DLP® DMD Technology: LIDAR ambient light reduction

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Introduction: One of the most exciting developments in recent technology has been the progression towards autonomous vehicles. These cars use a combination of many sensors in order to see and detect the world around them, including GPS, radar, camera systems, and LIDAR systems. Of all these sensors, LIDAR is of special interest, because it has the best potential to provide geometric data of the world around the car at a very high resolution.

However, today's LIDAR sensors struggle to meet the ambitious specifications that car manufacturers request. For example, the range of today's sensors is not long enough for a self-driving car to drive at full highway speeds while leaving enough room and time to come to a full stop if needed. Additionally the resolution of some sensors is insufficient to distinguish small obstacles, especially obstacles at a great distance from the sensor. Finally, the field of view of some systems is limited, requiring several LIDAR units in order to see the geometry completely surrounding the vehicle.

Aside from needing better performance for nominal conditions, most LIDAR systems suffer degradation under adverse environmental conditions. The ambient light from the sun and the environment is seen by the LIDAR system's photodetector, and this light generates noise that limits the performance of the system. Additionally, LIDAR systems struggle in weather conditions like fog and rain, so they must have sufficient margin so that the degraded performance in these weather conditions is adequate.

A new development in LIDAR systems is the use of a Digital Micromirror Device (DMD) to filter out the ambient light from the photodetector. Such an addition can significantly improve the performance of the associated LIDAR system. This paper demonstrates how the DMD functions to filter ambient light, estimates the impact of the DMD on the signal-to-noise ratio (SNR) of the system, and relates that SNR improvement to improvements in range, resolution, field of view, and frame rate. These performance metrics make up a figure of merit for the LIDAR system, and the DMD is estimated to improve this figure of merit by a factor of 5.2! This improvement corresponds to a choice of either 2.3 times more range, 5.2 times more resolution in a single dimension, 2.3 times better field of view in both dimensions, or 5.2 times faster frame rate!

1 Background: comparison of LIDAR architectures [1][2]

Before explaining the capability of the DMD to reject ambient light, it is useful to give some background about different LIDAR systems. LIDAR systems can be characterized both by the method of signal modulation used (which defines how distance information is generated) and by the method of discriminating between different objects in the field of view (which determines how the 3D geometry is generated). A good review of signal modulation techniques is given in [1], but is not in within the scope of this paper. There are three main LIDAR architectures that exist to generate 3D geometry; they are here called flash LIDAR, mechanical LIDAR, and scanning LIDAR.

Any LIDAR system has physical constraints which fundamentally limit its performance. Because the system relies on transmitted energy to give information about the object, the amount of energy must be finite. This transmitted energy is kept below a certain level so that the LIDAR system will not emit potentially harmful radiation (as determined by eye safety limitations). Additionally, there will also be some noise inherent to the system. This noise, along with a finitely strong signal, limits the system from being able to detect miniscule objects at an infinite distance. This limitation is expressed as the signal-to-noise ratio, or SNR. A higher SNR yields better performance of the LIDAR system.

A flash LIDAR system makes multiple range measurements by using multiple detectors. Each detector is aligned so that it only detects light coming from a certain direction. The transmitted light from the LIDAR system illuminates all the objects to be detected, while each detector only receives light from the objects that are in its field of view. One difficultly of the flash LIDAR system is finding a powerful laser source with high enough peak power that can illuminate the whole scene with a very short pulse. Due to this, the transmitted power may be limited by the capability of today's lasers, instead of being limited by laser eye safety limits.

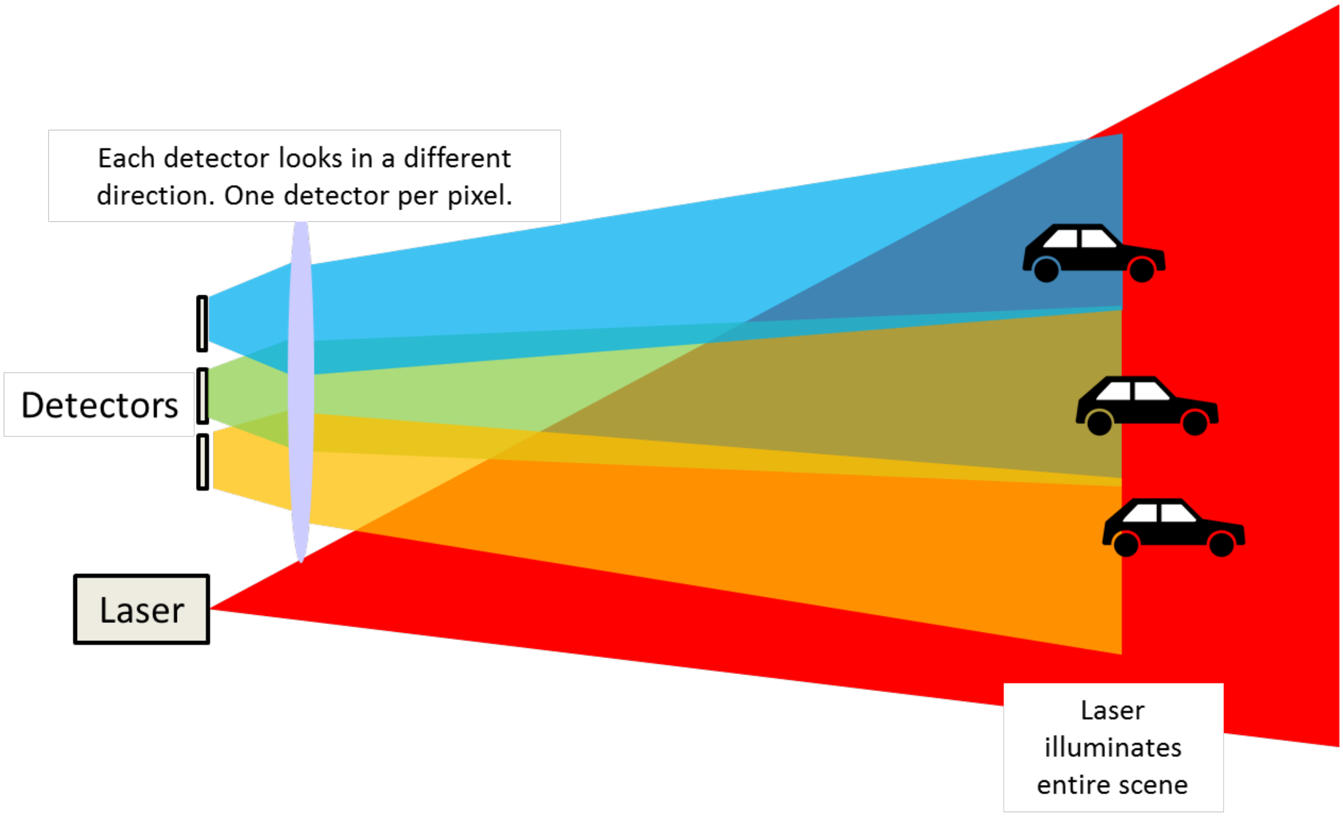


Figure 1. Flash LIDAR architecture

(1) DLP is a registered trademark of Texas Instruments.
(2) All other trademarks are the property of their respective owners.

Mechanical LIDAR systems work by mechanically moving a single point LIDAR system so that the system is pointed in different directions at different points in time. Typically, a system might spin around one axis to generate multiple measurements in the horizontal direction, while employing multiple detectors in the vertical direction similar to a flash LIDAR system. The primary concern with this type of system is the reliability of the mechanical nature of the design; in a typical system, the entire LIDAR subassembly must spin at a fast rate of hundreds of rotations per minute.

