# SiPMs in Direct ToF Ranging Applications

*This white paper is intended to assist in the development of SiPM (Silicon Photomultiplier) based LiDAR (Light Detection and Ranging) systems. The following sections contain information on the design and implementation of a direct ToF (Time-of-Flight) rangefinder, in terms of the laser, timing and optical parameters and detailed analysis of key aspects that must be considered when integrating SiPMs in such systems.*

# SiPMs in Direct ToF Ranging Applications

## Introduction

LiDAR is a ranging technique that is increasingly being employed in applications such as mobile range finding, automotive ADAS (Advanced Driver Assistance Systems), gesture recognition and 3D mapping. Employing an SiPM as the photosensor has a number of advantages over alternative sensor technologies such as APD, PIN diode and PMT particularly for mobile and high volume products. **onsmi** SiPMs can offer:

- Single Photon detection from 250 nm to 1100 nm
- High Photon Detection probability
- Low voltage – easy to implement system requirements
- Low power – lower operating voltages and simple readout electronics allow a low power design
- High bandwidth and fast response time – minimize range measurement time
- Ability to take advantage of low laser power direct ToF ranging techniques
- Low noise and high gain – good signal to noise ratio (*SNR*) is achievable
- Standard CMOS fabrication process – low cost, highly uniform and scalable production
- Small size packaging

Transitioning to SiPM sensor technology presents a different set of constraints when compared to other sensors. This white paper is intended to help the user maximize the benefits of the technology and achieve a working set-up with SiPM sensors as quickly as possible. To this end, **onsemi** has created a python waveform simulation tool:

- A detailed python model of a direct ToF system has been created to facilitate the simulation of an SiPM−based ranging application. The model can be used to support ranging system design and may be modified to simulate a wide variety of applications and implementations.

## Design of a Direct ToF Ranging System

The basic components required for a direct ToF ranging system, as illustrated in Figure 1, are:

1. A pulsed laser with collimation optics
2. A sensor with detection optics
3. Timing and data processing electronics

This document focuses on system design of the laser, sensor, readout and application environment. The single-point, direct ToF baseline work performed in this white paper may be extended to more complex scanning and imaging systems.

In the direct ToF technique, a periodic laser pulse is directed at the target, typically with eye-safe power and wavelength in the infrared region. The target diffuses and reflects the laser photons and some of the photons are reflected back towards the sensor. The sensor converts the detected laser photons (and some detected photons due to noise) to electrical signals that are then timestamped by the timing electronics. This *time of flight*, $t$, can be used to calculate the *distance*, $D$, to the target from the equation $D=c\Delta t/2$, where $c$ = *speed of light* and $\Delta t$=*time of flight*. The sensor must discriminate returned laser photons from the noise (ambient light). At least one timestamp is captured per laser pulse. This is known as a single-shot measurement. The signal to noise ratio can be dramatically improved when the data from many singleshot measurements are combined to produce a ranging measurement from which the timing of the detected laser pulses can be extracted with high precision and accuracy. Several different readout techniques exist to capture the timing information from the detected laser photon pulse, as summarized below.

## Readout Techniques for Ranging

- LED (leading edge discrimination) – Involves the detection of the rising edge of a multi-photon signal. Timing accuracy is determined by the ability to discriminate the rising edge of the returned optical signal. This technique is not affected by laser pulse width.
- Full waveform digitization – The full waveform is digitized and can be over-sampled to improve accuracy. Can be difficult to implement with short laser pulses or high repetition rate sources
- TCSPC (time correlated single photon counting) – Provides the highest accuracy and greatest ambient light rejection. This technique requires that less than one signal photon is detected per laser pulse. This technique can be immune to ambient light but a short pulse duration, high repetition rate and fast timing electronics are required to achieve fast and accurate measurements.
- SPSD (single photon synchronous detection) – A form of TCSPC which provides high ambient light rejection. Electronics must be designed to deal with range ambiguity.

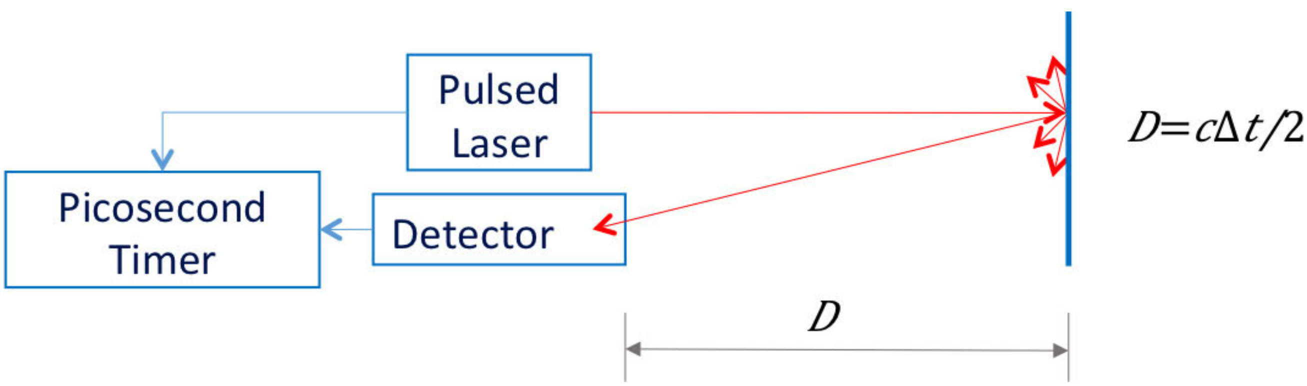


**Figure 1. Direct ToF Ranging Technique Overview**

## Modelling A Direct ToF Ranging System

A python model of a direct ToF system has been created. A block diagram of the model is shown in Figure 2. The purpose of the model is to predict the overall performance of a system given a set of system parameters similar to those shown in Table 2.

The first step consists of analytically calculating the light levels at the sensor (both ambient and laser light) given a chosen optical scenario which can be varied by changing the corresponding system parameters. By comparing the calculated light levels to the saturation limit of the sensor, the chosen setup can be validated as suitable for ranging. In the event that the particular setup is not suitable for ranging, improvements on the setup itself can be evaluated by varying the system parameters.

The second part of the model consists of a Monte Carlo waveform where the stochastic properties of the sensor, mainly the photon detection efficiency (*PDE*) and the timing jitter, are reproduced. This step allows a realistic output of the sensor to be obtained by simulation. In contrast to the analytic part, this step takes into account timing information such as the acquisition time, the repetition rate of the laser and the laser pulse width and SiPM uncorrelated and correlated noise (i.e. dark count rate *DCR*, prompt and delayed optical cross–talk *pXT*, *dXT* and afterpulsing *AP*). The outcome of the Monte Carlo simulation is passed to a Waveform Analysis, typically a discriminator followed by a TDC (Time to Digital Converter), which produces a histogram of timestamps from which a range measurement can be extracted.

Simulations were performed for Next Generation **onsemi** SiPM device, with main parameters presented in Table 1.

**Table 1. TYPICAL SiPM PERFORMANCE PARAMETERS USED IN SIMULATION**

| Parameter | | MicroFC–10020 | RDM–0112A20 | Next Generation |
|---|---|---|---|---|
| PDE | 905 nm | 1.8 % | 15.3 % | 30% |
| | 940 nm | 1.2 % | 10.3 % | 21 % |
| $N_{\mu cells}$ | | 1296 | 806 | 1500 |
| pXT | | 4 % | 21 % | 12 % |
| dXT | | 2.4 % | 7 % | 5 % |
| DCR | 25°C | 38 kHz | 76 kHz | 50 kHz |
| | 105°C | – | – | 1 GHz |

