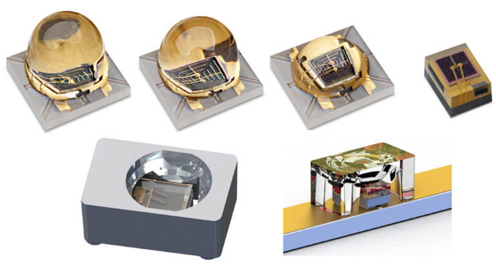
WHITE PAPER

LUXEON IR Emitters for Surveillance Cameras



This white paper focuses on the challenges IR illumination faces in a surveillance system and how to address those challenges.

- Section 1: Summary of noise sources in a camera system and the definition of Signal-to-Noise Ratio (SNR)
- Section 2: Dependence of SNR on illumination parameters (wavelength, output flux and Field of View (FOV)), setup configuration (distance to object and camera integration time) and external factors (ambient temperature)
- Section 3: Calculation example showing how to derive illuminator's specifications from camera's parameters and the noise requirements of the applications
- Section 4: Conclusion and guidelines

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1. IR Illuminators for Video Surveillance

The market for global video surveillance products has been growing in recent years. New artificial intelligence based analytical techniques and hardware are creating a new paradigm shift, a shift from passive human monitoring to active event driven monitoring. New cameras with embedded video analytics, such as object detection of humans, pets and vehicles, people and vehicle counting, intrusion and perimeter monitoring, license plate recognition and face recognition are being implemented by government, enterprise, and residential/consumer customers. These analytical features make these cameras “Smart”; they effectively eliminate the need to transmit data to a central server, thus enabling an efficient use of bandwidth and need for human oversight.

To enable this new paradigm, surveillance cameras need to generate images with greater fidelity and improved signal-to-noise ratio. Along with the 2D image, information on depth is also required. The quality of the image is a strong function of the ambient light conditions, indoor and outdoor lighting, and the distance to the object.

The properties of the sensor, such as sensitivity, dynamic range, dark noise, etc., play a critical role in the overall performance of the surveillance system. In addition to the sensor, design factors such as camera lens (field of view, f-number, transmission, which determine the amount of light collected by the sensor) and the illumination of the scene (which determines the amount of light available for collection in the first place), play an important role.

During daytime, sunlight is typically enough for obtaining good quality images. However, during night time or in enclosed spaces with no access to natural light, additional illuminators are needed. These illuminators can provide visible white light (WL) or infrared (IR) light.

Typically, surveillance cameras switch between WL (day time) and IR (night time) modes when the amount of white light falls below a certain threshold. For daytime operation, most cameras[1] have a low pass IR filter installed in front of the sensor; for night time operation, the IR illuminators are turned on and this filter is automatically removed, so that the sensor can “see” IR light.

The obvious question is, “Why not use WL only? Why use a more complex camera system that can do both WL and IR?” The answer is that for some applications using WL it’s either impractical, not allowed or too intrusive, as exemplified below:

- Avoid light pollution – this can be an issue for large areas (e.g. surveillance of an industrial site, where illuminating the whole perimeter would create significant light pollution), but also for small areas (e.g. home security, where having visible lights on during the night is not comfortable)
- Covert security – for the situations where the presence of a surveillance camera should not be noticed
- Night time traffic monitoring – in this case, using WL would be disorienting for the drivers
- Invisible illumination (for humans) can be required in cases where surveillance illumination might be mistaken for signal lights (e.g. railway tracks)

1.1 Signal-to-Noise Ratio (SNR)

How much IR light is needed to obtain a good image? In order to figure out the luminous flux needed, a metric is needed to measure the image quality. Typically, this is done via the Signal-to-Noise Ratio (SNR); image noise is defined as “random variations of brightness/signal” and is calculated as shown below.

$$SNR = \frac{Signal}{Noise} \tag{1}$$

It is expressed in dB:

$$SNR_{dB} = 20 \log \mathrm{SNR} \tag{2}$$

1. Silicon-based imaging sensors (including CCD and CMOS) are sensitive to IR light. That’s why a low pass IR filter is typically installed in front of the sensor or in the lens when operating in day time mode (since the “standard” Red, Green and Blue pixels are also used to detect IR). A less common situation is for the sensor to have dedicated IR pixels (besides the RGB ones); in this case a dedicated filter might not be needed.

1.2 Noise Sources

In a camera system there are multiple sources of noise and are typically classified in two categories:

1. Random noise – varies randomly over time for each pixel and can be reduced by averaging multiple images
2. Pattern noise – a spatial noise that doesn't change significantly from one frame to the next

Pattern noise is a propriety of the image sensor and it's usually specified as signal variation from one pixel to another. Various methods for calibrating or suppressing it exists. On top of that, the electronic circuitry tasked with converting the sensor signal to a voltage introduces its own noise.

The main types of noise associated with the image sensors are listed below. This document focuses mostly on random noise, since this is the type of noise introduced by illuminators.

- Fixed pattern noise (FPN)
- Photo-response non-uniformity (PRNU – pattern noise)
- Photon shot noise – due to the statistical distribution of photons; this type of noise is directly related to the illumination (random noise)
- Thermal (dark) noise – due to thermal effects, electrons are generated within the pixels even in total absence of incoming photons; this type of noise is temperature dependent (random noise)
- Reset noise – due to pixel resetting, it is temperature dependent and also depends on the pixel's capacitance (random noise)
- Flicker noise (also called 1/f noise) – occurs due to junction conduction fluctuations; it is inversely proportional to the operating frequency of the electronic circuitry
- Quantization noise – rounding due to Analog-to-Digital signal conversion

Describing random noise is done via statistical parameters, usually the variance or the standard deviation of a certain parameter, like the number of photons incident on a pixel during a given time. When summing up multiple noise sources, the standard deviation is given by:

$$Stdev_{total} = \sqrt{{Stdev_{NoiseSource1}}^2 + {Stdev_{NoiseSource2}}^2 + \cdots + {Stdev_{NoiseSourceN}}^2} \qquad (3)$$

1.3 Photon Shot Noise

Shot noise originates from the discrete nature of photons, while the average photon flux over time is constant; at any given moment, the instantaneous photon flux varies around this average value. This variation is called "photon shot noise" and it is given by the formula below:

$$N_{PhotShotNoise} = \sqrt{N_{phot}} \qquad (4)$$

Where N_{phot} is the total number of photons incident on the detector in a given time (the actual signal). This means that increasing the number of photons leads to a higher shot noise; however, keeping in mind that the SNR is given by $\frac{Signal}{Noise}$, this means that the $SNR = \frac{N_{photB}}{\sqrt{N_{phot}}} = \sqrt{N_{phot}}$ also goes up. This is exemplified in Figure 1 below, which shows that by increasing the total number of photons the SNR increases, despite the increase in the absolute value of the shot noise.

