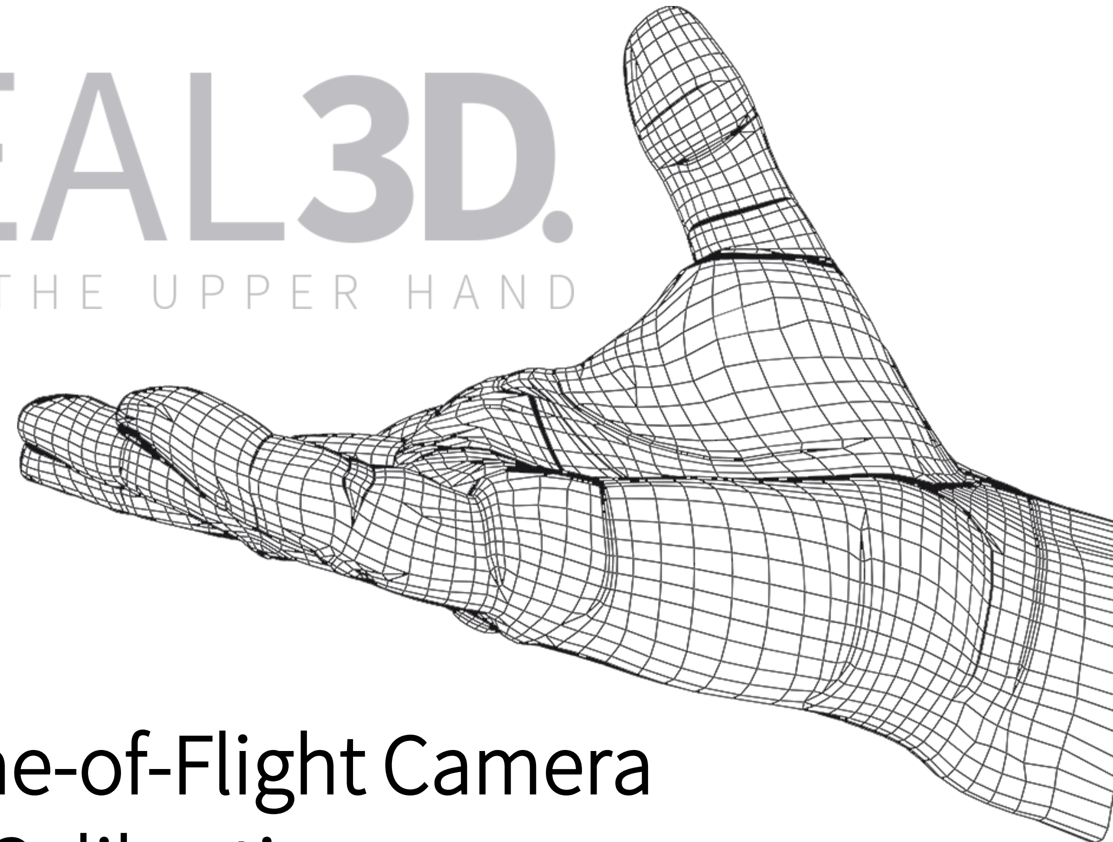
REAL3D.
GAIN THE UPPER HAND



pmd Time-of-Flight Camera Calibration

Calibration overview

pmdtechnologies – 30-06-2016

Outline

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- Calibration Basics / Prototype Calibration
- Calibration in Mass Production (1)
  - What needs to be calibrated?
- Calibration in Mass Production (2)
  - Box Calibration
- Customer support

Motivation

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Why do time-of-flight cameras need to be calibrated?

- Cameras are not inherently perfect.

- Global effects:
  - Evaluate once for every camera type.
  - Globally correct for all cameras of the same type.

- Individual effects
  - Evaluate for each individual camera.
  - Individually correct for each camera.

Calibration of time-of-flight cameras is very important for good quality, both for prototypes and for mass production.

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Camera calibration

Calibration Basics / Prototype Calibration

Calibration topics

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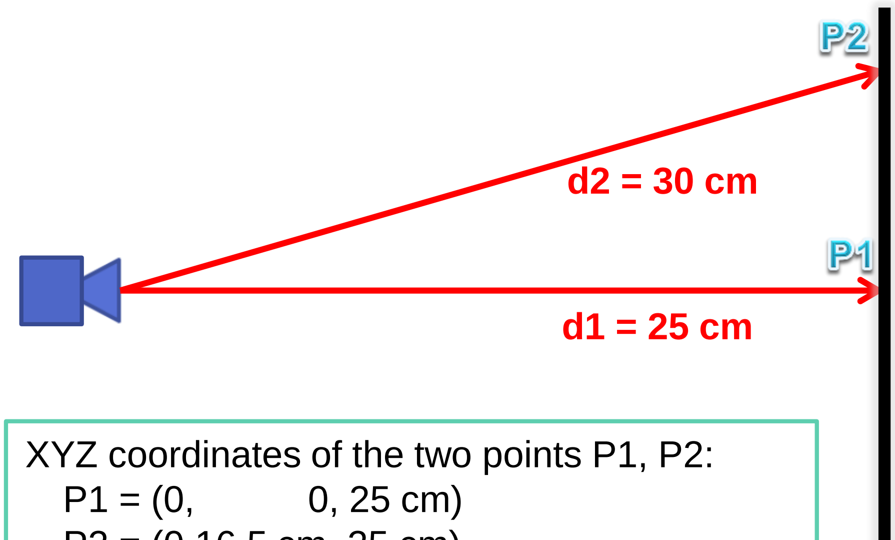
- **Lens calibration**
  - Cartesian 3D coordinates from distance data (via lens parameters)
- **FPN (fixed pattern noise)**
  - Every pixel has an individual intensity offset
- **FPPN (fixed phase pattern noise)**
  - Every pixel has an individual distance offset
- **Temperature drift**
  - Measured distances shift over temperature
- **Wiggling**
  - Phase-dependent corrections
- **Illumination mask**
  - Mismatch of field-of-views of illumination and sensor
- **Noise parameters**
  - Noise prediction from amplitude values

Lens calibration (1)

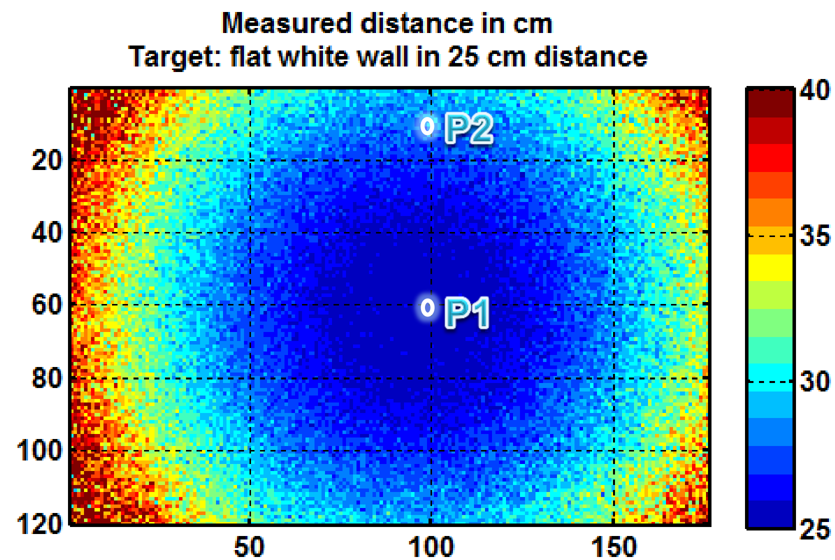
Background:

- A time-of-flight pixel measures a radial distance only.
- 3D coordinate calculation (XYZ) require knowledge of the direction, in which every pixel looks.

Example: Flat white wall in 25 cm distance



XYZ coordinates of the two points P1, P2:
P1 = (0, 0, 25 cm)
P2 = (0,16.5 cm, 25 cm)



The viewing angles depends on

- focal length and lens distortion parameters
- lateral positioning of the lens in respect to the sensor chip

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Lens calibration (2)

Recommended calibration procedure (prototypes):

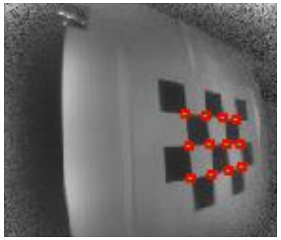
- Take intensity images of checkerboard patterns from different viewing angles.
- Use free software libraries (e.g. OpenCV) to calculate all lens parameters.

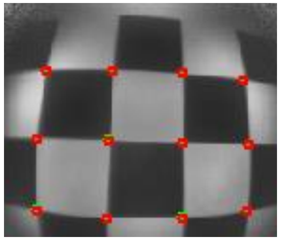
Comment:

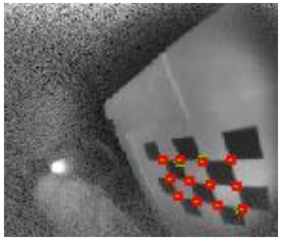
- Whether or not global values may be used depends on:
  - manufacturing precision of the lens (focal length, lens distortion)
  - manufacturing precision of the camera module (lateral positioning of the lens and the sensor chip)
  - the required absolute measurement precision.

For example (PicoS lens): Lateral positioning tolerances of 10 µm lead to an additional 3D coordinate error of 4 mm per meter viewing distance when using global lens parameters.