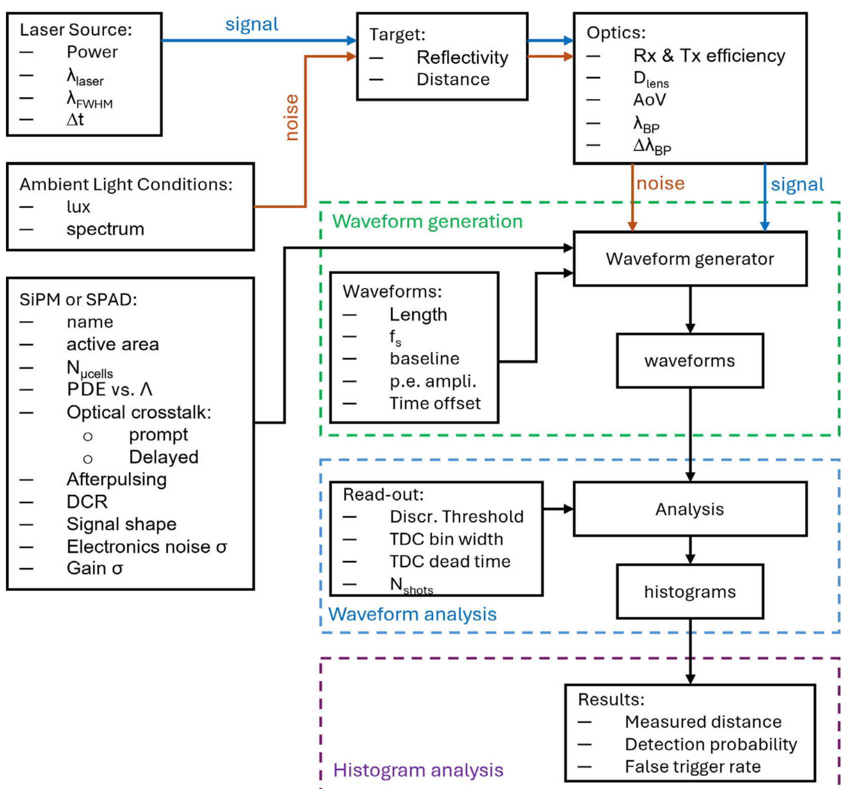


**Figure 2. Calculations of Light Levels are Paired with a Monte Carlo Simulation so that a Full System Output can be Reproduced**

Table 2. VARIABLES IN AN SIPM DIRECT TOF RANGING SYSTEM

| Symbol | System Parameter | Definition |
|---|---|---|
| | Acquisition method | This could be leading edge detection (LED) or time correlated single photon counting (TCSPC). |
| $f$ | Laser repetition rate | Clock rate of the laser. This is the same as the detector single−shot rate. |
| $W_{laser}$ | Laser pulse width | |
| $\lambda_{laser}$ | Laser wavelength | Wavelength of the laser beam. |
| $FWHM_{laser}$ | Laser FWHM | Spectral FWHM of the laser beam. |
| $P_{laser}$ | Laser peak power | Peak power of each laser pulse. |
| $\theta_{laser}$ | Laser beam divergence | The angle at which the laser beam diverges from a point source. |
| $d$ | Laser−sensor distance | The perpendicular distance between the laser diode and the sensor limits the minimum range. Ideally this should be 0. |
| $D_{lens}$ | Collection lens diameter | A plano convex lens is placed directly in front of the sensor. Effective aperture after mounting of the lens. |
| $F_{lens}$ | Collection lens focal length | |
| $BP$ | Optical filter bandpass wavelength | Filter placed between sensor and collection lens. |
| $FWHM_{BP}$ | Optical filter FWHM | |
| $AoV$ | Sensor angle of view | The angle at which the field of view of the sensor diverges from a point source. |
| $SiPM$ | SiPM | SiPM sensor. |
| $N_{\mu cells}$ | Number of micro−cells | Number of micro−cells in SiPM device |
| $PDE$ | Photon detection efficiency | SiPM Photon detection efficiency vs. wavelength |
| $pXT$ | Prompt optical crosstalk | SiPM prompt optical crosstalk probability |
| $dXT$ | Delayed optical crosstalk | SiPM delayed optical crosstalk probability |
| $AP$ | Afterpulses probability | SiPM afterpulses probability |
| $A$ | Amplifier gain | SiPM signal amplifier. |
| $V_{th}$ | Threshold voltage | Comparator threshold. Dictates minimum light level required to be considered an event. |
| $t_{acq}$ | Acquisition time | The total time during which samples are recorded by the sensor for inclusion in the data. = 1/frame rate. |
| $LSB_{TDC}$ | TDC resolution | TDC bin size limits the single−shot resolution. The use of multiple single−shot measurements can yield resolution significantly better than the TDC bin size. |
| $R$ | Target reflectivity | |
| $D$ | Distance to target | Distance between the ranging module and the target. |
| $E_v$ | Ambient illuminance | The maximum illuminance on the sensor due to ambient light. |

## The Ranging Histogram

Each time the laser is pulsed the acquisition system performs a single-shot measurement. Depending on many factors including the laser power and distance to the target, the number of detected laser photons per pulse may be low. Ideally, each detected photon would be timestamped. However, number of timestamps per single-shot measurement may be limited by the dead time of the TDC. Usually, many single-shot timing measurements, each containing one or more timestamps, are combined to produce a frame. The complete timing data obtained over the course of a single frame may be plotted in the form of a histogram as shown in Figure 3. The system ranging performance is limited by the quality of the histogram data, which in turn is affected by the system parameters. There are some limiting factors and some trade-offs that can be made, as can be seen from the analysis of system parameters detailed in the **The Effect of Changing System Variables Section** on page 7. The ranging histogram used below also provides a visual representation which is useful in describing the effects of various parameters on the data obtained. The basic histogram signal and timing parameters are explained below.

The histogram signal to noise ratio, $SNR_H$, is the ratio of the signal peak to the maximum noise peak:

$$SNR_H = \frac{\text{Signal peak value}}{\text{Noise peak value}} \quad \text{(eq. 1)}$$

In the model the following terms apply to the measurement time:

$$f = \text{laser frequency} \quad \text{(eq. 2)}$$

The laser repetition rate limits the maximum ToF that can be measured without ambiguity and this defines the time per single-shot measurement:

$$\text{Single shot Measurement time, } t_{ss} = \frac{1}{f} \quad \text{(eq. 3)}$$

The frame size is the number of single-shot measurements per histogram. A larger frame size can improve $SNR_H$ and produce a better quality histogram. The ranging speed is defined by the frame rate:

$$\text{frame rate} = \text{number of range measurements per second} = \frac{1}{t_{acq}} \quad \text{(eq. 4)}$$

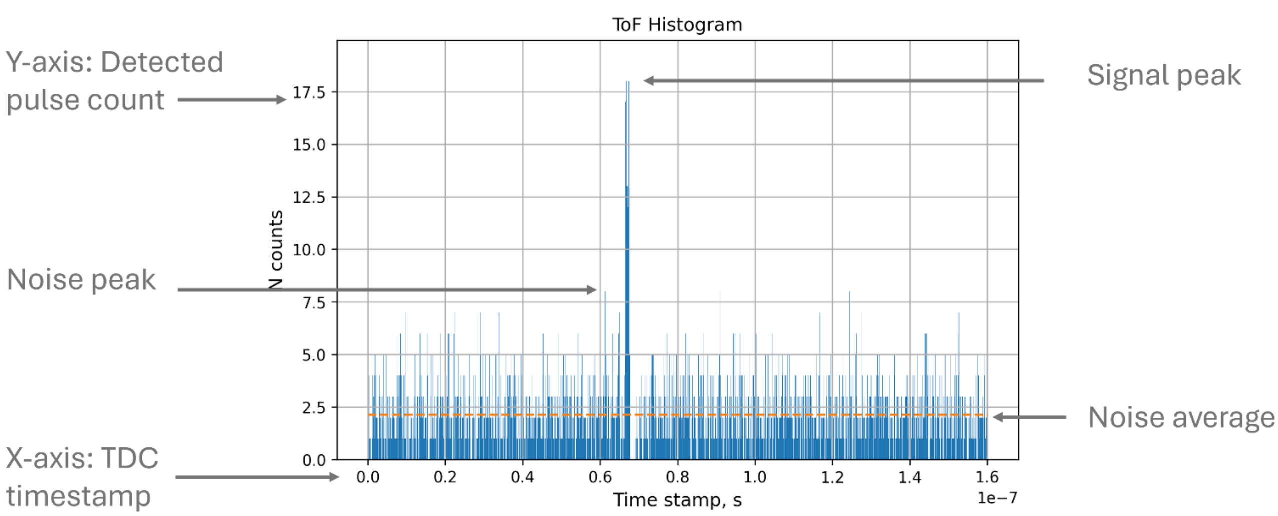


**Figure 3. Histogram Example from Simulation Showing Signal, Noise and Time of Flight**

## The Effect of Changing System Variables

System design parameters will vary based on the requirements of a specific application. The purpose of this section is to demonstrate, using the model of a direct ToF ranging system, how the acquired data is affected by each of seven key parameters. The effect of distance to target and ambient light level are also shown. The key points are summarized in Table 3.

