# Quantum software test limits

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## Abstract

This document provides additional information about the Quantum software 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.

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## 1. Introduction

The aim of the Quantum software is to provide an easy to use application for testing pmd sensor based ToF systems. The individual test criteria and related limits have to be defined individually for the single customer. The software is supposed to be suitable for testing predefined performance critera as well as to identify hardware failures e.g. in the framework of an incoming or outgoing quality control (IQC or OQC).

The current implementation of the Quantum software processes:

- 20 amplitude frames (all pixels, including invalid/defect pixels, 8 bit resolution),
- 1 point cloud frame (XYZ data, 32 bit floats, only valid pixels).

All frames are acquired in a Validation Box [1] environment with a structureless, diffusive reflectiving planar target at a fixed distance (e.g. 50 cm). 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 Quantum software 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 this dataset.

## 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 minimum and maximum values as well as the mean and the standard deviation for each pixel. In short, these image-size matrices of values are called MinAmplitude, MaxAmplitude, MeanAmplitude, StddevAmplitude, or simply “Min”, “Max”, “Mean”, “Stddev”.

The second step of the processing is to reduce these data arrays to single scalar values by calculating the same statistics values again. This yields the minimum, maximum, mean and standard deviation for each array. In Quantum, these values are labeled as e.g.:

- “MinOfMeans”: the lowest pixel value of an averaged image
- “MeanOfStddevs”: the averaged standard deviation value
- “StddevOfMeans”: the standard deviation of averaged pixel values.

The third step is to compare these scalar values with predefined lower and upper limits. Thus, in the current Quantum implementation there exist in total 2x4x4 = 32 limits that are applied to the amplitude data.

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 is shown in Figure 1.

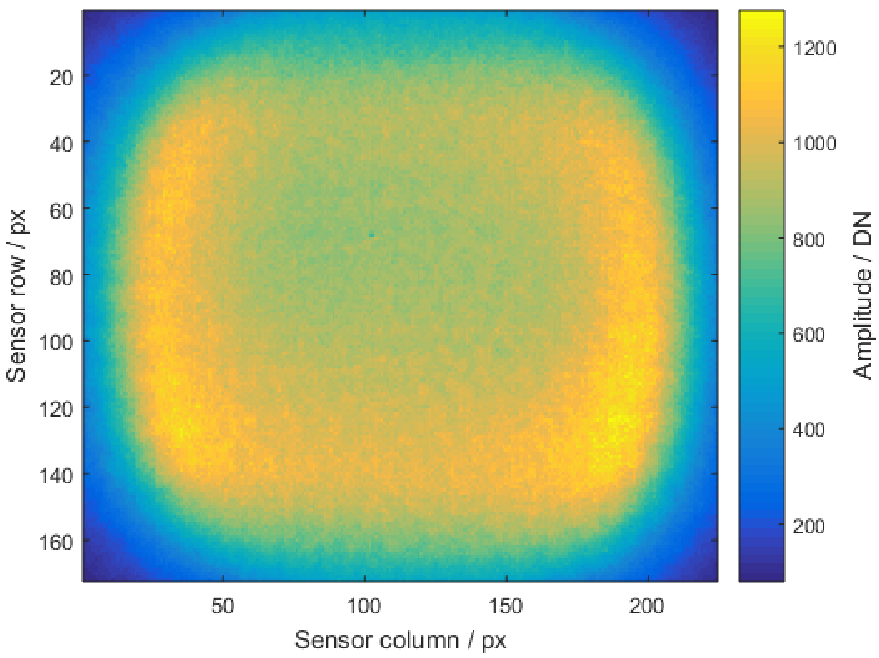


**Figure 1: Example of a mean amplitude image**

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. MeanOfMeans

The MeanOfMeans 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. MinOfMeans

The MinOfMeans is given by the mean amplitude value of the worst performing pixel. If the amplitude data does not only contain valid pixels but also defect pixels the lower limit will be set to zero in order to tolerate these pixels. The upper limit will typically be set to exclude saturation. Since the MinOfMeans only contains the information of one single pixel it cannot be used to e.g. rate the time-of-flight performance.

#### 2.1.3. MaxOfMeans

The MaxOfMeans 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 MeanOfMeans.

#### 2.1.4. StddevOfMeans

The standard deviation of all pixels of the mean amplitude profile 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 Quantum software but might be implemented in future versions.

