# AND9781/D

# Gen1 Ranging Demonstrator Description

ON Semiconductor®

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APPLICATION NOTE

## INTRODUCTION

This document describes the specification and operation of the Gen1 3D 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.

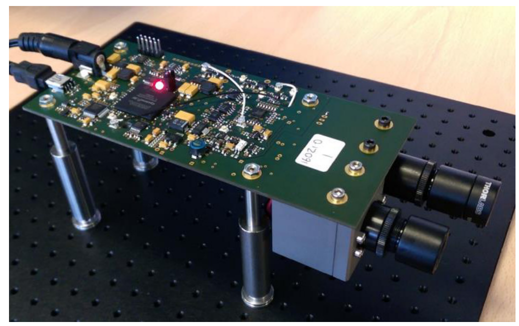

**Figure 1. The 3D Ranging Demonstrator PCB 1.1**

**Table 1. FUNCTIONAL SPECIFICATION**

| Parameter | Specification | Comment |
|---|---|---|
| Range | 0.1 to 15 m | |
| Accuracy | 0.1% (TBC) | < 3 mm |
| Resolution | 1 mm (TBC) | < 1 mm |
| Acquisition Time | 400 ms | |
| Minimum Target Reflectance | 5% | |
| Maximum Target Reflectance | 90% | |
| Max Brightness | 100 klux | |
| Ranging Method | Direct ToF | |
| Sensor | MicroFC−10020−SMT | |
| ON Semiconductor SiPM Family | C−Series | |
| Sensor Angle of View | 1.4° | 50 mm FL/ 25.4 mm optics |
| LASER Class | 1 | |
| Spotting or Visible Laser | Yes | |
| Laser Wavelength | 905 nm | |
| Laser pulse width | 150 ps | |
| Laser Frequency | 2 kHz to 2 MHz | |
| Laser beam divergence | 1 mrad | |
| TDC Resolution | 93.75 ps | Sigma, single shot accuracy |
| Power Requirements | 5VDC | |
| Power Consumption | < 5 W | |
| Interface | HS USB to PC software | |
| Form Factor | PCB Board | |
| Mounting Fixtures | Optical Breadboard | |
| Case / Housing | None | |
| Operating Temp | Room Temperature | |
| Temperature Compensation | No | |
| Board(s) Revision | SiPM_Laser_ Range_Finder_V2P0 | |

## SYSTEM DESIGN

### System Block Diagram

A block diagram of the 3D Ranging Demonstrator is shown in Figure 2.

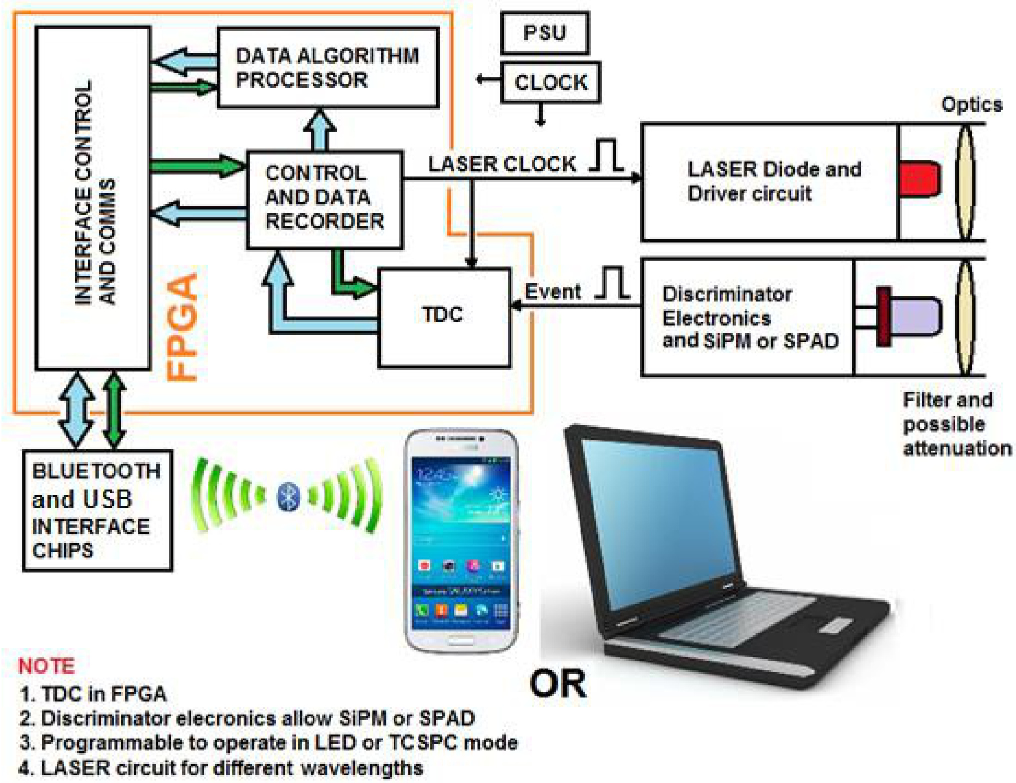


**Figure 2. 3D Ranging Demonstrator Block Diagram (Bluetooth Not Implemented in Rev 1)**

The design comprises of 6 main sections:

* Optical Interface
* LASER Diode and Driver Circuitry
* SiPM Sensor (SPAD also Possible) and Discriminator Circuitry
* FPGA Containing TDC, Readout and Communications Circuitry
* Communications Interface (HS−USB. Bluetooth not implemented in Rev 1)
* PC Software (Android also Possible)

**Figure 3. Laser Collimation Tube and Mounting Adapter for the Laser Diode**

### Optical Interface

*Laser Collimation*

Currently off the shelf components from Thorlabs are used to collimate the laser diode mount the laser diode as shown below.

**Table 2. COLLIMATING LENS SPECIFICATION**

| | |
|---|---|
| Manufacturer | Thorlabs |
| Part Number | C260TMD−B |
| Effective Focal Length | 15.29 mm |
| Numerical Aperture | 0.16 |
| Outer Diameter | 9.2 mm |
| Clear Aperture | 5.00 mm |
| Working Distance @780 nm | 12.43 mm |
| Anti−reflection Coating Range | 600−1050 nm |
| Magnification | ∞ |
| Glass | D−ZK3 |