The histograms shown in the following sections are obtained through simulation and each histogram can be assumed to include the entire dataset obtained in a single frame. For computational speed, the histograms shown correspond to a short acquisition time.

### 1. Reference Histogram

Figure 4 shows the reference histogram obtained by simulation for Next Generation onsemi SiPM device (for more details please see Table 1) under the conditions listed in the blue call-out box on the right. This configuration is used as a reference point to show the effects of alternative system parameter values.

The system parameters used in the following analysis were chosen to provide a reference point of a typical 40 m ranging application. Some of the parameters were chosen for ease of simulation and illustrative purposes rather than to reflect an optimized setup.

In each of the following sections one parameter only is modified and the simulation re-run to illustrate the effect that parameter has on the system in terms of collected data.

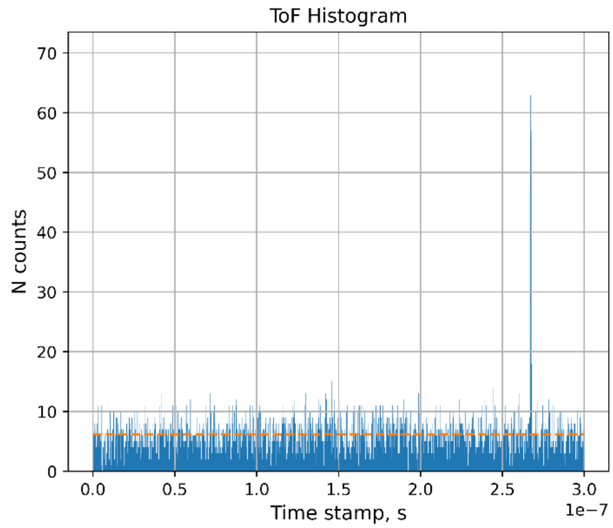


**Figure 4. Reference Histogram**

$t_{acq}$ = 1 ms

$P_{laser}$ = 2 W

$f$ = 200 kHz

$D$ = 40 m

$E_v$ = 100 klux

$W_{laser}$ = 250 ps

$\lambda_{laser}$ = 905 nm

$R$ = 50%

$D_{lens}$ = 15 mm

$FWHM_{BP}$ = ±5 nm

$AoV$ = 0.1°

**$SNR_H$ = 4.7**

**Table 3. SUMMARY OF EFFECTS OF KEY PARAMETERS**

| Parameter | Summary | Section |
|---|---|---|
| **Laser Source Parameters** | | |
| Laser pulse repetition rate | Affects quality of data that can be collected in fixed time interval. | 2 |
| Laser pulse width | May be dictated by laser availability. Only the front edge of the laser is required for LED therefore shorter laser pulses are more efficient. | 3 |
| Laser wavelength | Optimal wavelength may be chosen in terms of solar irradiance model. | 4 |
| **Sensor Parameters** | | |
| Collection lens aperture | Essential that this is limited to prevent sensor saturation in high ambient light conditions. | 5 |
| Sensor angle of view | Essential that this is limited to prevent sensor saturation in high ambient light conditions. | 6 |
| Optical filter bandpass | Should be as narrow as possible to eliminate all spurious noise. | 7 |
| **Conditions** | | |
| Sensor temperature | Limits achievable SNR when DCR is comparable with ambient light level. | 8 |
| Distance to target | Dictates required laser power and achievable accuracy. | 9 |
| Ambient light | Limits achievable SNR and affects quality of data. | 10 |
| SiPM selection | Selection of SiPM with high PDE significantly improves $SNR_H$ and ranging capability. | 11 |

## 2. Laser Pulse Repetition Rate

A higher laser pulse repetition rate improves the quality of the histogram by increasing the number of single-shot measurements allowing more returned laser photons to be detected for a given acquisition time. The maximum noise peak also increases as more noise counts are acquired. But, because the noise is not correlated, overall $SNR_H$ increases, as shown in Figure 5.

There is an upper limit on the maximum laser repetition rate that may be chosen because the rate limits the distance to target that may be ranged without ambiguity. For example, if 300 m is the maximum ranging target distance then a maximum repetition rate of 1 MHz can be used. If 100 m is the maximum target distance then 3 MHz may be used.

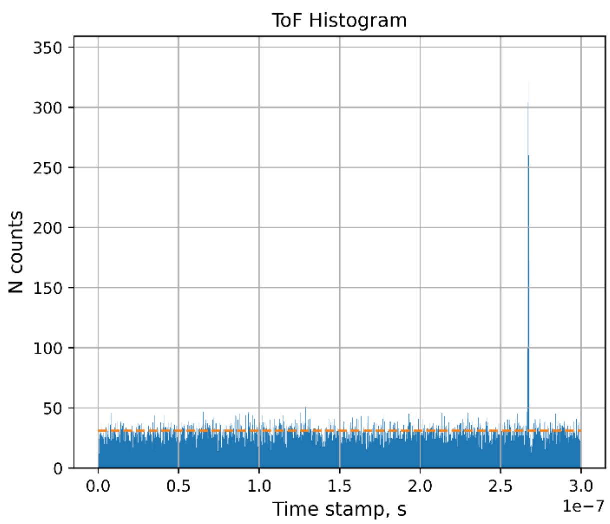


**Figure 5. Effect of Laser Repetition Rate**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| **$f$ = 1 MHz** | $D$ = 40 m |
| $E_v$ = 100 klux | $W_{laser}$ = 250 ps |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| $D_{lens}$ = 15 mm | $FWHM_{BP}$ = ±5 nm |
| $AoV$ = 0.1° | |

**$SNR_H$ = 6.3**

## 3. Laser Pulse Width

A wider laser pulse width leads to a wider signal peak in the histogram, as shown in Figure 6. With a square pulse it is necessary to discriminate the leading edge of the pulse to locate only the time of flight of the first photons detected. Subsequent photons do not carry useful ToF information. For this reason shorter laser pulses are optimal. However the availability of suitable lasers may be the deciding factor in a practical setup.

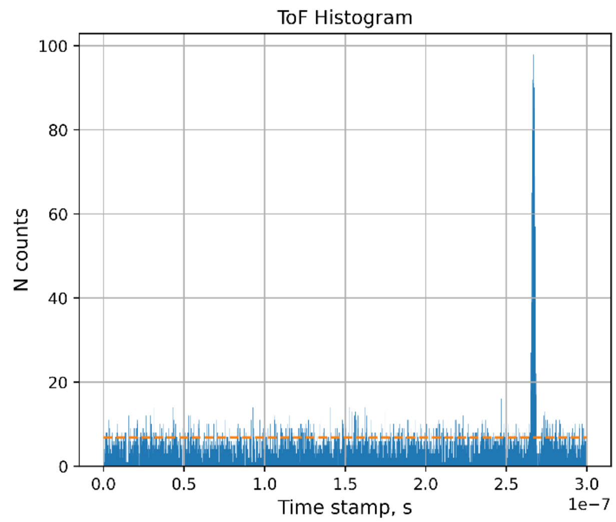


**Figure 6. Effect of Wider Laser Pulse Width**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| $f$ = 200 kHz | $D$ = 40 m |
| $E_v$ = 100 klux | **$W_{laser}$ = 2 ns** |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| $D_{lens}$ = 15 mm | $FWHM_{BP}$ = ±5 nm |
| $AoV$ = 0.1° | |

**$SNR_H$ = 6.1**

## 4. Laser Wavelength

Selection of the laser wavelength is influenced by a number of factors including eye safety and availability of low cost lasers at particular wavelengths. Laser wavelength selection also influences ranging performance due to solar irradiance and sensor detection efficiency at different wavelengths.

For a system subject to solar noise, a longer wavelength may be chosen to exploit the corresponding reduction in solar irradiance at the longer wavelength. The effect can be seen from the model of solar irradiance in Figure 8.

With a laser wavelength of 940 nm, the PDE of the modelled SiPM is reduced from ~30% to ~21%. Keeping all other parameters constant, the detection efficiency of both the laser photons and ambient light photons is reduced. For this particular setup the net effect is an increase in $SNR_H$ due to lower ambient counts, as shown in Figure 7. Of course, if another system level parameters which leads to low ambient level (i.e. smaller $\theta_{det}$, shorter $FWHM_{BP}$) were used the effect might be opposed. Similarly, if another SiPM were chosen that has bigger PDE reduction at 940 nm, the resulting histogram signal count would be smaller than and $SNR_H$ would be reduced.