Example views for lens calibration:







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FPN (pixel offsets for intensity image)

Background:

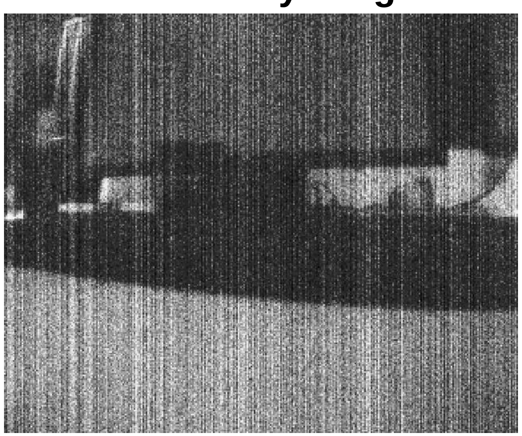
- The intensity image shows a so-called “fixed pattern” (well-known from 2D imagers)
- This pattern has no impact on the distance/amplitude images. It is only relevant if an intensity image output is desired (currently only used for distance noise calculation).

Recommended calibration procedure:

- Measure the offset image with gray scale images with low exposure times

  (No special setup required, very fast calibration step).

Intensity image



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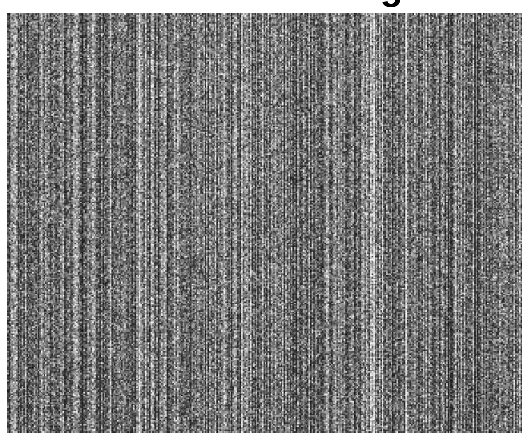
Pixel offset image



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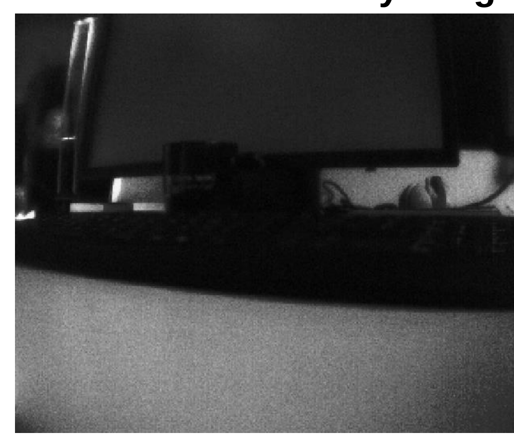
Offset free intensity image



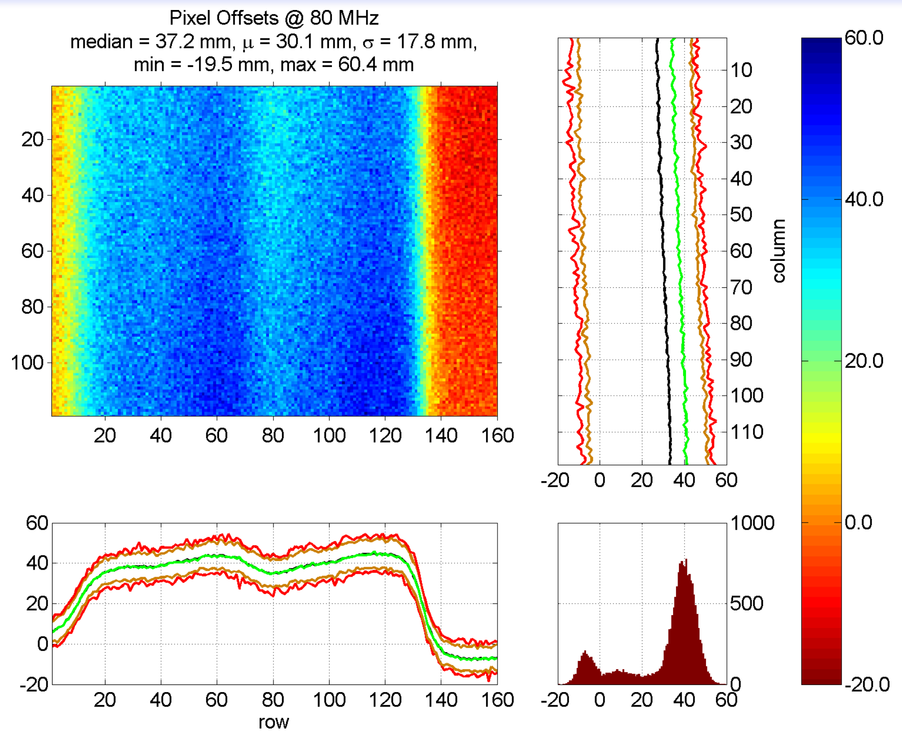
FPPN (pixel offsets of phase images)

Background:

- Every pixel has an individual distance offset (about max. 8 cm deviations @ 80 MHz).
- The pixel offsets are random due to the manufacturing process and need to be calibrated.

Recommended calibration procedure:

- Measure the distance of a known flat bright surface (multiple images to avoid noise).
- Calculate the pixel offsets image applying the lens parameters.



Temperature drift

Background:

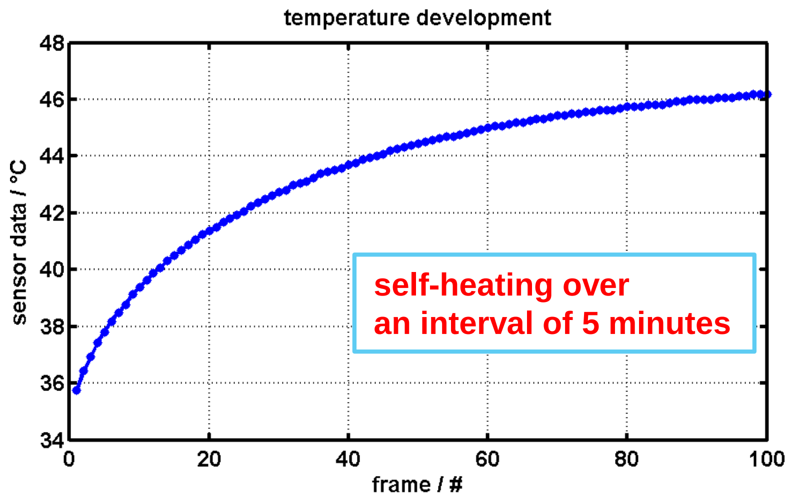
- Measured distances change with temperature.
- A typical camera module heats up over several minutes of operation and the offsets have to be adjusted.

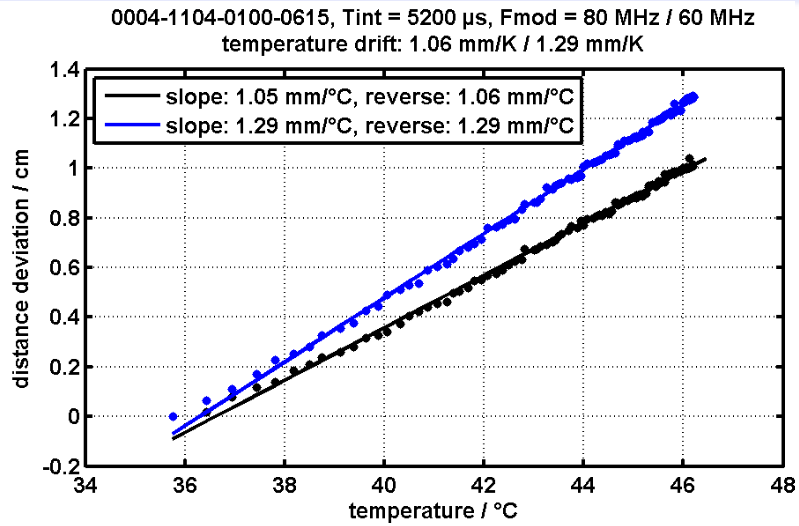
Recommended calibration procedure:

- Aim the camera at a static target (e.g. a white wall).
- Start the camera and track distance and temperature values.
- Create look-up-table or use an appropriate fit function for compensation (e.g. linear)
- <u>Alternative</u>: cool and pre-heat the camera to defined temperatures and measure the distance

Comment:

- Cameras of the same model behave similar and global parameters can be used (if heat dissipation is similar)





Phase Wiggling

Background:

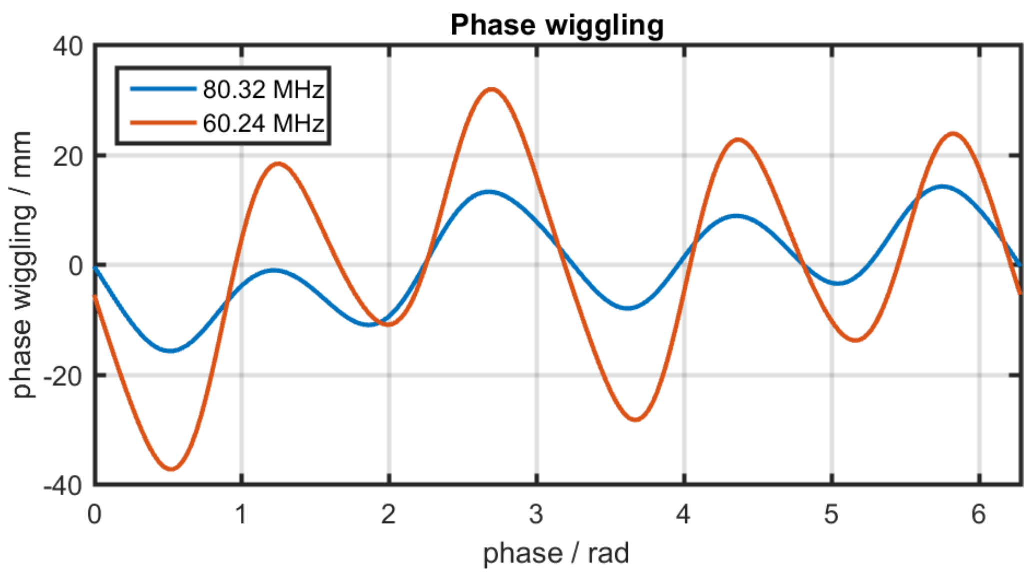
- pmd-tof measurement correlates optical and electrical modulation signals and yields a phase value. The used calculation method assumes perfect sinusoidal signals of the multiple phase delayed measurements. In reality, signals and timings are not perfect. This leads to errors in the calculated phase values, which are systematical for each individual camera system.

Recommended calibration procedure:

- Mount a camera system on a linear translation stage and measure the phase error for several distances.
- Compensation can be achieved either by appropriate fit functions or by look-up-table.

Comment :

- If absolute precision in the cm range is required, wiggling needs to be compensated.



Usually cameras of the same model show a similar wiggling error. A global calibration setting may be applied. <u>Note</u>: Due to manufacturing tolerances (e.g. illumination driver), the wiggling can change significantly. Therefore care has to be taken that signal shapes stay sufficiently similar and a global wiggling compensation should at least be verified regularly.

Amplitude Wiggling

Background:

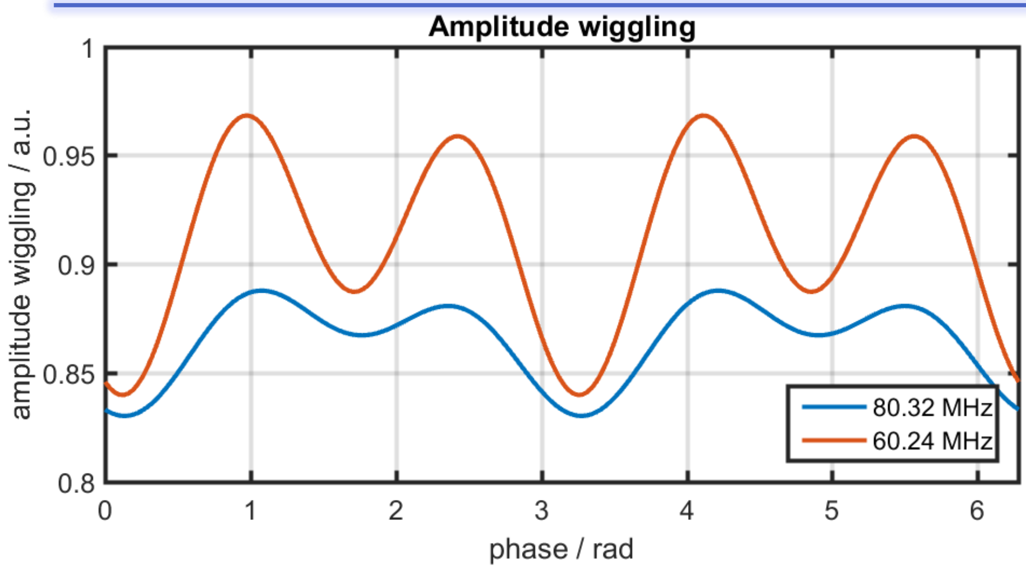
- The amplitude of a pmd-tof measurement represents the signal strength of the correlation between optical and electrical modulation signals. The magnitude depends on the intensity of received modulated light, the demodulation contrast, the actual signal shapes and on the phase shift value. The phase dependence is called “amplitude wiggling”. Calibrated amplitudes can be used for data consistency checks.

Recommended calibration procedure:

- Mount a camera system on a linear translation stage and measure amplitude, phase and intensity for several distances. The ratio of amplitude and intensity exposes the amplitude wiggling.
- Compensation can be achieved either by appropriate fit functions or by look-up-table.

Comment :

- Amplitude wiggling has no direct impact on the actual distance values.



Illumination Mask

Background:

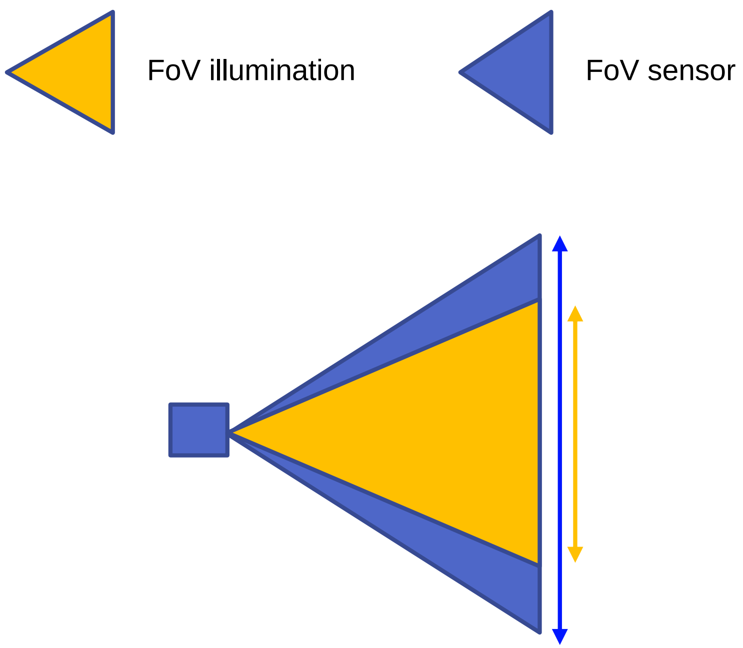
- The illumination FoV (field-of-view) and the sensor FoV may not match.
- Not-illuminated areas in the sensor FoV need to be masked, as they may yield false measurements

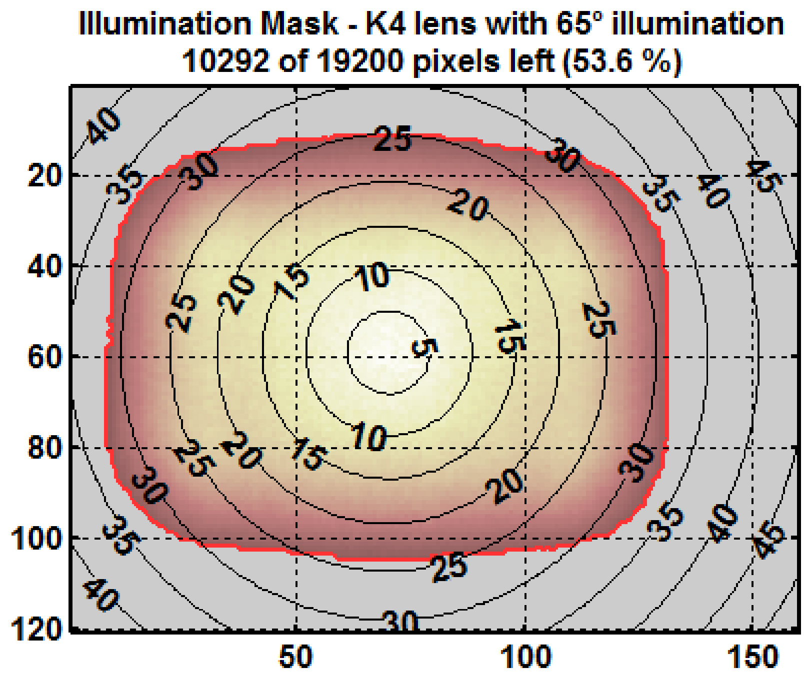
Recommended calibration procedure:

- Aim the camera at a flat white surface
- Apply appropriate amplitude limits

Comment:

- This step may not be necessary, if the different FoVs match.