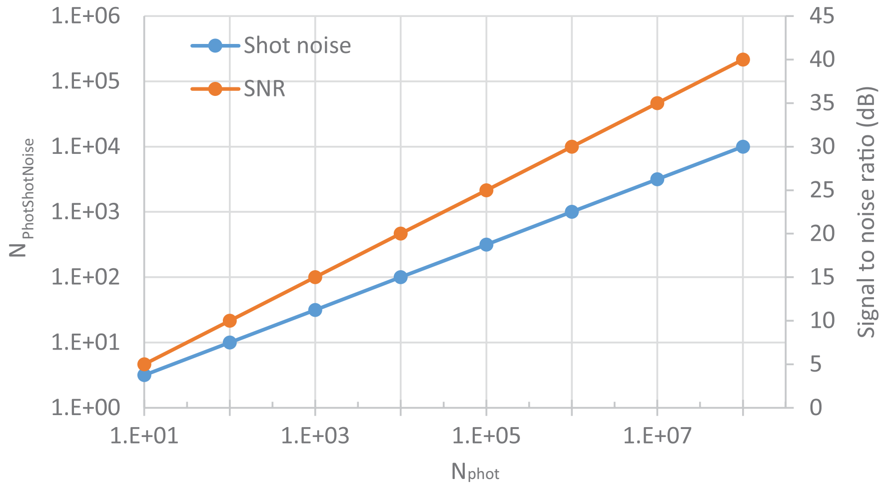

Figure 1. Shot noise and SNR_{dB} vs. total number of photons, showing that increasing the luminous signal (total number of photons) leads to higher SNR.

When calculating the actual SNR of the sensor, one must keep in mind that not all photons incident on a pixel are converted to electrons. The number of generated electrons (the actual signal read as a voltage) is lower thant the initial number of photons. The ratio between these two quantities is called Quantum Efficiency (QE), and it characterizes how good a given image sensor is at converting photons to electrons. QE is wavelength dependent.

Thus, the actual SNR for a luminous flux Φ < W > incident on a pixel of an image sensor with the quantum efficiency QE is give by:

$$SNR = \sqrt{n_{phot}^2} = \sqrt{\frac{QE(\lambda) \cdot \Phi_{pix} \cdot t_e}{h \cdot c / \lambda}} \tag{5}$$

Where t_e is the integration time of the sensor, h is Boltzmann's constant, c is the speed of light and λ is the wavelength of the incident light.[2]

Using the standard 20 log rule, we have:

$$SNR_{dB} = 20 \log \mathrm{SNR} = 20 \log\left(\sqrt{\frac{q_e \cdot \Phi_{pix} \cdot t_e}{h \cdot c / \lambda}}\right) \tag{6}$$

Based on the above consideration, it becomes clear that collecting as much light as possible is always a good idea; for a given scene and camera setup (sensor, lens, object reflectivity), this means that increasing the amount of light provided by the (IR or WL) illuminators should be maximized.

In fact, as long as there is plenty of light available, the photon shot noise is the main contributor to the overall noise budget of the sensor.

One note of caution: this section might give the impression that, as long as the scene is flooded with light, the image sensor specs are not that critical. After all, an arbitrary high SNR can always be reached by increasing the amount of light used for illuminating the scene. However, this is not the case even in those situations when plenty of light is available. First, each sensor pixel can store a limited amount of electrons, which limits the maximum SNR ratio achievable regardless of the number of photons available. Second, a given scene can contain objects located at different distances from the camera and/or having different reflectivity; this means that, for a given exposure time, not all pixels will be "filled" in with electrons, so at least for some pixels in the scene the overall noise will not be determined mainly by the photon shot noise. Therefore, the sensor needs to be carefully chosen for each application.

2. The $h \cdot c/\lambda$ part of the formula is in fact the energy of a single photon of a given wavelength.

1.4 Required SNR

The obvious question is "what's the minimum SNR to obtain a good image"? The answer depends on the application requirements. For example, detecting the presence of a car can be done at lower SNR than accurately identifying its registration plate. The way of processing the images also makes a difference: automated processing (machine vision) has different requirements compared to a person watching the images. On top of that, the ability to recognize an object in a noisy image depends on the object size (bigger objects can be identified at lower SNRs; see ***"The Scientist and Engineer's Guide to Digital Signal Processing,*** *Chapter 25: Special Imaging Techniques,****"*** which makes it clear that the SNR (and, by consequence, illumination) requirements must be tailored to the application.

For the rest of this document, a simple rule of thumb will be used to assess the illuminator's performance:

- Camera SNR_{dB} > 20 dB – high image quality
- Camera SNR_{dB} > 15 dB – general image quality
- Camera SNR_{dB} > 10 dB – minimum recommended image quality

The above rule of thumb is valid for video output of the camera; for still images, requirements might be higher, though it's worth mentioning that individual images with higher SNR can be obtained from video streams (e.g. by averaging multiple frames).

1.5 IR Illuminator – How to Specify It

As discussed previously, the image sensor and lens will determine how much light needs to be collected to meet the required SNR performance, based on which the needed illumination of the scene can be calculated. However, besides the total amount of light needed, there are several other factors that must be considered when designing an IR illuminator:

- What is the Field of View (FOV) of the camera? Ideally, the FOV of the illuminator should match the camera's.
- Is the security system supposed to be fully covert? If so, the illuminator must be invisible to the human eye.
- What are the ambient conditions? An outdoor illuminator will experience a much wider range of temperatures than an indoor one; since the emitted luminous flux is temperature dependent, this also needs to be factored in during the design phase, keeping in mind that the image sensor performance is also temperature dependent.

2. SNR Measurement with ON Semiconductor and Lumileds IR Evaluation Kits

This experimental section shows how illumination, distance to object, wavelength and integration time influence SNR. To this end, a camera + illumination setup is used, consisting of:

- ON Semiconductor's CMOS image sensor evaluation kit built around the AR0237-IR image sensor
- Lumileds illumination kit

2.1 ON Semiconductor AR0237IRSH00SHRAH3-GEVB

A full description of the ON Semiconductor evaluation boards can be found on the Mouser Electronics or Digi-Key Electronics product catalog sites.

Besides the usual RGB pixels, the AR0237IR image sensor also has dedicated pixels sensitive to IR light, as shown in Figure 2 below, which allows it to take daytime WL images and night time IR images without additional mechanical IR filters.

Camera: ON Semiconductor AR0237IR sensor (see Figure 2):

- 2.1 megapixels
- Lens information: SUEX DSL945D
- Camera resolution: 1920X1080 pixels

- 3.0 µm X 3.0 µm pixel size
- /2.7 (6.6mm) inch optical format
- 30 fps
- SNR_{MAX}: 41dB

The camera is fitted with a lens and dual band filter that transmits visible and 850nm IR light with the following characteristics:

- Lens: SUEX DSL945D
- Dual band IRCF: SUNEX IRC40 for 650/850nm
- 4x4 RGBIR processing image quality and color correctly recover dominate by dual-band IRCF, lens and offline image processing; recommend consulting sensor, optical and ISP for RGBIR image tuning

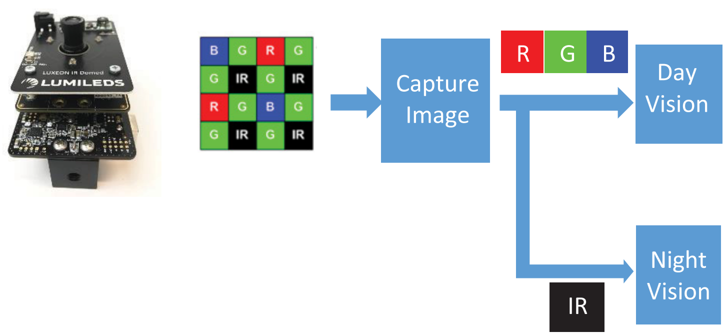

Figure 2. AR0237 development kit work flow.