### 2.2. MinAmplitude and MaxAmplitude

Far pixel deviations from the MeanAmplitude values are a strong indicator for performance stability issues (e.g. power supply instabilities). Typically, it is safe to keep all corresponding limits of MinAmplitude and MaxAmplitude identical to the MeanAmplitude limits.

## 2.3. StddevAmplitude

Some StddevAmplitude test criteria are strong indicators for unstable time-of-flight performance, e.g. due to unstable power supplies in the device.

In the following some limits will be described in more detail.

### 2.3.1. MeanOfStddevs

In accordance to the theoretical noise model of the time-of-flight camera there is a defined relationship between mean amplitude and the amplitude's standard deviation (see Figure 2). The lower limit of MeanOfStddevs can be set in accordance to this correlation. Large values of MeanOfStddevs indicate transmission errors in the communication with the time-of-flight sensor. In the current version of the Quantum software this is accounted for by setting the upper limit of MeanOfStddevs to a value in the order of 6-8 DN. Future versions of the Quantum software might include test criteria combining the MeanOfMeans and MeanOfStddevs.

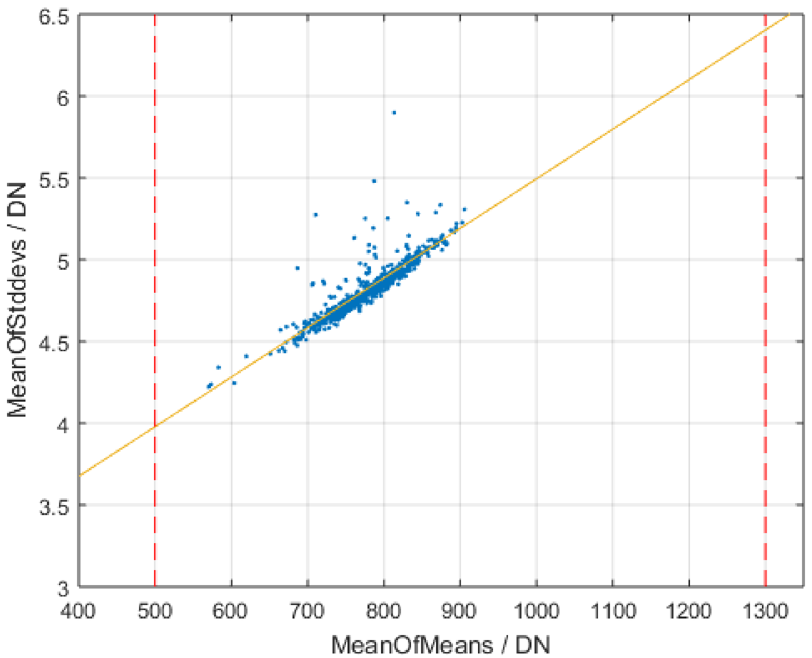


**Figure 2: Correlation between MeanOfMeans and MeanOfStddevs**

### 2.3.2. MinOfStddevs, MaxOfStddevs and StddevOfStddevs

The interpretations of these test criteria are not straight forward, i.e. when the amplitude values are downscaled or quantized. Therefore, in the current version of the Quantum software the corresponding limits are set to values far beyond typical distributions of the criteria. If the amplitude data does not only contain valid pixels but also defect pixels the lower limit of MinOfStddevs will be set to zero in order to tolerate these pixels. In case the amplitude data is not quantized and does only contain valid pixels, the lower limit of MinOfStddevs could be set to a value larger than zero and can thus be used as an indicator for defective pixels. For future versions of the Quantum software the test criteria will be modified or even completely removed.

# 3. Point cloud data processing

## 3.1. MinPixels

The pixel count of the point cloud represents the number of pixels that have passed all flagging criteria within the processing pipeline. This flagging includes defect pixel removal of pixels that have been identified during module calibration, image corner pixels with too low optical signal as well as scene dependent flagging. Since the test scene (Validation Box) should enable correct measuring for all pixels, the pixel count should be equal or close to the maximum number of usable time-of-flight pixels. Also performance requirements given by the individual customer can be reflected in the MinPixels criterion.

## 3.2. Plane Fit

The point cloud consists of XYZ values of only valid 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. Please note: It is usually not the distance measured from the surface of the device. The shift of the XYZ data to some arbitrary point with respect to the device is done by applying an extrinsic lens calibration. This, however, is currently not part of a calibration on module level.

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

### 3.2.1. Distance_LimitLow and Distance_LimitHigh

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. ErrorStddev_LimitHigh

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.

<u>Note</u>: The CDD defines accuracy in a slightly different way since it uses a quantile based definition. In future versions of the Quantum software a more CDD-like test criterion “Q90Norm” will be implemented.