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Noise parameters

Background:

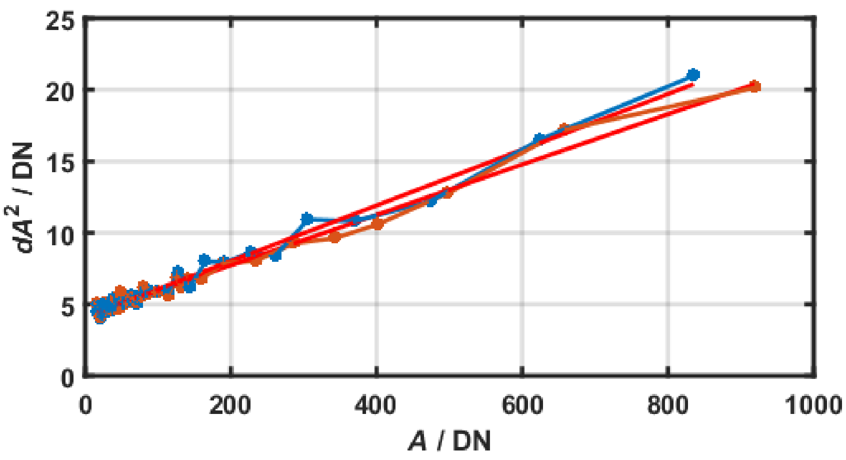
- The strength of the correlation signal in a pmd-tof camera measurement (the “amplitude”) and the background light intensity (e.g. sunlight) fully determine the phase measurement noise. A calibrated pmd camera can therefor predict the noise for a distance measurement of every individual pixel. This information can be used for post-processing algorithms.

Recommended calibration procedure:

- Mount a camera system on a static setup and measure the amplitude noise while varying exposure time and background light intensity.

Comment:

- The noise parameters are system specific, but do not vary significantly for individual devices. A quick-check of the phase noise for a given amplitude measurement during calibration is sufficient to confirm the validity of global noise parameters (e.g. during FPPN calibration).



Phase noise from amplitude noise:

$$d\varphi = \frac{dA}{A}$$

Linear correspondence:

$$dA^2 = aA + b + cI$$

φ: phase
A: amplitude
I: intensity (background light)
a, b, c: fit values

(below SBI threshold)

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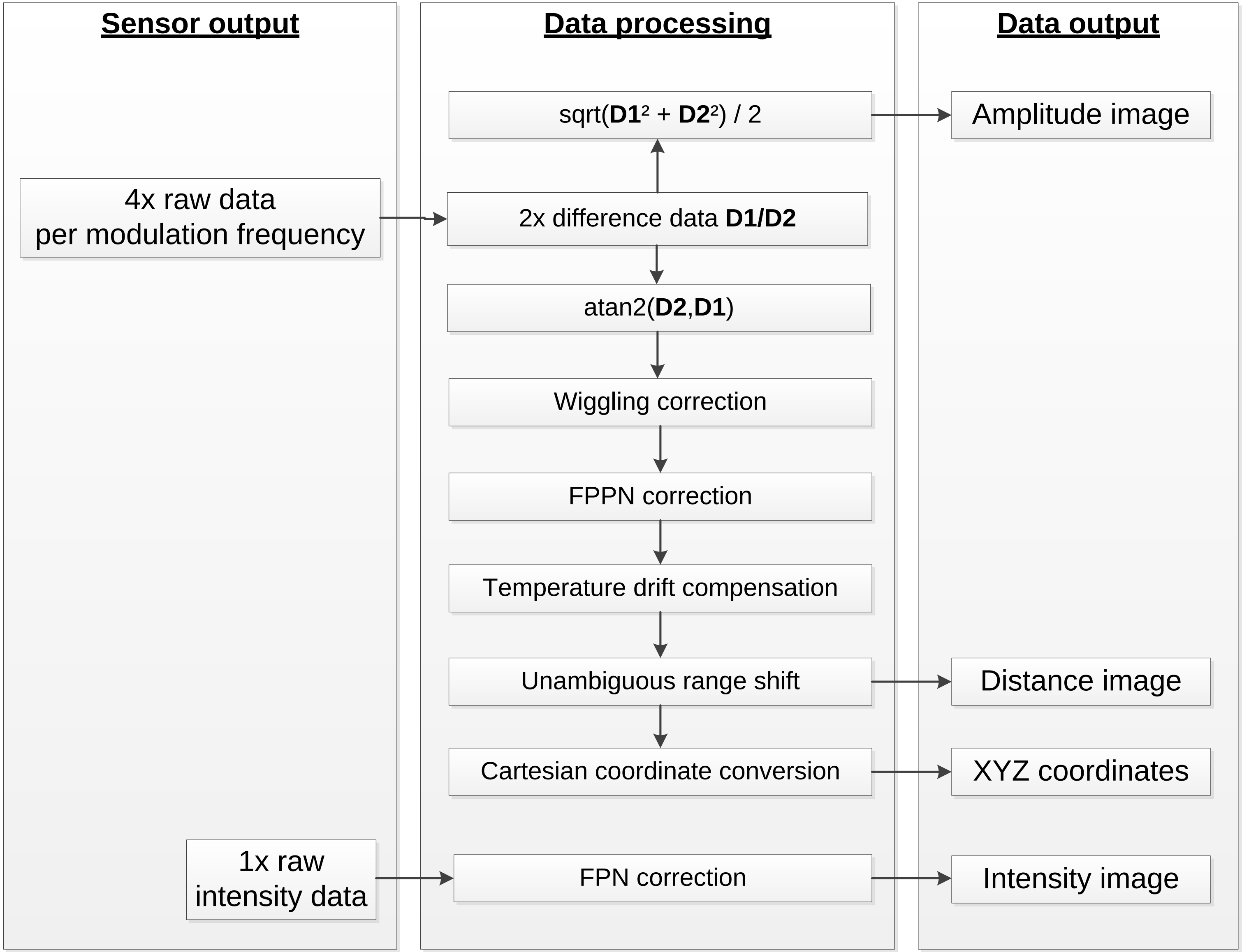
Data processing chain



c o n f i d e n t i a l

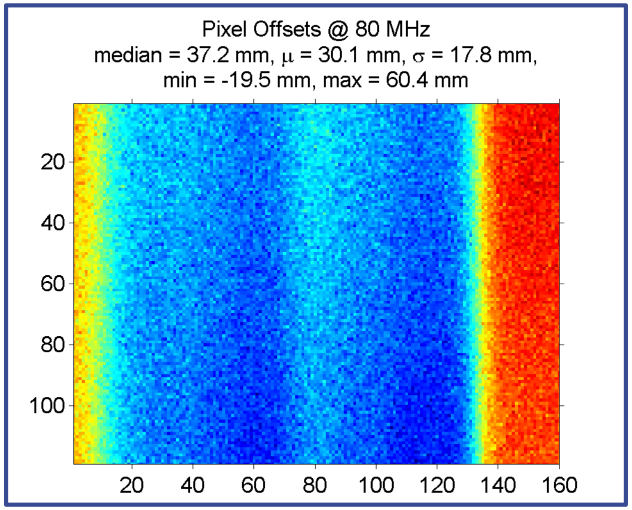
Camera calibration

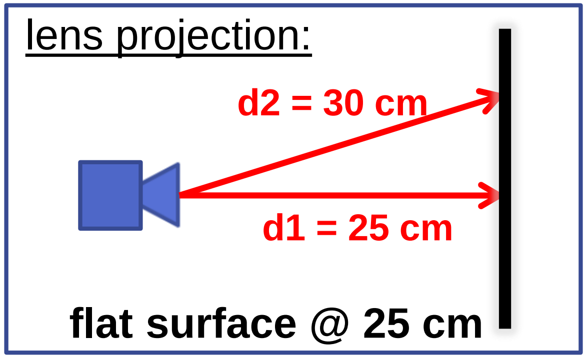
Calibration in Mass Production (1) What needs to be calibrated?

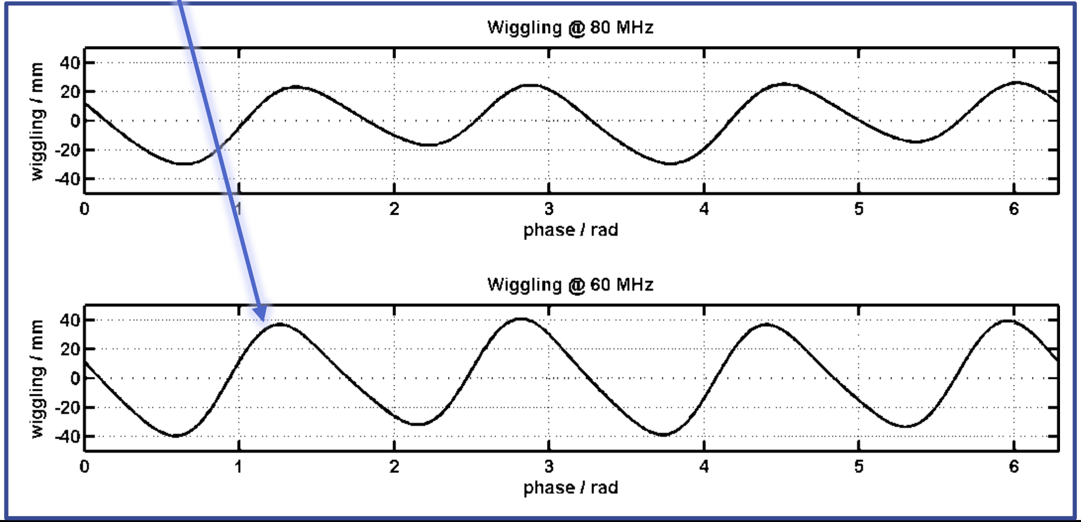
What *really* needs to be calibrated?