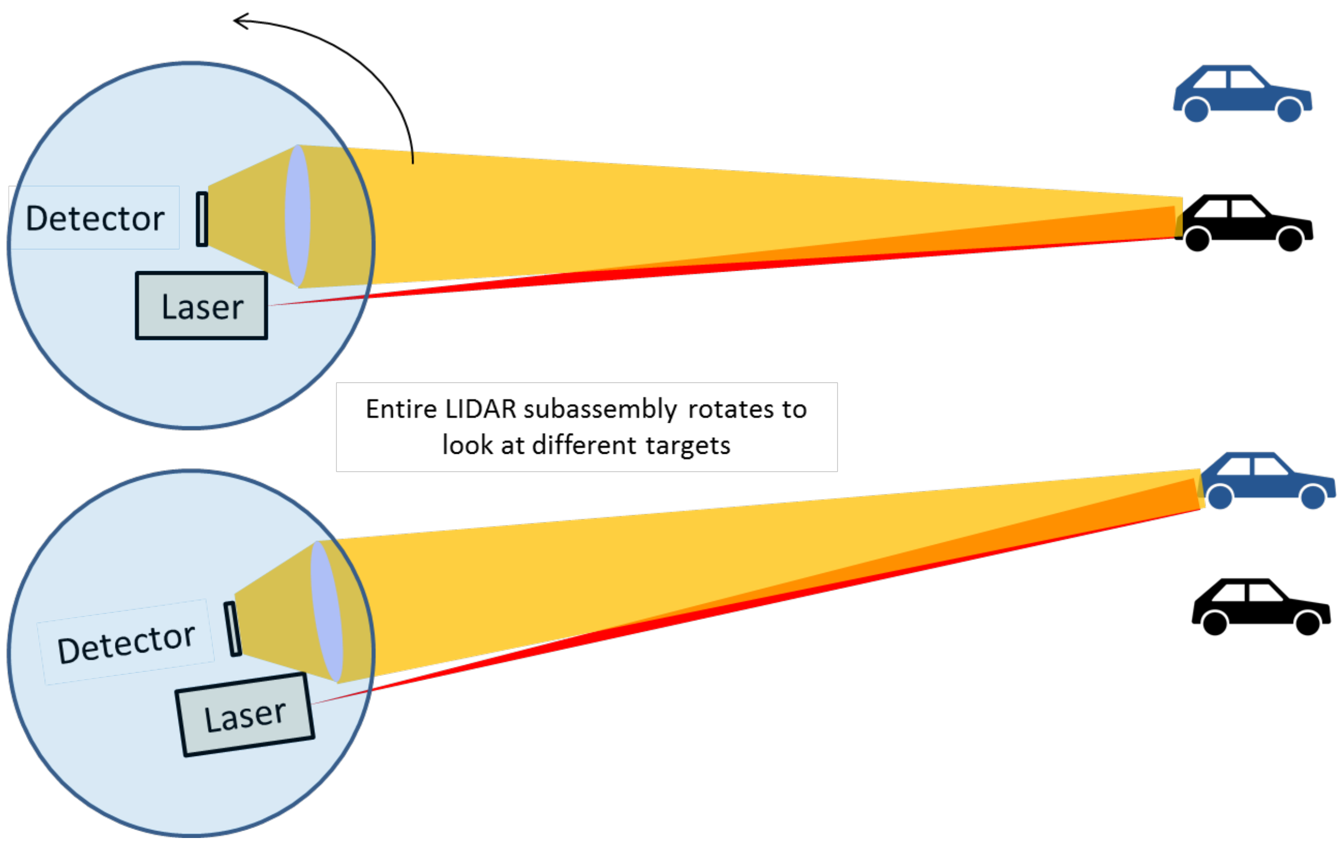


Figure 2. Mechanical LIDAR architecture

Scanning LIDAR systems scan the transmitted light across the field of view. However, the detector is stationary, while at the same time able to receive light from any direction that the LIDAR system transmits it. The consequence of this design is that because the detector is able to receive light from a wide field of view, it can become blinded or saturated by ambient light or other light sources. Fortunately, this problem can be solved by using a DMD to dynamically block the ambient light while at the same time passing the signal to the detector.

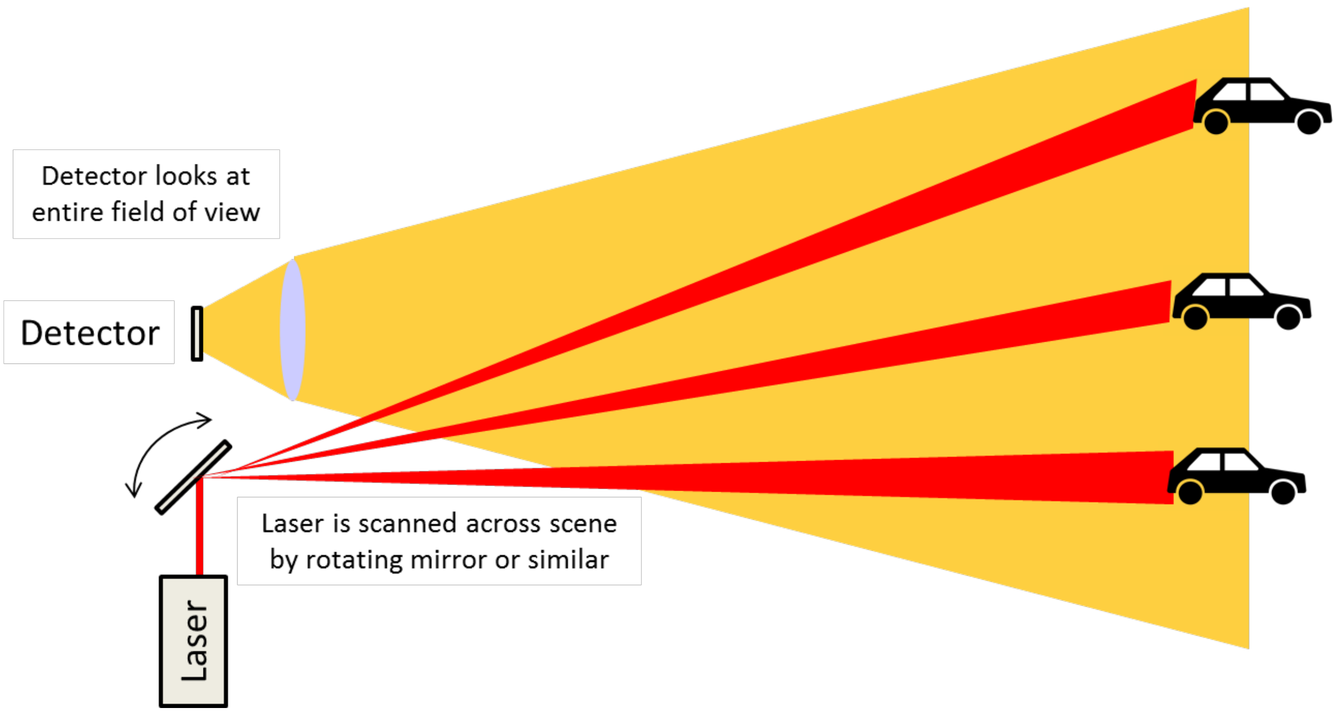


Figure 3. Scanning LIDAR architecture

Many LIDAR systems use a combination of these approaches to implement the horizontal and vertical dimensions of the field of view.

While the DMD is able to improve the SNR in scanning LIDAR systems, it cannot be used in mechanical LIDAR systems or flash LIDAR systems. This is due to the fact that in mechanical and flash LIDAR systems, the laser light is captured by the entire field of view of the photodetector combined with the ambient light, so it is impossible to physically separate the two. In a scanning LIDAR system however, only a small portion of the field of view of the detector receives the laser light, so ambient light outside this field of view can be filtered out.

2 Constraints on the signal to noise ratio

2.1 Ambient light causes shot noise

The performance of the LIDAR system is determined by the amount of signal and noise in the system, so understanding the sources of noise in the system is important. There are two main sources of noise in a LIDAR system. One source is the noise that comes from the amplification of the signal; this can also be understood as the noise from the electronics in the system. As the amplification of the signal is typically called the Analog Front-End, this noise may be called "AFE noise". The source of this noise is typically due to thermal noise of the feedback resistors in the amplifiers.