**Figure 4. C260TMD−B f = 15.29 mm, NA = 0.16, Mounted Geltech Aspheric Lens, AR: 600−1050 nm**

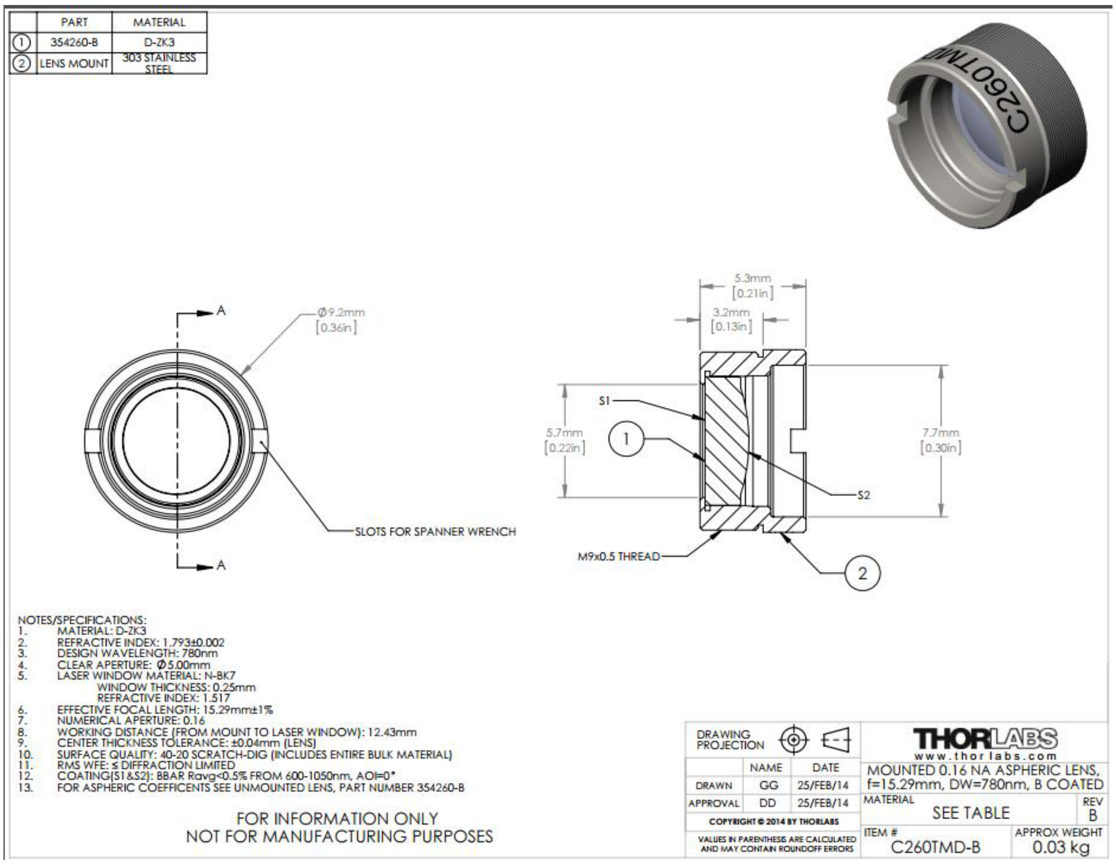


**Figure 5. CAD Drawing of the C260TMD−B Lens**

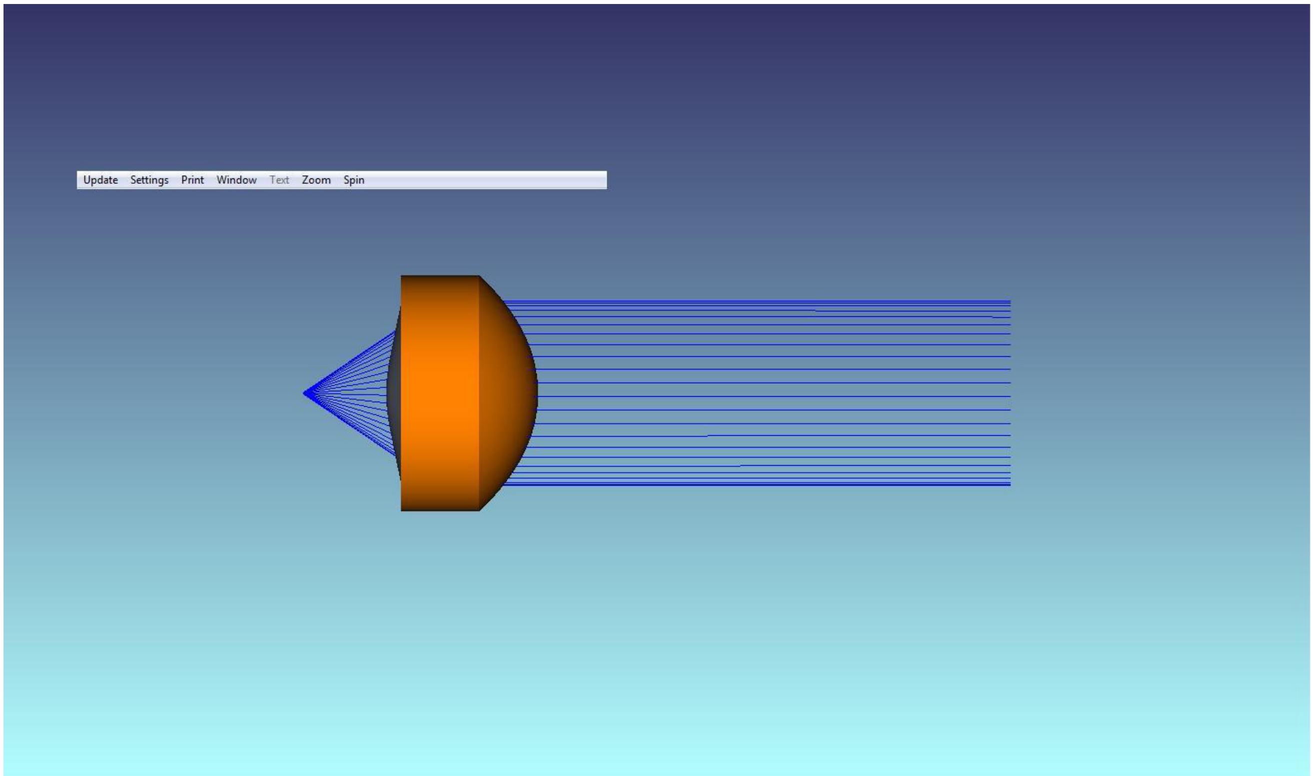


**Figure 6. Optical Layout for 905 nm Laser Module. Assemblies were Realized using LightPath 354330−B Aspheric Lenses**

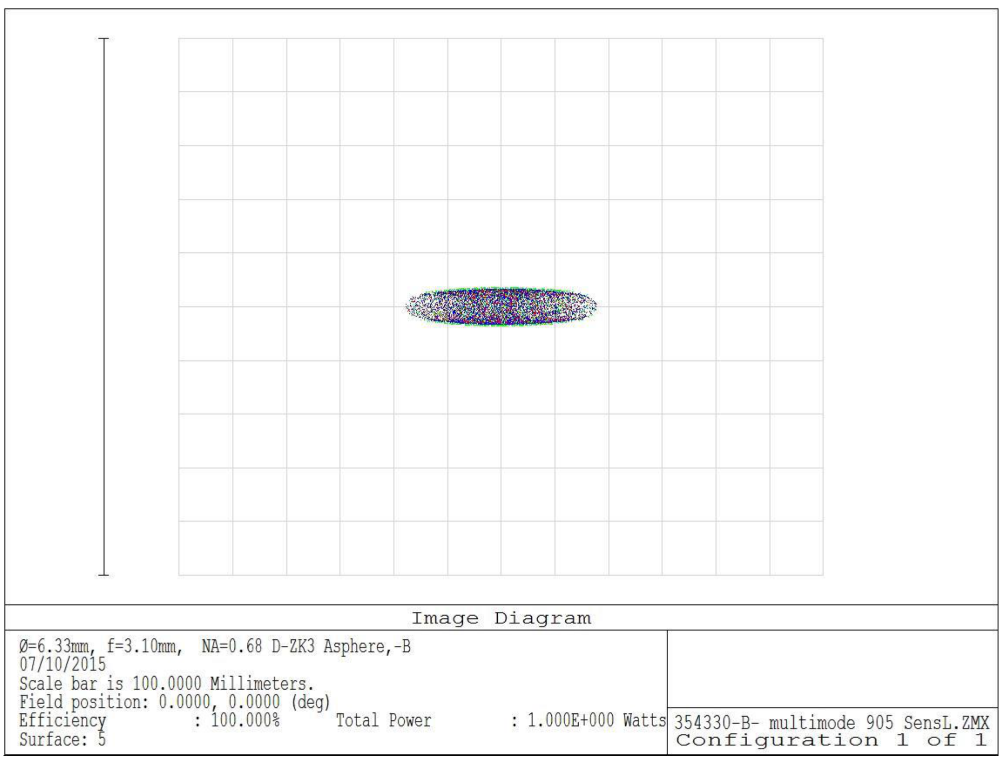


**Figure 7. Image Diagram at 10 m Distance for 905 nm Laser**

### Detector Collection Lens, Filter and Optomechanics

The detector PCB (Detector Section) fits into a XY translating lens mount for Ø1/2″ Optics in light-tight setups as shown in Figure 8. This allows the XY position of the detector to be optimized for maximum return signal.

The collection lens used is the LA1304−B−ML from Thorlabs, as summarized in Table 3.

**Table 3. SPECIFICATION OF THE COLLECTION LENS**

| | |
|---|---|
| Manufacturer | Thorlabs |
| Part Number | LA1304−B−ML |