Current status based on experience and analysis of prototype calibrations of first batch:

- Lens calibration:
  - lens tolerances/positioning inaccuracy
- FPPN:
  - individual pixel distance offsets: **8 cm**
- ~~Temperature drift: global parameters~~ (see statistics)
- Wiggling:
  - systematic distance error
    as function of distance: **2 cm to 8 cm** (peak-to-peak, depends on system)

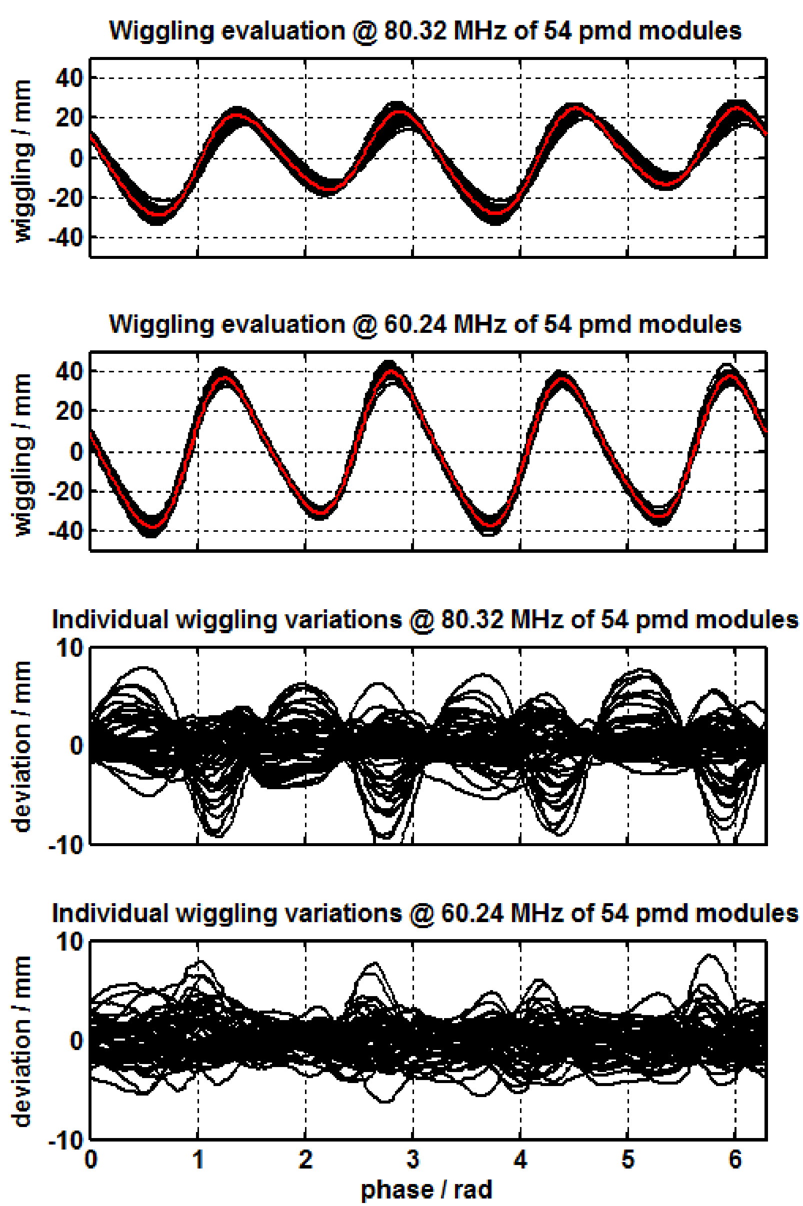


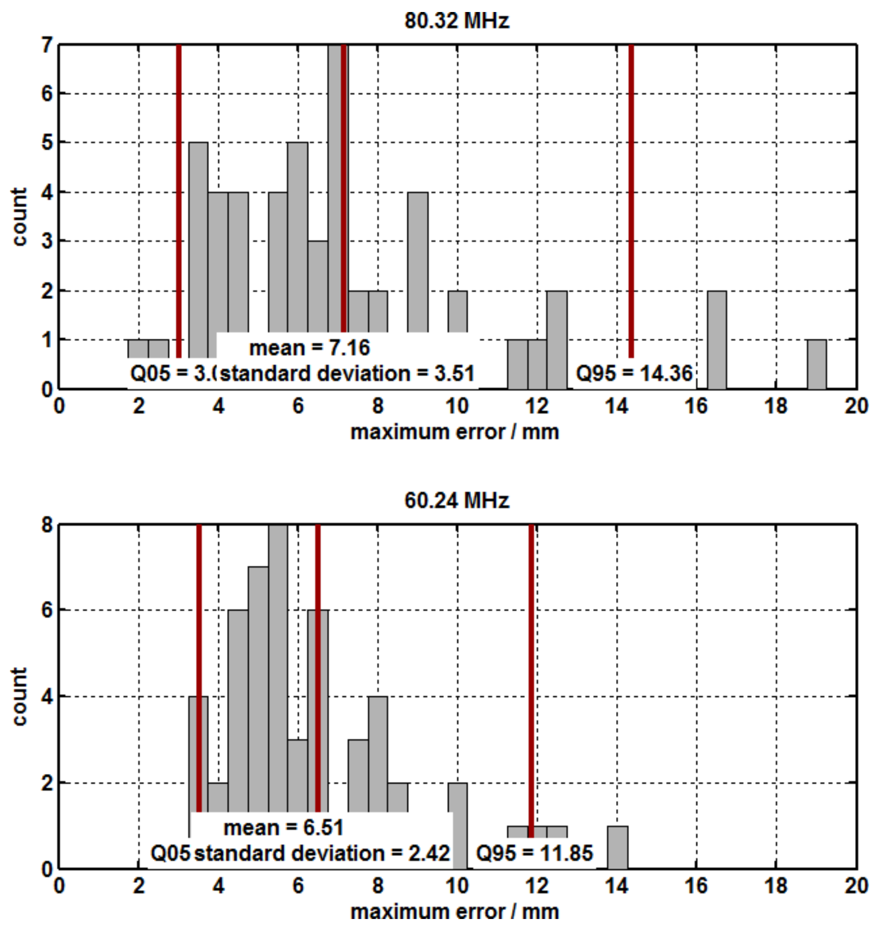




Statistics of standard wiggling calibrations

Prototypes, Summer 2014





“maximum error”
= peak-to-peak deviation if using global calibration

PicoFlexx phase wiggling statistics

August 19, 2015

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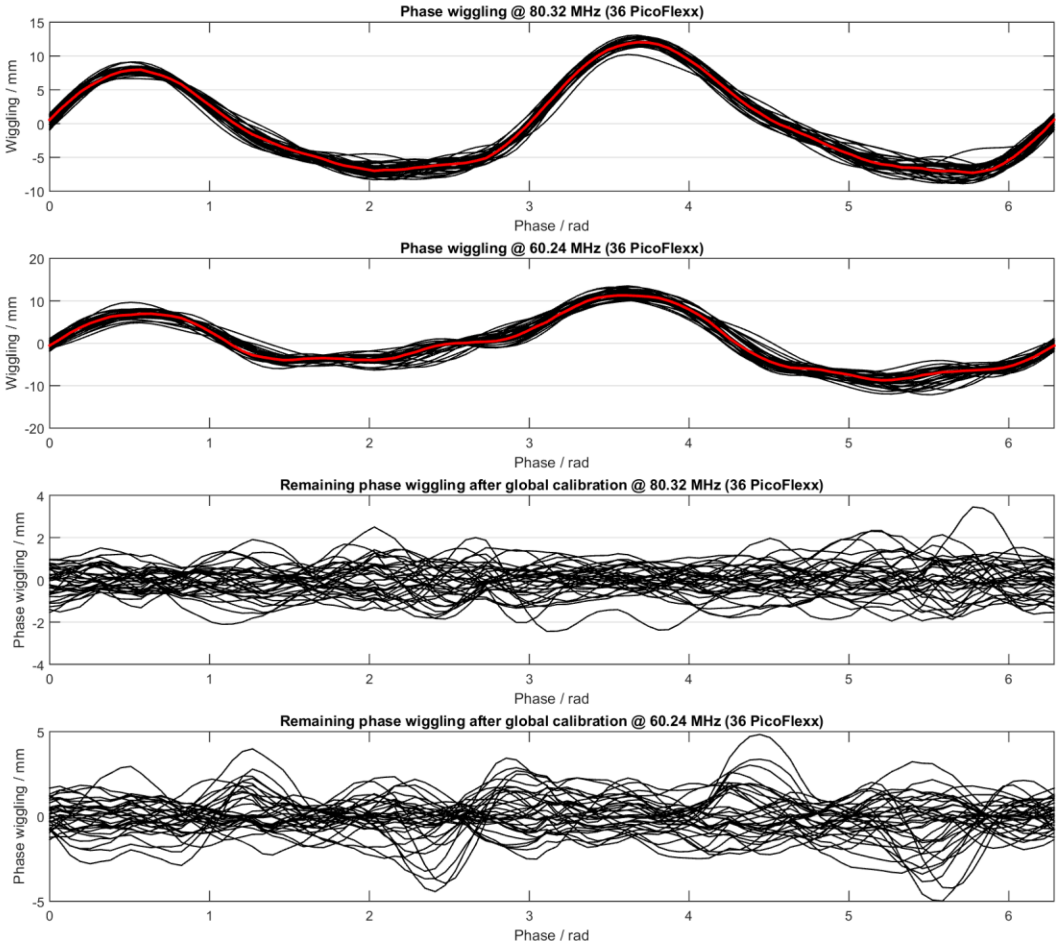
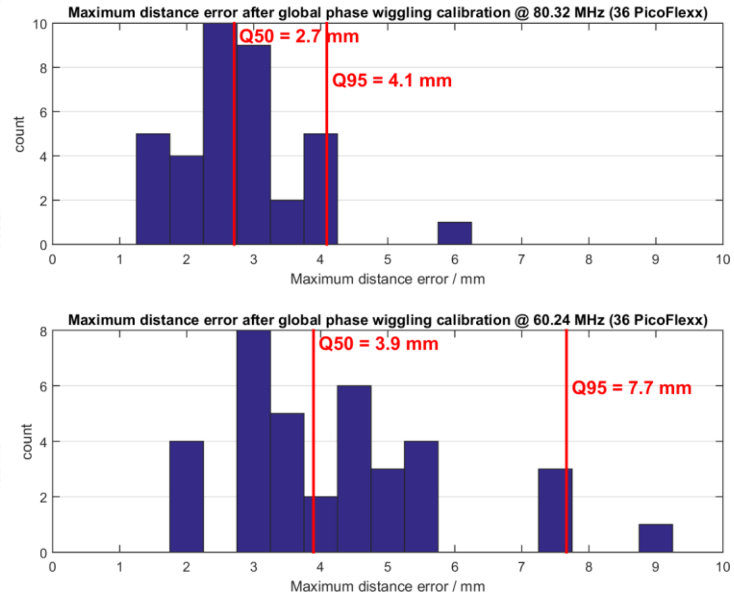
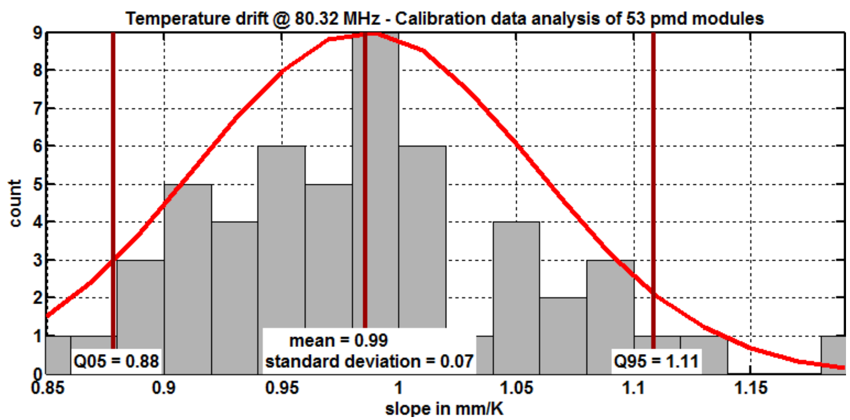
- Newer generation pmd modules:

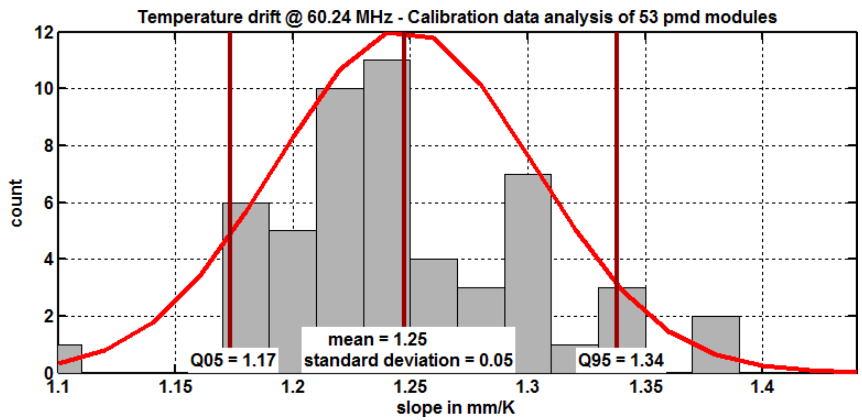




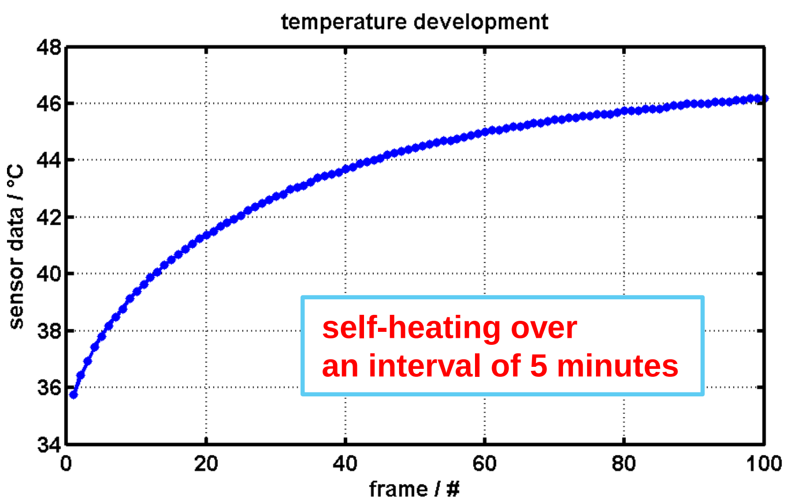
“maximum error”
= peak-to-peak deviation if using global calibration

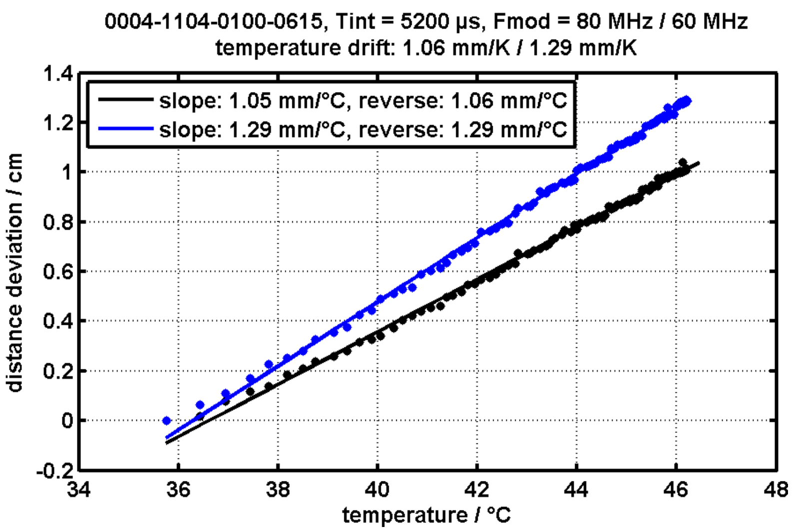
Statistics of temperature drift calibration





Exemplary calibration data:





Achievable accuracy without calibration

	without calibration	global calibration	with calibration
FPPN	8 cm	n/a	< 0.5 cm
Wiggling	2 cm to 8 cm	1 cm to 2 cm	< 0.5 cm
Lens	n/a	depending on manufacturing tolerances	< 1 %

c o n f i d e n t i a l

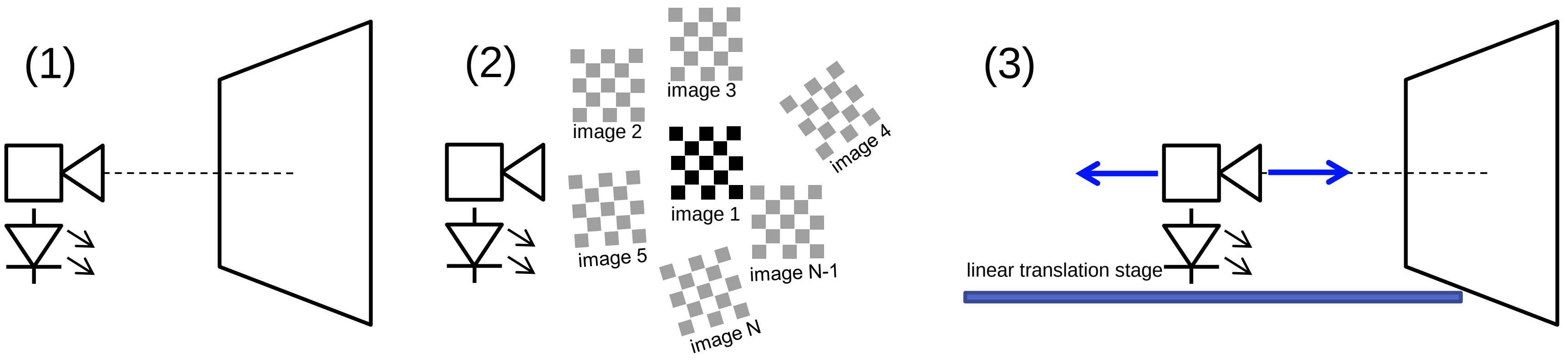
Camera calibration

Calibration in Mass Production (2)
Box Calibration

Calibration – how to (prototypes)

