AFBR-S50-BAS

Time-of-Flight Basics

Application Note
Version 1.0

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AFBR-S50-BAS Time-of-Flight Basics Application Note

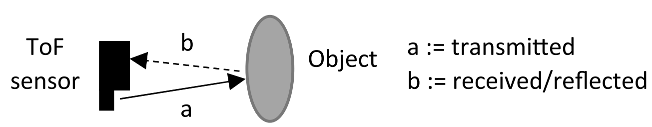
1 Introduction

The time-of-flight (ToF) sensor technology has become more and more established for distance and motion measurement scenarios that demand a high dynamic range, high speed, high accuracy, and independency of an aimed surface material. On the other side, those scenes require that system integrators and sensor users must carefully verify the needs of their application and the specification of a potential sensor. To facilitate this process, this application note provides the basic information of the Broadcom® ToF technology, as well as a general understanding of the measurement principles and introduces the product variety of the AFBR-S50 sensor platform.

2 Measurement Principles

The wording "time-of-flight" already reveals the basic idea of the optical measurement methodology. It indicates a utilization of the travelling time of light through air (~ 30 cm/ns air) emitted by a transmitter (Tx) and reflected back from any object to a receiver (Rx).

Figure 1: ToF Principle



In principle, two different methods derive a distance out of this physical phenomenon.

2.1 Direct ToF

Also known as pulsed ranging method, a direct ToF device measures the elapsed time of a single pulse voyaging through a and b (see Figure 1). The equation to calculate the final distance d is the following:

$$d = \frac{c_0 \, \Delta T}{2} \quad (1)$$

With c_0 = 299 792 458 $^{m}/_{s}$ as velocity of light in vacuum and ΔT as elapsed time from transmitting until receiving. Besides a high peak power and high bandwidth for the transmitter, this ranging technique requires precise time-to-digital conversion, single-pulse edge detection, and is bound to one-dimensional range measurements with economically reasonable hardware complexity.

2.2 Indirect ToF

Unlike a direct acquisition of the trip time of light, there exists the possibility to use a modulated continuous-wave (CW) pattern and measure of the phase difference between transmitted and received signals. The equation to calculate the final distance d is the following:

$$d = \frac{c_0}{2 f_{mod}} \frac{\Delta\varphi}{2\pi} \quad (2)$$

Beside c_0, the calculation also requires the laser modulation frequency f_{mod} as well as the determined phase difference $\Delta\varphi$. While the phase shift $\Delta\varphi$ is formed by the travel time of light through a and b (see Figure 1), f_{mod} defines the unambiguous range of the indirect ToF sensor which is explained in Section 3.2, Ambiguity and Unambiguous Range.

In contrast to direct ToF, using a CW signal has the following advantages:

- No electronic signal amplification is required (avoids additional noise source).
- An order of magnitude lower transmitter peak power is required than for direct ToF
- No pulse edge detection is required, complete pulse shape is correlated and integrated.
- Relaxed single pulse shaping requirements are available.
- Reduced ASIC complexity exists for 3D ranging and motion detection.
- Smaller module form factors are used.

As Broadcom's AFBR-S50 sensor technology is based on the indirect method, all further explanations on ToF are referred to as iToF.

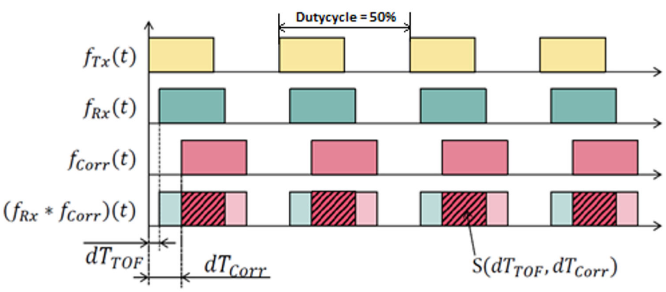
3 Terms and Definitions

3.1 Calculation of Range and Amplitude

As mentioned in the previous section, the AFBR-S50 sensor outputs are generated based on a phase shift. This is realized in the iToF ASIC by performing a cross-correlation of the received and a phase shifted correlation signal, which is derived from the driven transmitter signal. By default, the Broadcom iToF devices are configured to work with four phase shifts at $\pi/2$, π, $3\pi/2$, and 2π namely referred to as the S0, S1, S2, and S3 samples which are the raw output values of the sensor.

The following figure exemplary shows the timing of acquiring sample S0 with a $\pi/2$ shifted correlation signal.

Figure 2: iToF Correlation Schematic

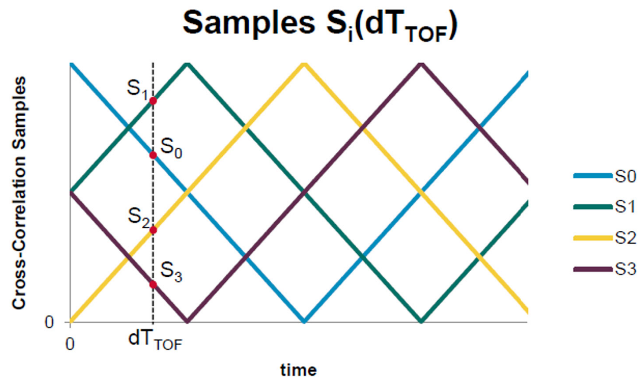


with:

dT_{TOF} : iTOF delay time
dT_{Corr} : Phase delay time
$f_{Tx}(t)$: Transmitter signal
$f_{Rx}(t)$: Receiver signal
$f_{Corr}(t)$: Correlation signal
$(f_{Rx} * f_{Corr,i})(t)$: Convolution of receiver and correlation signal which is phase shifted i-times, with i = 4

The Broadcom iToF laser sources are always modulated with rectangular pulses with a fixed duty-cycle of 50% and, thus, the output of the convolution results in triangular-shaped charts for all four phases, which are shown in the following figure in dependency to dT_TOF.

Figure 3: Four Phase Samples



With those four samples, the device software in the connected microcontroller (MCU) then performs the post-computations for the following:

i. Phase Difference $\Delta\varphi$
ii. Amplitude A
iii. Distance d

To ease calculations, the so-called linearized sine and cosine signals are used and defined by the following equations:

$$\begin{aligned} s &\equiv S_2 - S_0 \\ c &\equiv S_3 - S_1 \end{aligned} \quad (3)$$

Hence, the phase difference $\Delta\varphi$ is calculated with the following case structure depending on *s* and *c*.

$$\Delta\varphi(\pi) = \frac{1}{4}\begin{cases} 1 + \dfrac{s + c}{2A} & s < 0, c \geq 0 \\ 3 + \dfrac{s - c}{2A} & s \geq 0, c \geq 0 \\ 5 + \dfrac{-s - c}{2A} & s \geq 0, c < 0 \\ 7 + \dfrac{-s + c}{2A} & s < 0, c < 0 \end{cases} \quad (4)$$

with *A* as the amplitude or signal strength defined by the following:

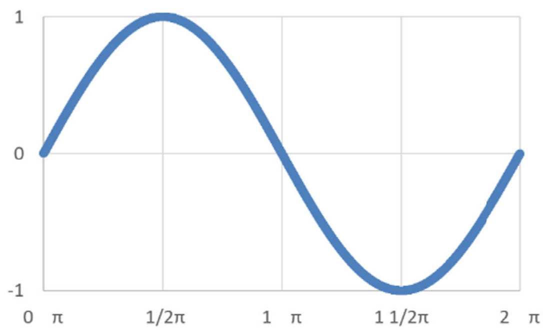
$$A \equiv \frac{1}{2}(|s| + |c|) \quad (5)$$

and the final distance calculated according to (2).