The plot below (Figure 3) shows that the QE at 940nm is significantly lower than the QE at 850nm (28% vs. 12%, respectively).

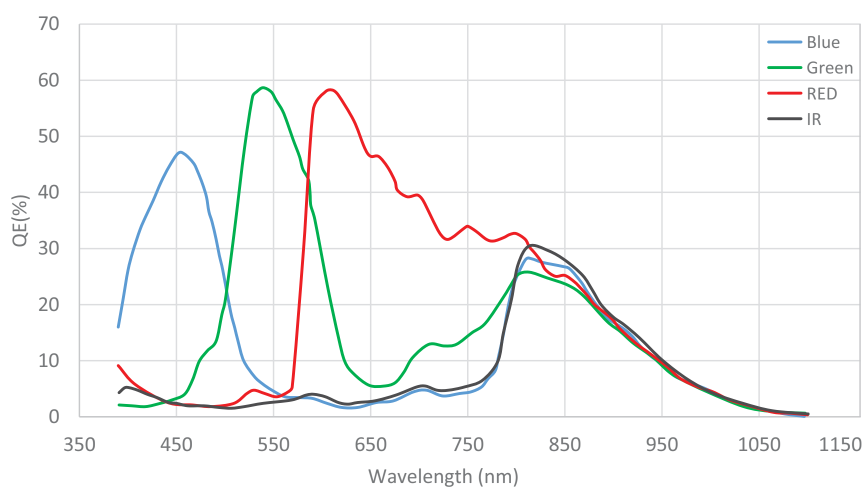

Figure 3. Quantum efficiency vs. wavelength for AR0237-IR.

The evaluation kit includes the DevWare X software suite, which, amongst other functions, allows the measurement of SNR within a user-defined area by calculating the average signal and its standard deviation of all pixels included in the area over multiple frames.

2.2 Lumileds IR Evaluation Kit for ON Semiconductor AR0237IRSH00SHRAH3-GEVB

Lumileds developed a series of illuminator boards for the ON Semiconductor evaluation kit (L2I0-0AAABBBEVK200, where AAA stands for the wavelength – 850nm or 940nm, and BBB stands for the FOV – 060, 090 and 150 respectively). There is a total of 3 LEDs on each illuminator board, and the drive current can be manually adjusted from 0 to 1000mA. The actual forward current of the illuminators can be measured across two pads on the board. LUXEON IR Domed 60°-850nm, 60°-940nm, 90°-850nm and 90°-940nm illuminator boards were used in this test (more details found in LUXEON IR Family datasheets).

- LED: LUXEON IR Domed (all versions)
- Driver: Adjustable DC-DC step down converter; max current 1Amp
- Power Supply: 15-24V DC of at least 15 Watt with 5.5mm x 2.5mm barrel connector
- Radiant Power: 3 x 1.35 W = 4.05 W (850nm) or 3 x 1.45 W = 4.35 W (940nm) at 1A drive current

The Lumileds board is shown separately and mounted on the ON Semiconductor evaluation kit in Figure 4 below.

Figure 4. Left: Lumileds IR illumination board with LUXEON IR LEDs. Right: Lumileds board mounted on top of an ON Semiconductor AR0237IRSH00SHRAH3-GEVB kit.

2.3 Test Scene

The scene used for testing consists of a white paper sheet,[3] which does not produce specular reflections. The reflectivity[3] of the paper is 100%. Within the image, four square test areas (50 x 50 pixels) are defined, as shown in Figure 5 below.

- Area 1: in the upper left corner of the image, corresponding to a view angle of 30° (equivalent to a diagonal FOV of ~60°)
- Area 2: the top middle of the image, corresponding to a view angle of 15° (equivalent to a vertical FOV of ~30°)
- Area 3: the left side edge of the image, corresponding to a view angle of 27° (equivalent to a horizontal FOV of ~54°)
- Area 4: the center of the image, corresponding to a view angle of 0°

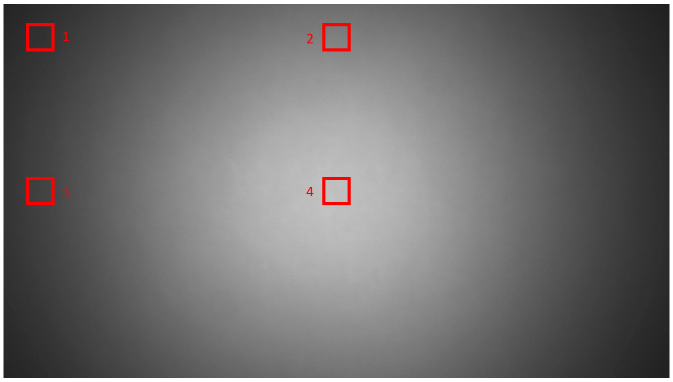

Figure 5. The target scene, illuminated with 3 x LUXEON IR 850nm 60° emitters, indicating areas used for SNR measurements.

3. Measured with a reflection probe, calibrated against an Avantes WS-2 reflectance tile for diffuse reflection measurements.

2.4 Influence of the Distance on the SNR

According to the inverse square law of power shown in Figure 6, as light travels away from the source it spreads out; the greater the range or the divergence, the more quickly the irradiance (energy per unit area) decreases. Doubling the distance means that the same energy is spread over four times the area, hence the intensity will drop to one fourth. According to expression (6), the SNR is proportional to the square root of the sensor energy, so a doubling of the distance will lead to a ~6 dB decrease in SNR; an increase of the distance by a factor 1.5 would lead to a decrease of SNR by ~3.5 dB. To compensate for the doubling of the distance, the output flux needs to be increased four times in order to keep the same SNR (see section 3.2 for a more detailed overview of how changes in distance and output flux impact SNR).

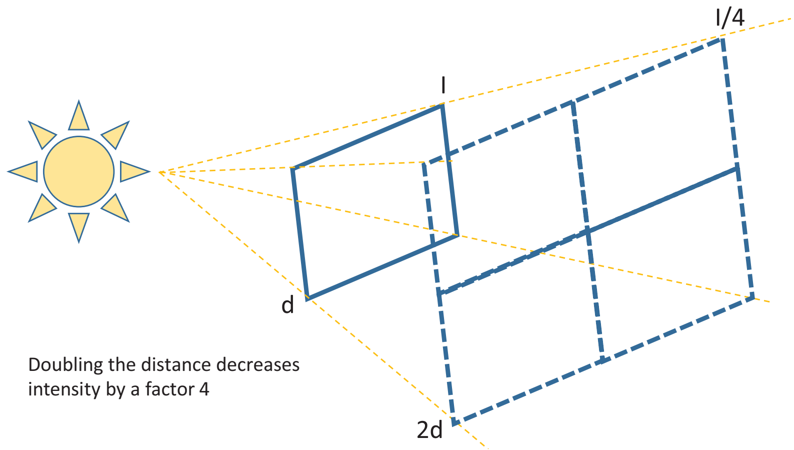

Figure 6. Inverse square law of power.