The second source of noise comes from unwanted optical power that reaches the detector. This unwanted optical power primarily comes from the sun, but may also come from other LIDAR systems or other sources of light in the environment. If this optical power simply created a DC signal on the detector, then the only concern would be to avoid saturating the detector, since the DC bias can easily be filtered out with a high-pass filter. However, the DC bias on the detector also causes white noise that cannot be easily filtered out.

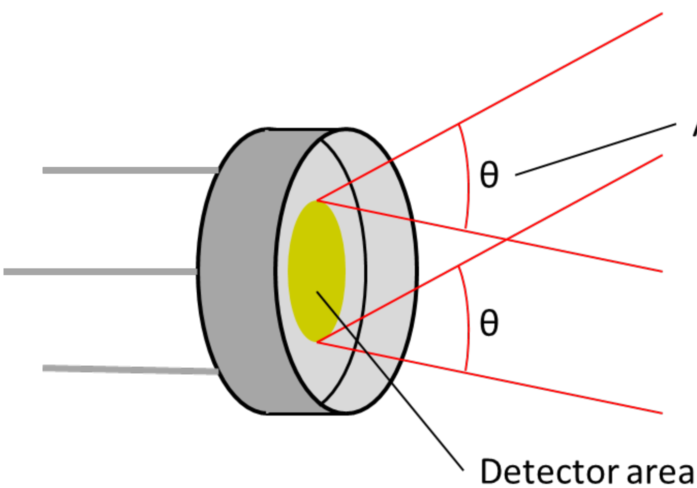
The detectors that are used to detect the received light may be PIN photodiodes, avalanche photodiodes (APDs), single-photon avalanche diodes (SPADs) or, silicon photo-multipliers (SiPMs). All of these detectors are built upon the *p-n* junction of the diode, and are therefore subject to a type of noise known as shot noise. Shot noise comes from the uncertainty of when individual electrons are able to cross the threshold of the *p-n* junction. It manifests as white noise, and is proportional to the square root of the DC current passing through the *p-n* junction. A summary of shot noise and other noise sources can be found in [5].

AFE noise and shot noise do not add linearly. Since they are independent noise sources, the total noise can be determined as the RMS sum, i.e. $n_{total} = \sqrt{n_{AFE}^{\ 2} + n_{shot}^{\ 2}}$. Due to this, whichever noise source is greater will tend to dominate the noise floor of the system.

2.2 Wide FOV designs limit effective aperture

To further analyze the performance of the LIDAR system, the geometry of the detector must be considered. The amount of signal that can be received is determined by the area of the detector and the acceptance angle of the detector. (The acceptance angle of the detector represents the highest angle of incidence that a light ray can fall upon the detector and still be detected.) Of course, a larger detector is also an electrically slower detector, due to the additional capacitance.

In the design of the LIDAR system, the challenge is to sense a large field of view (FOV) and still obtain a high signal-to-noise ratio. The goal is to optimize the receiver light collection area which determines how much light is collected by the receiver. But this must be traded off against parameters such as the detector size and the FOV. This physical relationship can be described using conservation of etendue or optical invariant.



$$Etendue = \pi * Area * sin^2(\theta/2)$$

Figure 4. Etendue of a photodetector

In designing a LIDAR system, a critical parameter is the receiver light collection area, which is determined by the size of the receiver optical entrance pupil. The larger the receiver entrance pupil is, the more light that can be gathered to improve signal-to-noise ratio. The simplest solid-state receiver consists of a detector and a lens that images the scene onto the detector. Knowing the detector size and the acceptance angle of the detector, the etendue relationship defines the receiver pupil size. By conservation of etendue, or optical invariant, the following equation holds:

$$Dsin(\theta/2) = Rsin(FOV/2)$$

"*R*" is the receiver entrance pupil diameter and " θ " is the full cone angle at the detector. Solving for the receiver pupil diameter yields the following:

$$R = Dsin(\theta/2)/\sin(FOV/2)$$

This equation suggests that if we want a large receiver area we also want a large detector and a small FOV. Generally speaking, the detector size should be minimized to reduce capacitance and maximize bandwidth. From a system standpoint it is also desirable to maximize the FOV. In designing an actual system, all of these factors must be balanced to produce the best overall system performance.

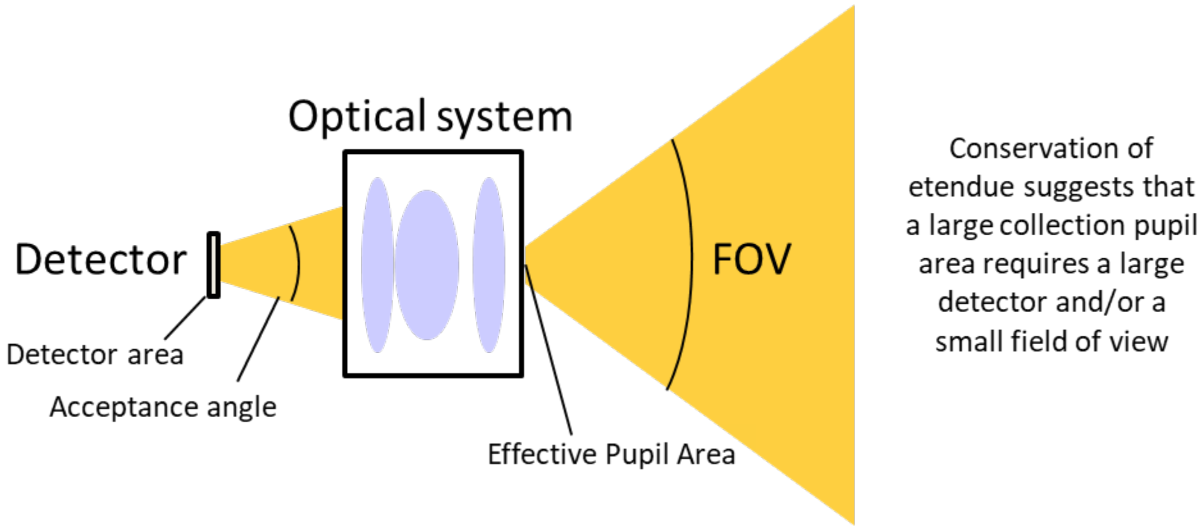


Figure 5. Relationship between detector etendue and system FOV

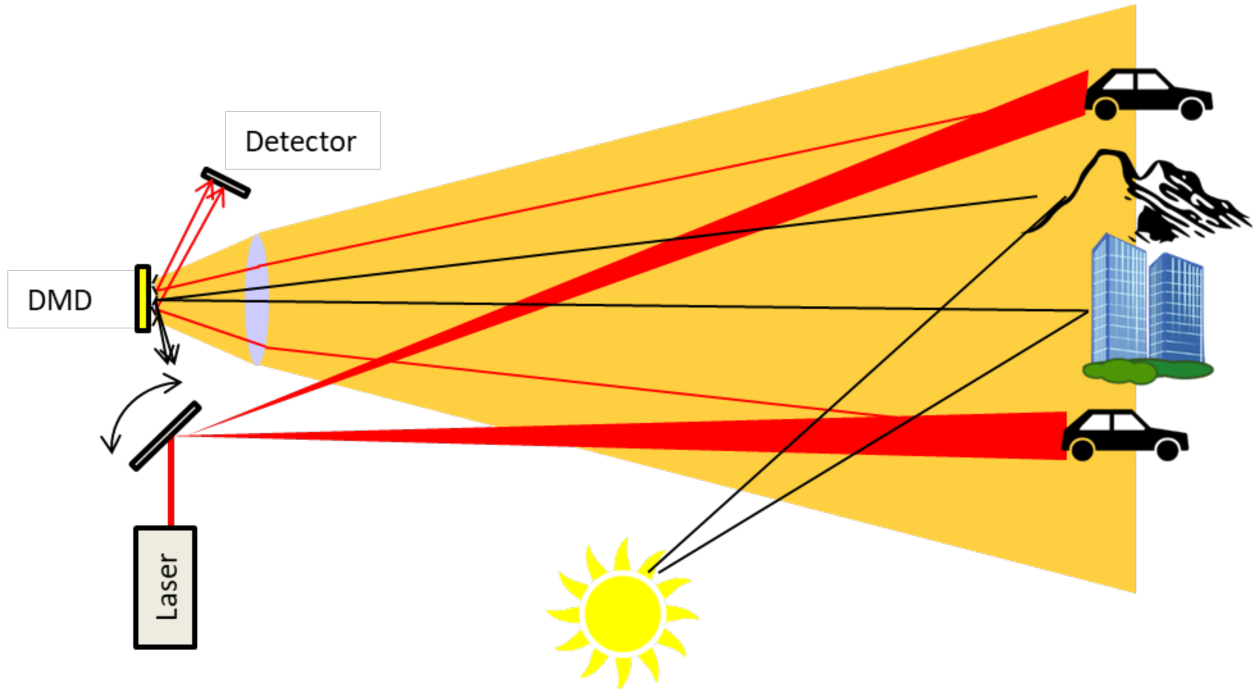
This relationship affects both flash LIDAR and scanning LIDAR architectures, and it has the same impact whether or not a DMD is used in the system. This phenomenon does not affect the mechanical LIDAR architecture in the same way, because the mechanical LIDAR architecture does not expand its field of view by changing the geometry of the optics, but by maintaining a small field of view and reorienting the optics over time.

