Time-of-Flight validation

*by **pmd**technologies*

Abstract

This document provides additional information about the time-of-flight (ToF) validation process as well as the relevant test limits. Test criteria and test limits mentioned within this document are given as examples only and might be adopted for the individual customer/application.

Table of Contents

1. Introduction

The calibration of a ToF module is one the most important steps during production. The Validation Box [1] was designed to enable a quick validation of the successful calibration of the module. On top it can be used as a setup for an outgoing quality check (OQC). Validation software algorithms are provided by the “validatePlane” software tool. This tool processes raw measurement data together with the created calibration data and yields several numerical values that are performance indicators. These values are supposed to be suitable for testing predefined performance critera as well as to identify hardware failures. A customer may use “validatePlane” to create an own ToF validation application and apply test limits for PASS/FAIL analysis. The individual test criteria and related limits have to be defined individually for the single customer.

The current implementation of the validatePlane software tool processes a raw dataset that typically contains 20 raw frames. These raw frames are further processed to result in

- 1 amplitude image for each modulation frequency (based on averaged raw data),
- 1 amplitude noise image for each modulation frequency (per-pixel standard deviation),
- 1 point cloud frame (based on averaged raw data).

All frames are acquired in a Validation Box environment with a structureless, diffusive reflectiving planar target at a fixed distance (e.g. 50 cm). In order to be able to identify an insufficient or imperfect calibration it is important that this distance is chosen in a way that it differs from the size of the Calibration Box 1 (LED Box [2]). The setup is designed so that all calibrated time-of-flight pixels should be able to record non-biased measurement data for evaluation.

The algorithms of the validatePlane software tool create various statistics values (e.g. mean or standard deviation) from the amplitude frames that can be used as test criteria. The point cloud data is used to evaluate accuracy by performing a plane fit and evaluating its key values (e.g. normal distance to the camera or per-pixel deviation from the plane). In addition the number of valid pixels is retrieved from the calibration data.

2. Amplitude data processing

The first processing step for the amplitude data is to create per-pixel statistics taking the 20 recorded frames into account. This yields the mean and the standard deviation for each pixel. In short, these image-size matrices of values are called MeanAmplitude and StddevsAmplitude, or simply “Mean” and “Stddevs”.

The second step of the processing is to reduce these data arrays to single scalar values by calculating the minimum, maximum, mean and standard deviation of each array. Within the validatePlane software these values are labeled as e.g.:

- “Amplitude1_MinOfMean”: the lowest pixel value of the averaged image for the first modulation frequency
- “Amplitude2_MeanOfStddevs”: the averaged standard deviation value for the second modulation frequency
- “Amplitude2_StddevsOfMean”: the standard deviation of averaged pixel values for the second modulation frequency.

The third step is to compare these scalar values with predefined lower and upper limits. Thus, in the current validatePlane implementation there exist in total 2x2x4x2 = 32 limits that are applied to the amplitude data.

Please note: The calibration data contains a mask of invalid pixels. These pixels are typically corner pixels or defect pixels. Before validatePlane calculates any statistics values, it applies this calibrated invalid pixel mask. Therefore if the calibration process is valid, there cannot be any defect pixels in the statistics (e.g. defect pixels with zero amplitude).

In the following subsections the most relevant limits are described in more detail.

2.1. MeanAmplitude

The MeanAmplitude is given by the averaged amplitude values of a static scene. Thus, the statistical, temporal noise has been reduced. A typical distribution of the MeanAmplitude recorded in a Validation Box is shown in Figure 1.