Measured SNR in the center of the image (Figure 5, Area 4) as a function of output flux with the test scene at different distances (using LUXEON IR Domed 60° and 90° 850nm emitters, driven at 1A) is shown in Figure 7 below. Camera integration time was set to 10ms for all measurements.

Both LUXEON IR 60° and 90° are used for these measurements; while their output flux is the same[4] regardless of the dome used, the 60° version emits a higher flux in the forward direction by a factor of 1.5. Since the SNR is measured in the center of the image, this means that the irradiance (flux over area) over this area is about 1.5 times higher for the 60° illuminator, which corresponds to an expected ~1.9 dB increase in SNR as shown in Figure 7 below.

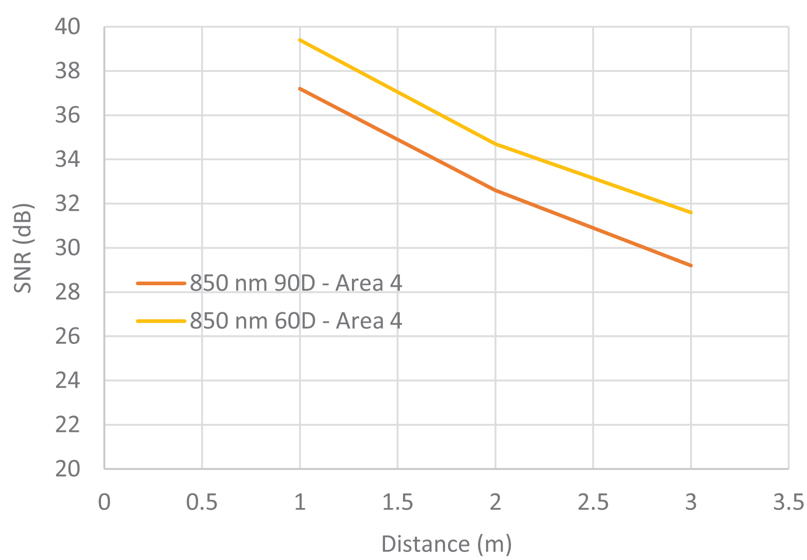

Figure 7. SNR vs. illuminator's flux, measured at different distances in the center of the test scene (Area 4).

4. For a given wavelength; the typical flux at 940nm is slightly higher than at 850nm, see the product datasheet for LUXEON IR Domed Line for further details

2.5 Influence of Wavelength on the SNR

Illumination wavelength has an influence on SNR because the QE of silicon detectors is higher at 850nm than at 940nm; this means that for the same amount of light (luminous flux) collected, more electrons will be generated[5] when using 850nm, leading to a higher SNR.

For the SNR vs. wavelength measurements, the integration time was set to 10ms for all measurements. Per Figure 3, the QE of ON Semiconductor AR0237IR sensor are 28% and 12% for 850nm and 940nm illuminators respectively. The camera lens has slightly lower transmission at 940nm than at 850nm by a factor of 0.77.

The product for 850nm and 940nm illuminators are respectively 0.26*1.35=0.351 and 0.11*1.45=0.160. The expected SNR difference between the 2 wavelengths (assuming both emitters are driven at 1A, and accounting for the slightly higher output flux of the 940nm LED – 1.45 W vs. 1.35 W for the 850nm LED) is:

$$\Delta_{SNR_{dB}} = 20\log\sqrt{\left(\frac{0.28 * 1.35}{0.12 * 1.45 * 0.77}\right)} = 4.5\ dB$$

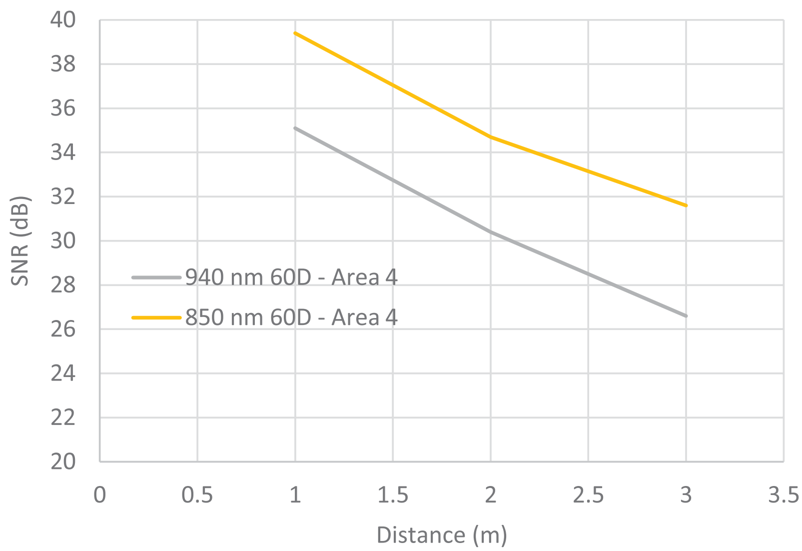

Figure 8. Measured SNR using 850nm 60° and 940nm 60° emitters driven at 1A, showing the SNR difference due to wavelength.

2.6 Influence of the Integration Time on the SNR

Increasing the integration time is, in a way, equivalent to increasing the illumination, since it allows collecting more photons for each frame. However, the maximum integration time allowed is determined by the frame rate (FPS) required by the application. Figure 9 below shows the SNR improvement obtained by adjusting the integration time between 5 and 1000ms. For this measurement, a LUXEON IR Domed 60° 850nm illumination board was used, with the drive current set to 1A (for a total flux of 1.35W*3 = 4.05W) for the measurements, and camera integration time was adjusted from 1 to 30ms. By increasing the integration time, the SNR of the pixel output signal can be increased up to SNR value of the sensor (SNR_{MAX}=41 for ON Semiconductor AR0237IR).

Of course, increasing the integration time is not always possible or practical (for example, in order to get 24 FPS, the maximum integration time is ~40ms). Even shorter integration times might be needed to prevent image blur for fast-moving objects, but this section shows that, for a given illumination, maximizing the integration time increases SNR.

5. As a side note, the longer wavelength photon energy is lower, which means that, for the same luminous flux, there will be more 940nm photons incident on a pixel than 850nm photons. However, this effect is relatively small (the photon energy difference between these two wavelengths is ~15%) with respect to the QE variation (QE at 850nm is typically 50% to 100% higher than at 940nm in silicon detectors).

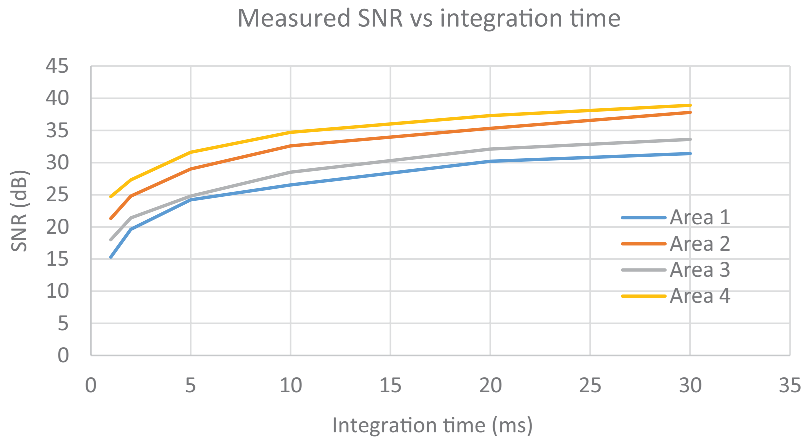

Figure 9. SNR vs. integration time, measured with 850nm 60° emitters at a distance of 2 meters.