3.2 Ambiguity and Unambiguous Range

An iToF sensor, which is based on the phase correlation of a transmitted and received signal, has a physical limitation that is called the ambiguity. Because phase is a periodical information, its value is repeatedly bound to 2π, as indicated in the examplary sinusoid in the following figure.

Figure 4: One Period in Radians



The inherent ambiguity results in equal distances after the phase exceeds the 2π value. In other words, this is the case if an object appears not *within* but *after* one period as shown in the following figure.

Figure 5: Distance Ambiguity

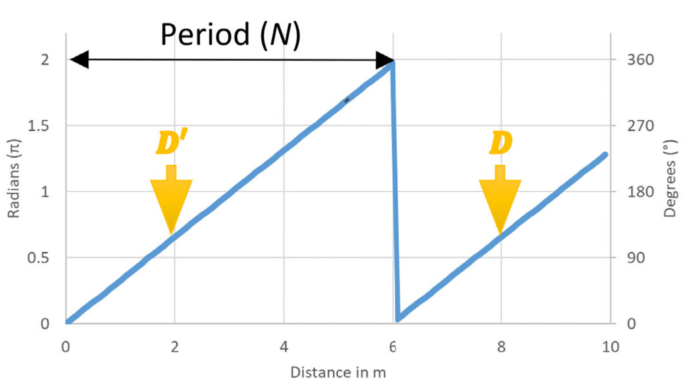


Figure 5 presents an exemplary iToF sensor which reaches 2π at 6 meters and is not able to distinguish between an object being located at 8 meters (D) or 2 meters (D'), mathematically expressed by extending (2) to the following equation:

$$d = \frac{c_0}{2f_{mod}}\left(\frac{\Delta\varphi}{2\pi} + N\right) \quad (6)$$

with N = 0, 1, 2… as Nth – period or window

To get a better understanding of why this occurs, look deeper at equation (2):

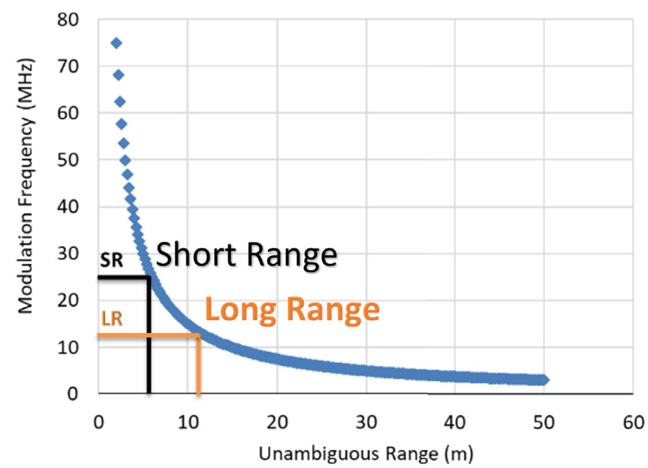
$$d = \frac{c_0}{2f_{mod}}\frac{\Delta\varphi}{2\pi}$$

When using a phase shift of $\Delta\varphi=2\pi$, the equation is canceled by the second term, resulting in the following equation:

$$d = \frac{c_0}{2f_{mod}} \quad (7)$$

Now it becomes apparent that the distance is solely dependent on the modulation frequency f_{mod}. The following figure shows this relation between modulation frequency and unambiguous range of an iToF sensor.

Figure 6: Modulation Frequency vs. Unambiguous Range



The blue series in Figure 6 reveals that the unambiguous range is increasing with decreasing modulation frequency.

Another indication shown in Figure 6 is that there are two default, non-adjustable modulation frequencies that are used for the AFBR-S50 sensors from Broadcom.

Table 1: AFBR-S50 Range Modes

Broadcom AFBR-S50 Specification		
Mode	**Unambiguous Range[a]**	**Modulation Frequency**
Short Range	6.25 m	24 MHz
Long Range	12.5 m	12 MHz

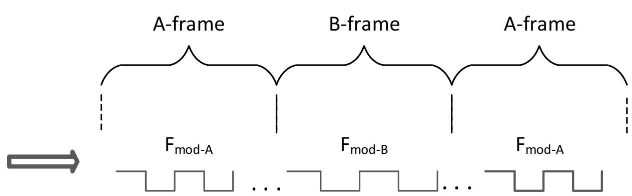
a. Without DFM; see Section 3.3, Dual Frequency Mode.

Because the natural ambiguity of these iToF sensors seem to border the measureable distance, the following section introduces a method to overcome and extend the unambiguous range limitation.

3.3 Dual Frequency Mode

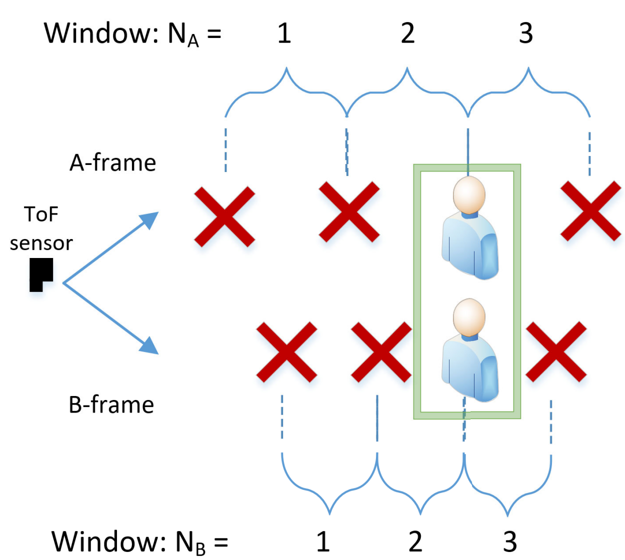
Dual frequency mode (DFM) acquires phase information of consecutive frames with two different modulation frequencies. Those frequencies are derived and just slightly detuned from the nominal modulation frequencies of short and long ranges.

Figure 7: DFM Framing



Because different modulation frequencies have different unambiguous ranges, it is possible to exactly determine the location of an object (for example, human) as there will be just one phase shift for each frequency resulting in a common distance.

Figure 8: DFM Procedure



The algorithm of the DFM is now trying to find the right windows N_A and N_B such that the distances d_A and d_B are equal.

How does this impact the unambiguous range?

The advantage of this method is that it leverages the delta frequency of the A and B frequencies given by $\Delta f = f_B - f_A$.

This changes equation (7) to the following:

$$d = \frac{c_0}{2(f_A - f_B)} = \frac{c_0}{2\Delta f}$$

with, for example, f_A = 22.5 MHz and f_B = 25.5 MHz (x8 DFM mode).

Considering a single modulation frequency of 24 MHz (short range mode) and a minimum delta frequency Δf of 3 MHz, the following ratio reveals the increased unambiguous range:

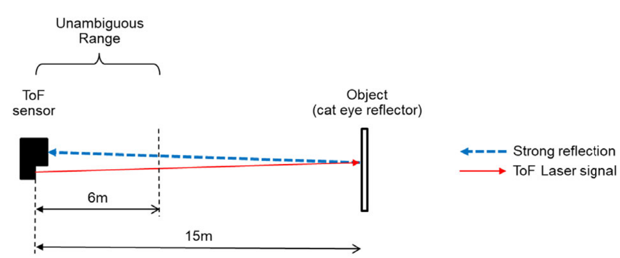
$$Ratio_{f_{mod}} = \frac{24\ MHz}{3\ MHz} = 8$$

In other words, when using two modulation frequencies with a relative difference of 3 MHz instead of one at 24 MHz, **it is possible to increase the unambiguous range by a factor of eight**.

