AN6048

Application note

Guidelines and design tips for keystone correction using the VL53L1 Time-of-Flight ranging sensor

Introduction

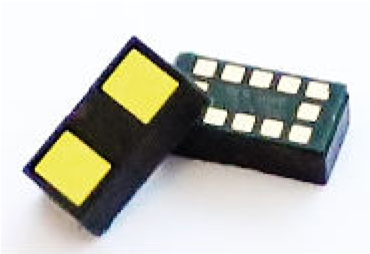
An angular detection solution based on STMicroelectronics' VL53L1 multizone scanning feature could enable support for geometry correction such as keystone correction for projectors.

With existing keystone correction camera module solutions, projectors take a long time to correct the projected image geometry and with a number of limitations. Therefore, more and more projector makers are seeking a seamless angle detection solution to improve the end user experience. The VL53L1 with its multizone scanning feature could bring new innovative ideas to achieve this function, with the ability to range up to 8 m, and detect both horizontal and vertical angle tilt information. This document provides an overview of how to obtain angle information with multizone range input.

This document outlines the principles and API functions used to measure the tilt angle of a wide flat target, such as a white wall, by using the VL53L1 module with Maint6 driver. The VL53L1 is a ranging sensor module (see VL53L1 datasheet).

This document focuses on the basic principles for measuring the tilt angle, and explores methods to improve the measurement tolerance.

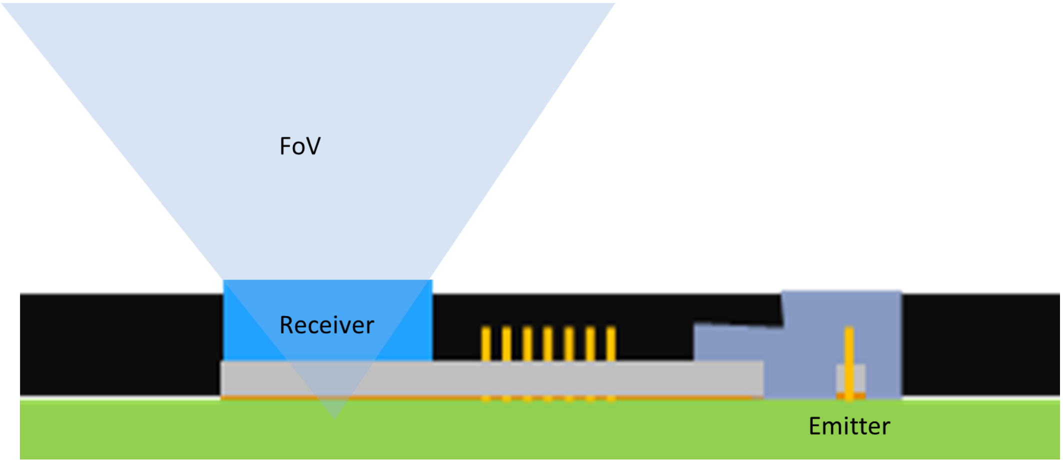
Figure 1. VL53L1 ranging sensor module



1 VL53L1

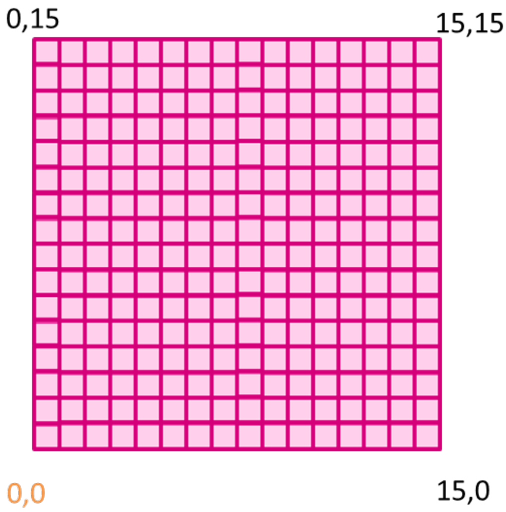
The STMicroelectronics ToF sensors share a similar mechanical structure. Each module is composed of an IR VCSEL and a group of SPAD array receivers. The VL53L1 sensors have a FoV of 27° as illustrated in the following figure.