c o n f i d e n t i a l

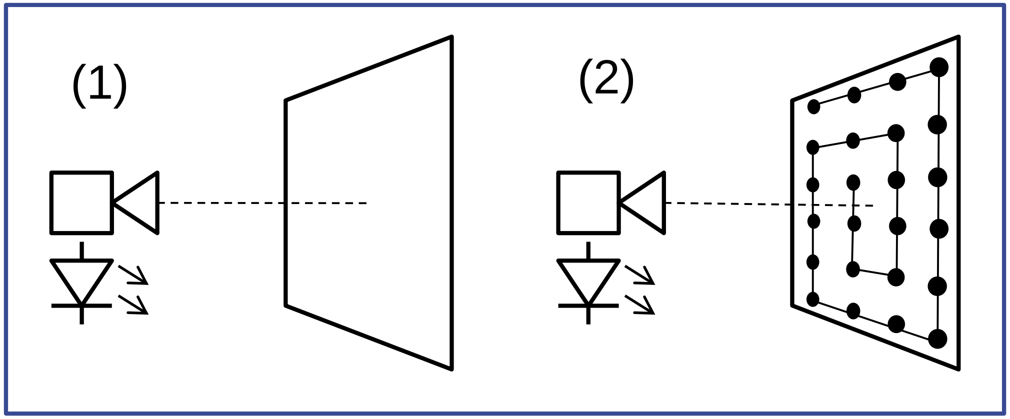
step	prototyping
fppn (1)	single shot image of a well positioned plane wall duration: few seconds
lens (2)	using ‚open cv‘ toolbox and several images of a manual positioned checkerboard at different positions (about 40 images) duration: few minutes (can be optimized)
wiggling (3)	using several images of a plane wall in defined distances in unambiguous range duration: about 15 minutes (can be optimized)
total	**approx. 20 minutes**



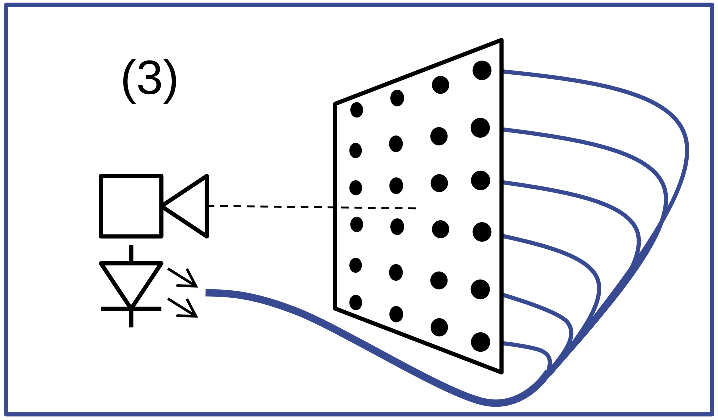
Calibration – how to (mass production)

step	prototyping	mass production
fppn (1)	single shot image of a well positioned plane wall duration: few seconds	single shot image of a well positioned plane wall duration: 2.2 seconds
lens (2)	using ‚open cv' toolbox and several images of a manual positioned checkerboard at different positions (about 40 images) duration: few minutes (can be optimized)	single shot image of a well positioned dot pattern duration: 1.0 second
wiggling (3)	using several images of a plane wall in defined distances in unambiguous range duration: about 15 minutes (can be optimized)	single shot image of well defined time of flights using fibers to simulate different distances duration: 2.5 seconds
total	**approx. 20 minutes**	**approx. 5.7 seconds**

Box 1



Box 2*



*Notice: A linear translation stage is still required for the mass production setup in order to provide golden samples. These are required to calibrate the box 2 setup. See next slide for details.

c o n f i d e n t i a l

Calibration – Golden Samples

Background:

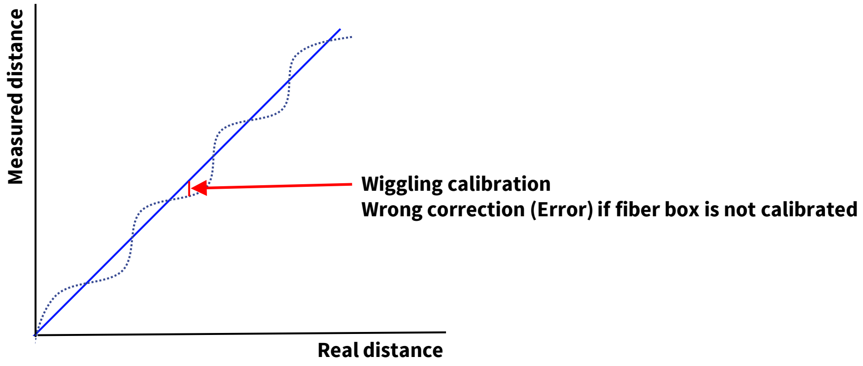
- The calibration box 2 (Fiber Box) itself needs to be calibrated at setup.
  - Reason: The length of the fibers can vary slightly from box to box
- Therefore a “Golden Sample” device is used

Golden Sample:

- A device (identical to the devices, which should be calibrated in the box), which was calibrated on
  - a linear translation stage or
  - in a previously calibrated box (risk of error propagation – never been tried by pmdtec).

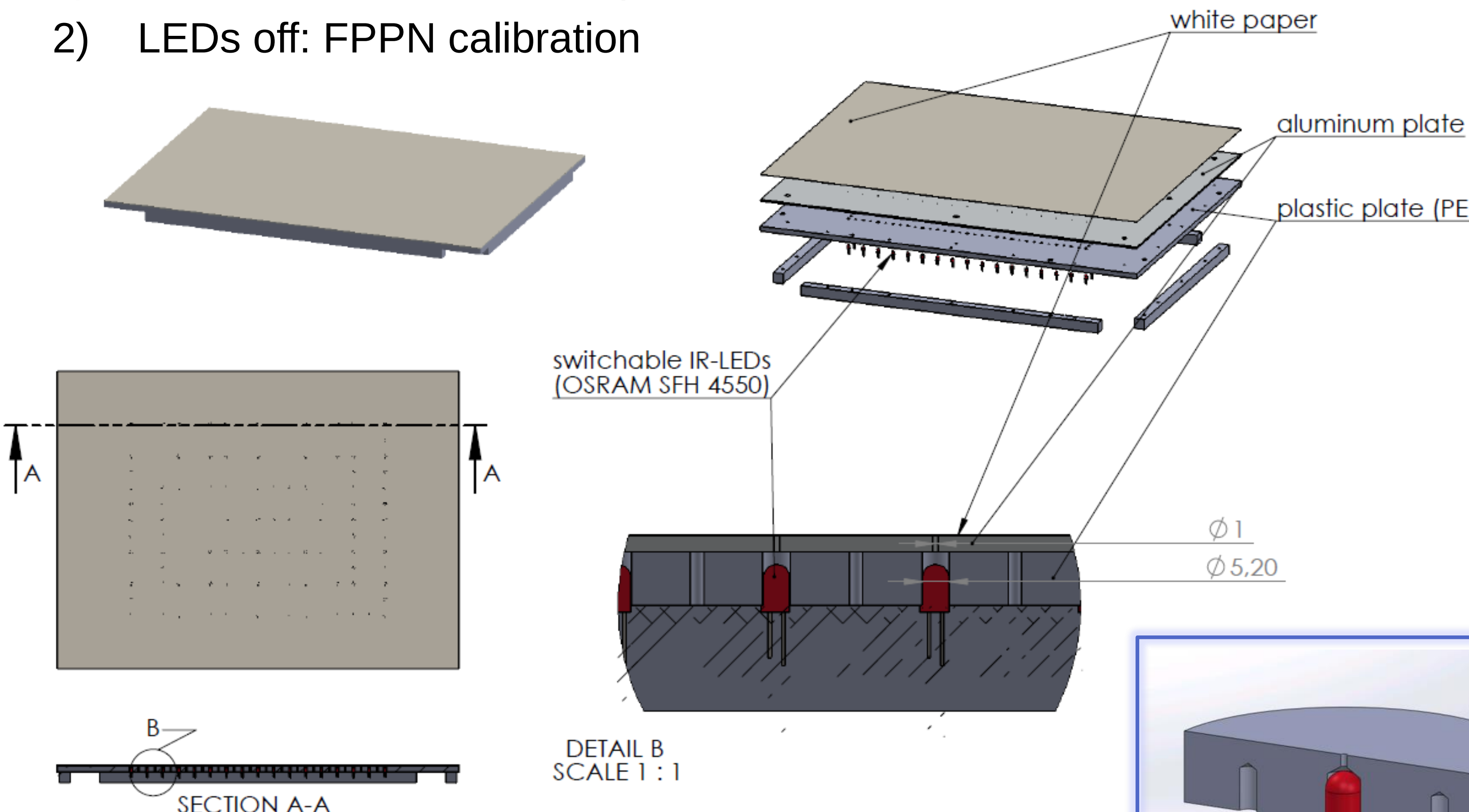
If no golden sample is available:

- **Issue:** If the fiber box is not calibrated using a golden sample, wiggling effects cannot be compensated resulting in a decreased performance.
- **Workaround:** If no golden sample is available but a calibrated box with tray from a different module/device (=different form factor or component placement) is available this box could be used anyway. **BUT:** If the tray/device is changed there will also be an error due to the different position of the trays. **NOTICE: This workaround has not been tried before by pmd.**