What's the effect in the application?

Imagine the situation depicted in the following figure with an iToF sensor pointing to a highly reflective object (for example, a cat eye) at 15 meters. Assuming an unambiguous range of 6 meters, the sensor would end up in a distance of 3 meters instead of the actual 15 meters. Applications for items, such as collision avoidance, would be wrongly triggered by such a sensor.

Figure 9: Ambiguity in the Application

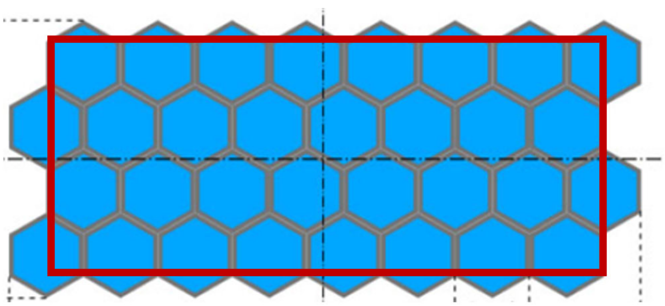


With the DFM, it is possible to detect objects beyond the specified iToF range and thus, from an application point of view, react correctly on highly reflective objects in the far distance. Due to the necessary comparison of more frames (at least three frames) and an additional filtering being required, a consequence of this method is an increased reaction time (three frames instead of two frames) and a reduced maximum frame rate of 100 Hz compared to a single frequency operation mode.

3.4 Field-of-View (FoV)

The FoV is one of the most important parameters when working with iToF sensors, because it defines the spatial scope of these devices. All of the AFBR-S50 sensors have a 32-pixel array on the receiving side consisting of four rows and eight columns. By design, each pixel has a FoV of 1.55° × 1.55° which results in a total Rx FoV of 12.4° × 6.2°. Due to the hexagonal nature of the pixels, the effective FoV with 100% fill factor is 11.7° × 5.1° as indicated by the rectangle in Figure 10. In average, the Rx FoV is equal to 12.4° × 5.4°.

Figure 10: Rx Pixel Array



There is a difference of the FoV definition between, for example, looking through a binocular and using an optical sensor for distance measurements. For the latter, the transmitting side also plays a significant role. More precisely, the iToF pixel array does not respond for an object that is not illuminated by its transmitting part.

3.4.1 Transmitter Spot Size

To better understand this concept, look at some of the optical parameters specified for the AFBR-S50MV85G iToF sensor.

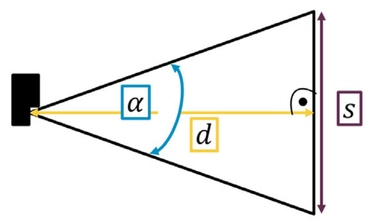
Table 2: Exemplary Optical Parameters

Parameter	Typ.
Tx beam divergence	4°
Light spot diameter at 1m	70 mm
Pixel FoV at 1m	27 mm

The beam divergence is the transmitter's counterpart of the receiver or pixel FoV. It calculates the light spot diameter at a certain distance. This is done by assuming a conical shape of the emitted beam and applying a simple trigonometrical approach as shown in the following figure. The following parameters are defined:

α :	Beam divergence
d :	Distance to the object
s :	Spot size

Figure 11: Spot Size Calculation



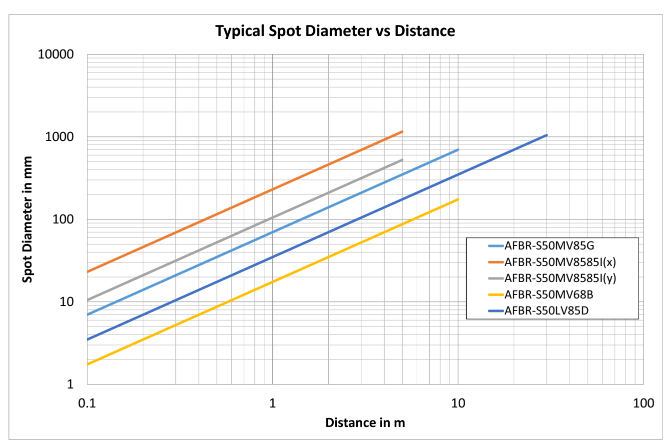
By applying simple trigonometry, the spot size can be calculated with the following equation.

$$\tan\frac{\alpha}{2} = \frac{s/2}{d} \qquad s = 2d\tan\frac{\alpha}{2} \approx d\tan\alpha$$

$$\rightarrow s_{Spot} = d \times \tan\,\alpha \qquad (8)$$

The following chart shows the typical resulting spot sizes, *s*, of the AFBR-S50 sensor modules at different distances using equation (8).

Figure 12: Typical Spot Diameter vs. Distance

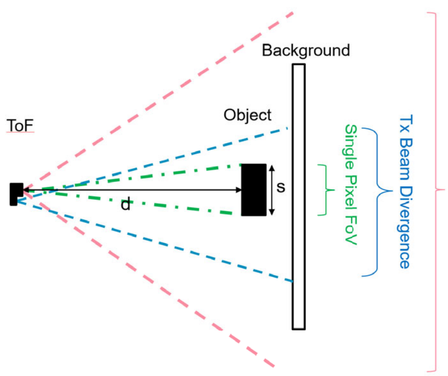


Note that the beam divergence typically has a Gaussian-like intensity profile and no hard limit. The spot size is typically referred to the extension of the beam, at which the intensity is reduced to $1/e^2$ (13.5%) from the maximum.

3.4.2 Minimum Object Size

While the beam divergence defines the transmitter spot size, the pixel FoV is the crucial parameter when it comes to the minimum object size the sensor is able to resolve. The following figure shows an overview and a colored indication about all field-of-views having an effect on a measurement. The illustrated ratio of FoVs in this figure is taken for the AFBR-S50MV85G sensor with typically a 4° beam divergence.

Figure 13: Sensor FoVs



The preceding schematic reveals the determining parameter, which is the FoV of a single pixel defined with 1.55° × 1.55°. Hence, equation (8) can again be used to derive a minimum detectable object size.

$$\begin{aligned} s_{Object} &\geq d \times \tan 1.55° \\ &\geq d \times 0.027 \end{aligned} \qquad (9)$$

To ease calculations and mitigate environmental influences, the formula can be simplified to the following:

$$s_{Object} \geq {}^{3}/_{100} \times d \qquad (10)$$

The inverse relation of the maximum distance *d* for a given object size *s* can accordingly be approximated as the following:

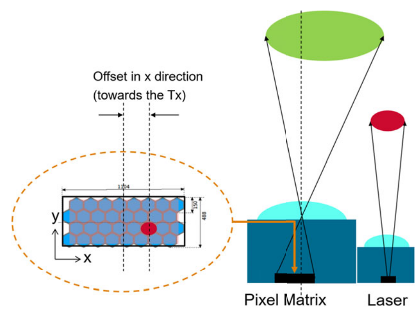
$$d_{maximum} \leq 33 \times s \qquad (11)$$

3.4.3 Interaction of the Tx and Rx FoVs

3.4.3.1 Parallax Effect

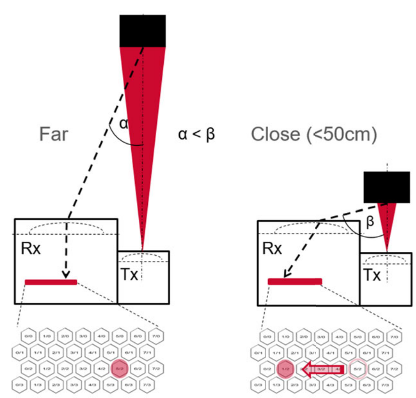
The following figure shows the optical and mechanical design of the AFBR-S50 modules. As indicated by the red pixel in the array, the Rx lens apex is shifted towards the transmitting side. This focal area of the Rx lens and also the maximum received signal intensity is intended to target pixel (5/2), which is not applicable for the AFBR-S50MV85I..