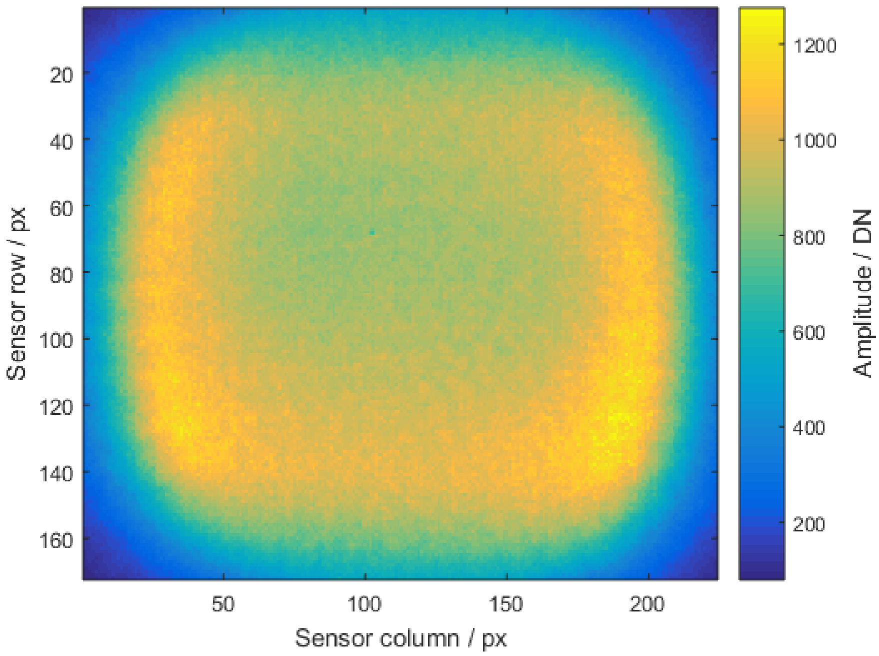

Figure 1: Example of a mean amplitude image

The values represent the modulated signal strength for every time-of-flight pixel, which is based on absolute optical power, optical power distribution, imager sensitivity and contrast, F-number and relative illumination of the lens, target reflectivity, filter glass absorption, and so on. There is a direct correlation between amplitude values and amplitude noise, phase noise and thus temporal noise of the distance measurements of a time-of-flight camera. Typically, a higher amplitude corresponds to less temporal noise.

Too low amplitude values indicate high temporal noise and thus the evaluation of device accuracy is limited. In contrast, too high amplitude values can indicate saturation and thus must be avoided during validation. Thus, the amplitudes must not exceed 1700 DN to avoid saturation. The best performing amplitude range is around 1400 DN. In the following some limits will be described in more detail.

2.1.1. MeanOfMean

The MeanOfMean value is an indicator for time-of-flight depth (noise) performance. The lower test limit corresponds to the minimum required depth performance (e.g. given by the CDD specification) whereas the upper limit is typically set to exclude saturation effects. In addition, for a fixed exposure time all devices should be within a reasonable amplitude range to ensure comparable device performance.

2.1.2. MinOfMean

The MinOfMean is given by the mean amplitude value of the worst performing pixel. Since validatePlane does not process defect pixels, the lower limit should be higher than zero. The upper limit will typically be set to exclude saturation. Since the MinOfMean only contains the information of one single pixel it cannot be used to e.g. rate the time-of-flight performance.

2.1.3. MaxOfMean

The MaxOfMean is given by the mean amplitude value of the brightest pixel. If this maximum is too high although the mean is within specification, this can indicate a hot spot within the illumination profile. By setting an appropriate upper limit these hot spots can be identified and the compliance of the time-of-flight camera with national or international eye safety regulations can be substantiated. The lower limit is of no importance and can thus be set to e.g. any value larger than the lower limit of MeanOfMean.

2.1.4. StddevsOfMean

The standard deviation of the mean amplitude of all pixels is an indicator for the homogeneity of the amplitude distribution. Thus it is a quality factor and must have reasonable upper and lower limits in accordance with performance requirements.

On top of this simple approach it might be reasonable to test the illumination profile according to the specification of the VCSEL in use. This more advanced approach might include precise tests of the actual beam profile, e.g. such as tests of the steepness of the rising and falling edges of the profile. However, such tests are not foreseen in the current implementation of the validatePlane software.

2.2. StddevsAmplitude

In accordance to the theoretical noise model of the time-of-flight camera there is a defined relationship between the amplitude and the amplitude's standard deviation. If this is not the case for a camera device, it is a strong indicator for unstable time-of-flight performance, e.g. due to unstable power supplies in the device or data transmission errors.