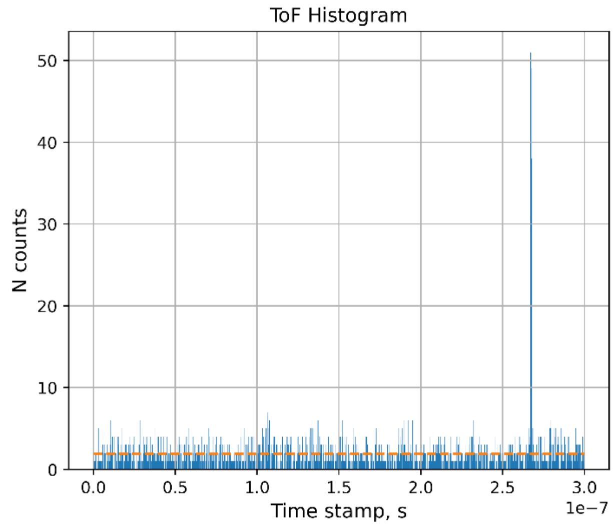


**Figure 7. Effect of Increased Wavelength on Histogram**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| $f$ = 200 kHz | $D$ = 40 m |
| $E_v$ = 100 klux | $W_{laser}$ = 250 ps |
| **$\lambda_{laser}$ = 940 nm** | $R$ = 50% |
| $D_{lens}$ = 15 mm | $FWHM_{BP}$ = ±5 nm |
| $AoV$ = 0.1° | |
| **$SNR_H$ = 4.6** | |

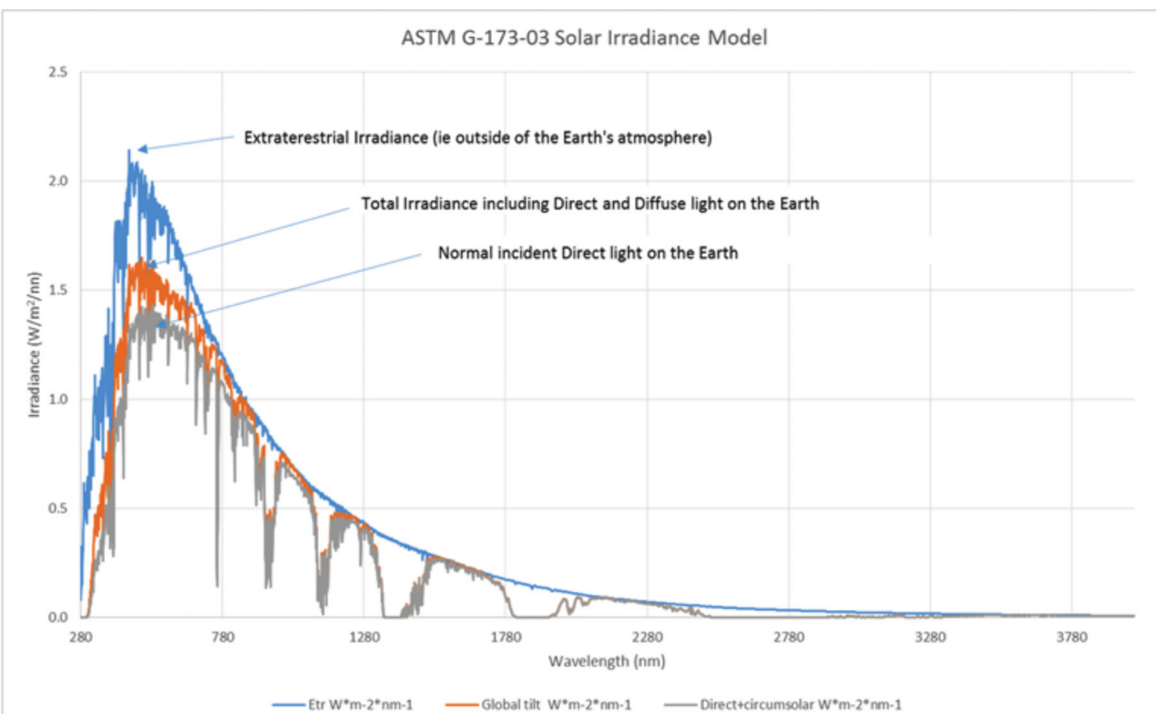


**Figure 8. Solar Irradiance Model**

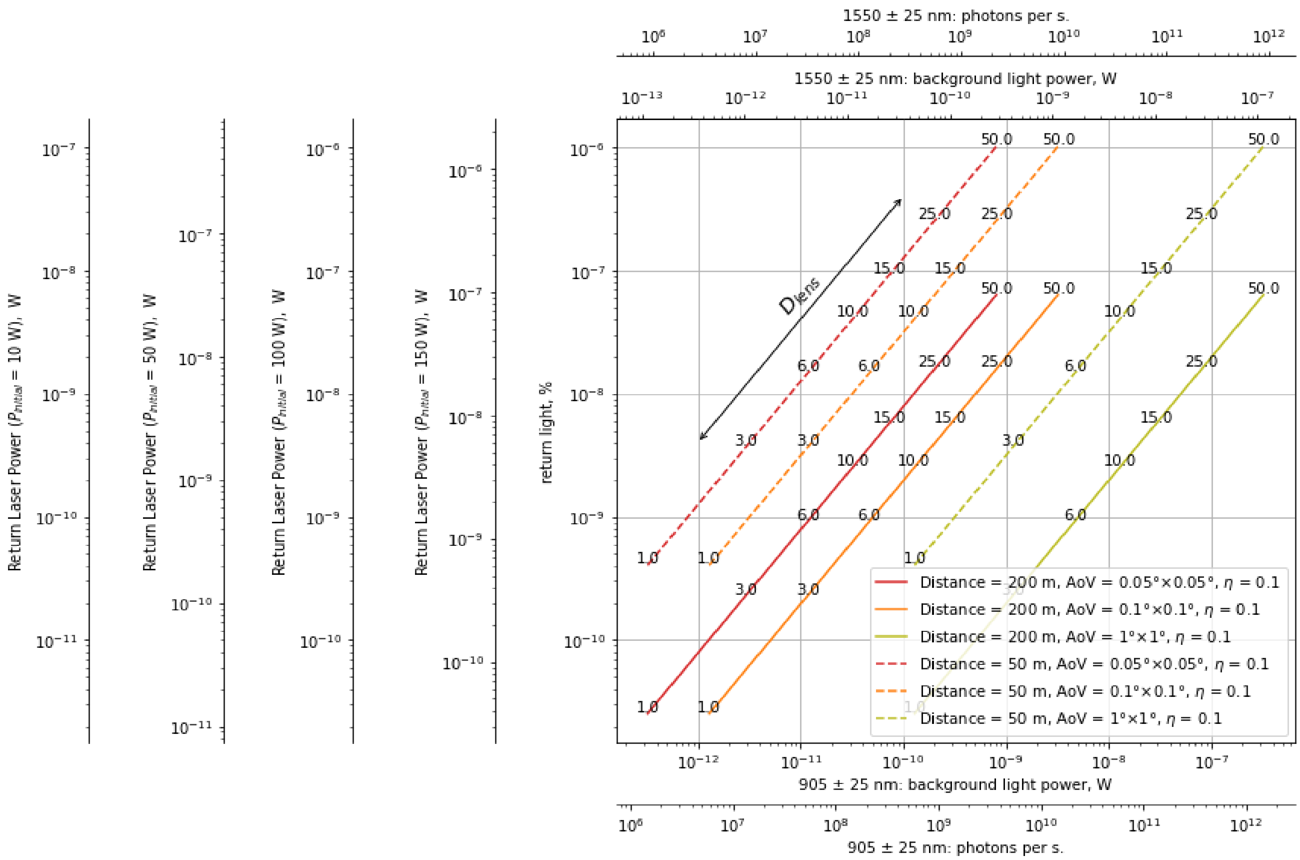


**Figure 9. Return Laser Power (expressed in percentage and watts for initial laser power of 150, 100, 50 and 10 W) as a Function of Background Light Power (expressed in Watts and photons per second) for 905 and 1550 nm Systems. Results presented at different $D_{lens}$ and AoV values and for two target distances of 200 m and 50 m.**

## 5. Collection Lens Diameter

When the lens aperture is widened, more ambient and laser photons are detected as shown in Figure 9. Therefore, the aperture size (i.e. $D_{lens}$) should be optimized for each system to get optimal $SNR_H$.

The SiPM is now prone to saturation as is evident from the large overshoot at the start of the histogram window in Figure 10. When the sensor is saturated the laser photons can no longer be detected by the SiPM, leading to a lower signal detection rate and lower overall $SNR_H$.