2.7 Matching Illuminator and Camera FOV

Surveillance cameras' FOV covers a very wide range, from several degrees (for zoom cameras) to more than 120 degrees (for dome cameras). The illuminator must fill this field of view; it's not only a matter of covering the whole field of view of the camera, but also providing an illumination as uniform as possible within this field of view. For the ON Semiconductor AR0237IR kit, the horizontal and vertical viewing angles are 54.4° and 30.8° respectively, and the diagonal viewing angle is 62°. To avoid dark corners in the camera, the illuminator beam angle should be equal to or slightly larger than the sensor lens field of view to prevent dark areas within camera's FOV or wasting light that falls outside camera's FOV (Figure 10). Choosing the right optics for the illuminator means better quality and best possible efficacy.

For this reason, the LUXEON IR family includes a series of domed emitters that provide an illumination FOV of 60°, 90° and 150°; moreover, any illumination FOV can be obtained by pairing a LUXEON IR emitter, including the compact version, with secondary optics. For more information on secondary optics available from partners, please contact your local Lumileds representative.

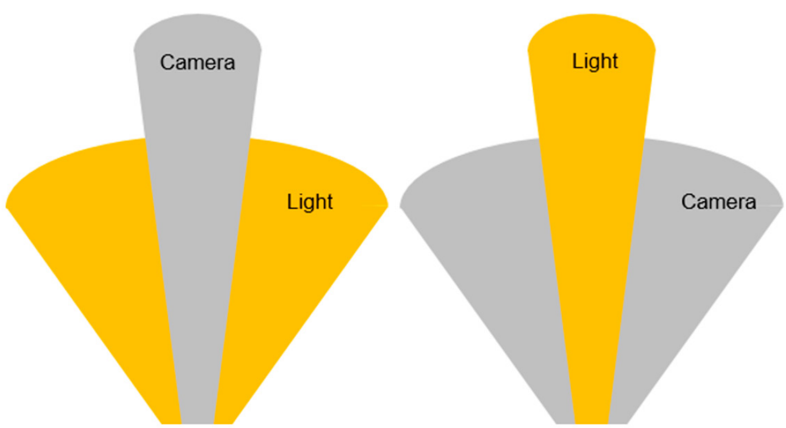

Figure 10. Illuminator and camera FOV. The light FOV is bigger than camera FOV (left) leading to loss of light, and the light FOV is smaller than camera FOV (right), leading to poorly illuminated areas in the camera FOV.

Typically, the FOV of the camera is not circular, but rectangular (due to rectangular aspect ratios of TV screens). Therefore, a circular illumination profile cannot fit exactly the FOV of a camera.

Recently, Lumileds launched the LUXEON IR Domed Asymmetric, a new domed IR emitter with an asymmetric emission profile of 95° x 58°. As shown in Figure 11 below, this emission profile maintains a wide FOV in the horizontal direction, but decreases the FOV in vertical direction.

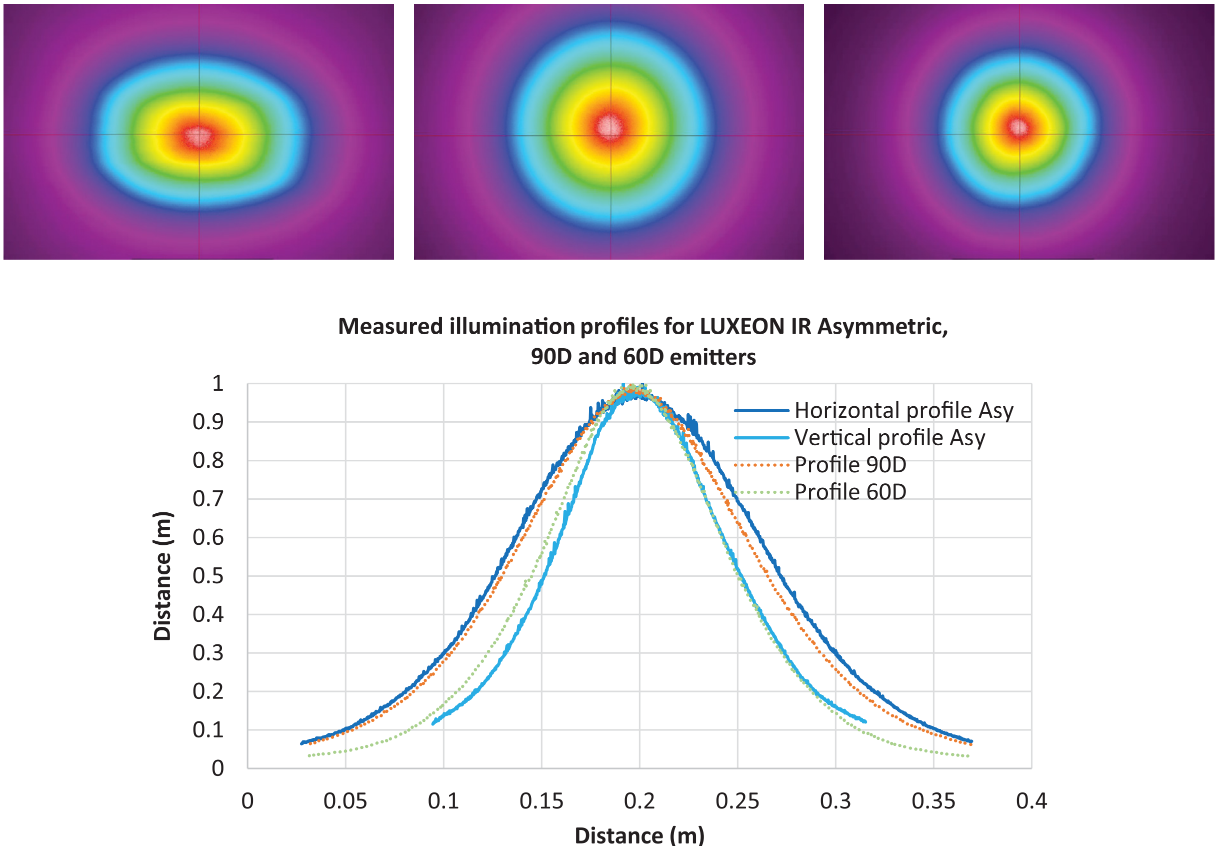

Figure 11. Top: Illumination profiles on a flat surface of LUXEON IR Asymmetric (left), 90° (center) and 60° (right) emitters installed on an illumination board as shown in Figure 4. Bottom: Cross sections through the illumination profiles for different emitters, showing that in horizontal direction, the LUXEON IR Domed Asymmetric emitter has a profile similar to a 90° domed emitter, while in vertical direction it's similar to a 60°. NOTE: Irradiance normalized to peak value.

This allows for a better match with real-life scenes, where typically the objects in the lower parts of the FOV are closer to the camera than the objects in the center. Illuminating both areas with the same amount of light can lead to overexposure of the objects located nearby; an asymmetric emitter prevents this by compensating the distance difference through the illumination asymmetry. The test scene shown in Figure 12 below illustrates this concept.