| Optic Diameter | 12.7 mm (1/2″) |
| Focal Length | 40.0 mm |
| Diopter | +25.0 |
| Radius of Curvature | 20.6 mm |
| Centre Thickness | 2.8 mm |
| Edge Thickness | 1.8 mm |
| Back Focal Length | 38.0 mm ±1% |
| Working Distance | 35.3 mm |
| Apparent Field of View | 1.4° |
| Anti-reflection Coating | 650−1050 nm |
| Lens Aperture Diameter in Housing | 11.4 mm |
| Housing Interface | SM05−Threaded Mount |

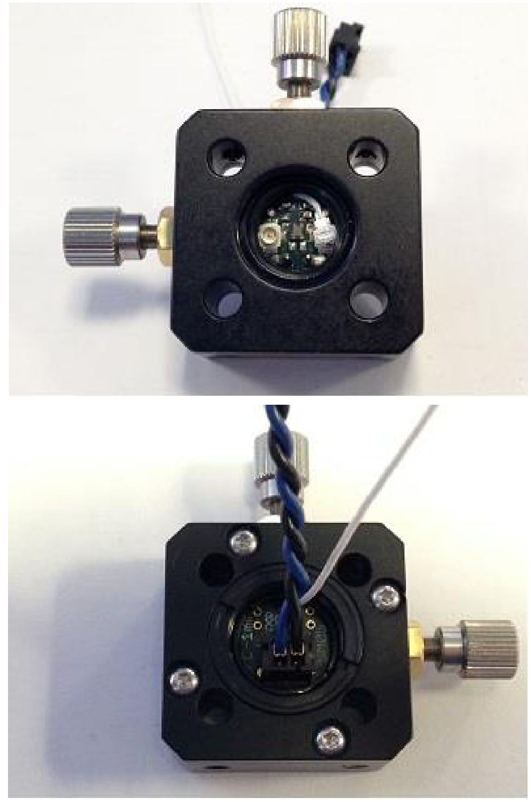

**Figure 8. Front and Back Views of the SiPM PCB Mounted in the Thorlabs SCP05T**


**Figure 9. Image of the LA1304−B Lens**

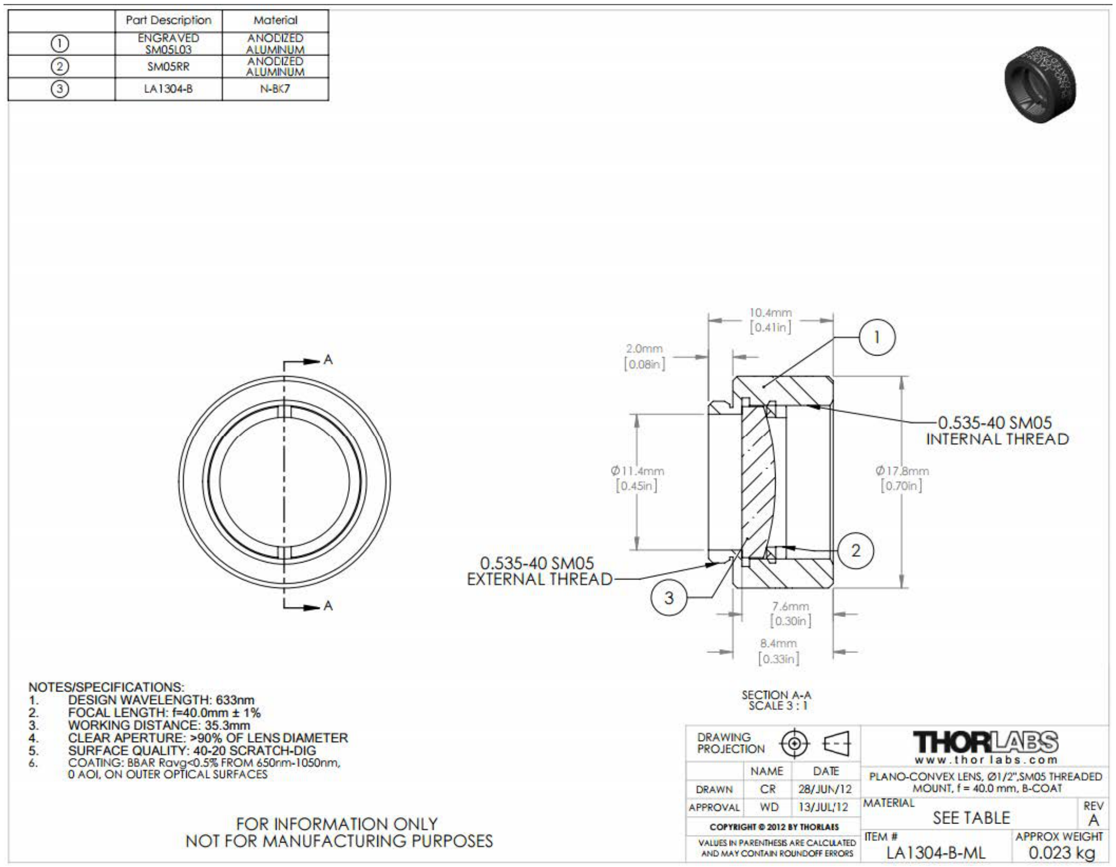


**Figure 10. CAD Drawing of the LA1304−B Lens**

A 905 nm optical bandpass filter is placed in the optical path between the detector and lens. The Filter used is available from Edmund Optics part number #65−669 whose specifications are outlined in Table 4. The transmission of the 905 nm filter is shown in Figure 11.