### 3.2.3. MaxError_LimitHigh

The PointCloud::MaxError 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 noise due to (low) signal strength, its upper limit should be set at some value close to the maximum allowed temporal noise 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. NormalAngle_LimitHigh

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 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.

## 4. Current test limits

At the time of writing this document, all test limits in the Quantum software are defined in one file “TestLimits.h”. As reference, typical contents can be seen below. The labels should be in correspondence with the explanation of sections 0 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.**

```
// TestAmplitudes parameters
const float TestLimits::Amplitudes::MeanOfMeans_LimitLow = 500.0f;
const float TestLimits::Amplitudes::MeanOfMeans_LimitHigh = 1300.0f;
const float TestLimits::Amplitudes::MinOfMeans_LimitLow = 0.0f;
const float TestLimits::Amplitudes::MinOfMeans_LimitHigh = 500.0f;
const float TestLimits::Amplitudes::MaxOfMeans_LimitLow = 800.0f;
const float TestLimits::Amplitudes::MaxOfMeans_LimitHigh = 1700.0f;
const float TestLimits::Amplitudes::StddevOfMeans_LimitLow = 100.0f;
const float TestLimits::Amplitudes::StddevOfMeans_LimitHigh = 500.0f;

const float TestLimits::Amplitudes::MeanOfMins_LimitLow = 500.0f;
const float TestLimits::Amplitudes::MeanOfMins_LimitHigh = 1300.0f;
const float TestLimits::Amplitudes::MinOfMins_LimitLow = 0.0f;
const float TestLimits::Amplitudes::MinOfMins_LimitHigh = 500.0f;
const float TestLimits::Amplitudes::MaxOfMins_LimitLow = 800.0f;
const float TestLimits::Amplitudes::MaxOfMins_LimitHigh = 1700.0f;
const float TestLimits::Amplitudes::StddevOfMins_LimitLow = 100.0f;
const float TestLimits::Amplitudes::StddevOfMins_LimitHigh = 500.0f;

const float TestLimits::Amplitudes::MeanOfMaxs_LimitLow = 500.0f;
const float TestLimits::Amplitudes::MeanOfMaxs_LimitHigh = 1300.0f;
const float TestLimits::Amplitudes::MinOfMaxs_LimitLow = 0.0f;
const float TestLimits::Amplitudes::MinOfMaxs_LimitHigh = 500.0f;
const float TestLimits::Amplitudes::MaxOfMaxs_LimitLow = 800.0f;
const float TestLimits::Amplitudes::MaxOfMaxs_LimitHigh = 1700.0f;
const float TestLimits::Amplitudes::StddevOfMaxs_LimitLow = 100.0f;
const float TestLimits::Amplitudes::StddevOfMaxs_LimitHigh = 500.0f;

const float TestLimits::Amplitudes::MeanOfStddevs_LimitLow = 1.0f;
const float TestLimits::Amplitudes::MeanOfStddevs_LimitHigh = 8.0f;
const float TestLimits::Amplitudes::MinOfStddevs_LimitLow = 0.0f;
const float TestLimits::Amplitudes::MinOfStddevs_LimitHigh = 8.0f;
const float TestLimits::Amplitudes::MaxOfStddevs_LimitLow = 1.0f;
const float TestLimits::Amplitudes::MaxOfStddevs_LimitHigh = 50.0f;
const float TestLimits::Amplitudes::StddevOfStddevs_LimitLow = 0.0f;
const float TestLimits::Amplitudes::StddevOfStddevs_LimitHigh = 8.0f;

// TestPixelCount parameters
const unsigned TestLimits::PixelCount::MinPixels = 37000;

// TestPointCloud parameters
const float TestLimits::PointCloud::ErrorStddev_LimitHigh = 0.003f;
const float TestLimits::PointCloud::MaxError_LimitHigh = 0.1f;
const float TestLimits::PointCloud::Distance_LimitLow = 0.491f;
const float TestLimits::PointCloud::Distance_LimitHigh = 0.509f;
const float TestLimits::PointCloud::NormalAngle_LimitHigh = 2.5f;
```

## 5. Literature

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

## Document History

Document title: quantum software test limits – CAL-10-1-AN

| Revision | Origin of Change | Submission Date | Description of Change |
|---|---|---|---|
| 0 | SBe | 2016-07-21 | New Application Note |
| 1 | UFr | 2016-09-15 | Update due to current interpretation of test limits |