2.3 Crosstalk from other LIDAR systems and multipath interference

Besides SNR performance limitations there may be other sources of interference in the system. For example, multiple LIDAR systems in a single environment may interfere with one another. Additionally, within a single LIDAR system there may be interference due to the multiple paths that a received signal may return to the detector. Both of these sources of interference may lead to false readings. However, a system with sufficient spatial filtering will be more immune to these types of interference. The DMD can significantly reduce the probability of error due to interference in a scanning LIDAR system. The DMD is able to block these signals because they are outside of the part of the field of view of the detector receiving the signal.

3 SNR improvement from ambient light rejection

Summarizing so far, the performance of the LIDAR system is dictated by the SNR of the system. Three factors determine the SNR: the selection of the detector, the amount of shot noise, and the amount of AFE noise. Of these three, the DMD can greatly reduce the shot noise in a scanning LIDAR system by passing the light from the returning signal while rejecting the ambient light which causes the majority of the shot noise. This is possible because the returning signal will come from a certain direction, while the ambient light will pass to the detector from all directions. When using the DMD in the optical system, turning on and off different mirrors corresponds to passing or rejecting light through the optical system. In this case, mirrors are turned on to pass the signal, and other mirrors are turned off to reject the ambient light. Since the DMD can dynamically update the orientation of the micro-mirrors at a very fast update rate, the subset of mirrors on the DMD passing the light can track the scan rate of the laser.



The DMD is put in an optical system where each mirror sees some small part of the field of view. The micro-mirrors are first oriented so that light from the target illuminated by the laser passes to the detector, while all other light is directed away from the detector. Then, as the laser scans to other targets, the micro-mirrors are changed on the DMD to follow the path of the laser.

Figure 6. Reduction of ambient light by using DMD

3.1 Performance analysis

This section discusses how much performance improvement can be realized from using the DMD in a LIDAR system. The DMD is effective enough to reduce the shot noise to a negligible level compared to the other noise components in the system. The capability of the DMD to improve performance of a LIDAR system is directly related to the pattern refresh rate, the contrast, and the optical efficiency of the DMD.

TI has many different DMD chipsets that could be used for this application. This paper focuses on the DLP5531-Q1 for automotive applications, but other non-automotive DMDs may be suitable for industrial applications. Since different DMDs have different pattern update rates and optical efficiencies, the performance described here will vary by DMD. Please consult the datasheet or TI with any questions on the performance of a specific DMD chipset.

3.1.1 Aperture size and pattern refresh rate

First, not all of the mirrors can be oriented to reject the ambient light. Some mirrors must be oriented in order to pass the received signal to the detector. These mirrors will also pass a small amount of ambient light to the detector. The amount of ambient light that still passes to the photodetector can be calculated as a simple ratio of the area of the dynamic aperture relative to the area of the DMD.

$$ambient\ light_{on\ mirrors} = ambient\ light_{incoming} * \frac{A_{on\ mirrors}}{A_{DMD}}$$

The dynamic aperture on the DMD should be made as small as possible, in order to reject as much ambient light as possible. Ideally, the returning laser beam would be focused to a very small point, such that the smallest aperture possible would be limited to the size of a single micro-mirror. However, this is limited by the pattern refresh rate of the DMD. Typically, the rate of laser pulses will be faster than the pattern refresh rate of the DMD, and the aperture of the DMD will need to be large enough to encompass multiple laser pulses. By assuming that at some point during the frame time every mirror will need to be oriented to pass the laser signal, the size of the aperture can be derived by dividing the pattern update rate time by the frame rate time, and multiplying by the DMD size. If the ambient light rejection is to be calculated, the DMD size cancels out of the equation.

$$ambient\ light_{on\ mirrors} = ambient\ light_{incoming} * \frac{Pattern\ Update\ Rate\ (\mu s)}{Frame\ Rate\ (\mu s)}$$

The pattern update rate varies by DMD. Texas Instruments has experimentally demonstrated pattern update rates of 35 μs with the DLP5531-Q1 DMD. However, due to overhead time required for the mirrors to transition to a new pattern, there are practical limitations on how fast the update rate can be within the system. In this document, a pattern update rate of 100 μs is assumed. Please contact TI for more information on capabilities of different update rates. Assuming a frame rate of 20 Hz, this would yield a rejection of ambient light of 500:1. However, this is not the only path for ambient light to get to the detector.

3.1.2 Contrast

The second contribution to the DMD ambient light rejection performance is the contrast of the DMD and the surrounding optical system. Contrast is a standard specification in projection systems. In a projection system, the contrast refers to the ratio of the brightest intensity the projector is able to display to the dimmest intensity. The contrast can be defined a number of ways; this paper will use the definition of full-on full-off contrast (FOFO), which is the ratio of light throughput when all the mirrors are turned on (light passes from input to output of system) relative to the light throughput when all mirrors are turned off (light is directed away from the output path). The contrast performance is mainly due to the fact that, even when a mirror is turned off, some small amount of light is still scattered in the on direction. Diffraction and scatter from mirror edges, etc. can redirect this light in the wrong way.

The contrast of the optical system depends greatly on the DMD, but also on the optical system, so the optical system itself must be designed with great care with this in mind. The contrast can be used to determine the contribution of ambient light that reaches the detector.

$$ambient\ light_{off\ mirrors} = ambient\ light_{incoming} * \frac{1}{Contrast\ (FOFO)}$$

The contrast will vary depending on the DMD type and the design of the optics, but as a reasonable starting point, assume the contrast is 500:1. In that case, the DMD with all the mirrors turned off is capable of reducing the power of the ambient light by a factor of 500.

The contribution from the on-state mirror and the off-state mirrors can be added together to give a representation of the whole ambient light rejection capability.

$$ambient\ light_{detector} = ambient\ light_{on\ mirrors} + ambient\ light_{off\ mirrors}$$

$$ambient\ light_{detector} = ambient\ light_{incoming} * \left(\frac{Pattern\ Update\ Rate\ (\mu s)}{Frame\ Rate\ (\mu s)} + \frac{1}{Contrast\ (FOFO)}\right)$$

In this case, the two addends have an equal contribution to the sum. The ambient light spatial filtering capability of the DMD can then be estimated as a 250 times reduction in ambient light. In dB terms, this represents a 24-dB reduction in ambient light, and a 24-dB reduction in shot noise!