**Table 4. OPTICAL BANDPASS FILTER SPECIFICATIONS**

| | |
|---|---|
| Manufacturer | Edmund Optics |
| Part Number | #65−669 |
| Diameter | 12.5 +0.00/−0.25 mm |
| Mount Thickness | 7.5 ±0.1 mm |
| Centre Wavelength CWL | 905 ±2 nm |
| Full Width Half Maximum FWHM | 10 nm |
| Minimum Transmission @ 905 nm | ≥ 50 % |
| Blocking Wavelength Range | 200−1200 |
| Optical Density OD | ≥ 3.0 |
| Surface Quality | 80−50 |
| Construction | Mounted in Black Anodized Ring |
| Operating Temperature | −50 to 75°C |
| Angle Sensitivity | Intended for Collimated Input |

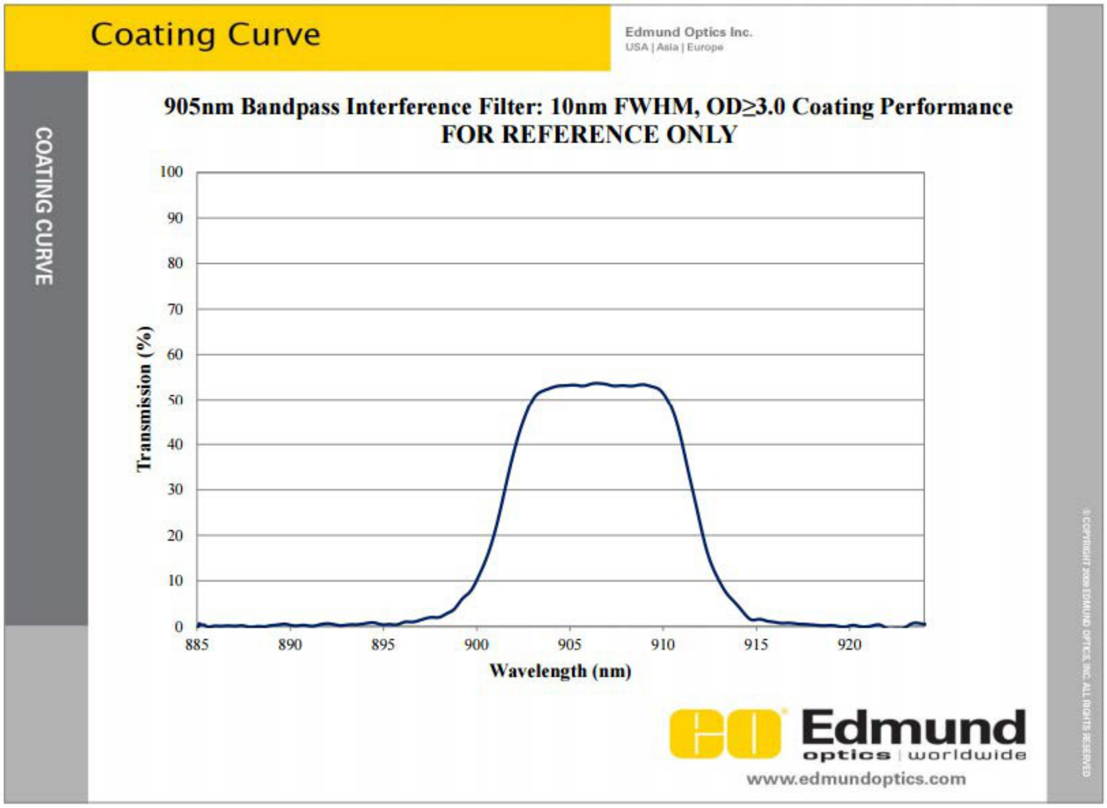


**Figure 11. Transmission Response of the 65669 Filter**

The components of the optomechcanical assembly are shown with the assembled module in Figure 12.

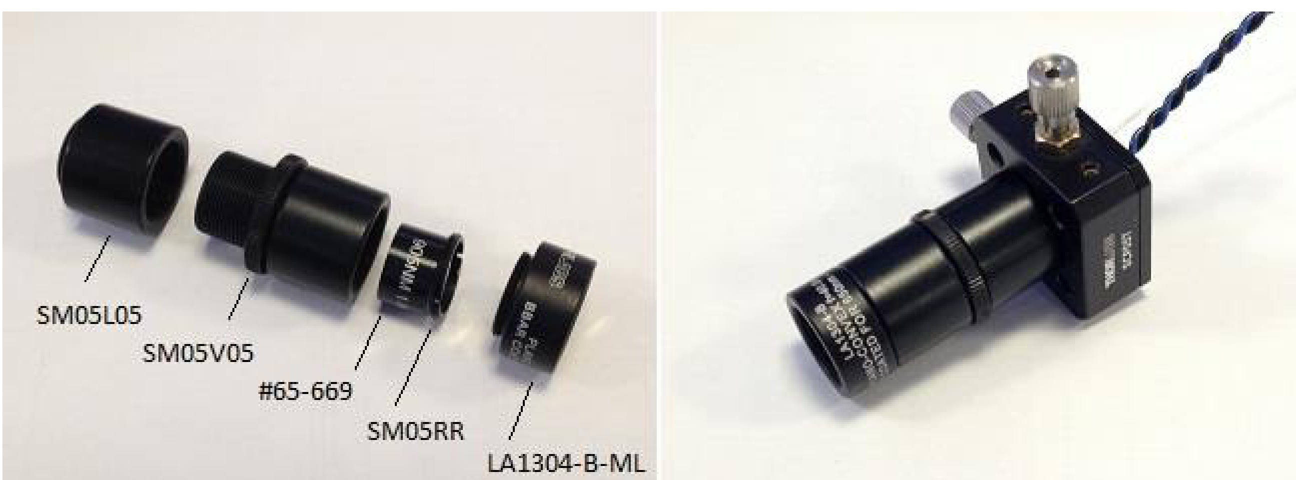


**Figure 12. Detector & Collection Lens Assembly**

### Laser Diode and Driver Electronics

**Table 5. LASER DIODE**

| Wavelength | Manufacturer | Part Number | Package | Optical Peak Power | Laser Aperture |
|---|---|---|---|---|---|
| 905 nm | OSRAM | SPLPL90 | TO−18<br>5 mm Radial Plastic Package | 25 W | 200 μm × 2 μm |

The laser diode in Table 5 is used to illuminate the target with a 905 nm pulse. The laser may be pulsed at a frequency between 2 kHz and 2 MHz. ON Semiconductor use the laser to fire short laser pulses in the order of hundreds of picoseconds to give high peak power while maintaining eye safety.