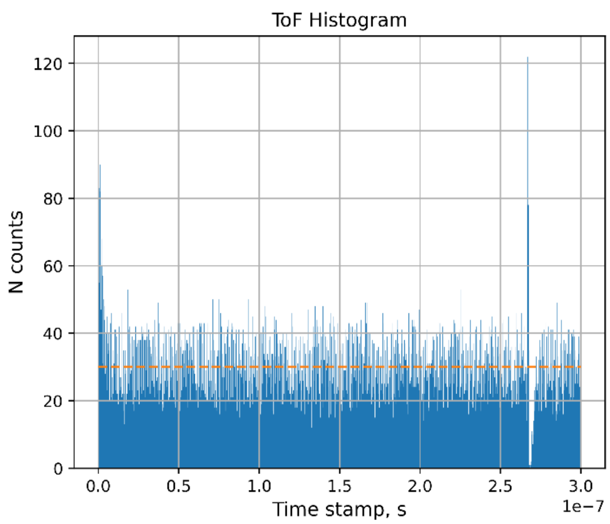


**Figure 10. Effect of Increased Collection Lens Aperture**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| $f$ = 200 kHz | $D$ = 40 m |
| $E_v$ = 100 klux | $W_{laser}$ = 250 ps |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| **$D_{lens}$ = 50 mm** | $FWHM_{BP}$ = ±5 nm |
| $AoV$ = 0.1° | |

**$SNR_H$ = 1.1**

## 6. Sensor Angle of View

The sensor angle of view is determined by the sensor size and the focal length of the collection lens. When the sensor angle of view is increased to 1°, significantly more ambient light is incident on the SiPM. It then becomes saturated to the point that no laser pulses can be discerned by the system, as is the case in Figure 11.

It is crucial to limit the sensor angle of view to cover the field of the laser only and avoid this situation.

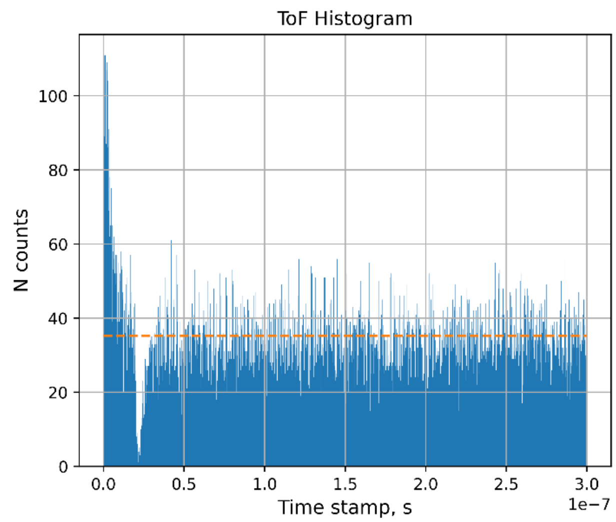


**Figure 11. Effect of Increased Sensor Angle of View**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = W |
| $f$ = 200 kHz | $D$ = 40 m |
| $E_v$ = 100 klux | $W_{laser}$ = 250 ps |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| $D_{lens}$ = 15 mm | $FWHM_{BP}$ = ±5 nm |
| **$AoV$ = 1°** | |

**$SNR_H$ = N/A**

## 7. Optical Filter Bandpass

An optical bandpass filter is used to limit the ambient noise arising from light at wavelengths other than the laser wavelength range.

In this case the optical filter bandpass range is 50 nm $FWHM_{BP}$ (Full Width Half Maximum). This allows a wider range of wavelengths of ambient light through to the SiPM, increasing the measured background noise and worsening $SNR_H$ as shown in Figure 12. In the model, the laser wavelength is exactly 905 nm only and the acquired laser signal is not affected by the bandpass $FWHM_{BP}$. In real systems, the laser center wavelength may have a relatively wide variation and this may have a bearing on the choice of bandpass filter.

## 8. SiPM Temperature

LiDAR temperature affects also SiPM performance, in particular dark count rate. At high temperatures the *DCR* might become comparable with ambient light photon rate. As a result, an increased number of *DCR* events triggering a sensor and all other conditions constant, more noise events are acquired for every single−shot measurements. The noise counts per bin over the entire frame increases accordingly and $SNR_H$ is negatively affected. Figure 13 shows the ToF for SiPM device with $DCR$ = 1 GHz. That the peak at 40 m is still discernible and therefore ranging is still possible with this configuration at this light level, but the range capability will now be reduced.

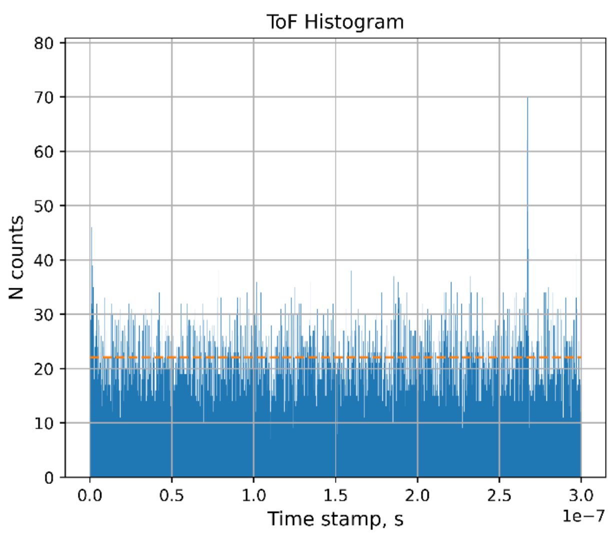


**Figure 12. Effect of Wider Sensor Optical Bandpass**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| $f$ = 200 kHz | $D$ = 40 m |
| $E_v$ = 100 klux | $W_{laser}$ = 250 ps |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| $D_{lens}$ = 15 mm | **$FWHM_{BP}$ = ±25 nm** |
| $AoV$ = 0.1° | |
| **$SNR_H$ = 1.5** | |

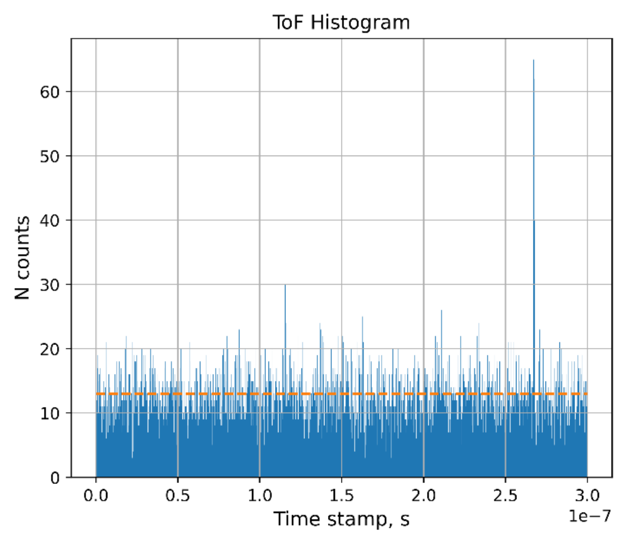


**Figure 13. Effect of SiPM Temperature (DCR)**

| | |
|---|---|
| $t_{acq}$ = 1 ms | **$DCR$ = 1 GHz** |
| $f$ = 200 kHz | $P_{laser}$ = 2 W |
| $E_v$ = 10 klux | $D$ = 40 m |
| $\lambda_{laser}$ = 905 nm | $W_{laser}$ = 250 ps |
| $D_{lens}$ = 15 mm | $R$ = 50% |
| $AoV$ = 0.1° | $FWHM_{BP}$ = ±5 nm |
| **$SNR_H$ = 2.2** | |

## 9. Distance to Target

The plot in Figure 14 superimposes histograms ranging at 10 m, 20 m, 30 m, 40 m and 50 m from the target. The spacing of the signal peaks on the x-axis corresponds to *ToF = 2*distance/c*. As the distance increases the number of acquired counts from the laser is reduced because the density of laser photons at the sensor decreases with $1/d^2$ (where d is the sensor-target distance) but the ambient noise remains constant because the number of ambient photons diffused back from the target does not change with distance. The configuration may of course be optimized to perform ranging at this distance (refer to the **Ranging Demonstrator Modelled to 100 m** Section 3 on page 17 for a setup that models ranging at long distance).