The relationship between mean amplitude and the amplitude's standard deviation is exemplarily depicted in Figure 2. The lower limit of MeanOfStddevs can be set in accordance to this correlation. Very large values of MeanOfStddevs may indicate hardware/power instabilities or transmission errors in the communication with the time-of-flight sensor. Currently, this should be accounted for by setting the upper limit of MeanOfStddevs to a value in the order of 6-8 DN. Future versions of the validatePlane software might include test criteria combining the MeanOfMeans and MeanOfStddevs.

The upper and lower limits for MinOfStddevs, MaxOfStddevs and StddevOfStddevs can be derived in analogy to the description above.

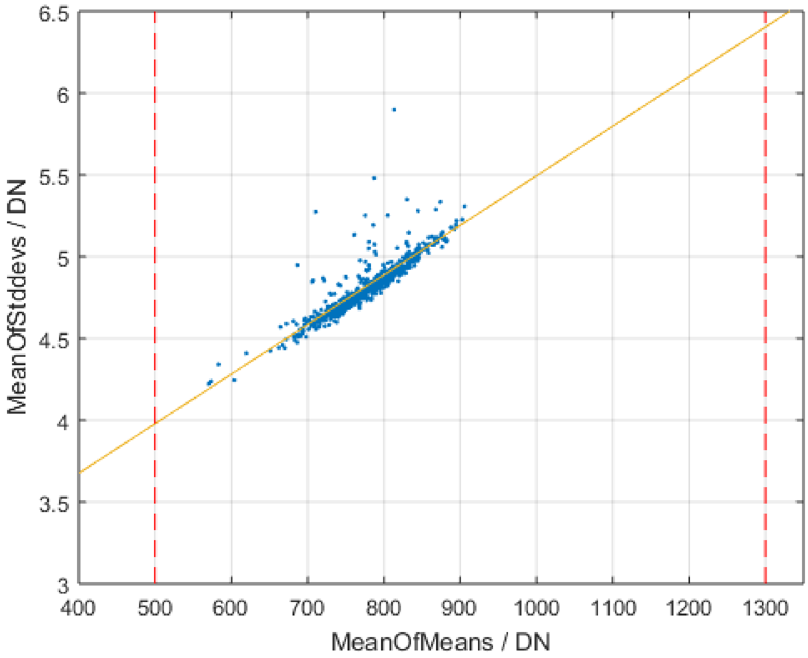

Figure 2: Correlation between MeanOfMeans and MeanOfStddevs

3. Point cloud data processing

3.1. Number of pixels

The pixel count of the point cloud (valid_pixel_count) represents the number of pixels that were not masked during module calibration. This flagging includes e.g. defect pixel removal or image corner pixels with too low optical signal. Since the test scene (Validation Box) should enable correct measuring for all pixels, the validatePlane software algorithm does not flag any additional pixels. It will therefore return the number of usable time-of-flight pixels stored in the calibration data, which was determined by the calibration process.

3.2. Plane fit

The point cloud consists of XYZ values of only non-masked pixels. Therefore all pixels can be used for a planar fit, performed using a least squares algorithm. The result is a plane vector, from which the plane distance and plane orientation can be deduced.

Since the XYZ data is only based on an intrinsic lens calibration, the calibrated plane distance should be the normal incident distance of the plane with respect to the so-called “entrance pupil position” of the lens. This position varies for different lenses and can be deduced from the lens design data. For the K6 lens this position is at the front of the lens.

In the following the limits applied to the point cloud data will be described in more detail.

3.2.1. Plane distance

The limits applied to the reconstructed plane distance should account for the true size of the Validation Box as well as for all related accuracy requirements given by the customer. In most cases and without special requirements a corridor of +/- 1 cm around the true distance has been proven to be good choice.

3.2.2. Plane error standard deviation

The “absolute plane error” of every pixel is deduced by calculating the normal distance of a pixel’s XYZ data to the fitted plane. The standard deviation of these values is a measure of the homogeneity of the plane and thus is a measure of single-shot data accuracy.

