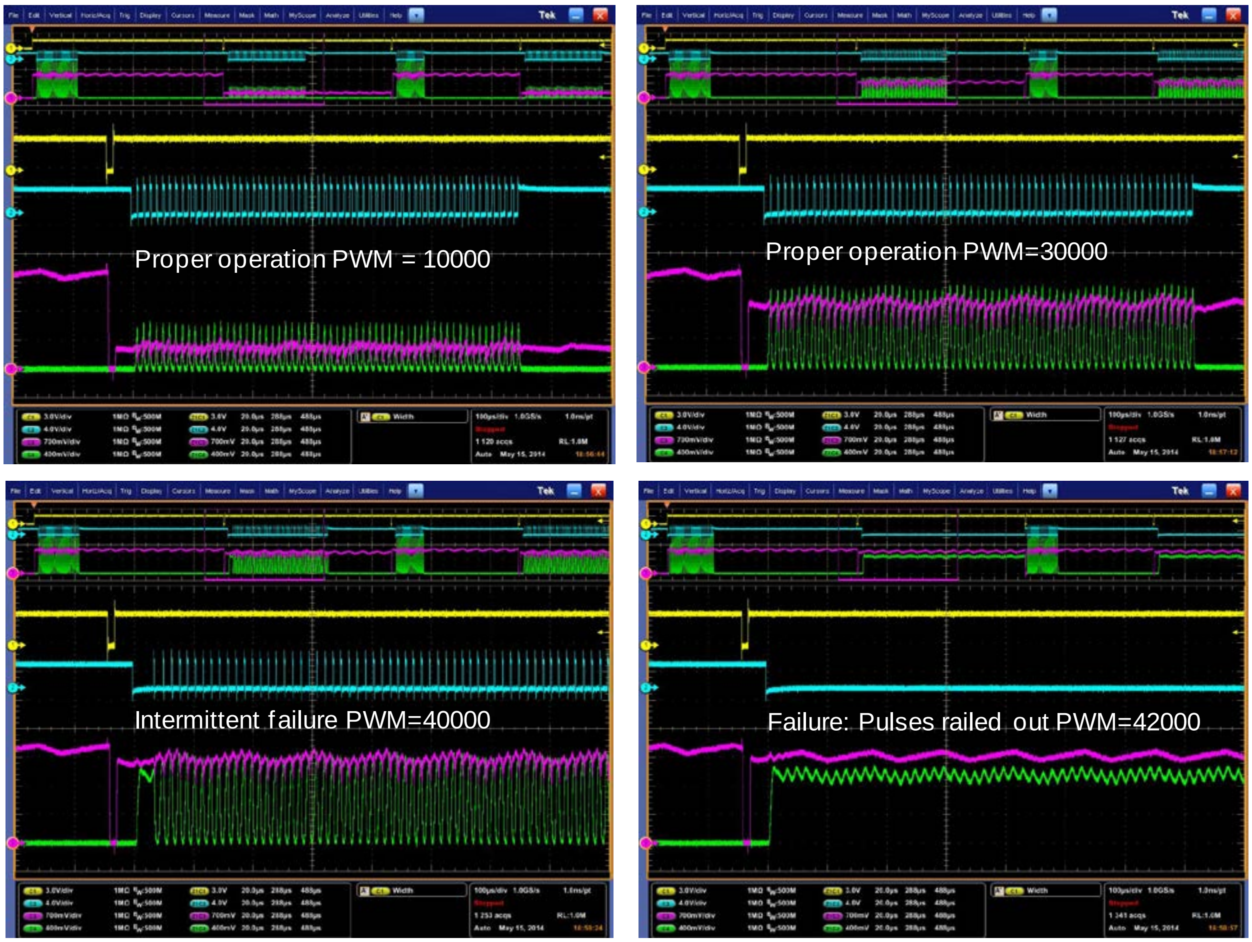

Figure 22: Discontinuous Mode operation and dim LED condition

CH1	DEN
CH2	SEN
CH3	PWM_OUT
CH4	External Photosensor

The image will start to flicker in the intermittent failure mode, while the image will be much brighter than intended in the “pulses railed out” failure mode.

4.1.4 The Solution: Protecting against over bright conditions in Discontinuous Mode

The microcontroller (Piccolo in TI's system) should monitor the LED driver and DLPC120 for any indication that the LEDs have dimmed unexpectedly, the photodiode has shifted, or the photodiode has failed. A few possible methods are:

1) Enable DLPC120 **pulse count error interrupt**
    a. Set DLPC120 I2C register 0x2:bit 25 to enable the interrupt
    b. When HUD_INTR triggers a Piccolo interrupt, read I2C register 0x1
    c. If 0x1:bit 25 is set, too many or too few DM light pulses were created during the frame