3.1.3 Performance cost due to optical efficiency

Finally, the optical efficiency of the DMD must be considered when analyzing the performance boost from adding a DMD to the system. The optical efficiency of the DMD varies depending on wavelength, and often a window with an anti-reflective coating specific to the desired wavelength is chosen. Although TI has some DMDs that are optimized for infrared wavelengths, the DLP5531-Q1 is optimized for visible wavelengths. In the near infrared (900 nm to 1100 nm), assuming an efficiency of 40% through the entire DMD is a good starting point. (DMDs that are optimized for infrared wavelengths can have efficiencies around 70%.) This means that the received signal is attenuated by 60% relative to using no DMD. This represents a 4-dB loss in laser light, and an 8-dB loss in signal power.

The optical efficiency also applies to the incoming ambient light as well, meaning that there is also an additional 4-dB reduction in ambient light when using the DMD as opposed to a system with no DMD. This doesn't cancel out the losses on the signal side, but it does provide a small benefit that can be added to the calculation of signal-to-noise ratio.

3.1.4 APD bias can be increased

One additional part of the design that should be taken into account is the biasing of the photodetector. In APDs and SiPMs, the bias voltage of the photodetector can be increased with a corresponding increase in signal, but an even greater increase in shot noise. If shot noise is dominant in the system, then increasing the bias voltage degrades the SNR because the noise increases faster than the signal. However, if some other noise source, such as AFE noise, is dominant in the system, then the SNR can be improved by increasing the bias voltage until the contributions from shot noise and AFE noise are equal (or until the maximum voltage bias of the photodetector is reached). Because the use of the DMD greatly reduces shot noise in the system, DMD based systems are capable of supporting higher photodiode bias voltages than LIDAR systems with higher ambient light.

3.1.5 SNR improvement from using DMD: a case study

Finally, in order to compare the SNR performance improvement given by the DMD, the level of AFE noise must be taken into consideration. The absolute level of AFE noise and ambient light are not needed to perform these calculations; rather, the ratio of AFE noise to ambient light must be known. Both the amount of AFE noise and the amount of ambient light may vary; the AFE noise is dependent on the noise performance of the amplifiers used, the level of noise in the power supply, and the PCB design which may couple noise in from undesired sources, while the ambient light will vary depending on the brightness of the day and the reflectivity of the surroundings. To account for the variation in AFE noise in different systems, two different levels of AFE noise are considered. A system with low AFE noise is assumed to have 1 pA/√Hz of input referred noise; another system with more typical AFE noise is assumed to have 10 pA/√Hz of AFE noise.

The impact of using the DMD on the noise in the system is analyzed first, followed by the impact to the signal. In a system with no DMD, the contributions from AFE noise and shot noise are added together. First, the AFE noise is given.

$$n_{AFE} = 1\, pA/\sqrt{Hz}\ (low\ AFE\ noise)$$

$$n_{AFE} = 10\, pA/\sqrt{Hz}\ (typical\ AFE\ noise)$$

To estimate the shot noise, full solar brightness of 100 klux is assumed. One must also assume an average background reflectivity, optical FOV and effective pupil diameter. In this case, the shot noise was estimated at the following magnitude:

$$n_{shot\ no\ DMD} = 100\ pA/\sqrt{Hz}$$

To find the total noise, the RMS sum of the two independent noise sources is used.

$$n_{total\ no\ DMD} = \sqrt{{n_{AFE}}^2 + {n_{shot\ no\ DMD}}^2} = 100.0\, pA/\sqrt{Hz}\ (low\ AFE\ noise)$$

$$n_{total\ no\ DMD} = \sqrt{{n_{AFE}}^2 + {n_{shot\ no\ DMD}}^2} = 100.5\, pA/\sqrt{Hz}\ (typical\ AFE\ noise)$$

Note that the level of AFE noise doesn't really matter in this case, because the system is dominated by shot noise.

Next, the DMD is used to reduce the amount of shot noise. The DMD reduces shot noise by reducing ambient light, the source of the shot noise. From the previous section, the ambient light spatial filtering capability of the DMD was estimated, as well as the optical efficiency. These two terms are multiplied to calculate the total reduction in ambient light.

$$ambient\ light\ reduction = spatial\ filtering * optical\ efficiency = \frac{1}{250} * 0.4 = 0.0016$$

This corresponds to a proportional reduction in DC current of the photodetector and a reduction in the shot noise by the square root.

$$DC\ current\ reduction = ambient\ light\ reduction = 0.0016$$

$$shot\ noise\ reduction = \sqrt{DC\ current\ reduction} = 0.04$$

This reduction is applied to the level of shot noise.

$$n_{shot\ with\ DMD} = 0.04 * 100\ pA/\sqrt{Hz} = 4\ pA/\sqrt{Hz}$$

Now the total noise can be recalculated.

$$n_{total\ with\ DMD} = \sqrt{n_{AFE}{}^2 + n_{shot\ with\ DMD}{}^2} = 4.1\ pA/\sqrt{Hz}(low\ AFE\ noise)$$

$$n_{total\ with\ DMD} = \sqrt{n_{AFE}{}^2 + n_{shot\ with\ DMD}{}^2} = 10.8\,pA/\sqrt{Hz}(typical\ AFE\ noise)$$

By dividing the total noise with the DMD by the noise without the DMD, the noise reduction can be calculated. This is expressed in dB.

$$total\ noise\ reduction = 20\log\frac{n_{total\ with\ DMD}}{n_{total\ no\ DMD}} = 27.7dB(low\ AFE\ noise)$$

$$total\ noise\ reduction = 20\log\frac{n_{total\ with\ DMD}}{n_{total\ no\ DMD}} = 19.4dB(typical\ AFE\ noise)$$

By using the DMD, the noise is now dominated by the AFE noise in the typical AFE noise case. The shot noise is much reduced, but still a significant factor in the low AFE noise case. The last step to calculate the total SNR improvement is to subtract the loss in signal due to optical attenuation of the DMD, which was estimated earlier as 8 dB. Also, the voltage bias can also be increased leading to an additional SNR boost. The calculation of this extra SNR boost is beyond the scope of this paper, but it is estimated here as an additional 3 dB.

$$SNR\ gain = total\ noise\ reduction - signal\ loss + signal\ boost_{higher\ V\ bias}$$

$$SNR\ gain = 22.7dB(low\ AFE\ noise)$$

$$SNR\ gain = 14.4dB(typical\ AFE\ noise)$$

The main assumptions used to derive this result were the performance of the DMD, especially the contrast and optical efficiency of the DMD, and the ratio of shot noise to AFE noise before the DMD is added to the system. As shown in this case study, the SNR of the LIDAR system can be greatly improved by using a DMD to reject ambient light!

3.2 Optics considerations

When using a DMD in a scanning LIDAR system to reduce the amount of ambient light, there are a few optical considerations of which the designer must be aware. These include considerations of the optical design affecting contrast, the effective pupil diameter, and awareness of the available etendue of the DMD.

As shown in the equations in the previous section, the contrast of the optical system is very important for the ability of the DMD to filter ambient light. The most important parameter to consider when designing an optical system for good contrast is the F-number of the system. A higher F-number will have higher contrast because the acceptance angle for stray light to get to the sensor is smaller. However, this type of design will also restrict the amount of signal that can be received by the system. The two design considerations are in direct opposition! Because of this, the design must be carefully studied, and the impact of the F-number on contrast and signal attenuation must be quantified.

Another design parameter to consider is the etendue of the DMD. The etendue of the DMD is obviously determined by the DMD size and working F-number. The optical system can be thought of as imaging the scene onto the DMD followed by a relay from the DMD to the detector. It is important in the design of the system that the DMD not limit the system etendue. The best results are generally obtained by matching the etendue of the DMD with that of the detector. This results in minimal light loss.

The most common optical design for a 12-degree-tilt DMD is an F/2.4 imaging lens. F/2.4 uses the maximum cone angle without interference between the light incident the DMD and the light reflected. As in a DMD projector, a TIR prism is typically used to separate the incoming and the outgoing light rays. If a better contrast ratio is desired, the imaging optic can be apertured to a higher F-number at the expense of light collection. If more etendue is desired, a lower F-number imaging optic can be used at the expense of contrast. For the low F-number case contrast loss can be minimized by forming an asymmetric imaging cone such that the F-number is 2.4 in the direction of the mirror tilt, but a lower F-number in the orthogonal direction. This can be accomplished by either using an anamorphic imaging optics or a non-circular aperture in the imaging lens.