OSRAM also supply the device as a die, which is suitable for use in high volume production design, as shown in Figure 13.

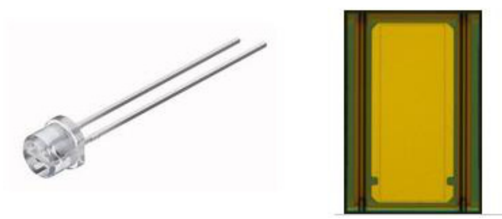

**Figure 13. Osram 905 nm Laser Diode in TO−18 and Die Format**

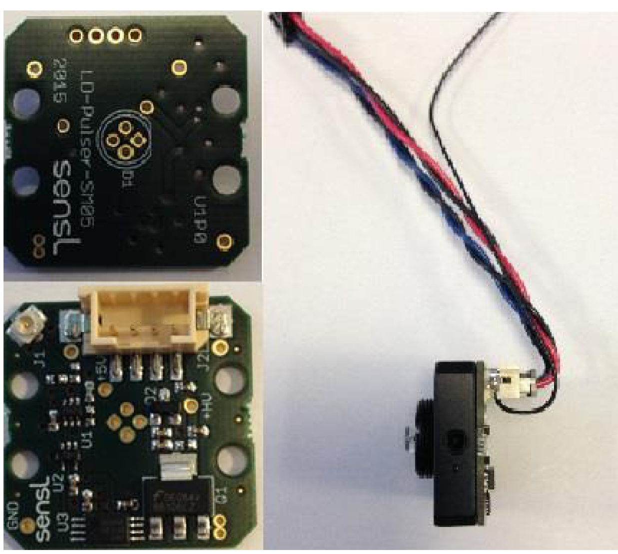

**Figure 14. Top and Bottom Views of the Laser Driver PCB and Side View of the PCB Mounted to the Laser**

The laser diode interfaces with a circuit board designed by ON Semiconductor which pulses the laser. Images of the PCB and the PCB attached to the laser mount are shown below. The PCB is designed to fit the form factor of the Thorlabs SP02 cage plate (25 mm × 25 mm) and the laser diode connects to the centre of the PCB.

Due to the high frequency switching of the Laser diode it is important to shield the driver circuitry from the rest of the system. A shielded enclosure was custom made to provide the necessary shielding. The complete assembled module is shown in Figure 15.

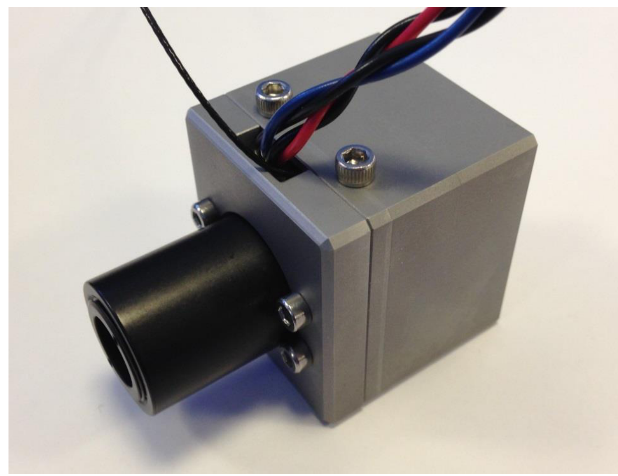

**Figure 15. Pulsed Laser Collimation Module with EMR Shield**

*Laser – Sensor Field of View Overlap*

The non-zero distance between the laser and the sensor causes the laser beam and the angle to overlap starting from a minimum distance below which ranging is not possible due to the laser not being seen by the sensor. We here calculate the minimum ranging distance as a function of the laser-sensor distance.

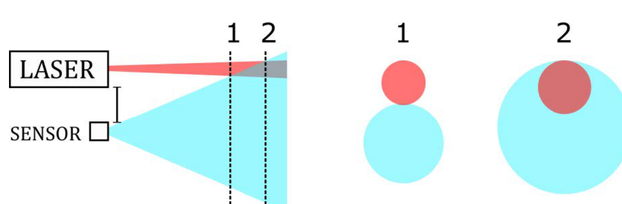


**Figure 16.**

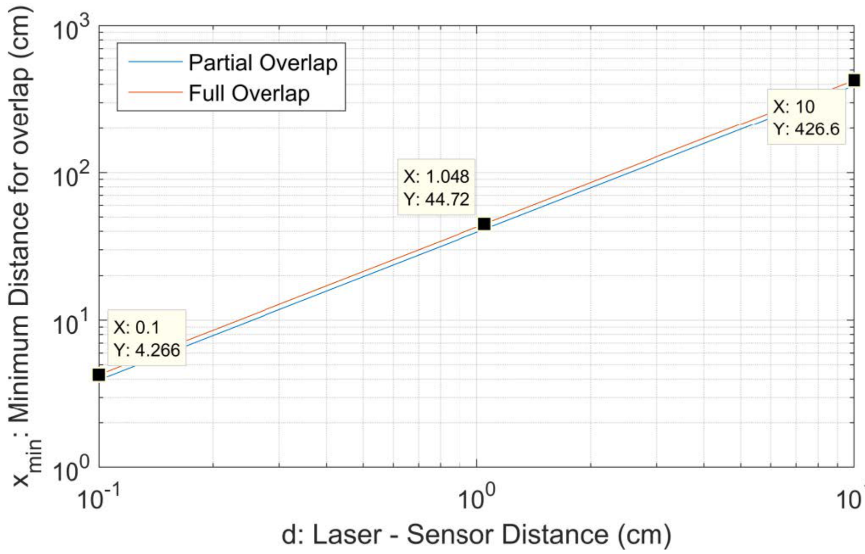


**Figure 17. $\theta_{AoV}$ = 1.4° Angle of View of the Sensor**

$\theta_b$ = 1 mrad **divergence of laser beam**

$d$ **= laser-sensor distance** (x-axis in Figure 17)

$r_b(x)$ laser spot radius at distance $x$: $r_b(x) = x \cdot \tan\theta_b$

$r_s(x)$ sensor FoV radius at distance $x$: $r_s(x) = x \cdot \tan\theta_{AoV}$

Minimum **partial overlap** distance $x_{min}$:
$r_s(x_{min}) = d - r_b(x_{min})$ (blue line)

Minimum **full overlap** distance $x_{min,full}$:
$r_s(x_{min,full}) = d - r_b(x_{min,full})$ (red line)

For a given laser-sensor distance d, the minimum ranging distance can be read on the graph in Figure 17.

**Table 6.**

| Laser – Sensor Distance (d) | Minimum Ranging Distance (Full Overlap) |
|---|---|
| 3 cm | 128 cm |

### Detector and Discriminator

A simplified block diagram of the sensor and discriminator circuit is shown in Figure 19.