Figure 14: AFBR-S50 Optical/Mechanical Design



This mechanical/optical design compensates the parallax effect for close objects. It occurs because the angle between emitted and reflected light captured by the Rx lens becomes larger the closer an object gets to the module.

Figure 15: Parallax Illustration



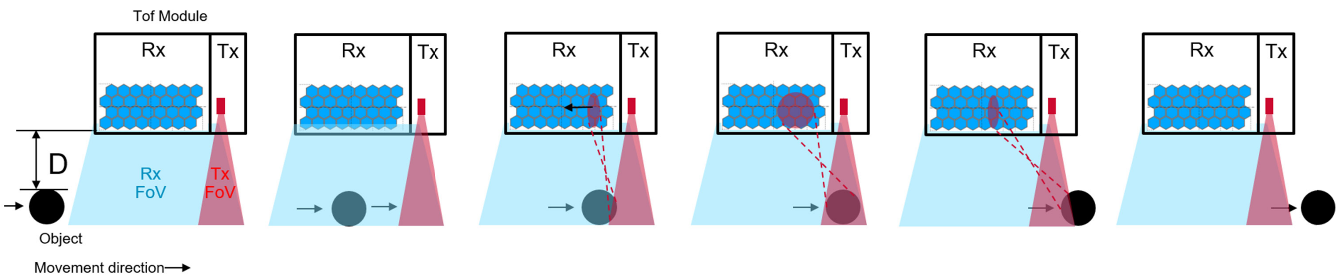
As shown in Figure 15, the parallax region is entered for objects closer than 50 cm, which is typically defined by the distance between the optical axes of Tx and Rx. It causes a shift of the focus area to the left side on the pixel array.

NOTE: This design feature lets all AFBR-S50 sensors leverage the 32 pixels array with the advantage to compensate the parallax effect and makes it possible to even measure distances down to a cm.

3.4.3.2 Typical Detection Paradigms

The following two schemes unveil the optical detection dynamic of the AFBR-S50 sensors with an object in distance d to the sensor moving through the Rx and Tx FoVs on the horizontal (x) as well as vertical (y) axis of the pixel array exemplarily shown with the **AFBR-S50MV85G** module. This derivative is the perfect candidate because it combines a sufficiently wide beam divergence for movement detection, although narrow enough to measure far distances up to 10 meters. Therefore, for the detection, it uses just a limited number of typically 7 pixels (also known as flower) on the receiving side. The background is assumed to be infinity in this scenario.

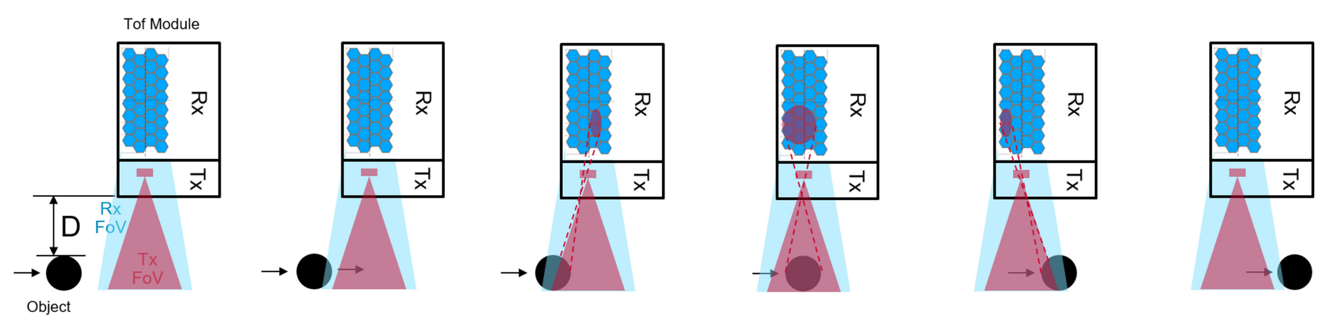
Figure 16: Detection Dynamic (Horizontal)



	1	2	3	4	5	6
Binned Range	∞	∞	D	D	D	∞
	Object not in FoV	Object only in Rx FoV	Object entering Tx FoV	Object completely in FoV	Object leaving Tx & Rx FoV	Object not in FoV

NOTE: The object is not recognized by the sensor unless it appears in the transmitter FoV. When it enters the Tx FoV, the backscattered light is captured by the Rx lens, which illuminates a pixel area according to the "degree of immersion" of the object in the Tx and Rx FoV.

Figure 17: Detection Dynamic (Vertical)

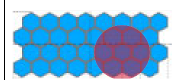
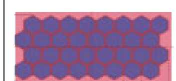
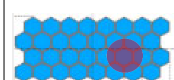
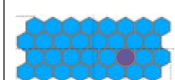


	1	2	3	4	5	6
Binned Range	∞	∞	D	D	D	∞
	Object not in FoV	Object entering Rx FoV	Object entering Tx & Rx FoV	Object completely in Tx & Rx FoV	Object leaving Tx FoV	Object leaving Rx FoV

3.4.4 AFBR-S50 Module Family – Overview of Detection Characteristics

The following table shows the variances between the single sensor modules and their different detection characteristics. It becomes apparent that a direct relation exists between the Tx beam divergence and the maximum distance the sensor is able to measure. As previously mentioned, the AFBR-S50MV85G is a compromise between both. If an application requires purely distance measurement, the AFBR-S50LV85D is the best choice because it offers the largest distance range but a small FoV. In contrast, the AFBR-S50MV85I aims for object and gesture recognition applications and is capable of using all 32 pixels with a maximized FoV (Tx beam shape equals Rx FoV).

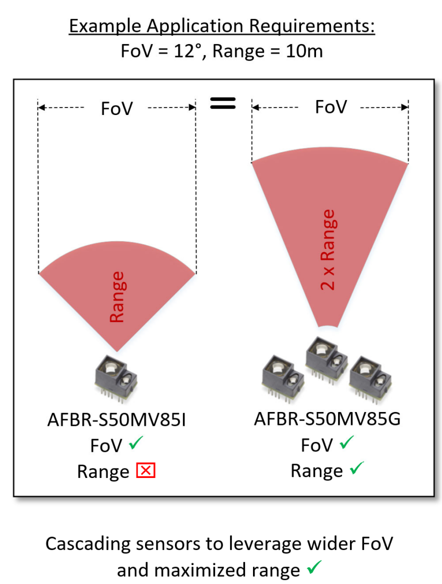
Table 3: AFBR-S50 Modules – Overview of the Detection Characteristics

Type	Wave-length (nm)	Typ. Beam Divergence (X° × Y°)	Distance Range (m)	2D Spot Shape	Tx Spot Size at 1m Distance	Rx Single Pixel Spot Size at 1m Distance	Typ. Number of Active (=Illuminated) Pixels	Detection Modes
AFBR-S50MV85G	850	4 x 4	0.01–10	Circular	7 cm × 7 cm	2.7 cm × 2.7 cm	7–16 	Distance, Direction, 1D/3D Speed
AFBR-S50MV85I	850	13 x 6	0.01–5	Rectangular	23 cm × 10.5 cm		32 	Distance, Gestures, Direction, 1D/3D Speed
AFBR-S50LV85D	850	2 x 2	0.01–30	Circular	3.5cm × 3.5cm		1–3 	Distance, 1D Speed
AFBR-S50MV68B	680	1 x 1	0.01–10	Circular	1.75cm × 1.75cm		1–2 	Distance, 1D Speed

Due to the different FoVs and maximum ranges, the AFBR-S50 modules can be used in a large variety of applications. Additionally, because of the high possible frame rates, implementers leverage the possibility to extract 1D speed ((towards or away from the module) information even for non-multiple pixel sensors, such as the AFBR-S50LV85D or AFBR-S50MV68B. Multi-pixel sensors additionally can be applied to applications that require an x-y movement and speed detection, respectively.