4 System performance impact

The case study suggests that, depending on the level of AFE noise in the system, using the DMD will improve the SNR of the LIDAR system by 14.4 dB to 22.7 dB under peak ambient light conditions, relative to using no DMD. In order to make this performance improvement more relatable, the SNR improvement can be expressed in terms of improvement to the range, resolution, FOV, and frame rate of the system. An increase in any one of these design parameters results in a decrease of the signal for the system; therefore, a better SNR is required if an improved performance of the LIDAR system is needed. A more mathematical representation of the relation of each of these parameters to the SNR is given in Appendix A, but a short summary of each of these parameters is given here.

Range of a LIDAR system is important to detect objects at a great enough distance that an autonomous vehicle has sufficient reaction time. When the transmitted light reflects from the target to be detected, the light is reflected in all different directions, and only some light is reflected back to the LIDAR sensor. The amount of received light decreases by the square of the distance to the target. Therefore, a linear increase in range requires a quadratic increase of SNR.

Resolution of a LIDAR system is important so that enough data points are present on an object to distinguish hazardous objects from non-hazardous objects. However, in order to increase the resolution, the beam size of the transmitted laser beam must be smaller. This results in less light that illuminates the target, and the signal correspondingly decreases. A linear increase in resolution in one dimension requires a linear increase in SNR. Increasing the resolution in both dimensions requires a quadratic increase in SNR.

FOV of a LIDAR system is important to cover more surroundings, such as lanes of traffic or side streets. As mentioned before, increasing the FOV results in decreasing the collection aperture of the optics, which reduces the signal. When making the small angle approximation, a linear increase in FOV in one dimension requires a linear increase in SNR, while an increase in FOV while keeping a constant aspect ratio requires a quadratic increase in SNR.

Frame rate of a LIDAR system is important to quickly observe changes in the environment and provide low latency data to the processor. When increasing the frame rate, less time is available to transmit all the laser pulses, and the power of each individual pulse must be reduced to keep the average transmitted power below eye safety power limits. Due to this, a linear increase in frame rate requires a linear increase in SNR.

Since each of these four parameters depends on SNR, the parameters may be combined into a figure of merit that allows different LIDAR systems to be compared against each other. A proposed figure of merit, called the **NO**rmalized **L**idar **EN**vironmental unit (**NOLEN**), as well as a proposal for how it should be measured, is given in Appendix B. It is proportional to the square of the range performance times the points per second of the LIDAR system.

Finally, the relation between the SNR gain and all of the LIDAR performance metrics can be shown. For metrics that have a linear relationship with SNR, the performance improvement can be calculated just by converting the SNR gain from decibels to linear units. For metrics that require a quadratic improvement in SNR, the square root of the improvement should be taken after conversion into linear units. For example, for the typical AFE noise case,

- Range could be improved by a factor of 2.3
- Resolution could be improved by a factor of 5.2 in one dimension, or 2.3 in both dimensions
- FOV could be improved by a factor of 5.2 in one dimension, 2.3 in both dimensions
- Frame rate could be improved by a factor of 5.2

Of course the system could be improved by some combination of these as well, for example the range could be improved by a factor of 1.5 while the frame rate is improved by a factor of 2.3. Another way to represent the improvement is by expressing the improvement of the figure of merit; the NOLENs of the system also increase by a factor of 5.2. For the low AFE noise case, parameters that require a quadratic increase in SNR such as the range could be improved by a factor of 3.7, while parameters that only require a linear increase in SNR could be improved by a factor of 13.6.

5 Conclusion

In this paper, several important concepts were discussed. First, the architecture differences between mechanical LIDAR systems, flash LIDAR systems, and scanning LIDAR systems were explained. Then, the concepts of shot noise and the limited receiving area of the photodetector were introduced as key mechanisms which limit the SNR of a LIDAR system, and therefore the performance of the LIDAR system. At this point, the DMD was shown to reduce the shot noise in the LIDAR system which leads to an SNR improvement. The usefulness of the SNR improvement was quantified to show its impact on range, resolution, field of view, and frame rate. A figure of merit encapsulating these performance metrics is given in Appendix B. In the case study, adding the DMD to a system with typical AFE noise increases the resolution or field of view or frame rate by a factor of 5.2, or increases the range by a factor of 2.3!

As the performance of LIDAR systems improve and their availability increases, many new technologies are enabled. The most exciting of these, the autonomous vehicle, has the potential to bring great economic benefit and disrupt many industries. The use of the DMD to filter ambient light may help enable the next big improvement in this industry, and pave the road towards full automation!

Relation of SNR to system performance metrics

A.1 LIDAR/RADAR equation

The dependence of different performance metrics on the SNR can be derived from the "radar equation" or "LIDAR equation" which describes the amount of received power by the photodetector for a LIDAR system. The equation is given as

$$P_r = P_0 T_t \rho_d \frac{A_r}{\pi d^2} T_r \; [2]$$

where

$$P_r = received\ signal\ power$$

$$P_0 = laser\ output\ power$$

$$T_t = optical\ efficiency\ of\ trasmit\ optics$$

$$\rho_d = Lambertian\ reflectance\ of\ target$$

$$A_r = area\ of\ receive\ aperture$$

$$d = target\ distance$$

$$T_r = optical\ efficiency\ of\ receive\ optics$$

The equation describes the change in light energy as it passes through the system. First, the laser has a base output power. This is attenuated based on the optical efficiency of the transmit optics. Then, the light propagates through the air to reach the target. Attenuation of the light through the air is assumed to be negligible in this equation. Additionally, it is assumed that the beam divergence of the laser is small enough that the resulting spot size is smaller than the target. If this is not the case, then another term must be added to the equation which is proportional to $1/d^2$. When the light reaches the target, some of the light is reflected, but some light is also absorbed. The Lambertian reflectance represents the fraction of the incident radiation that is scattered into a hemisphere rather than absorbed. The object is considered to be Lambertian which means it scatters with a radiance that falls off with the cosine of the angle from the surface normal. The scattered target radiance is then integrated over the solid angle of the receiver resulting in a factor of $\frac{A_r}{\pi d^2}$. Finally, the remaining light is further attenuated by the optical efficiency of the receive optics.

A.2 Eye safety limits

The calculation of the laser eye safety limits can be complicated requiring calculation of limits over a variety of conditions. The complete calculations required for compliance to these limits is beyond the scope of this document and are described in detail in **IEC document 60825-1**. Here we provide an approximate calculation making several assumptions, and we do not assure compliance to laser eye safety requirements.

As mentioned earlier, the laser power emitted by the system will be finite, typically limited either by the Accessible Emission Limit (AEL) required for a certain laser class, or by the maximum output of the laser itself. The AEL may be described in units of energy (Joules) or power (Watts) for a particular wavelength and pulse duration. Because the LIDAR system will continuously emit pulses, it is subject to two power limitations. First of all, the maximum amount of power in one pulse must be within the limits for a pulse of that duration (single pulse energy limit). Secondly, the average power emitted must be within the limits for continuous wave operation. For this analysis, it is assumed that the AEL is limited by the average power emitted by the laser.