Figure 2. Mechanical diagram



As described in the datasheet, the receiver part of the VL53L1 is a 16x16 SPADS array, shown in Figure 3. Receiver SPADS array. Each SPAD has an ID, defined from (0,0) to (15,15). By default, photons are captured by these 256 SPADS and the ranging distances are calculated and reported following a sequence of internal operations, such as ADC, TDC processing.

Figure 3. Receiver SPADS array



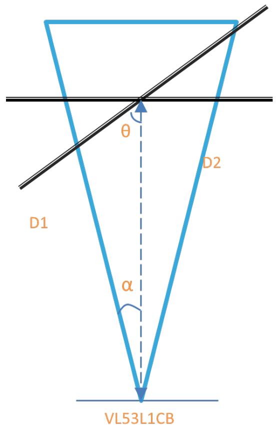
This feature allows photons reflected from different locations on the target to be adjusted by configuring the receiver ROI. For detailed configuration methods, refer to the user manual UM2133. The minimum ROI window for valid ranging is 4x4.

2 Tilt angle measurement principle

In the real world, the position of the VL53L1 module relative to the wide flat target must be considered in a 3-dimensional coordinate system, including both horizontal and vertical tilt. However, for simplicity, we assume that there is no tilt in the vertical direction.

The horizontal tilt angle of the target can be obtained through basic triangular calculations, as illustrated in the following figure.

Figure 4. Concept of horizontal tilt angle measurement



In the figure, the variables are defined as follows:

- D1 and D2: the range data reported from the sensor. It indicates the distance difference in the two directions. If D1 is equal to D2, there is no tilt.
- θ: the complementary angle of the tilt angle
- α: coefficient of FOV/detection zone.

3 Examples and operation flow

3.1 Multizone scanning operation flow

Thanks to the lens of the VL53L1 and the SPAD array at the receiver side, the VL53L1 is able to obtain multi-ROI ranging data sequentially. This is called multizone scanning. Two ROI configuration examples are shown in Figure 5. Examples of ROI configuration selection, but final keystone correction ROI selection may vary. Therefore, ROI configuration methods should not be limited to these two examples.

The examples below illustate that D1 and D2 can be obtained in the horizontal direction. For complex considerations, calculate the components or weights among the ROIs in the 3-dimensional coordinate system.

Figure 5. Examples of ROI configuration selection

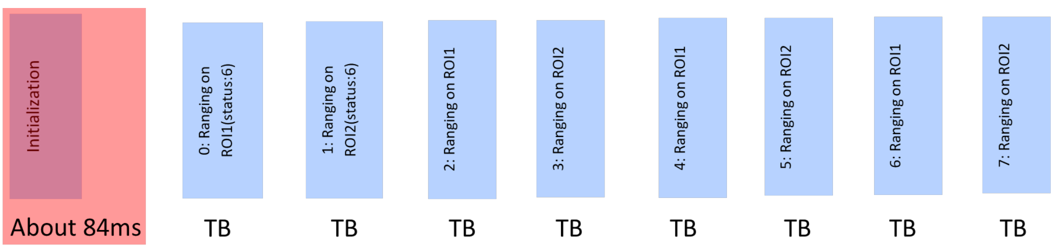
You can follow the operation flow below to get the ROI range data. For more details, refer to the API user manual UM2133.

1. Power on and initialize the sensor.
2. Set the TimingBudget and set the preset mode as 2 (Multizone scanning mode).
3. Configure ROI0 and ROI1.
4. Set the ROI configuration to the device.
5. Start ranging.

Figure 3. Receiver SPADS array shows the range flow of two ROIs. There is an initialization period before the first ranging, which may take around 84 ms in the driver. Considering that the first frame for both the left and right ROI will not be able to perform the wraparound check, the time to get the first angle will be 84+2*(n+1))*TB ms, where TB is the timing budget parameter in the driver, and n is the maximum possible frame number (for example, 10), which could be less dependent on target reflectance.

For example, if the timing budget is set to 66 ms, and the rolling average is used for five frames for each ROI, it takes a total of 876 ms (84 + 2*(5+1) * 66) to obtain the first averaged angle.

Figure 6. Range flow on single ROI



3.2 Reference code library

STMicroelectronics provides lib files that can help customers conduct a quick evaluation. To use the lib, L1 two ROI ranging results need to be passed as parameters, the horizontal tilt angle value is returned. To call the angle_calculate function, four parameters are needed:

- `int16_t range1_milimeter`: Left zone raw ranging result data;
- `int16_t range2_milimeter`: Right zone raw ranging result data;
- `float detection_zone_coefficient`: coefficient tuned for calculating angle;
- `float* HorizontalAngle`: calculated horizontal angle.