2) Sample **LED high side voltage** (HSV) with Piccolo ADC
    a. Configure DLPC120 AST function to sample during the green pulse (see section 4.2)
    b. Configure Piccolo ADC to trigger off AST function and sample high side voltage feedback (see reference code)
    c. Store ADC value after conversion is complete
    d. On subsequent frames, set AST function to sample red, then blue LEDs
    e. If all three samples show voltages indicating the LEDs are at the current limit for the LDC, the photodiode might have failed open or the LEDs have railed out for another reason
        i. Each LDC entry has a defined current limit for all three colors in Discontinuous Mode
        ii. Calculate the voltage corresponding to the current limit by using the I-V curves in the LED datasheets and adding the expected voltage drop across the RGB enable FETs and current sense resistor

    *Note AST current measurements cannot be used as the current thru the sense resistor is constant in Discontinuous Mode

3) **Auxiliary photodiode**
    a. Design an auxiliary photo feedback circuit that integrates across the total frame time (16.67ms)
    b. Configure the microcontroller to sample the value each frame and reset the integrator
    c. If sampled frame brightness exceeds the expected maximum for a given backlight, this could indicate the primary photodiode has failed open or the PWM is set too high

To prevent driving the display too bright after a failure is detected, possible options are:

1) Set all LED PWM compare levels equal to 0 (shut off the display)

2) Iteratively decrease backlight value, clear the interrupt, and monitor for further failure indications

3) If a new calibration file is programmed and a failure consistently occurs when a given LDC is selected, decrease the maximum PWM values used in the LDC entry

4.2 Configuring and Using ADC Sampling Timer (AST)

To create a frame of video, the DLP HUD displays a sequence of very fast, interleaved red, green, and blue pulses. The human eye integrates these fast pulses into a full color image.

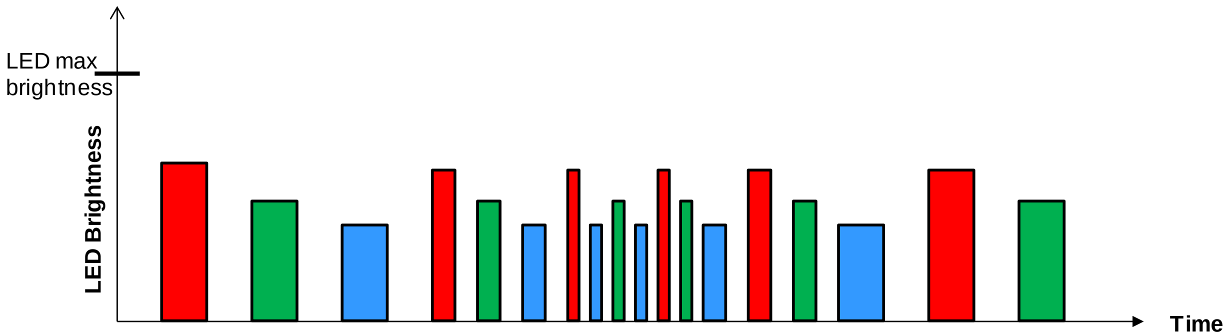

Figure 23: DLP HUD sequence

As such, in order to sample the amplitude of a specific LED's current or brightness, the sample must be synchronized to the desired pulse. To facilitate this, the DLPC120 AST function provides a timing signal to trigger the ADC sample during the desired color and bit during the frame.