*Detector*

The demonstrator design uses a MicroFC−10020−SMT SiPM. The SiPM fast output is employed. The SiPM is mounted on a small 12.6 diameter PCB as shown in Figure 18. The PCB has two connectors, one twisted pair to provide bias and another U.FL series coaxial connector for the signal readout.

**Figure 18. MicroFC−10020−SMT Detector Mounted at the Centre of the Readout Board**

*Discriminator*

The system uses a high power fast readout discriminator circuit to detect the laser pulse leading edge. The fast output of the SiPM is passed through an RF amplifier chain (2 × ADI HMC580ST89ETR in series) to provide a signal suitable for use with a standard comparator. The comparator (ADI ADCMP567BCPZ) has a programmable threshold that can be set to trigger for signal levels down to a single photon. The output of the comparator is fed to the input of a pulse generator compatible with the TDC input.

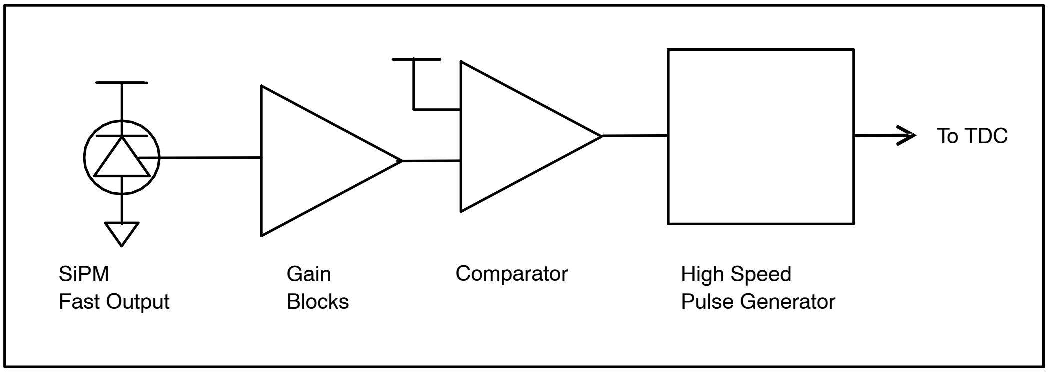


**Figure 19. Discriminator Circuit Block Diagram**

### FPGA Implementing TDC, Readout and I/O Circuitry

The FPGA handles the following tasks:

- Communication with the host for configuration
- Measuring LIDAR Start-Stop sequences using internal TDC
- Saving a histogram of the LIDAR events in internal RAM
- Transferring the histogram data to the host

Due to the requirements of the TDC design it is necessary to use an Altera CYCLONE II FPGA. The FPGA chip used is an EP3C25F324C6.

As well as implementing a TDC within the FPGA, an external, low cost TDC manufactured by Texas Instruments (TDC7200), is also included. This allows the system to compare the performance of an FPGA TDC with a more established commercially available device.

The theoretical minimum LSB of the FPGA is 15.625 ps. The demonstrator employs a LSB of 93.75 ps.

The LSB of the TI device is achieved through calibration, its nominal value is 55 ps.

### Communications Interface

*High Speed USB*

The USB interface is implemented using the FTDI FT232H chip.

### Software

The PC software, written in C, is being developed for both demonstration and research purposes. The 3D Ranging Demo software plots the detected laser pulses as a histogram, performs a Gaussian fit of the data and calculates the distance to the target using some additional calibration parameters.

*Parameters under Software Control*

The software allows the user to optimize certain system parameters as detailed below.

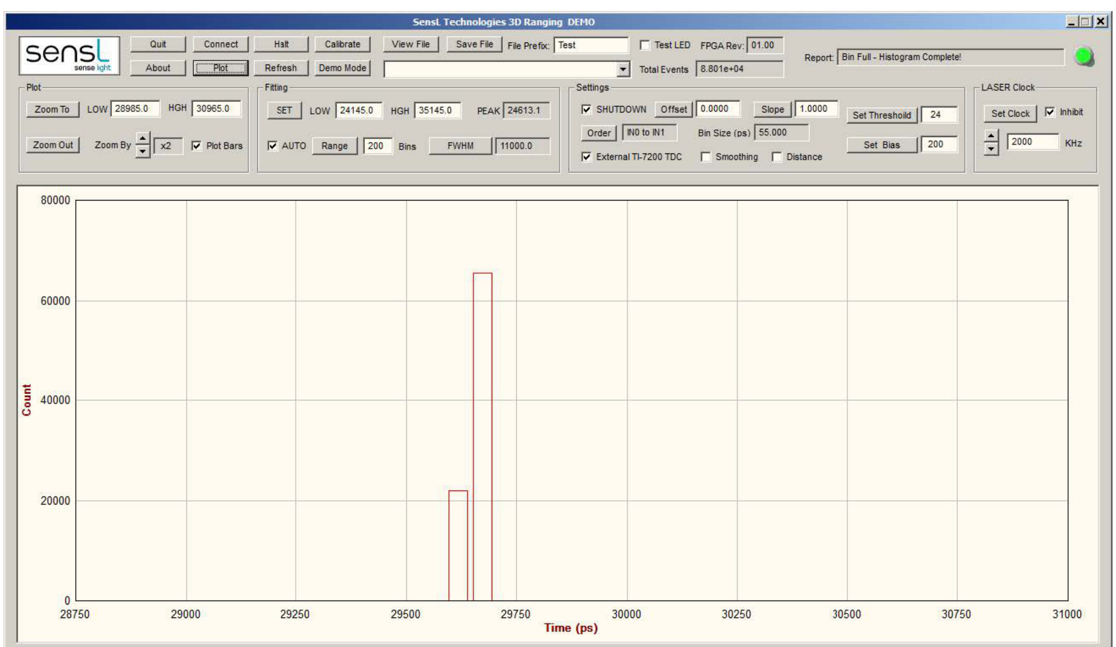


**Figure 20. Demonstrator Software GUI**

- The laser clock frequency is adjustable from 2 kHz to 2000 kHz (Set Clock)
- The bias voltage of the SiPM is adjustable (Set Bias) allowing the detector sensitivity to be adjusted. A 12-bit DAC is used to set the bias between 25 V and 40 V
- The comparator threshold can be adjusted (Set Threshold) to account for incoming laser pulse heights and noise. This parameter uses another 12-bit DAC to adjust the threshold voltage between 0 and 3.3 V
- The Gaussian fit range may be adjusted or the AUTO function may be used to find the highest histogram peak automatically
- Demo mode displays target distance

## 3D RANGING DEMONSTRATOR MATLAB MODEL

The 3D ranging demonstrator has been coupled with a full system MATLAB model as a tool for theoretical analysis to predict the performance of the system under selectable scenarios. The following subsections provide information and examples on the structure of the model and its outcome.