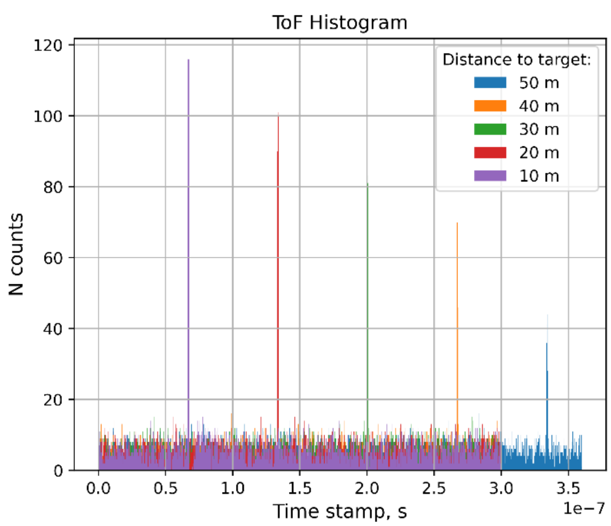


**Figure 14. Effect of Increasing Target Distance**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| $f$ = 200 kHz | **D = 10/20/30/40/50 m** |
| $E_v$ = 100 klux | $W_{laser}$ = 250 ps |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| $D_{lens}$ = 15 mm | $FWHM_{BP}$ = ±5 nm |
| $AoV$ = 0.1° | |
| $\boldsymbol{SNR_H}$ **= 7.7/6.7/6.3/4.7/3.1** | |

## 10. Ambient Light

Here the ambient light is decreased 10 times down to 10 klux. With a reduced number of ambient photons hitting the sensor and all other conditions remaining constant, more less photons are acquired for every single−shot measurement. The noise counts per bin over the entire frame reduces accordingly and $SNR_H$ is improved. Figure 15 shows that the peak at 40 m is still at the same position, however the average and peak noise values are reduced significantly.

Conversely, at high ambient light $SNR_H$ would be reduced due to high noise counts. Therefore, the ambient light level should be always kept as low as possible. This might be done through $FWHM_{BP}$ , $AoF$ and $D_{lens}$ optimization.

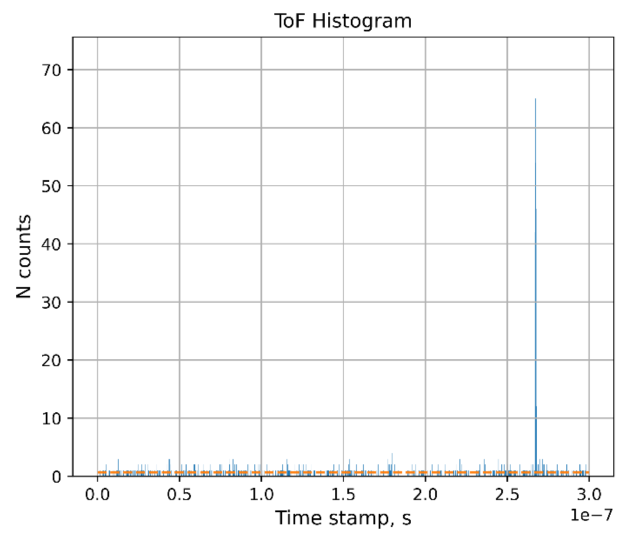


**Figure 15. Effect of Reduced Ambient Light**

| | |
|---|---|
| $t_{acq}$ = 1 ms | $P_{laser}$ = 2 W |
| $f$ = 200 kHz | $D$ = 40 m |
| $\boldsymbol{E_v}$ **= 10 klux** | $W_{laser}$ = 250 ps |
| $\lambda_{laser}$ = 905 nm | $R$ = 50% |
| $D_{lens}$ = 15 mm | $FWHM_{BP}$ = ±5 nm |
| $AoV$ = 0.1° | |
| $\boldsymbol{SNR_H}$ **= 18.0** | |

## 11. SiPM Selection

At long range LiDAR applications, typically only single shot is acquired for each distance measurements due to wide $FoV$ (120° × 20°) and small resolution ($AoV$ = 0.05° × 0.05°) and high frame rate of 30 FPS. Therefore, simulation of waveforms is preferable than histograms. The waveforms in Figure 16 shows the simulated response for three different onsemi SiPM devices (for more details please see Table 1) at 10% (top) and 90% (bottom) reflectivity target at 200 m distance illuminated by 100 W laser with 5 ns pulse width. At this ranging distance and under this configuration this change of SiPM does have a significant effect on the $SNR_H$.

| | |
|---|---|
| $t_{acq}$ = 2 μs | Next Gen/RDM/C−series |
| $f$ = 500 kHz | $P_{laser}$ = 100 W |
| $E_v$ = 100 klux | $D$ = 200 m |
| $\lambda_{laser}$ = 905 nm | $W_{laser}$ = 5 ns |
| $D_{lens}$ = 10 mm | $R$ = 10% / 90% |
| $AoV$ = 0.05° | $FWHM_{BP}$ = ±5 nm |

$SNR_H$ (10%) = 5.3/2.6/0.5

$SNR_H$ (90%) = 9.6/6.3/2.1

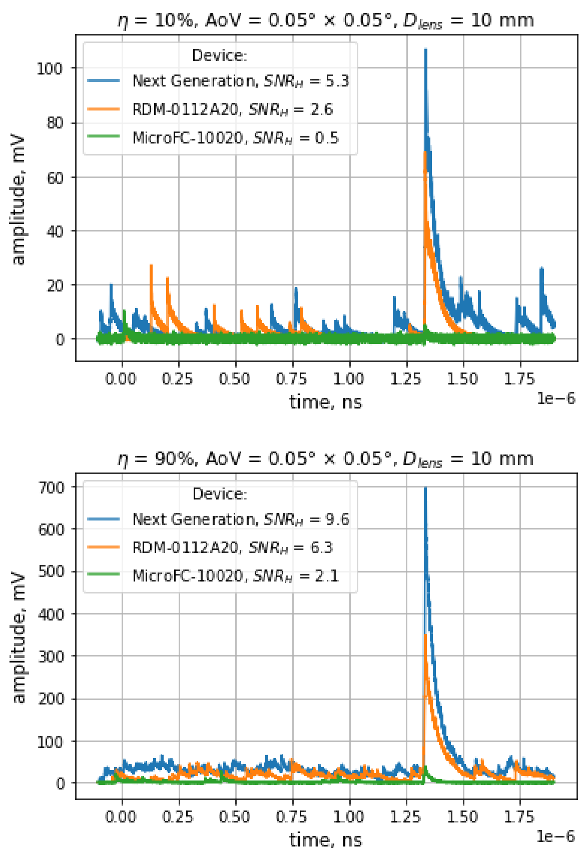


**Figure 16. Example of Simulated Waveforms for Three SiPM Devices**

## The Gen1 Ranging Demonstrator Description

The Gen1 Ranging Demonstrator is an evaluation system designed to provide an introduction to direct ToF ranging using SiPM sensors. The Gen1 features:

- Optical Interface including laser collimation lens, sensor collection lens and bandpass filter
- Laser diode and driver circuit
- SiPM sensor and discriminator circuit
- FPGA-based Time-to-Digital Convertor (TDC), readout and communications interface
- PC based software.

Figure 17 shows the system block diagram.

The demonstrator uses a 905 nm laser diode with a pulse width of 150 ps and a peak laser power of up to 2 W. The laser pulse repetition rate is 150 kHz. The laser output signal is collimated by a lens with a divergence of 0.06°.

At the receiver the reflected signal is focused on the sensor using a 40 mm focal length collection lens with an aperture of 11.4 mm diameter. The sensor angle of view is 1.4°. The signal is also filtered by an optical bandpass filter with a FWHM of 10 nm.

The detection signal chain consists of an **onsemi** MicroFC- 10020-SMT SiPM, a gain stage and a high-speed comparator, which performs leading edge discrimination, and pulse generator circuit. The resulting pulses are timestamped using either a standalone TDC or an FPGA based TDC and data acquisition system. The acquired data is transferred to PC software via a high speed USB link.

The system software builds the histogram from the acquired data, which is plotted for analysis. A curve fitting algorithm extracts the ToF, as described in The Ranging Histogram Section on page 6.

Software adjustable settings allow a range of configurations to be selected in order to optimize the system for a variety of applications.

The demo is portable and is powered by a 6 V source.

A full list of the Gen1 system parameters is given in Table 4.