Another advantage of using these sensors is the drop-in compatibility within the AFBR-S50 family. The following indicates the possibility of concatenating sensors; for example, to increase the sensing FoV by maintaining the capability to measure higher distances.

Figure 18: Extended FoV by Sensor Composition



4 Static and Dynamic Detection Algorithms

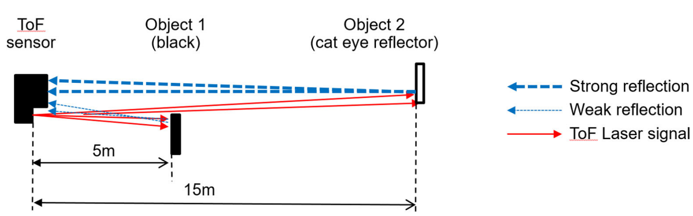
4.1 Static – Pixel Binning Algorithm (PBA)

Thinking of the usage in a real application, the iToF sensor must handle the situation that the transmitter spot overexposes an object, which directly leads to an interaction with the physical entities in the background.

What is the impact on the iToF range if the backscattered light is coming from two different locations?

Imagine the situation depicted in the following figure, which is similar to Figure 9 but with the sensor simultaniously illuminating two separated objects that are located at different distances. Object 1 with a low reflectivity (black) is located in 5 meters and object 2 with a high reflectivity (cat eye= retroreflector) is positioned in 15 meters distance to the sensor. Assume that some binned pixels receive reflected light from both and other binned pixels just from one object. Binned picxels are considered valid and contribute to the binned range.

Figure 19: Two Objects in the Tx FoV



In principle, different application requirements determine upon what a free space sensor shall react; however, usually it is necessary to show the closer object independent of the signal strength.

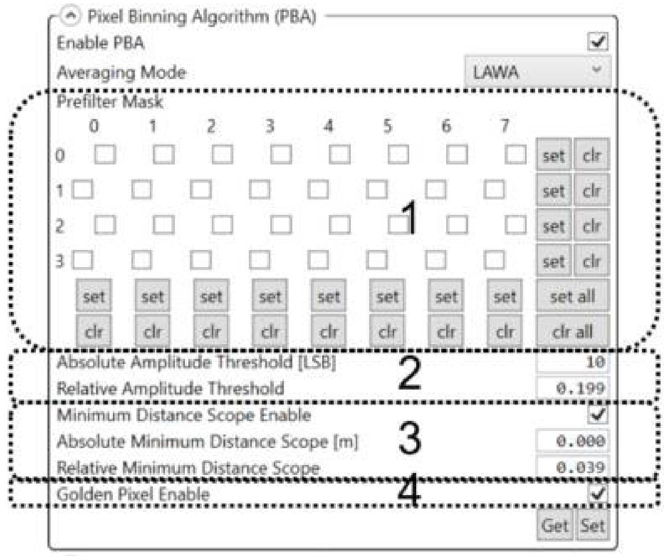
The AFBR-S50 application programming interface (API) is equipped with a piece of code called pixel binning algorithm (PBA), which is further described based on the explorer software which is part of the AFBR-S50 software develoment kit (SDK).

PBA is an algorithm that determines the 1D range by selecting the pixels that satisfy certain requirements in terms of amplitude (equals signal strength) and distance. Furthermore, it contains several averaging algorithms to obtain the best result.

The pixel binning filtering works in four consecutive stages:

1. Fixed pre-filter mask
   – Exclude pixels from binning
2. Amplitude thresholds
   – Bins' pixels according to their amplitude (for selecting only good signals)
3. Distance scope
   – Bins pixels according to their range (for selecting the nearest object)
4. Golden pixel*

Figure 20: PBA – AFBR-S50 Explorer

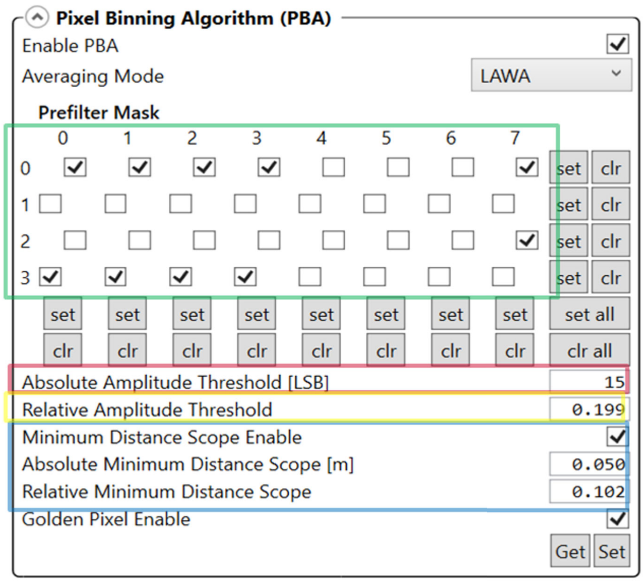


If none of the pixels satisfies the amplitude requirement of 2, the golden pixel is chosen (when enabled). This one is factory calibrated and is determined as the pixel with the highest signal strength.

4.1.1 PBA Example

The following example settings explain how the PBA works without the fallback solution of the golden pixel.

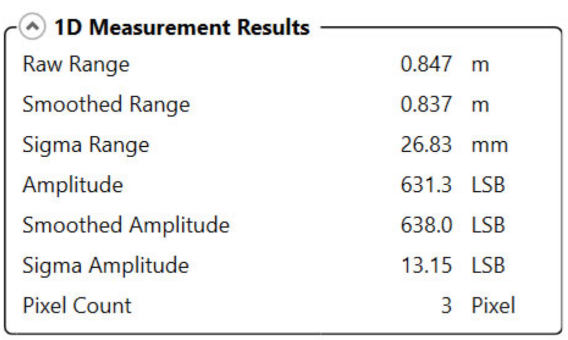
Figure 21: AFBR-S50 Explorer – PBA Example



NOTE: Work through the example with a running explorer by viewing the detailed tool-tips of the single parameters.

In this example, the 1D measurement results box from the explorer software shows the following values for range, amplitude, and binned pixel count.

Figure 22: AFBR-S50 Explorer – PBA Example – 1D Result



How did the algorithm get the raw range result of 0.847m?

To get a better understanding, a section of the raw data view with 16 example pixels is presented in the following figure.