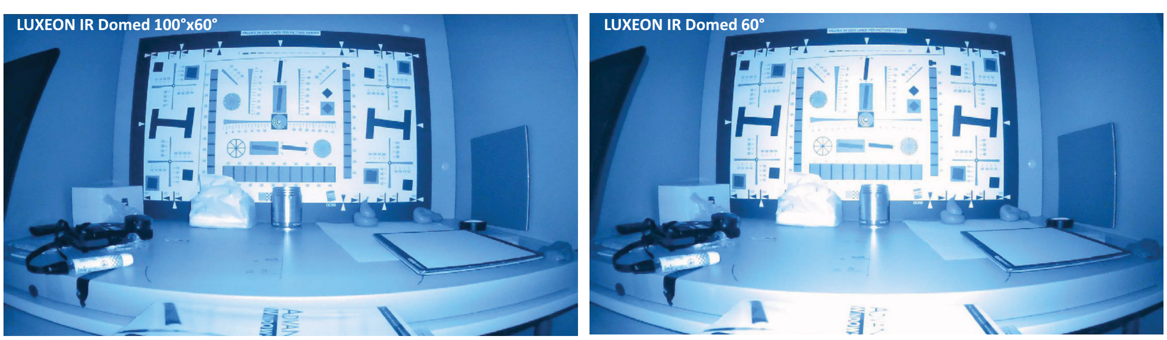

Figure 12. Scene illuminated with 850nm LUXEON IR Asymmetric (left) and 60° emitters (right), showing that an asymmetric illumination prevents overexposure of nearby objects.

The importance of matching the camera and illuminator's FOV is illustrated by the following comparison in Figure 13 between the 90° and 60° emitters; as already shown in Figure 8, 90° emitters provide a higher SNR towards the edge of the image. Figure 13 shows that the 60° emitter has a higher SNR in Areas 2 and 4 (corresponding to FOVs of 30° and 0° respectively), but a lower SNR in Areas 1 and 3 (corresponding to FOVs of 54° and 62° respectively). Thus, when designing an IR illuminator, one must carefully consider the light distribution through the whole FOV of the camera in order to insure that the SNR requirements are met across the whole image.

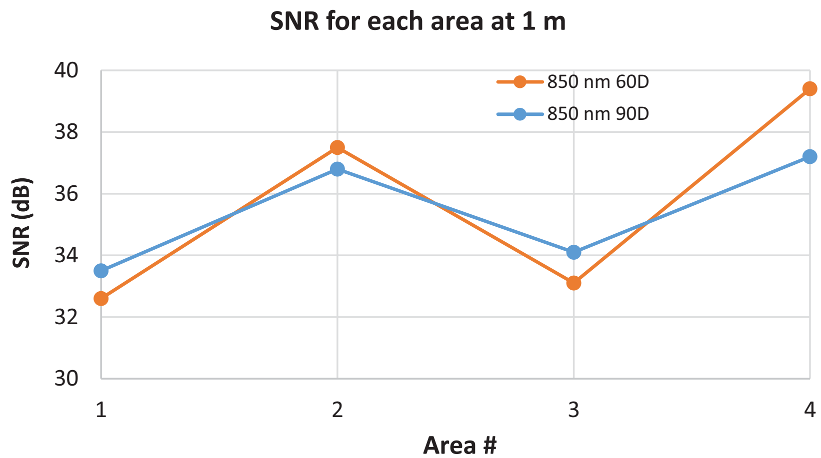

Figure 13. Measured SNR of 850nm 60° and 90° emitters for each area (drive current 1A, distance 1m).

Note that FOV, illumination profile and uniformity are defined by the optics used, and are not influenced by temperature or drive current.

2.8 Red Glow – Illuminator's Visibility to the Human Eye

The commonly used wavelengths of IR illuminators are 850nm and 940nm. However, since the LED output is not monochromatic, the illumination spectrum always has a "tail" extending significantly towards shorter wavelength.[6] During daytime, this faint "red glow" is not visible, but in dark conditions a human eye can see it (once it adapts to low light). The closer the illuminator center wavelength is to the visible light (360nm-780nm), the more serious the red glow issue will be. That means, 850nm illuminator has a significant red glow compared with 940nm at the same radiometric power. This may affect the application of IR illuminators on night surveillance, especially if the camera is not supposed to be noticeable by passers-by.

Using 940nm emitters is the obvious option when the surveillance system needs to be fully covert. If the very faint red glow present in this case needs to be completely removed, a long pass IR filter can be used to attenuate even more the wavelengths below 900nm (one example is given in Figure 14).

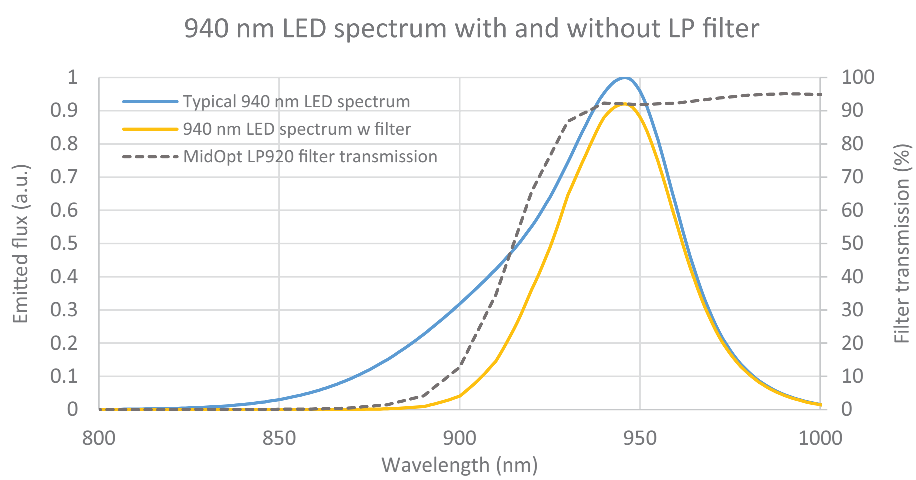

Figure 14. Emission spectrum of LUXEON IR 940nm LED, with and without Long Pass (LP) filter (MidOpt LP920). The LP filter cuts the short wavelength part of the spectrum susceptible to being seen by the human eye.

6. While typical FWHM of a LED spectrum is 30 to 50nm (depending on the center wavelength and temperature), it actually extends to more than 100nm from its center/peak wavelength towards shorter wavelengths.

2.9 Ambient Temperature Effects on Wavelength, Output Flux, and FWHM

One external factor that needs to be accounted for when designing an IR illuminator is the temperature range in which it will operate. For indoor applications this range is quite narrow, but for outdoor applications it can span more[7] than 100°. Since the LED output is sensitive to temperature, all relevant parameters' dependence on temperature changes are given in the official LUXEON IR Family datasheets. The expected operating temperature range must be included in the design, since both output flux and wavelength (peak and broadness of emitted spectrum) do change with temperature.