Although the limit for AEL is expressed in terms of Watts, the limit must be normalized by the aperture defined by the measurement standard as well as the measurement distance. The limit is measured by defining an aperture of a known size at a known distance, and limiting the laser power through this aperture over the specified time duration. Assuming the laser will scan uniformly across the field of view, the power must be constrained for any aperture at any angle relative to the transmitter. Thus, the eye-safety requirement can be expressed as a power level within a solid angle (radiant intensity). Assuming near-infrared wavelengths, and condition 3 applies (IEC 60825-1), the average power limit can be calculated within a solid angle formed by a 7-mm aperture at 100 mm from the source. Therefore the transmitted power of the laser can be represented as

$$P_0 = I_0 \Omega_0$$

where

$$I_0 = laser\ radiant\ intensity, \frac{W}{sr}\ (determined\ by\ eye\ safety)$$

$$\Omega_0 = laser\ transmitted\ solid\ angle, sr$$

The laser transmitted solid angle can be expressed in terms of the beam divergence of the laser in both x and y dimensions, giving

$$P_0 = I_0 \pi \theta_x \theta_y$$

which will be substituted into the LIDAR equation. θ_x and θ_y now represent both the horizontal and vertical components of the beam divergence of the laser, and also the horizontal and vertical angular resolution of the system.

Additionally, the LIDAR equation can be rewritten in terms of the SNR of the system. Making these changes to the LIDAR equation results in the following equation:

$$SNR * noise_{total} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{d^2} T_r$$

Finally, the relationship between SNR and most of the performance metrics can be analyzed. The SNR must remain above a certain threshold to ensure that the error of the LIDAR system stays within a certain bound. Therefore, in this equation the SNR can be assumed to be constant.

A.3 Application of LIDAR equation to performance metrics

In order to analyze how the noise reduction can improve the performance metrics, the impact of adding the DMD is added to the equation. The use of the DMD in the LIDAR system affects two parameters in this equation. First of all, the use of the DMD lowers the $noise_{total}$ term; although unfortunately it also lowers the T_r term. To simplify things slightly, the terms expressing the change in signal and noise from using the DMD are combined into a single term:

$$SNR * (noise_{no\ DMD} * noise\ reduction_{DMD}) = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{d^2} (T_r * signal\ reduction_{DMD})$$

$$SNR * noise_{no\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{d^2} T_r * SNRgain_{DMD}$$

This equation is used as the starting point in the following sections to show how adding the DMD to the system can improve the performance of the system. This equation with the SNR improvement of the DMD is compared to the same equation without the SNR improvement of the DMD. All of the variables will be assumed to be constant, except for a selected parameter of interest, which will be assumed to have a different value with and without the use of the DMD.

A.3.1 Range

First, the impact of SNR gain on the range of the system is analyzed. Starting with the equation with the DMD:

$$SNR * noise_{no\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{{d_{DMD}}^2} T_r * SNRgain_{DMD}$$

The equation is divided by the equation with no DMD:

$$SNR * noise_{no\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{{d_{no\ DMD}}^2} T_r$$

Giving the result:

$$\sqrt{SNRgain_{DMD}} = \frac{d_{DMD}}{d_{no\ DMD}}$$

This performance still assumes that the spot size of the laser beam is smaller than the target to be sensed. For long distances, this may cease to be true, and in those cases, the range performance is proportional to the fourth power of the distance rather than the square of the distance.

Besides adding the DMD to the LIDAR system, there are minimal changes needed to obtain this additional performance. It is possible that the dynamic range of the photodetector amplifier or the digitizer might need to be increased, but other changes are not needed.

A.3.2 Resolution

Second, the impact of SNR gain on the resolution is analyzed. Again, the LIDAR equation with the DMD is divided by the LIDAR equation without the DMD.

$$SNR * noise_{no\ DMD} = I_0 \theta_{x\ DMD} \theta_{y\ DMD} T_t \rho_d \frac{A_r}{d^2} T_r * SNRgain_{DMD}$$

divided by

$$SNR * noise_{no\ DMD} = I_0 \theta_{x\ no\ DMD} \theta_{y\ no\ DMD} T_t \rho_d \frac{A_r}{d^2} T_r$$

yields

$$SNRgain_{DMD} = \frac{\theta_{x\ no\ DMD} \theta_{y\ no\ DMD}}{\theta_{x\ DMD} \theta_{y\ DMD}}$$

In addition to adding the DMD to the system, the LIDAR system would need to be changed in order to realize this higher resolution. First of all, the repetition rate of the laser would need to be increased by whatever ratio that the resolution is increased by. In addition, the beam divergence of the laser beam would likely need to be reduced as well to prevent overlap. Finally, the mechanism for steering the beam may need to be modified in order to steer the beam to the additional points. All of these things could be done without using the DMD. But the addition of the DMD allows the resolution to be increased without loss in one of the other key parameters.

A.3.3 FOV

Next, the impact of the SNR gain on the FOV is analyzed. In order to analyze this, the LIDAR equation is first expressed in terms of the aperture size, which in turn defines the FOV due to the limited etendue of the photodetector. The first step is the same; the LIDAR equation with the DMD is divided by the LIDAR equation without the DMD.

$$SNR * noise_{no\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_{r\ DMD}}{d^2} T_r * SNRgain_{DMD}$$

divided by

$$SNR * noise_{no\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_{r\ no\ DMD}}{d^2} T_r$$

yields

$$SNRgain_{DMD} = \frac{A_{r\ no\ DMD}}{A_{r\ DMD}}$$

This equation is in terms of the receiving area of the LIDAR system, but the parameter of interest is the field of view of the system. Using the principle of the conservation of etendue, the area can be represented in terms of the FOV of the system with the following equation:

$$A_{entrance} = \frac{detector\ etendue}{sin^2(\theta_{FOV}/2)}$$

There is a false assumption here that the FOV is circular and symmetric, when in reality the FOV is rectangular and usually wider in the horizontal dimensions. However, this is a good approximation, and keeps the math much simpler. This equation can be substituted into the previous equation to show the effect on the SNR gain on the FOV:

$$SNRgain_{DMD} = \frac{sin^2(\theta_{FOV\ DMD}/2)}{sin^2(\theta_{FOV\ no\ DMD}/2)}$$

The form of this equation is still a little bit difficult to comprehend. If the small angle approximation is used, then the equation can be reduced to the following form:

$$\sqrt{SNRgain_{DMD}} = \frac{\theta_{FOV\ DMD}}{\theta_{FOV\ no\ DMD}}$$

To help visualize how close the small error approximation is, here is a plot of the quantity $\theta_{FOV\ DMD} / \theta_{FOV\ no\ DMD}$ for different values of SNR gain from the DMD.

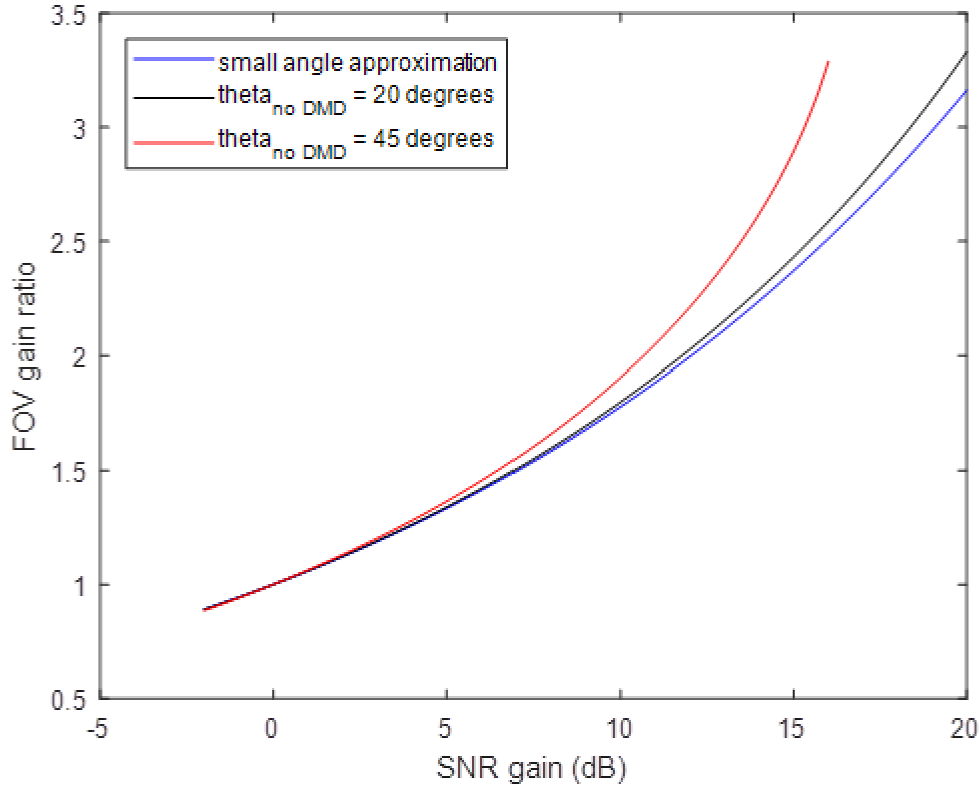


Figure 7. Small angle approximation for SNR vs FOV expansion

The small angle approximation is a good assumption for FOV of less than 20°, and in addition, it will always underestimate the gain from adding the DMD to the system.