Figure 23: AFBR-S50 Explorer – PBA Example – Raw Data

Colors indicate the PBA filter type from Figure 21. In the following, excluded pixels p(x,y) are listed per filter type:

- Pre-filter mask: p(3,0), p(3,3)
- Amplitude thresholds

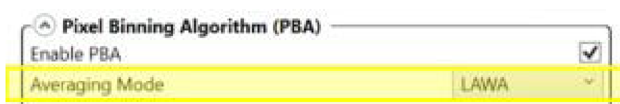
  Absolute: p(3,1), p(3,2), p(4,3)

  Relative: p(4,0), p(4,1), p(6,0), p(5,3), p(6,3) – Relative Threshold defined by → p(6,1) = 631 × 0.199=125 LSB
- Minimum distance scope: p(5,0), p(6,1), p(6,2), Threshold defined by → p(5,1) = 0.8187m (raw), 0.8187 ± 0.05 (=dx_abs) = 0.7687m / 0.8687m, 0.8187 ± 10.2% (=dx_rel) = 0.735 m / 0.902 m

  The maximum range of absolute and relative defines final binning; in this example, it is the relative scope.

Three pixels p(4,2), p(5,1) and p(5,2) are now determined to be the valid pixels for the distance calculation. By default, the explorer as well as the API choose the so-called linear amplitude weighted average (LAWA) method for averaging between the binned pixels.

Figure 24: AFBR-S50 Explorer – PBA Example – Averaging



$$Range_{binned} = \frac{\sum Range_{raw_i} \times Amplitude_{raw_i}}{\sum Amplitude_{raw_i}}$$
$$= \frac{(0.8601 \times 209) + (0.867 \times 536) + (0.8187 \times 489)}{(209 + 536 + 489)}$$
$$= 0.847\ m$$

4.2 Dynamic – Dynamic Configuration Algorithm (DCA)

The DCA is a control algorithm that adapts transmitted as well as received signal strengths to optimize the signal-to-noise (SNR) ratio within Laser Class I for changing environments, such as the following:

- Distance
- Reflectivity
- Ambient light

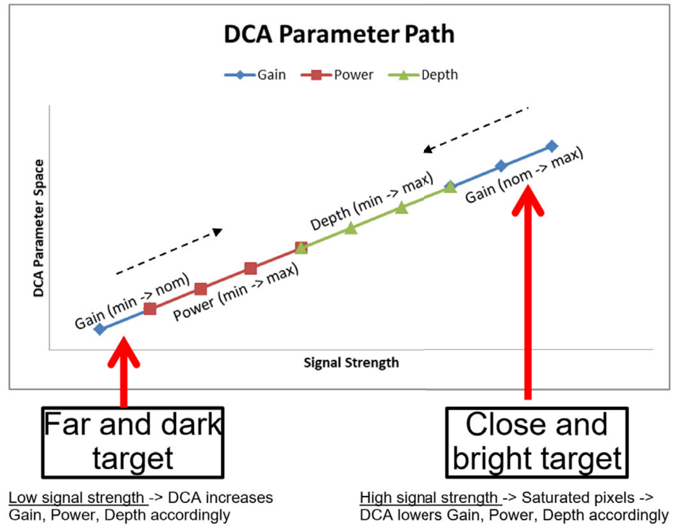
by monitoring the following:

- Saturated pixel count
- Signal amplitude (strength)

The following figure depicts the control loop with the three main output parameters namely referred to as Gain, Power, and (Integration) Depth versus the detected signal strength. Also shown are two entry points of the DCA for extreme conditions which are a far and dark target on the lower side and a close and bright target on the upper side of the DCA parameter space (y-axis). The algorithm starts with nominal values and adjusts the output parameters according to the monitoring values mentioned above.

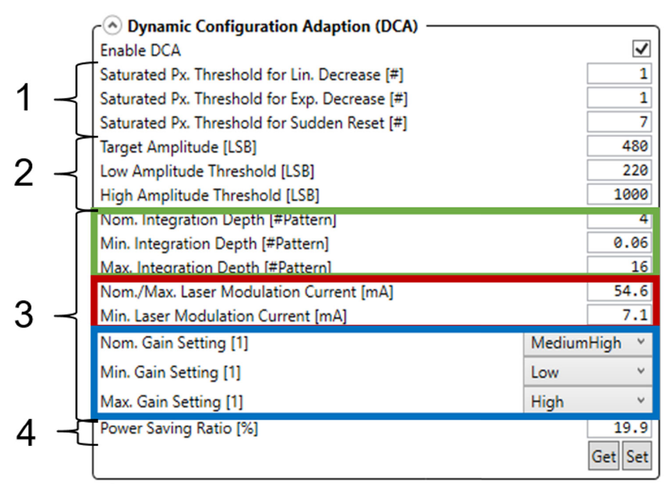
NOTE: Work through the example with a running explorer by viewing the detailed tool-tips of the single parameters.

Figure 25: DCA – Control Diagram



The default settings of the DCA are based on empirical data, which is sensor type specific. A more detailed description of the content is given with the DCA view of the AFBR-S50 explorer:

Figure 26: AFBR-S50 Explorer – DCA Default Example Settings



with the following:

1. The number of saturated pixels defined in thresholds for a reduction of the integration energy.

NOTE: This setting also defines the reaction speed when environmental conditions change.

2. Amplitude value as input parameter for the control loop

3. Correction parameters Depth, Power, and Gain.
4. Minimum idle time of the device per frame.

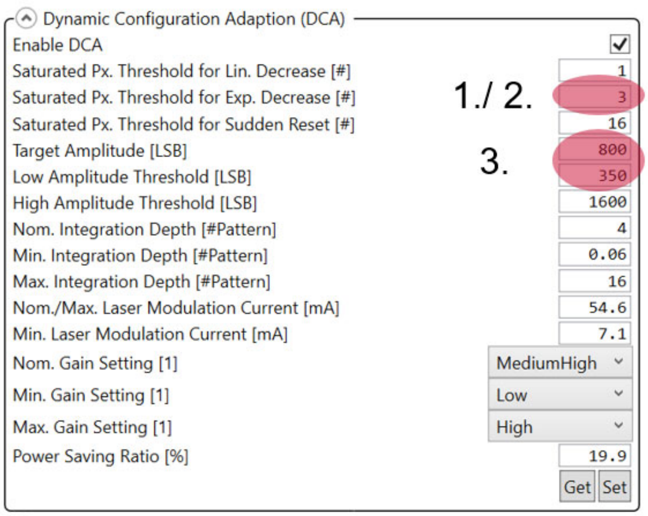
NOTE: This setting has less current consumption to the cost of digital integration.

Integration depth from the DCA is furthermore defined as analog integration becaise it defines the number of laser pattern repetitions. Additionally, the digital integration represents the averaged sample count of the acquired phases. Both types contribute to the final integration time. The digital integration is automatically set by the DCA to achieve lowest repeatability noise within the limits of Laser Class I.

4.2.1 DCA Example

This example is again performed with the AFBR-S50 Explorer and describes the control mechanism of the DCA in more detail. The DCA settings in the following figure were applied to the sensor.