Taking as an example the LUXEON IR Domed line (940nm), the datasheet indicates that:

- The output flux at 100°C is 20% lower than at 25°C, leading to a SNR decrease of ~1dB. This means that more LEDs might be needed to reach the required flux if the ambient temperature increases.
- The peak wavelength shifts by 0.29 nm/°C. In case a band pass filter is used (either in the camera to filter ambient light or in front of the LED to block red glow), this will affect the total illumination flux. Looking at Figure 14, a lower ambient temperature would mean that less light would pass through the filter (since the LED emission spectrum will shift to the left), while an increase in temperature means that more light passes through the filter (since the spectrum shifts to the right).
- The forward voltage (and the overall LED efficiency) changes with temperature. This means that the power consumption needed to obtain a given output flux also depends on temperature.

Besides factoring expected temperature variations in the design, additional steps can be taken to lower the internal temperature of the LEDs during operation,[8] like adding heatsinks or heat pipes. Operating at lower temperatures has the added benefit of increasing the LEDs lifetime.

3. How many emitters are needed?

The previous section dealt with measuring the performance of a camera and illumination setup. However, most of the time the problem to be solved is "how many IR emitters are needed for this camera?" Once the SNR requirements are known, it is possible to derive the requirements for the illuminators. This section deals with how to calculate the number of emitters needed and expected camera system performance at different distances.

3.1 Input Parameters for SNR Calculation

The calculations are done using the datasheet parameters of LUXEON IR Domed 60° 850nm and the ON Semiconductor AR0237IR evaluation kit. The relevant parameters are listed in the table below. Keep in mind that these calculations account for the shot noise only; this is a reasonable assumption as long as the number of electrons generated is high enough, but it should be used with caution in low-light conditions.

Table 1. Parameters used calculations, based on LUXEON IR Domed 60° 850nm (3 LEDs board) and ON Semiconductor AR0237IR IR evaluation kits datasheets.

INPUT PARAMETERS			
PARAMETER	**SYMBOL**	**VALUE**	**UNIT**
Sensor pixel size	d_{pix}	3	µm
Sensor horizontal dimension	l	5.78	mm
Sensor vertical dimension	w	3.26	mm
Integration time	t_e	10	ms
f# lens	$f_\#$	2.5	-
Target object reflectance	η_s	100	%
Sensor lens efficiency	η_l	57%	%
Sensor quantum efficiency	q_e	28	%

7. -40° to 85°C is a typical operating range for outdoor applications.
8. LED emitters always operate at a higher internal (junction) temperature than the ambient.

3.2 Calculated SNR

The amount of light incident on each pixel is calculated based on the amount of light on the target, target's reflectivity, sensor's parameters and distance to target. Based on the amount of collected light, the number of photons is calculated and then, after accounting for the QE, the number of photoelectrons. The SNR is then calculated, considering the shot noise due to the quantity of photoelectrons calculated at the previous step.

Calculated SNR as a function of total output flux and distance to target[9] is listed in Table 2 and Figure 16 (SNR values in dB).

Table 2. Calculated SNR (dB) vs. distance to target and output flux for LUXEON IR 850nm 60° emitter. Color coded according to criteria defined in section 1.4.

	CALCULATED SNR (dB)																
	# OF LEDS	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**36**	**45**	**60**	**90**	**120**	**150**
	FLUX <W>	**4.05**	**8.1**	**12.2**	**16.2**	**20.3**	**24.3**	**28.4**	**32.4**	**36.5**	**40.5**	**48.6**	**60.8**	**81**	**122**	**162**	**203**
	RELATIVE FLUX	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**15**	**20**	**30**	**40**	**50**
DISTANCE (m)	0.5	45.4	48.4	50.2	51.4	52.4	53.2	53.9	54.5	55.0	55.4	56.2	57.2	58.4	60.2	61.4	62.4
	1	39.4	42.4	44.2	45.4	46.4	47.2	47.9	48.4	48.9	49.4	50.2	51.2	52.4	54.2	55.4	56.4
	2	33.4	36.4	38.2	39.4	40.4	41.2	41.8	42.4	42.9	43.4	44.2	45.1	46.4	48.2	49.4	50.4
	3	29.9	32.9	34.6	35.9	36.8	37.6	38.3	38.9	39.4	39.9	40.6	41.6	42.9	44.6	45.9	46.8
	4	27.4	30.4	32.1	33.4	34.3	35.1	35.8	36.4	36.9	37.4	38.2	39.1	40.4	42.1	43.4	44.3
	5	25.4	28.4	30.2	31.4	32.4	33.2	33.9	34.5	35.0	35.4	36.2	37.2	38.4	40.2	41.4	42.4
	8	21.3	24.3	26.1	27.4	28.3	29.1	29.8	30.4	30.9	31.3	32.1	33.1	34.3	36.1	37.4	38.3
	10	19.4	22.4	24.2	25.4	26.4	27.2	27.9	28.4	28.9	29.4	30.2	31.2	32.4	34.2	35.4	36.4
	12	17.8	20.8	22.6	23.8	24.8	25.6	26.3	26.8	27.4	27.8	28.6	29.6	30.8	32.6	33.8	34.8
	15	15.9	18.9	20.6	21.9	22.9	23.7	24.3	24.9	25.4	25.9	26.7	27.6	28.9	30.6	31.9	32.9
	20	13.4	16.4	18.2	19.4	20.4	21.2	21.8	22.4	22.9	23.4	24.2	25.1	26.4	28.2	29.4	30.4
	30	9.9	12.9	14.6	15.9	16.8	17.6	18.3	18.9	19.4	19.9	20.6	21.6	22.9	24.6	25.9	26.8
	40	7.4	10.4	12.1	13.4	14.3	15.1	15.8	16.4	16.9	17.4	18.2	19.1	20.4	22.1	23.4	24.3
	50	5.4	8.4	10.2	11.4	12.4	13.2	13.9	14.5	15.0	15.4	16.2	17.2	18.4	20.2	21.4	22.4
	100	-0.6	2.4	4.2	5.4	6.4	7.2	7.9	8.4	8.9	9.4	10.2	11.2	12.4	14.2	15.4	16.4

Another way of figuring out system requirements is to look at how many emitters are needed to achieve the desired performance at different distances. Figure 15 below illustrates this concept by plotting the number of LUXEON IR 60° 850nm LEDs that can provide the required illumination on an object located at different distances so that a minimum SNR of 20 dB is achieved.

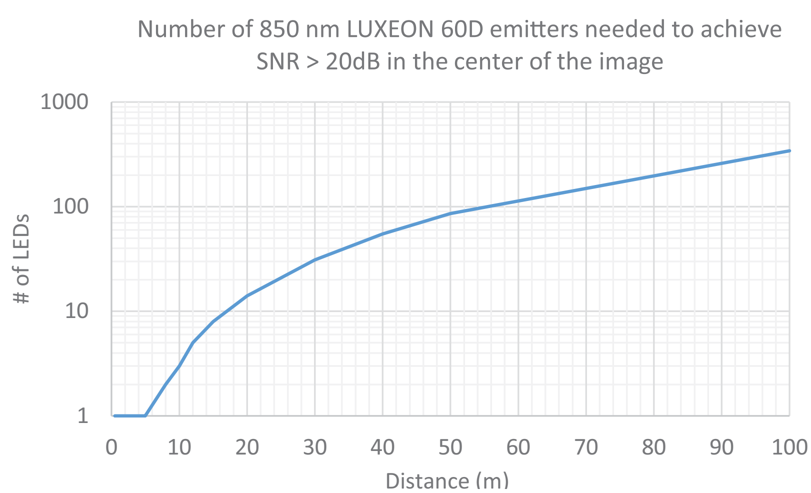

Figure 15. Number of LUXEON IR 60° 850nm emitters needed to obtain a 20 dB SNR at different distances from the object.