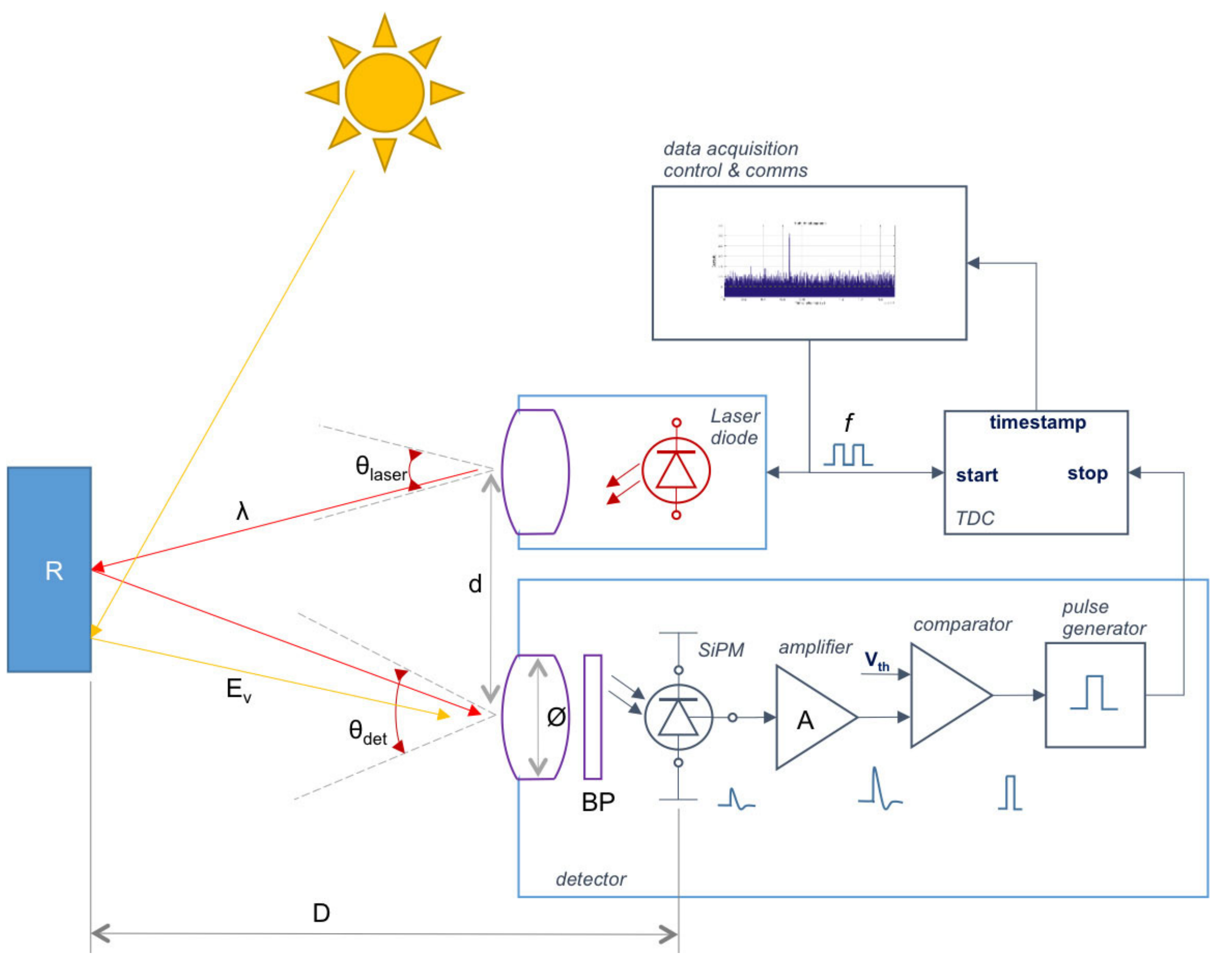


**Figure 17. The Gen1 Ranging Demonstrator Schematic Block Diagram**

**Table 4. GEN1 SYSTEM PARAMETERS FOR SENSOR-TARGET DISTANCES UP TO 5 M**

| Symbol | System Parameter | Value |
|---|---|---|
| | Acquisition method | LED |
| f | Laser repetition rate | 150 kHz |
| $W_{laser}$ | Laser pulse width | 150 ps |
| $\lambda_{laser}$ | Laser wavelength | 905 nm |
| $FWHM_{laser}$ | Laser FWHM | 7 nm |
| $P_{laser}$ | Laser peak power | 1.39 W |
| $\theta_{laser}$ | Laser beam divergence | 0.0573° (1 mrad) |
| d | Laser-sensor distance | 2.35 nm |
| Ø | Collection lens aperture | 11.4 nm |
| $F_{lens}$ | Collection lens focal length | 40 mm |
| BP | Optical filter bandpass wavelength | 905 nm |
| $FWHM_{BP}$ | Optical filter FWHM | 10 nm |
| $\theta_{det}$ | Sensor angle of view | 1.4° |
| SiPM | SiPM | MicroFC-10020 |
| A | Amplifier gain | 34 dB |
| $V_{th}$ | Threshold voltage | 40 mV |
| $t_{acq}$ | Acquisition time | 400 ms |
| $LSB_{TDC}$ | TDC resolution | 15.625 ps |
| R | Target reflectivity | 5% – 95% |
| D | Distance to target | 0.1 m – 5 m |
| $E_v$ | Ambient illuminance | Office lighting: 250 lux |

## 1. Performance of the Gen1 Ranging Demonstrator

The performance of the Gen1 Ranging Demonstrator has been measured in a number of use cases with varying distance to target and ambient light conditions.

A summary of the actual measured ranging data from 0 m to 5 m is shown in Figure 18 in the form of a ranging data histogram, the resulting measured range vs actual range characteristic and associated range error.

Table 5 summarizes the performance of the Gen1 system up to 5 m, under lab conditions of 250 lux ambient light.

**Table 5. PERFORMANCE SUMMARY FOR THE GEN1 SYSTEM UP TO 5M**

| Range | 0.3 m – 0.8 m | 5 m |
|---|---|---|
| Accuracy | <3 mm | <3 mm |
| Resolution | <1 mm | <1 mm |