The function is detailed below:

```
int32_t angle_calculate(int16_t range1_milimeter , int16_t
range2_milimeter, float fov_coefficient, float* HorizontalAngle)
```

3.3 How to use the angle detection library

1. Download the latest VL53L1 Linux driver STSW-IMG022 and keystone example package STSW-IMG047 from www.st.com.
2. Unzip the two packages, compare with the standard Linux driver.
   The differences between the standard Linux driver and the keystone example package should be as follows:

```
├── examples
│ ├── Example_1_calculate_angle.c //Data processing file.
│ ├── examples.h //.h file
│ └── libs
│ ├── arm64-v8a
│ │ └── libalgorithm.so //Android 64 bit so lib
│ ├── armeabi-v7a
│ │ └── libalgorithm.so //Android 32 bit so lib
│ ├── linux32
│ │ └── libalgorithm.so //Linux 32 bit so lib
│ └── linux64
│ └── libalgorithm.so //Linux 64 bit so lib
├── phio.c //The main function calls multizone mode
└── Makefile //Compilation script.
```

3. Copy the “examples” folder from the keystone example package into the Linux package ..\android\hardware\vl53l1_test
4. Copy phio.c and makefile from keystone example package and replace the phio.c and makefile inside the Linux package ..\android\hardware\vl53l1_test
5. Modify the make file as per your system request.
   – Compile with 32-bit by default, modify CC compiler as required.
   – Modify libalgorithm.so as required.

```
BITS ?= 32

#ifeq ($(BITS), 32)
#       CC = /usr/local/gcc-linaro-7.5.0-2019.12-x86_64_arm-linux-gnueabihf/bin/arm-linux-gnueabihf-gcc
#else
#       CC = /usr/local/gcc-linaro-7.5.0-2019.12-x86_64_aarch64-linux-gnu/bin/aarch64-linux-gnu-gcc
#endif

CC=arm-linux-gnueabihf-gcc

DRIVER_DIR=../../../driver/vl53L1
CFLAGS=-O0 -g -Wall -lm
CPPFLAGS=-I$(DRIVER_DIR) -I$(DRIVER_DIR)/inc -I$(ANGLE_SRC)
LDLIBS=-lrt

ANGLE_SRC=./examples
LDLIBS=./examples/libs/linux$(BITS)/libalgorithm.so
#LFLAGS += -Lexamples/libs/linux$(BITS) -lalgorithm -lm
ANGLE_OBJ = $(wildcard $(ANGLE_SRC)/*.c)
```

6. At last compile the phio.c and run the following command:

```
sudo ./phio -N "32949 4590"   -O="0 15 7 0, 8 15 15 0" -m=2 -t=100000 -s -K=10 -S
```

3.4 Tuning parameters

In the examples.h, three parameters need to be tuned:

```
/***********calculate angle need code*****************/
#define FOV_COEFFICIENT 3.58            //fov parameter
#define DEVIATION_MULTIPLE 2    //if the current standard deviation is greater than two times the previous standard deviation, the data is
considered to be jumping
#define DATA_PERCENTAGE 0.15    //If the current data differs from the previous data by more than 15%, the data is considered to be shaking
#define ANGLE_NOT_READY 255.0   //The angle was not calculated properly, resulting in an output of default error data.
#define ROI_LEFT 0
#define ROI_RIGHT 1
#define MAX(a, b) ((a) > (b) ? (a) : (b))
/***********calculate angle need code*****************/
```

1. Macro “FOV_COEFICIENT” defines the FOV angle parameter. It needs to be modified according to ROI selection.
2. The two parameters below are used to reset the buffers used to calculate the average ranging value for each zone. Increasing these values leads to more ranging tolerance while decreasing these values leads to a more frequent reset of the buffer and a delay in obtaining the angle.
   – Macro "DEVIATION_MULTIPLE" defines the maximum proportional coefficient between the current standard deviation and the previously calculated standard deviation. This parameter is used when the buffer is more than half full.
   – Macro "DATA_PERCENTAGE" defines the maximum proportional threshold between the current obtained data and the previous data. This parameter is used when the buffer is less than half full.