9. In this document, it is assumed that the illuminator is always co-located with the camera.

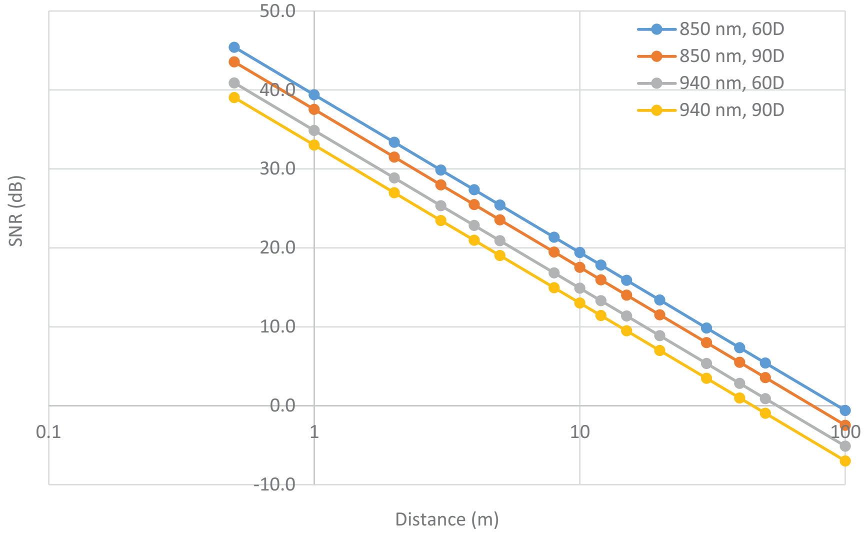

Figure 16. Calculated SNR as function of object distance for the ON Semiconductor AR0237IR camera when using various LUXEON IR Domed illumination boards (3 LEDs each, 1A drive current).

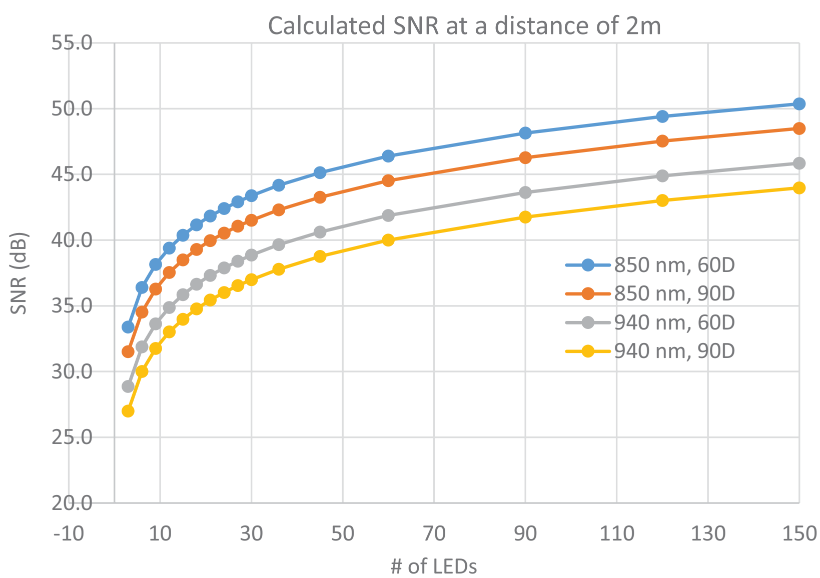

Figure 17. Calculated SNR vs. number of emitters for the ON Semiconductor AR0237IR camera when using various LUXEON IR Domed illumination boards (3 LEDs each, 1A drive current, 2m distance to target).

Figure 16 outlines some of the consequences of trade-offs when choosing FOVs and wavelengths; a 90° emitter has a 1.9 dB lower SNR (in forward direction) than a 60° emitter of same wavelength, while a 940nm emitter has a 4.5 dB lower[10] SNR than the equivalent 850nm emitter.

10. Keep in mind that this value is mostly due to differences in sensor's QE and lens transmission between the two wavelengths; using a different sensor and/or lens would also change the SNR difference between the two wavelengths.

Note that for certain distances and number of emitters, the calculated SNR is >41 dB (the upper limit of the AR0237IR sensor), which means that the sensor would be saturated at such short distances/high flux values. In this case, the integration time would have to be decreased in order to prevent saturation, or a sensor with higher maximum SNR should be used.

Based on the table/plots above and knowing the SNR application requirements, one can derive the number of emitters needed, or the maximum range achievable with a given number of emitters.

For example, achieving a SNR >20 dB at a range of 20m with LUXEON IR Domed 60° 850nm at room temperature, the output flux should be higher than 20W (which can be provided by 15 LEDs driven at 1A). Note that the typical forward voltage for each LED on the illuminator is 3.2V (see LUXEON IR Domed Line), thus the electrical power consumption of each LED is 3.2V * 1A = 3.2W, meaning a total of 48 W electrical power is required. For distances on the order of 100m, more than 100 emitters are needed, leading to electrical power requirements on the order of 0.5 kW (this is for a 60° FOV emitter—for a lower FOV, the intensity emitted in the forward direction is higher, so the required number of emitters is lower. For example, the same LED would provide about ~4 times more intensity for a 30° FOV,[11] thus reducing the number of needed emitters significantly).

Keep in mind that these numbers are valid at room temperature; if significant temperature variations are expected, they should be included in the calculations (e.g. at higher temperatures the flux output per LED is lower, which means that more LEDs might be needed to achieve the same total output flux).

4. Conclusions

Based on the previous sections of this document, several conclusions and rough guidelines can be drawn for designing an illuminator for a surveillance system:

- Collecting more light (either due to higher illumination flux or longer integration time of the camera) is always better...
- ... as long as the image sensor has the dynamic range to take advantage of it
- Photon shot noise dominates for high reflectivity/high illumination scenes, but in low light/low reflectivity situations the image sensor noise becomes critical
- For silicon image sensors, using shorter illumination wavelengths (850nm) leads to higher SNR...
- ... but longer wavelengths of 940nm are a better choice for covert surveillance systems
- Matching camera and illuminator's FOV is critical for a good coverage of the scene under surveillance
- Don't forget about ambient temperature, since it significantly affects the amount of emitted light, but also the image sensor noise

11. While the LUXEON IR domed family comes by default in 60°, 90° and 150° FOV versions, it is possible to customize the FOV within the range of 6° to 180° by using secondary optics – please contact your local Lumileds representative for more information on using secondary optics.

About Lumileds

Companies developing automotive, mobile, IoT and illumination lighting applications need a partner who can collaborate with them to push the boundaries of light. With over 100 years of inventions and industry firsts, Lumileds is a global lighting solutions company that helps customers around the world deliver differentiated solutions to gain and maintain a competitive edge. As the inventor of Xenon technology, a pioneer in halogen lighting and the leader in high performance LEDs, Lumileds builds innovation, quality and reliability into its technology, products and every customer engagement. Together with its customers, Lumileds is making the world better, safer, more beautiful—with light.

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