### Overview

The 3D ranging demonstrator model consists of two main parts. The first one is analytical and calculates the amount of light, expressed as photon flux (#photons/sec/area) incident on each SiPM cell due to noise (ambient light) and signal (laser light) coming from a reflecting target in the Field of View (FoV) of the cell itself. The block diagram in Figure 21 shows the input parameters (red, blue and purple boxes). The analytic part allows crucial conclusions to be drawn regarding the overall performance of the sensor, such as calculating the saturation threshold in the specified light conditions. The second part, performing Monte Carlo analysis (orange box), allows the output waveforms of the sensor to be simulated and directly compared to experimental waveforms from the 3D ranging demonstrator itself. Moreover, investigation on the readout circuitry and techniques can be implemented to extend the model to the full-system level allowing conclusions on the final performance of the system, i.e. ranging accuracy, to be drawn. As shown in the green box of the block diagram, this

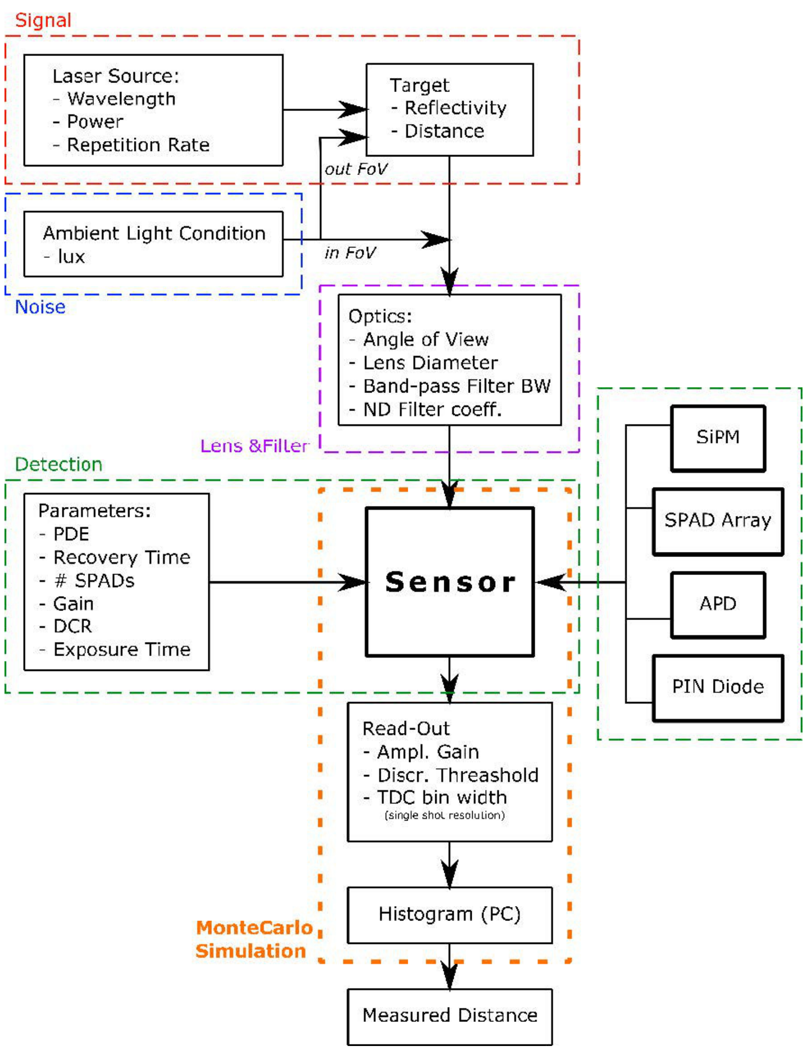


**Figure 21. 3D Ranging Demonstrator Model Block Diagram**

part of the model takes as input the main parameters of the SiPM sensor (such as PDE, recovery time etc.) and information on the readout circuitry (e.g. amplifier gain, TDC resolution) can be included to evaluate the overall accuracy of the system.

The structure of the model has been kept as simple as possible to provide fast simulation times. Moreover, all of the input parameters can be easily changed to adjust the model to the desired system configuration. Together with the SiPM sensor simulator, an APD/PIN-photo diode model has been developed to offer comparisons among the main typical sensor choices. Similarly, the read-out technique can be replaced to compare techniques such as Leading Edge Discrimination (LED) or Time Correlated Single Photon Counting (TCSPC).

### Examples

Examples of the outcome from the simulations are shown below.

*Photon Rate VS Ranging Distance*

The solar photon rate (blue line in Figure 22) is calculated as follows:

$$\phi_{solar} = PD_{sun}(\lambda \pm \Delta\lambda) \times \pi \left(r_{lens} + d_{range} \times \tan\frac{\theta}{2}\right)^2 \times \eta \times \frac{1}{2\pi d_{range}^2} \times \pi r_{lens}^2 \times \frac{\lambda}{hc} \quad \text{(eq. 1)}$$

where *DP_sun* is the solar power density calculated by integrating the spectral power density between $\lambda - \Delta\lambda$ and $\lambda + \Delta\lambda$ with $\Delta\lambda$ being half the bandpass of the optical filter on the detector. The parameters $r_{lens}$ and $\theta$ are respectively the radius and the angle of view of the lens on the detector. The ranging distance is expressed by the parameter $d_{range}$ while $\eta$ is the reflectance of the target.

The peak laser photon rate (red line) is calculated as:

$$\Phi_{laser} = P_{laser} \times \eta \times \frac{1}{2\pi d_{range}^2} \times \pi r_{lens}^2 \times \frac{\lambda}{hc} \quad \text{(eq. 2)}$$

Both photon rates are expressed in photons per second incident on the aperture.

The two lines are compared with the SiPM saturation level (dashed red line) calculated as:

$$\phi_{max} = \frac{N_{cells}}{PDE(\lambda) \times \tau_d} \quad \text{(eq. 3)}$$

Where $N_{cells}$, PDE and $\tau_d$ are respectively the number of microcells, the photo detection efficiency and the recovery/dead time of the SiPM. The simulated setup (described in previous sections) shows that the noise level is below the saturation level of the SiPM allowing ranging over all the desired distances. The decreasing signal-to-noise at longer distances suggests the necessity of TCSPC mode.

*Histogram*

An example of the output of the simulation iterated over a programmable number of cycle (can be linked to the repetition rate of the laser pulse and the exposure time of the TDC) is shown in Figure 23. The baseline of the histogram represents the photons coming from the reflected solar photons while the high pulse represents the laser pulse positioned on the ToF. This result is achieved by simulating a multi-event TDC (no conversion dead time, multiple event per cycle) with a bin width of 50 ps.