In addition to adding the DMD to the system, the focal length of the optics will also need to be changed in order to achieve a wider field of view. Additionally, the mechanism which steers the laser beam across the field of view will also need to be able to support scanning across a wider field of view. The total power of the laser will also increase. Although all these changes need to be implemented for a system with a wider field of view, the addition of the DMD gives the additional SNR that allows this increase in system performance.

A.3.4 Frame rate

Finally, the impact of SNR gain on the frame rate is analyzed. At this point, we note that the LIDAR equation defines the throughput of power through the system. However, as the measurements for each data point must be taken within the time constraint of a single frame, we realize that the important quantity is the received energy within a single frame. Therefore we rewrite the general LIDAR equation to take this into account.

$$\frac{E_r}{t_{fr}} = P_0 T_t \rho_d \frac{A_r}{\pi d^2} T_r$$

where

$$E_r = Received\ energy$$

$$t_{fr} = frame\ time$$

Adding this change to the derived equations that include the effect of the DMD, and rewriting the frame time as the frame rate, yields the following equation:

$$SNR * noise_{no\ DMD} * f_{fr\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{d^2} T_r * SNRgain_{DMD}$$

Note that as a result of this change, the variable representing noise now represents a quantity of energy instead of a power. However, this is not of consequence for the results. Finally, this equation is divided by the similar equation without the use of the DMD:

$$SNR * noise_{no\ DMD} * f_{fr\ no\ DMD} = I_0 \theta_x \theta_y T_t \rho_d \frac{A_r}{d^2} T_r$$

yielding

$$SNRgain_{DMD} = \frac{f_{fr\ DMD}}{f_{fr\ no\ DMD}}$$

This shows that if the DMD is added to a system, one opportunity for system improvement would be to increase the frame rate of the system.

In order to implement this change, the mechanism which steers the beam across the field of view would need to scan faster by a rate proportional to the desired frame rate increase. The laser repetition rate would also need to increase in order to collect all of the data within a shorter frame. Finally, the peak power of each laser pulse would need to be reduced, such that the average laser power remains at the same level and therefore below the required eye safety limits.

LIDAR figure of merit

B.1 LIDAR figure of merit

Keeping track of all of the performance metrics can be confusing, and deciding how to make tradeoffs in the system design is difficult. The many performance metrics also complicate comparison of different LIDAR systems offered by different manufacturers. Benchmarking and comparing systems is difficult when different systems are designed to perform well for different parameters. One effort to compare these is to model different systems while keeping the system specifications the same [1]. Also, in [3] a figure of merit is proposed, but this figure of merit is cumbersome to use, and also doesn't account for systems with different resolutions. To alleviate this difficulty, we propose a figure of merit to provide a shorthand method for evaluating the composite performance of a LIDAR system. The figure of merit follows from the previous analysis: it is chosen so that LIDAR systems with the same sensitivity or SNR will have the same figure of merit, but differ only in the system tradeoffs that were chosen. Here is that figure of merit:

$$LIDAR\ FOM = \frac{d^2 * \theta_{HFOV} * \theta_{VFOV} * f_{fr}}{\theta_x * \theta_y}$$

Most of the parameters of the figure of merit are easily obtained for a given system; the field of view and usually the resolution are static for any LIDAR system. The frame rate is sometimes adjustable, but easily known. The most difficult parameter to measure is the range. The reason the range is difficult to measure is that the range depends on many environmental factors. Therefore for an accurate comparison, the range for LIDAR systems should be measured under the same environmental conditions. A list of proposed conditions is given in Table 1.

Table 1. Environmental Factors

Environmental Factor	Test Condition	Comments
Weather	Clear day	Fog and rain will degrade a LIDAR's performance, but creating a repeatable environment would be very challenging
Solar Brightness	Clear day	The brightest day will occur with no clouds, midday, at latitudes near the equator. Ideally, the brightness conditions could be measured at the time of the test and normalized to some level.
Target Reflectivity	50% Lambertian	
Target Size	Larger than spot size	Targets smaller than the spot size will reflect less light and be harder to detect.
Target Orientation	Normal to the laser beam	

Of course this list only provides a rough guideline; a true specification would go into more detail, such as how to measure the ambient light, or even specifying a certain material to be used as the test target. Additionally, an accuracy metric would need to be defined as well. This accuracy metric would define the resolution and accuracy of the range measurement returned, as well as the probability of detecting a target at a given range. The authors of [4] explain how to translate a required detection probability into a minimum required SNR for the system.

Finally, the figure of merit can be normalized so that it is easier to understand and talk about. Without any normalization, the figure of merit has units of m^2/s , which is not very intuitive. Additionally, the magnitude of these numbers is rather large. Instead, consider a LIDAR system with specs that are close to what may be desired specs, but rounded to the nearest order of magnitude. The LIDAR performance unit baseline is defined below.

Table 2. LIDAR Performance Unit Baseline

Parameter	Value
Range	100 m
Field of View (horizontal and vertical)	10°
Resolution (horizontal and vertical)	0.1°
Frame Rate	10 Hz

This fictitious LIDAR system has a performance of $10^9 m^2/s$. This constant is picked as the normalization factor for the performance metric. For shorthand, this may be called **NO**rmalized **L**idar **EN**vironmental units, or **NOLEN**s. Additionally, note that the angular resolution, FOV, and frame rate may be combined into one term of the LIDAR system as points per second, giving another way to quickly define the figure of merit:

$$NOLEN \equiv \frac{d^2 * \theta_{HFOV} * \theta_{VFOV} * f_{fr}}{10^9 * \theta_x * \theta_y} = \frac{d^2 * pts/s}{10^9}$$

For a given LIDAR system, we can express the performance in NOLENs. For example, the Velodyne LIDAR Puck (VLP-16), according to its data sheet, has a range of 100 m, 360° horizontal field of view, 30° vertical field of view, 0.1° to 0.4° horizontal resolution, 2° vertical resolution, and 5-Hz to 20-Hz frame rate. The test conditions for the measurement of the range are not specified, so the measurement of the range could be different if it was not measured under bright ambient light conditions. This detail is ignored for the sake of demonstrating the calculation. Additionally, it is assumed that only the better horizontal resolution or the frame rate can be achieved at one time. Then, the NOLENs of the Velodyne LIDAR Puck can be calculated:

$$Velodyne\ LIDAR\ Puck\ NOLENs = \frac{100^2 * 360 * 30 * 5}{10^9 * 0.1 * 2} = 2.7 NOLENs$$

The validity of the range measurement is of utmost importance, since the figure of merit depends on the square of the range measurement—the actual performance of the Velodyne LIDAR Puck may be fewer NOLENs depending on the performance in bright sunlight. However, the important point to make is that there is a way to compare different LIDAR systems.

Regardless of which figure of merit or standard becomes most common, two concepts should be recognized. First, range, resolution, field of view and frame rate all exist as tradeoffs in a LIDAR system. Secondly, the reported performance of a LIDAR system should always list the environments conditions when the measurement was taken. Otherwise, comparing the performance of different systems is extremely difficult due to the large impact of the environment in the measured performance.

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