Figure 27: AFBR-S50 Explorer – DCA Example – Settings



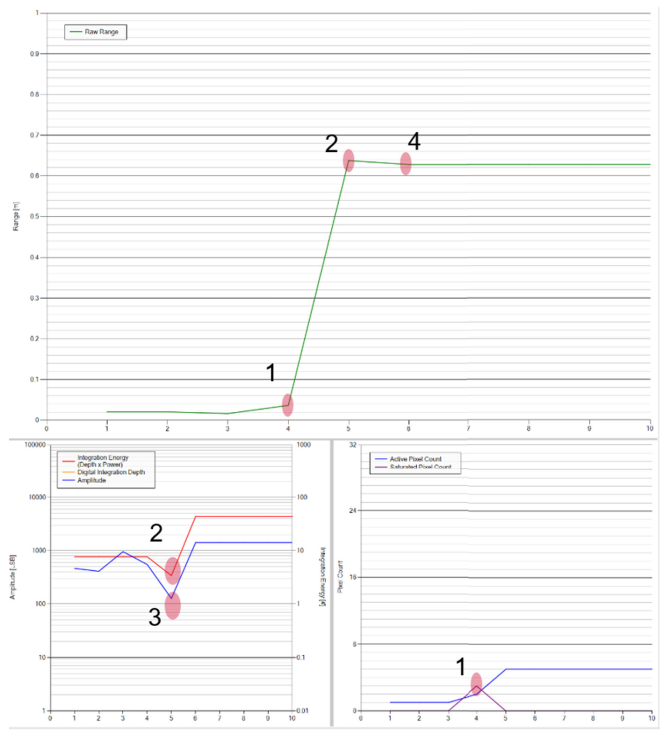
Furthermore, the device is using a frame rate of 1 Hz and the maximum value of the 1D plot X-axis is set to 10. To simplify the example, the DFM was switched off so that a single modulation frequency was used. Simulated is the situation that a close object suddenly disappears from the FoV of the sensor.

Sequence of occurrences:

1. Frame 3–4: Saturated pixel count is exceeding threshold of 3.
2. Frame 4–5: Integration Energy (Depth × Power) is halved.
3. Frame 5–6: Amplitude below low amplitude threshold of 350 LSB => Integration Energy (Depth x Power) is accordingly increased to reach at least target amplitude 800 LSB.
4. Frame 6: Final distance is reached three frames later.

All steps with their specific number can also be verified with the following figure.

Figure 28: AFBR-S50 Explorer – DCA Example – 1D Plot



To ease evaluation and facilitate the implementation of an AFBR-S50 iToF sensor, start working with the AFBR-S50 Explorer with its visualizing views.

5 Eye Laser Safety

The Dynamic Configuration Algorithm (DCA) keeps the SNR high by maintaining the laser class. When reading through the AFBR-S50 sensor data sheet, it is noted that the transmitter is rated as Laser Class 3B laser by nature, which might unsettle readers because the sensor itself is specified to be within Laser Class I.

This section provides additional information beyond the data sheet on how Laser Class I is ensured during operation.

The following summarize the basic safety assurance:

- Base for all calculations: IEC 60825-1, Ed. 3.0 2014-5.
- Laser Class 1 operation is ensured by both iToF ASIC and API by regulating the integration time per frame accordingly based on the given frame rate.
- The optical average power is factory calibrated for each device.
- iToF ASIC adds pauses into bursts to fulfill burst power requirements with at least 20% margin; this is done automatically by the hardware, based on the given configuration.
- With the AFBR-S50 API, an override of the laser class timing is not possible because direct register access is blocked.

5.1 Safety Measures Implemented in Hardware during Operation

The following are safety measures implemented by the hardware:

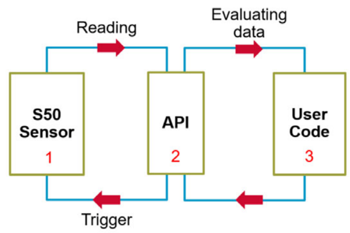
- Standard operation (using the API)
  - A laser pattern is used with low duty cycle < 2%.
  - A hardware timer is used that is independent of software malfunctions.
- Operation on an ASIC defect (for example, caused by ESD or EOS)
  - The ASIC is designed so that whenever the trigger is lost, it stops working. If no trigger signal is generated, neither pulses (patterns) nor continuous waves are sent to the laser.
  - Additionally, for 850-nm laser modules, the maximum peak current used is the maximum possible current of the implemented laser driver. The peak current cannot be increased.
  - If, and for any reason, a defect would cause a continuous wave output from the laser driver circuitry, the reference pixel monitoring the optical output on transmitter side can detect it if the allowed output power is exceeded.

5.2 Safety Measures Implemented in Software during Operation

Safety measures implemented by the software follow:

- Standard operation (using the API)
  - The DCA adapts the integration depth and laser current followed by an eye safety check after each frame.
    - The product of the integration depth, laser current, and frame rate is kept constant with the initial, default configuration as reference.
  - Eye-safety-related parameter adjustments are only possible under the shelter of the DCA. Therefore, accidentally setting of laser to emit under Laser Class 3B is not possible.
  - Single-threaded architecture

Figure 29: AFBR-S50 API Single-Threaded Architecture



- Operation under software/hardware malfunction
  - A software crash, hang, or even delay results in a loss of trigger (see Figure 29) for the ASIC and it stops its operation.
  - In case of a software hang or delay, measurements are not triggered but delayed until the data buffers are evaluated and cleared from software.
  - Reference pixel warning flags inform the system on a laser class violation.
  - SPI communication: Sporadic bit errors occur during communication.
    - DCA parameter eye-safety check is done after each frame, sporadic bit errors in one frame are cured at the next frame.
  - SPI communication: High number of bit errors occur during communication.
    - Time-out mechanism, no start of frame.

6 Application Programming Interface

This section provides an overview about the AFBR-S50 Application Programming Interface (API), also known as Argus API, that is part of the Software Development Kit (SDK).

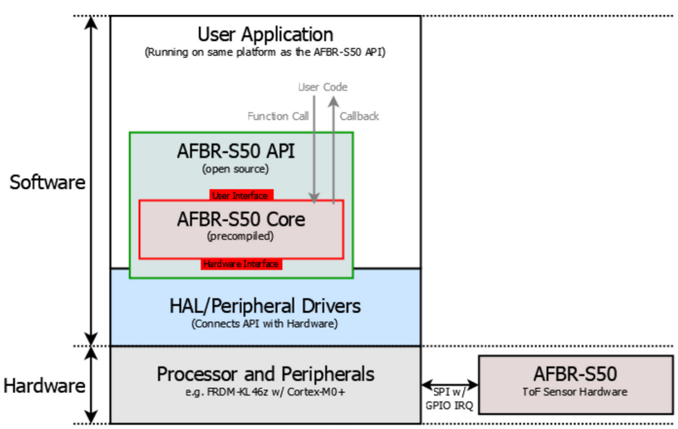
6.1 Overview

The AFBR-S50 sensor modules from Broadcom do not have a microcontroller (MCU) implemented, which lowers sensor costs for the end user and provides the freedom to connect it to any Arm Cortex-M series processors over serial peripheral interface (SPI) and one additional GPIO for IRQ handling.

As depicted in Figure 30, the API itself encapsulates the precompiled Core library, which handles the direct register access for a save device operation. Implementers can choose between several precompiled libraries for the most common Cortex-Mx architectures.

To enable a seamless implementation, the AFBR-S50 API has a software interface to communicate through function calls and callbacks with the user application, and it has a hardware interface to communicate over a hardware abstraction layer (HAL) with the MCU and other peripherals.

Figure 30: AFBR-S50 SDK Architecture for Integration into a User Application



By default, the code of the HAL refers to the FRDM-KL46z from the evaluation kit, which must be ported to another MCU platform, if required. To get started, a step-by-step porting guide is available for download (see Section 8, Document References).

The following figure gives an overview about modules that are accessible through the API.