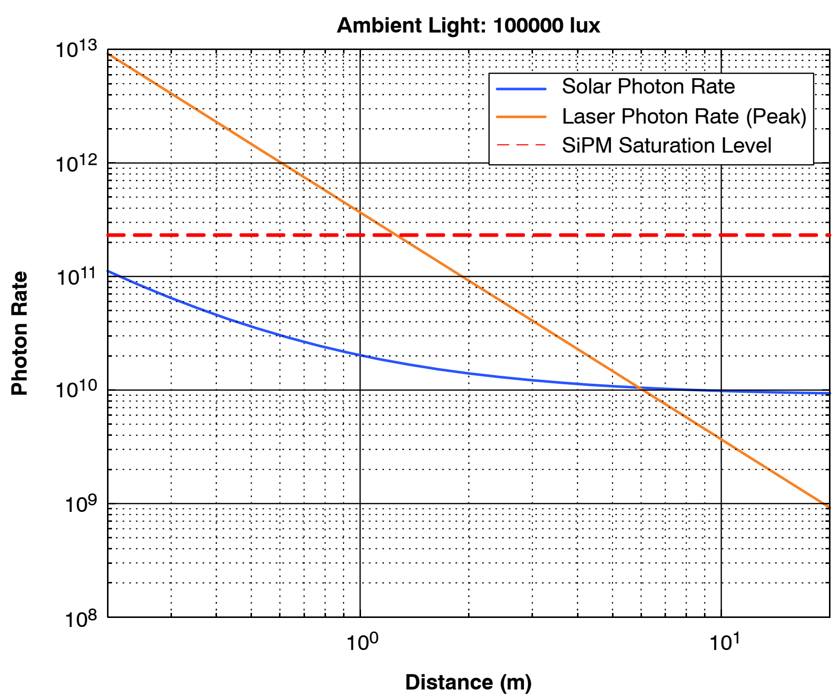


**Figure 22. Photon Rate (Solar and Laser) over All the Distance Range**

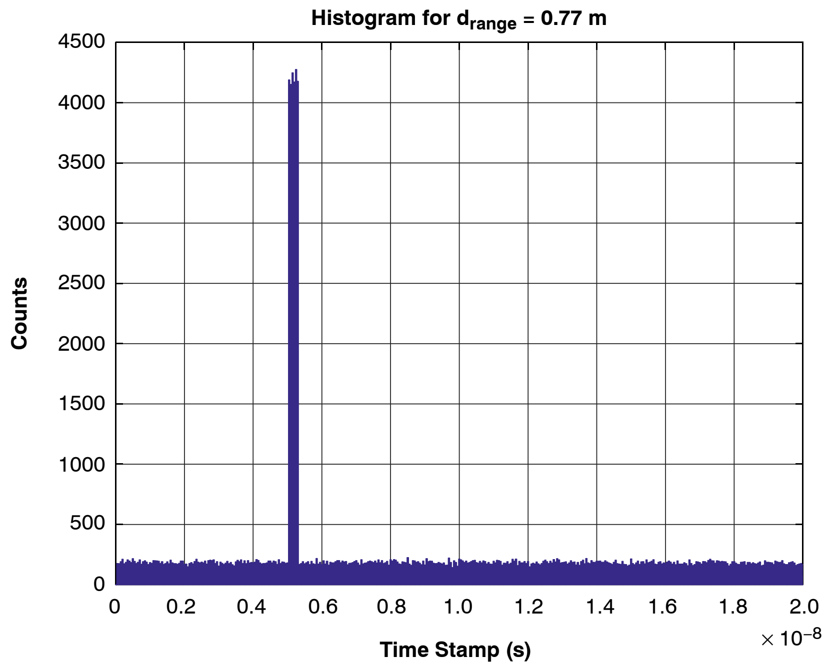


**Figure 23. Example of Simulated Histogram for a Simulated 4 ns Laser Pulse**

*Ranging Example*

By detecting the position of the peak of the histogram due to the laser photons, the ToF is estimated for each ranging distance. The simulated measurements are plotted against the expected values in Figure 24. The accuracy of the measurement is directly connected to the number of Monte Carlo iteration steps. Longer simulations can provide better accuracy.

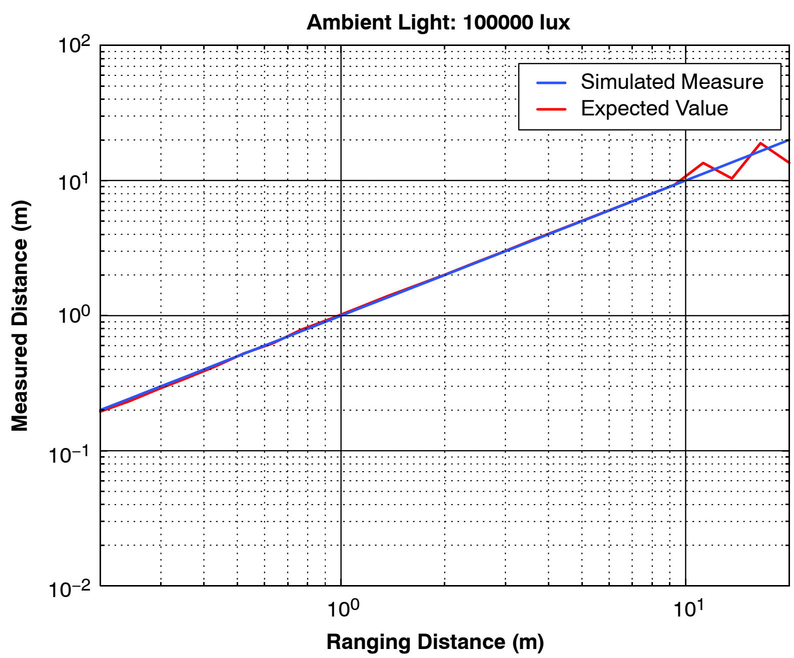


**Figure 24. Ranging Curve Simulated with a Number of Cycles per Distance Step = 2000**

## RANGING DEMONSTRATOR BOM

**Table 7. RANGING DEMONSTRATOR BOM**

| Component | Manufacturer | Part Number | Description |
|---|---|---|---|
| **LASER** | | | |
| Laser Diode | Osram | SPLPL90 | Pulsed laser diode, 905 nm, 25 W peak power |
| Collimator | Thorlabs | C260TMD−B | 0.16 NA aspheric lens, f = 15.29 mm, DW = 780 nm, B coated |
| **DETECTOR** | | | |
| Sensor | ON Semiconductor | MicroFC−10020−SMT | 1 mm x 1 mm sensor, 20 um microcell peak wavelength 420 nm |
| Bandpass Filter | Edmund Optics | 65−669 | 905 nm CWL, 10 nm FWHM, 12.5 mm Mounted between sensor and lens |
| Collection lens | Thorlabs | LA1304−B−ML | plano-convex lens, Ø12.7 mm, f = 40 mm, B coated, SM05 mount |
| Amplifier | ADI | HMC580ST89ETR | Gain Block, 22 dB, DC − 1 GHz (2x used in series) |
| Comparator | ADI | ADCMP567BCPZ | Dual ultrafast voltage comparator |
| FPGA | Altera | EP3C25F324C6 | CYCLONE III FPGA (implementing TDC & data collection & comms) |
| Alternate TDC | TI | TDC7200 | Time-to-Digital Converter for Time-of-Flight Applications (LSB 55 ps) |
| **INTERFACE** | | | |
| USB | FTDI | FT232H | Hi-Speed Single Channel USB UART/FIFO IC |



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