4 Test results

Based on the previous description, ST conducted a test with the VL53L1 using a 100 ms Timing Budget and configured two ROI (two 16x4 arrays, example 1) from a target distance of 1 m to 4 m.

Using a single typical part, the tilt angle tolerance error stays within ±1.5° (10-frame rolling average), under the following conditions:

- At 1 m and 2m distances: tilt angle range from -40° to +40°
- At 3 m distance: tilt angle range from -35° to +35°
- At 4 m distance: tilt angle range from -25° to +25°

Test results are shown in the following figures. The figures include the measured tilt angle and tolerance, where the tolerance error is equal to the measured tilt angle minus the real tilt angle.

Figure 7. Test result of 10 frames rolling average @1 m target distance

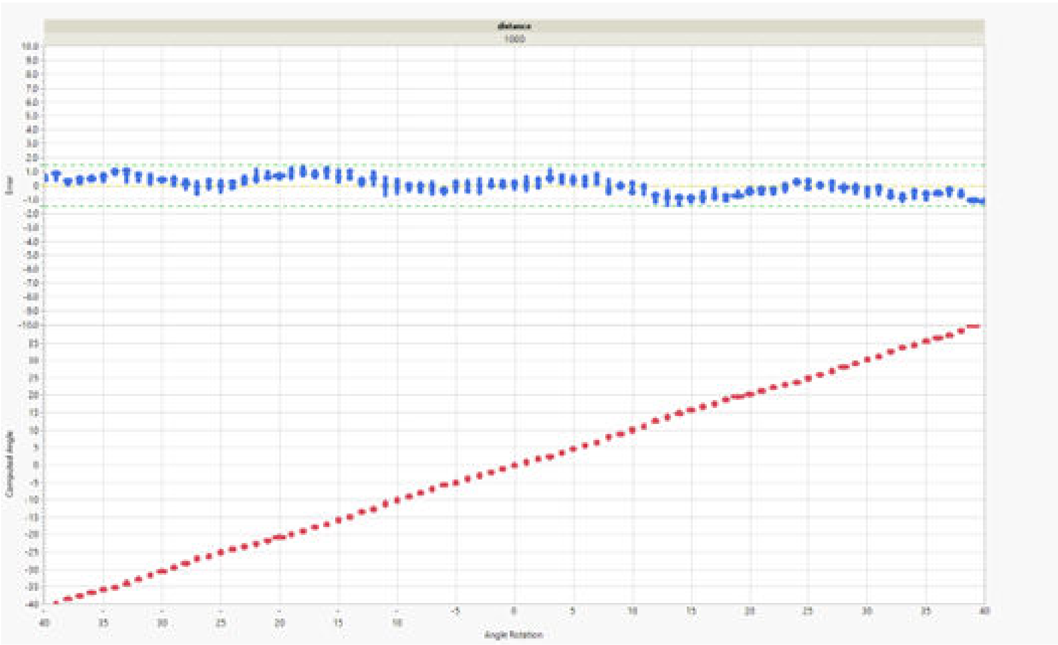


Figure 8. Test result of 10 frames rolling average @ 2 m target distance

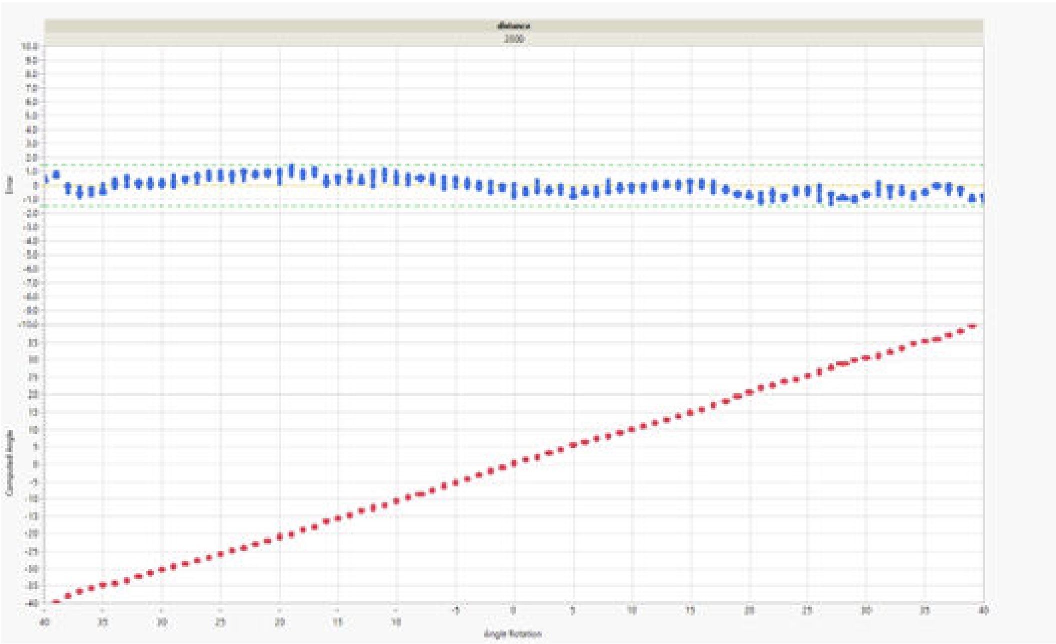


Figure 9. Test result of 10 frames rolling average @ 3 m target distance

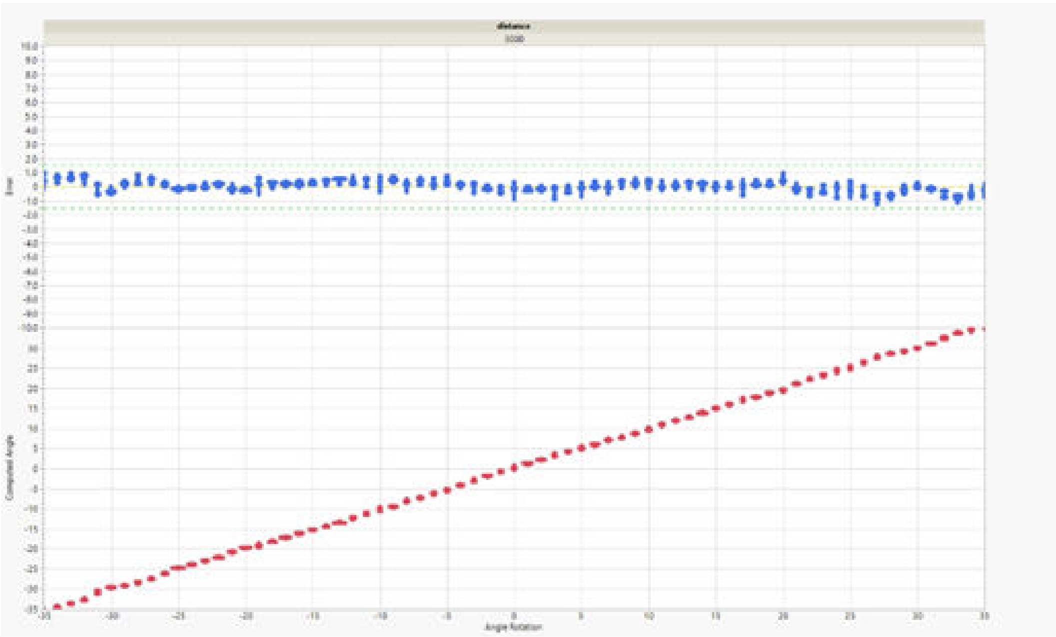
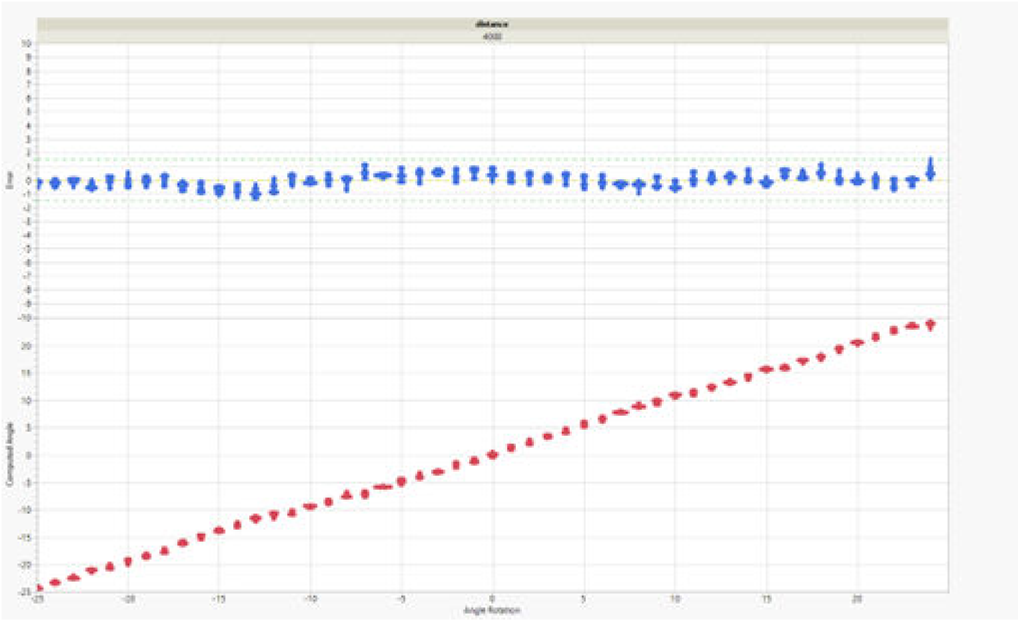