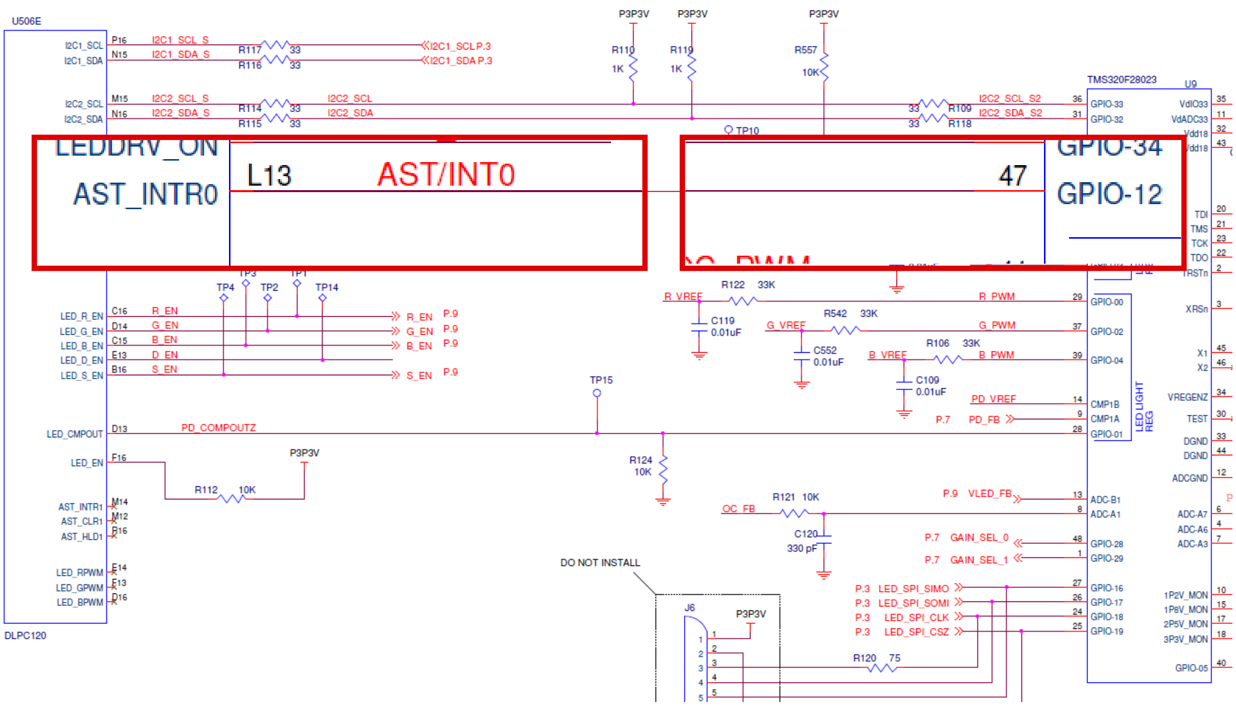

Figure 24: AST Interrupt Signal

AST is configured with several DLPC120 registers. Please see the I2C Programmers Guide for more information. The ADC trigger asserts once every frame at the time specified by the end of the sampling window. The sampling window times are specified in 38.6MHz clocks, where a value of 0 references the beginning of the frame.

For each color, the sample time will vary based on the sequence used (i.e. 70/30 vs. 50/50 and high bit depth vs. standard bit depth). To find the desired sample time, open the .cfg file provided by TI in the Automotive Control Program. See the breakout in the figure below.

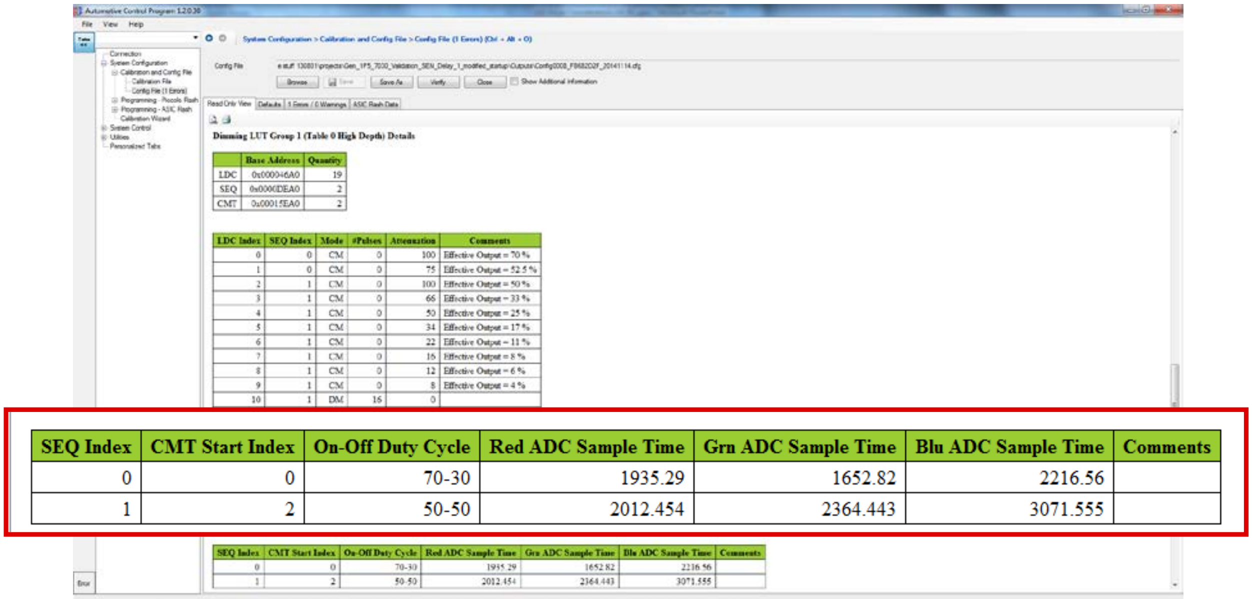

Figure 25: AST sample time in Automotive Control Program

For example, to trigger an ADC sample during the green pulse, while in the 70-30 sequence:

The green sample time found in the figure above is 1652.82us. Multiply 1652.82us by 38.6 clocks/second to get 0xF937 clocks. The window start time should be 0x100 less than the sample time (0xF937 - 0x100 = 0xF837).

```
Set 0xCE = 0x0              // disable AST
Set 0xC9 = 0xF837           // sample window start in 38.6MHz clocks
Set 0xCA = 0xF937           // sample window end in 38.6MHz clocks
Set 0xCC = 0x00000101       // intr point
Set 0xCD = 0x1FFF1FFF       // intr width
Set 0xCE = 0x00000201       // Enable AST, hold=active high, intr=active low
```

5 Revision History

Rev	Section	Release Date	Revisions
A	All	April 2015	Original release

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