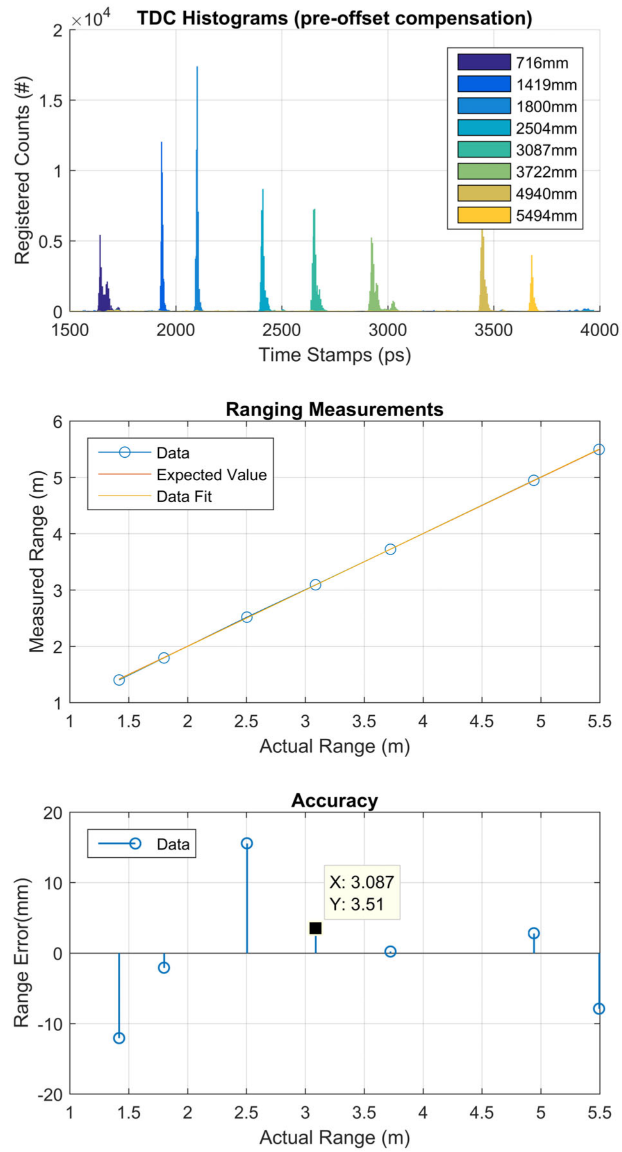


**Figure 18. Baseline Performance Data from the Gen1 System up to 5 m**

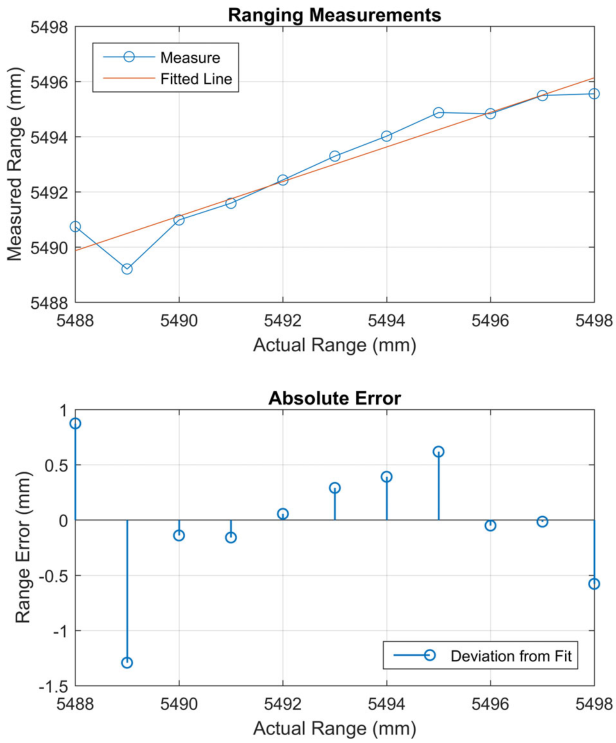


**Figure 19. Data taken with the Gen1 Ranging Demonstrator**

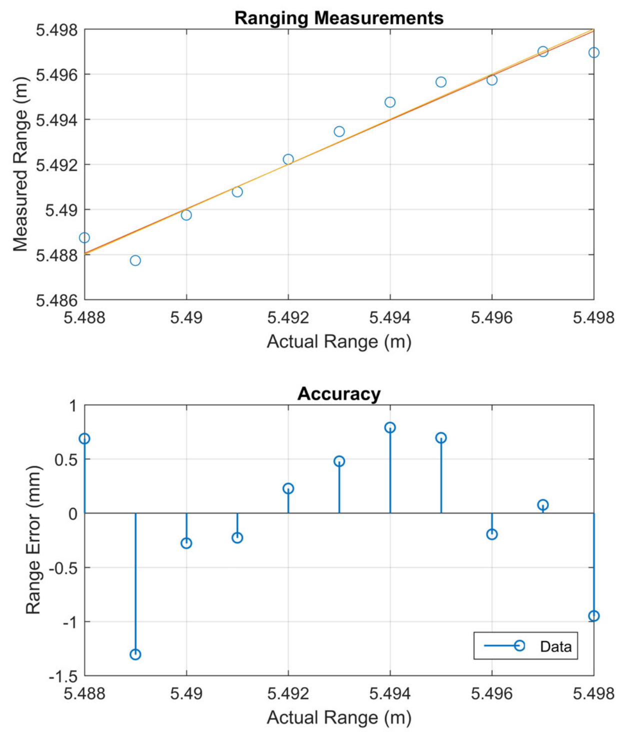


**Figure 20. MA TLAB Model Simulated Data**

## 2. Validation of the Model using the Gen1 System Measurements

The model was configured with the system parameters of the demonstrator and simulated with the same distance to target and ambient light conditions. The simulated results were then compared to the measured results from the Ranging Demonstrator with good correlation as shown in Figure 19 and Figure 20. This validates the model and provides a means to design a system for different use cases.

## 3. Upgrading the Gen1 System to the Gen2 to 100 m

The model was then used to develop a set of system parameters that would enable Gen1 system to be upgraded to be able to achieve 100 m ranging. This system upgrade is referred to as the Gen2 system. These parameter changes are shown in Table 6. Figure 21 shows the simulated histogram, Figure 22 shows the simulated range resolution at 100 m, and Figure 23 the ranging over the full 10 m – 100 m range showing good linearity. The resulting system performance is summarized in Table 7. The Gen2 can be seen in action in this video.

**Table 6. SYSTEM PARAMETERS FOR THE GEN2 UPGRADED RANGING DEMONSTRATOR SYSTEM**

| Parameter | Specification |
|---|---|
| Laser peak power | 10 W |
| Laser pulse width | 667 ps |
| Ambient illuminance | 100 klux |
| Acquisition time | 100 ms |
| Optical filter FWHM | 50 nm |
| Detector Angle of View | 0.2° |
| TDC resolution | 100 ps |

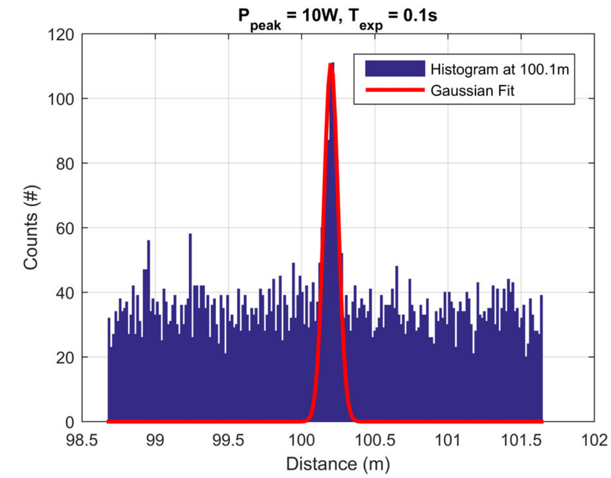


**Figure 21. Simulated Histogram for 100 m Distant Target using the Gen2 System Parameters**

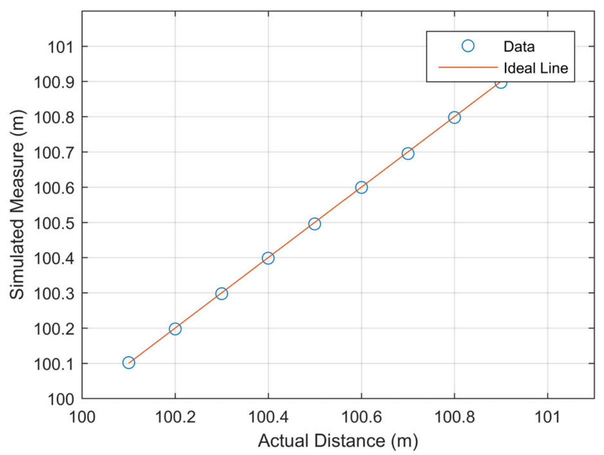


**Figure 22. Ranging at 100 m, Using the Gen2 System Parameters in Table 6 and Giving <10 cm Resolution**

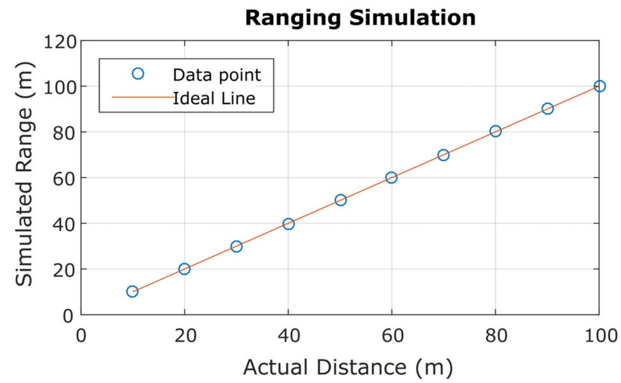


**Figure 23. Simulated Ranging Data for 10 m up to 100 m using the Gen2 System Parameters and Showing Good Linearity**

**Table 7. SIMULATED PERFORMANCE OF THE GEN2 RANGING DEMONSTRATOR FOR RANGING TO 100 M (100 KLUX, AMBIENT LIGHT, LED, 150 KHZ).**

| Long Range | |
|---|---|
| Range | 100 m |
| Accuracy | <10 cm |
| Resolution | <10 cm |

## Further Help

1. Ranging Demonstrator Description – This document describes the specification and operation of the Ranging Demonstrator. This demonstrator is an engineering prototype. Its purpose is to demonstrate SiPM technology in ranging applications and to provide feedback for modelling of future designs.
2. Introduction to SiPM – This document introduces the basic concepts of the Silicon Photomultiplier for those who are new to this type of sensor.
3. How to Evaluate and Compare SiPM Sensors – This document discusses some of the primary factors to be considered in the selection of the optimum SiPM.
4. C-Series Datasheet – The datasheet for the sensors used in this document.