Figure 31: AFBR-S50 API Modules

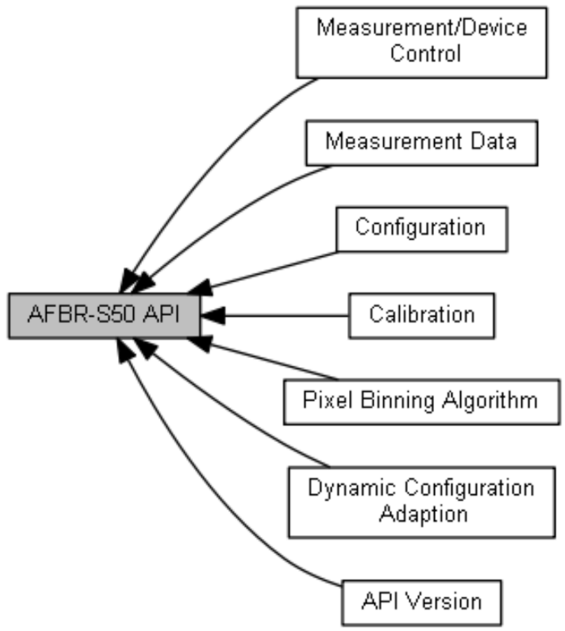


Table 4: Modules

Module	Description
Measurement/Device Control	Start and stop measurement, evaluate data, get status, execute functions for calibrations, and so on.
Measurement Data	Single pixel status and measurement data, binned range and amplitude results, and so on.
Configuration	Set frame time, measurement mode, and so on.
Calibration	Get and set calibration data, for example, xtalk, range offset, and so on.
Pixel Binning Algorithm (PBA)	Get and set PBA settings.
Dynamic Configuration Adaption (DCA)	Get and set DCA settings.
API Version	Get API version information.

6.2 EEPROM Data

The iToF ASIC has an EEPROM that contains device-specific information, such as the ChipID and data from the factory calibration. To adapt and apply the device-specific-register settings to the sensor, this data is read out once during initialization of the module. This EEPROM content is also accessed through the SPI pins, however, with a proprietary protocol using bit banging (toggling) in GPIO mode.

6.3 Minimum Memory Requirements

- RAM: 8 kB (4 kB Heap + 4 kB Stack)
- ROM/Flash: 128 kB

For more information, refer to the API reference manual, which is accessible through the help section of the AFBR-S50 Explorer or in the installation path of the SDK under the following directory:

```
<root>\AFBR-S50SDK\Device\Manual\AFBR-S50 API
Ref. Manual.pdf
```

7 FAQs

7.1 How can I get started with an iToF sensor from Broadcom?

The easiest way to get started is by purchasing an AFBR-S50 evaluation kit (see the links in Section 8, Document References). This empowers users to directly start working with a sensor without the need of programming a single line of code. A user guide and the powerful graphical user interface from the SDK provide a comprehensive set of information and tools to explore the performance of Broadcom's iToF sensors.

7.2 What is the FoV of an AFBR-S50 sensor and how many pixels does a sensor use?

In general, all AFBR-S50 sensors have 32 pixels on the receiving side. However, the number of used pixels primarily depends on the module type with its emitting beam divergence. See more information in Section 3.4, Field-of-View (FoV).

7.3 How is the operation under Laser Class I ensured?

See more information in Section 5, Eye Laser Safety.

7.4 What impacts the total performance of an iToF sensor?

1. Distance D: Signal strength ~ 1/D^2
2. Object/target reflectivity:
   - Retroreflector (for example, cat eye) object: Signal strength × Factor of ~1 (100%)
   - White object: Signal strength × Factor of >0.8 (80%)
   - Black object: Signal strength × Factor < 0.15 (15%)
3. Ambient conditions:

   Sunlight is increasing the shot noise on the receiving side, which leads to a performance drop in terms of sensitivity. A sun light exposure of about 100 kLux (AM1.5) can lead to a 50% reduction of the maximum possible range

7.5 Why would I use a pre-filter mask in the PBA?

It might be necessary to exclude pixels from the binning; for instance, if the sensor is covered by an aperture with fixed dimensions and there is a known, unavoidable reflection that generates a strong amplitude to some boarder pixels, which in turn, influences the final binned range. A correct pre-filter mask could exclude those pixels from the final range calculation.

7.6 How can I implement the AFBR-S50 API into my project?

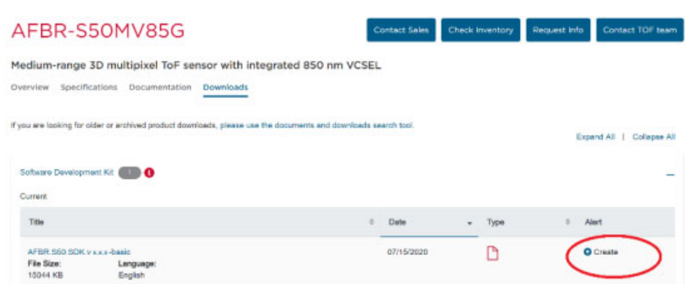
The AFBR-S50 Core Library is provided as a static ANSI-C library file (`lib*.a`) and the corresponding API is provided as ANSI-C header files (`*.h`). After setting up the linker to link the library, include the main header in the `/include` folder, `argus.h`. For more information, refer to the API reference manual, which is accessible through the help section of the AFBR-S50 Explorer or in the installation path of the SDK under the following directory:
`<root>\AFBR-S50SDK\Device\Manual\AFBR-S50 API Ref. Manual.pdf`

7.7 How do I know if a new version of the SDK is available for download?

The Broadcom homepage, www.broadcom.com, has an alert system implemented to inform subscribed users whenever a new version of a registered download is available.

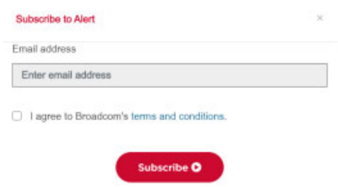
1. Enter the download section of any iToF sensor or evaluation kit, and click the highlighted Create button.

Figure 32: Create Button



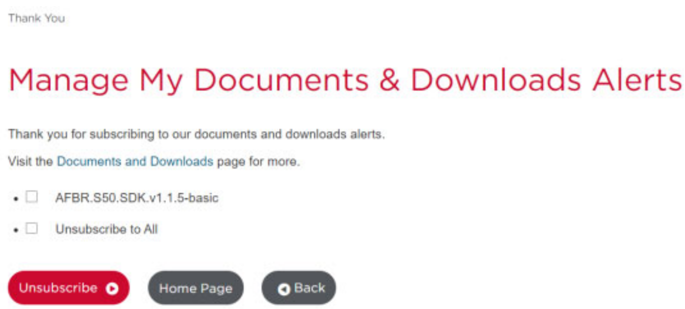
2. Subscribe for the alert.

Figure 33: Subscribe Button



3. Look at the confirmation and the overview about your subscriptions.

Figure 34: Manage My Documents & Downloads Alerts



8 Document References

Reference Name	Document Type	Link
AFBR-S50MV85G Sensor	Data Sheet	https://docs.broadcom.com/docs/AFBR-S50MV85G-DS
AFBR-S50MV85I Sensor	Data Sheet	https://docs.broadcom.com/docs/AFBR-S50MV85I-DS
AFBR-S50LV85D Sensor	Data Sheet	https://docs.broadcom.com/docs/AFBR-S50LV85D-DS
AFBR-S50MV68B Sensor	Data Sheet	https://docs.broadcom.com/docs/AFBR-S50MV68B-DS
AFBR-S50 Evaluation Kit Getting Started Guide	User Guide	https://docs.broadcom.com/docs/AFBR-S50-EK-UG
AFBR-S50 API Example Porting Guide	Programming Guide	See SDK which can be downloaded here: https://docs.broadcom.com/docs/12398582
AFBR-S50 Reference Design	Application Note	https://docs.broadcom.com/docs/AFBR-S50-RD-AN

Revision History

Version 1.0, February 10, 2021

- Initial release of the document.

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