Note: The CDD defines accuracy in a slightly different way since it uses a quantile based definition (see Section 3.2.5).

3.2.3. Maximum plane error

The maximum plane error (plane_error_max) is given by the largest deviation of one single pixel from the plane fit. Since this distance error is a combination of calibration (in-) accuracy and remaining noise due to (low) signal strength after averaging 20 frames, its upper limit should be set at some value close to the maximum allowed error in the processing chain. This means if the limit is exceeded there is a significant calibration inaccuracy which likely indicates a defect pixel that should have been detected and masked during module calibration.

3.2.4. Plane angle

The plane orientation is more or less arbitrary since it is only based on an intrinsic lens calibration. A small tilt of the plane is therefore absolutely valid and does not impair accuracy or 3D performance. After an extrinsic lens calibration on device level the plane orientation will be corrected using a rotation matrix. A large tilt however indicates some irregular rotation of the device under test and thus could have impact on the other test parameters.

3.2.5. Q90 of normalized depth error

The CDD is currently the most prominent requirement specification of ToF devices. Therein, 3D data quality is evaluated in terms of the 90% quantile of the relative deviation between measurement and ground truth for a single shot measurement. In the validatePlane software this definition is accounted for by the Q90norm parameter, given as the 90% quantile of the relative deviation from the point cloud with respect to the planar target of the Validation Box. The upper limit of Q90norm is typically set to 1%, in accordance to the CDD specification.

4. Current test limits

The below test limits can be used as a starting point for developing reasonable test limits. The labels should be in correspondence with the explanation of sections 2 and 3.

Note: All limits provided by pmd are defined in close contact with the individual customer but are to be understood as proposals only. The ODM/OEM is responsible for the final definition of the limits.

Amplitude Limits	Amplitude1		Amplitude2	
MeanOfMeans_LimitLow (Amplitude1)	400	DN	500	DN
MeanOfMeans_LimitHigh (Amplitude1)	900	DN	1100	DN
MinOfMeans_LimitLow (Amplitude1)	12	DN	15	DN
MinOfMeans_LimitHigh (Amplitude1)	900	DN	1100	DN
MaxOfMeans_LimitLow (Amplitude1)	580	DN	700	DN
MaxOfMeans_LimitHigh (Amplitude1)	1400	DN	1700	DN
StddevOfMeans_LimitLow (Amplitude1)	5	DN	5	DN
StddevOfMeans_LimitHigh (Amplitude1)	280	DN	340	DN
MeanOfStddevs_LimitLow (Amplitude1)	3	DN	3.5	DN
MeanOfStddevs_LimitHigh (Amplitude1)	5.5	DN	6	DN
MinOfStddevs_LimitLow (Amplitude1)	0	DN	0	DN
MinOfStddevs_LimitHigh (Amplitude1)	8	DN	8	DN
MaxOfStddevs_LimitLow (Amplitude1)	0	DN	0	DN
MaxOfStddevs_LimitHigh (Amplitude1)	100	DN	100	DN
StddevOfStddevs_LimitLow (Amplitude1)	0.1	DN	0.1	DN
StddevOfStddevs_LimitHigh (Amplitude1)	10	DN	10	DN
Pointlcoud Limits				
PixelCount	37000	-		
ErrorStddev_LimitLow	0	m		
ErrorStddev_LimitHigh	0.005	m		
MaxError_LimitLow	0	m		
MaxError_LimitHigh	0.1	m		
Distance_LimitLow	0.49	m		
Distance_LimitHigh	0.50	m		
NormalAngle_LimitHigh	2.5	°		
Q90 of normalized depth error	0.8	%		

Table 1: Exemplary list of test limits

5. Literature

[1] pmdtechnologies ag, „Cal-1-1-AN - Validation Box," 2016.

[2] pmdtechnologies ag, „Cal-1-2-AN - Calibraton Box 1," 2015.

Document History

Document title: ToF Validation – CAL-6-1-AN

Revision	Origin of Change	Submission Date	Description of Change
0	UFr	2016-10-07	New Application Note