Figure 10. **Test result of 10 frames rolling average @ 4 m target distance**



Tilt measurements are performed between 0 and 4 m, using an angle between 0° and 40°.

The table below summarizes the required valid conditions for keystone correction:

- Real maximum ranging distances are given in black color.
- Estimated maximum ranging distances are given in blue color. These measurements are estimated data based on VL53L1 maximum ranging distance (8000 mm).
- Invalid conditions are given in red color.

Compensation can be applied for any condition in black or blue.

Figure 11. **Tilt angle parameter in function of the distance**

Distance \ Tilt Angle	0	5	10	15	20	25	30	35	40
1000	1028	1054	1090	1138	1199	1278	1379	1509	1681
2000	2057	2109	2181	2276	2398	2556	2757	3018	3362
3000	3085	3163	3271	3414	3598	3833	4136	4527	5044
4000	4114	4218	4362	4552	4797	5111	5514	6037	6725
5000	5142	5272	5452	5689	5996	6389	6893	7546	NA
6000	6170	6327	6543	6223	6261	6317	6401	NA	NA
7000	7765	7777	7814	7965	NA	NA	NA	NA	NA

5 Tolerance improvement

Section 4: Test results shows that the measured tilt angle is almost linear. However, the tolerance is not. The tolerance has a wave change even though this change is symmetric from negative to positive.

During the test, the tolerance source comes from the following factors:

1. Sensor ranging accuracy.
2. Tolerance of the test rotation motor.
3. Ambient light interference.
4. Detection zone coefficient in the calculation formula.
5. 0-degree offset value.

It is recommended to use a fov_coefficient of 1.85 for 16x4, and 3.58 for 16x8.

5.1 How to tune the coefficient by P2P

Currently, in the STMicroelectronics tilt angle test with VL53L1, the fov_coefficient is set to 3.58 for two ROIs of 16x8 arrays each. It is an empirical value. The tolerance could be improved by adjusting the coefficient through numerical fitting and approximation from the test data. The fov_coefficient has to be fine-tuned depending on the ROI configuration and use case.

5.2 How to calibrate 0-degree offset

At the product line, the following method can be used:

- Put a test jig with a projector facing the 1.5 meter target perpendicularly.
- Leave the left ROI physical distance equal to the right ROI distance.
- Perform angle measurements several times and record them.
- Store the averaged angle as the 0-degree offset value.

5.3 How to calibrate fov_coefficient

It is recommended to use the default fov_coefficient tuned by STMicroelectronics. It ensures the best possible accuracy. However, this tuning can be changed, but the accuracy is not guaranteed. To modify the fov_coefficient, follow the procedure, and send data to ST for an updated coefficient.

To fine-tune the fov_coefficient, perform a ranging test at 1.5 meters with -20° and 20° rotation (the distance and tilt angle can be adjusted depending on project requirements).

By knowing the ranging data and the real tilt angle between the two positions, the best detection_zone_coefficient can be calculated using mathematical fitting.

Revision history

Table 1. **Document revision history**

Date	Version	Changes
15-Dec-2023	1	Initial release
2-Feb-2024	2	Modified title Corrected references of VL53L1CB to VL53L1
25-Nov-2025	3	Section 4: Test results: Updated information regarding the tilt angle tolerance error.

Contents

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