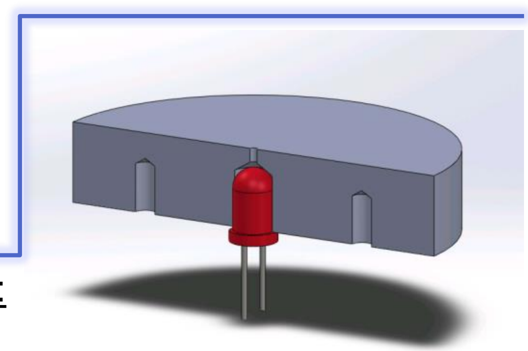


Box #1 – "LED box"

- Switchable LEDs behind white surface
  1) LEDs on: lens calibration pattern
  2) LEDs off: FPPN calibration

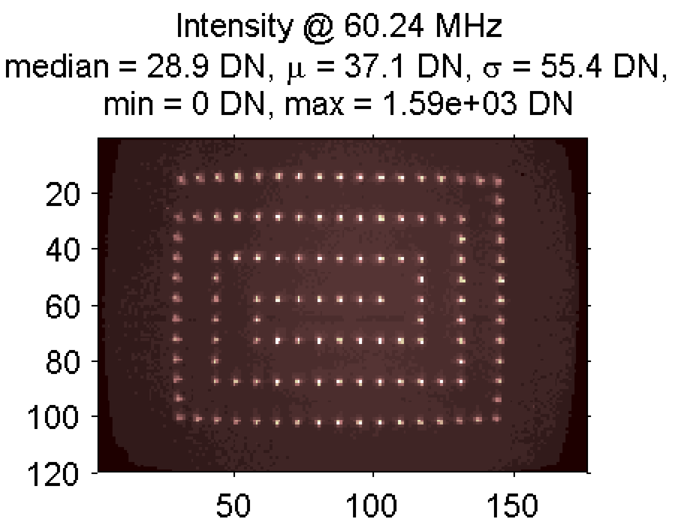


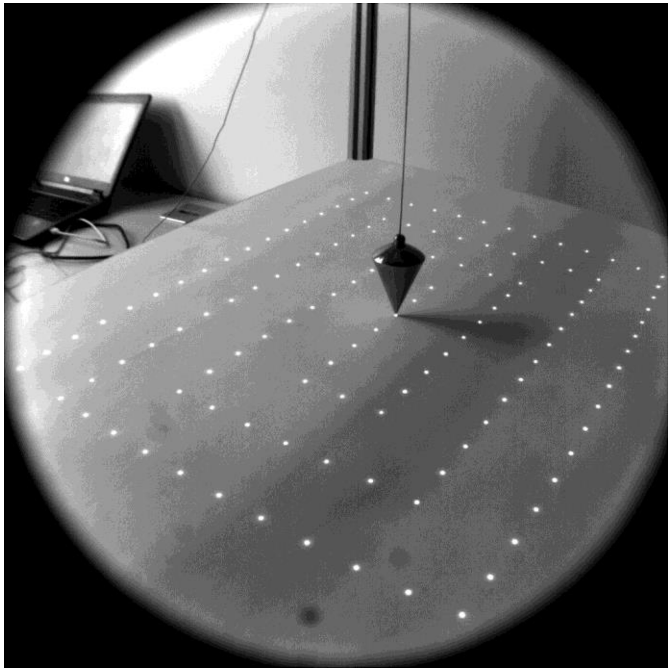
redesign with single target plate:

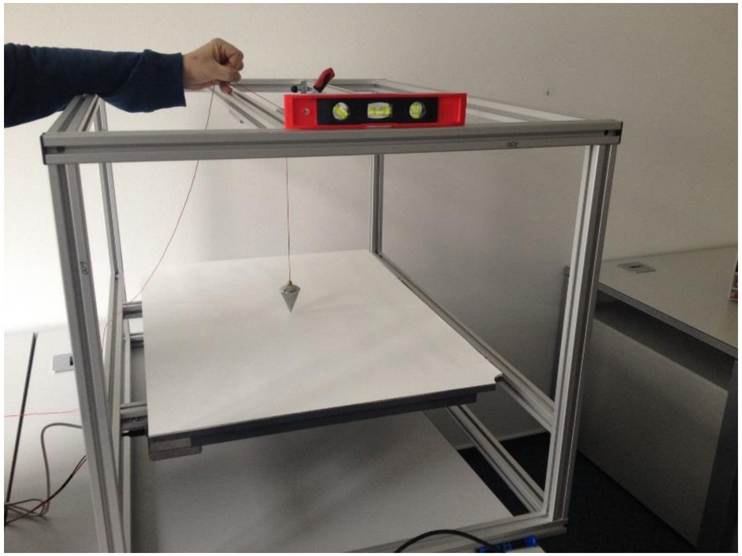


Box #1 adjustment

- Spirit level and plumb bob:
  - ➢ precise positioning/alignment of camera lens
- Method tested up to 110° field-of-view:
  - ➢ very high data quality after calibration







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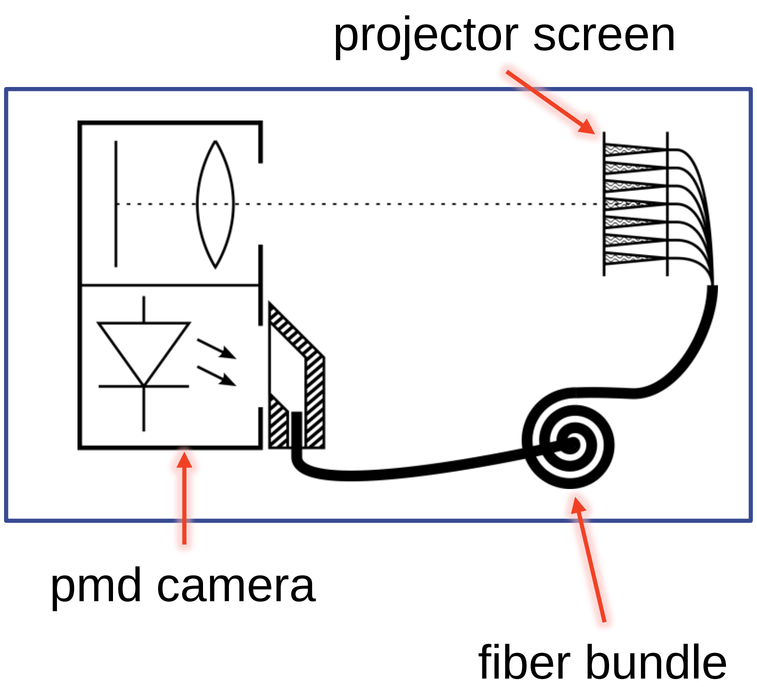
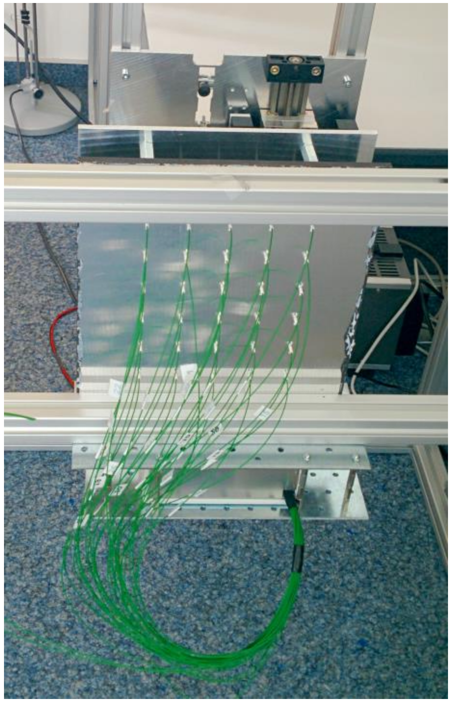
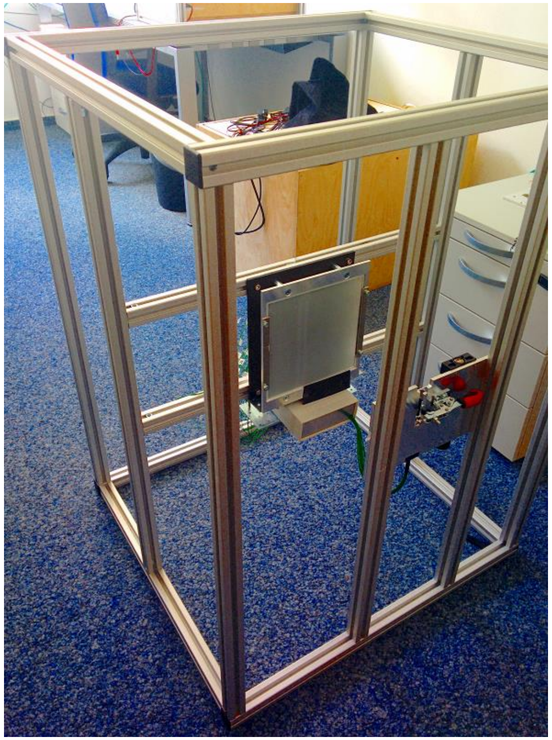
Box #2 – “fiber box”

- Array of optical fibers with multiple lengths
- Exact lengths of optical paths for each fiber have to be calibrated with reference modules → linear translation stage required!







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Camera calibration

Pass/fail evaluation

Camera pass/fail evaluation

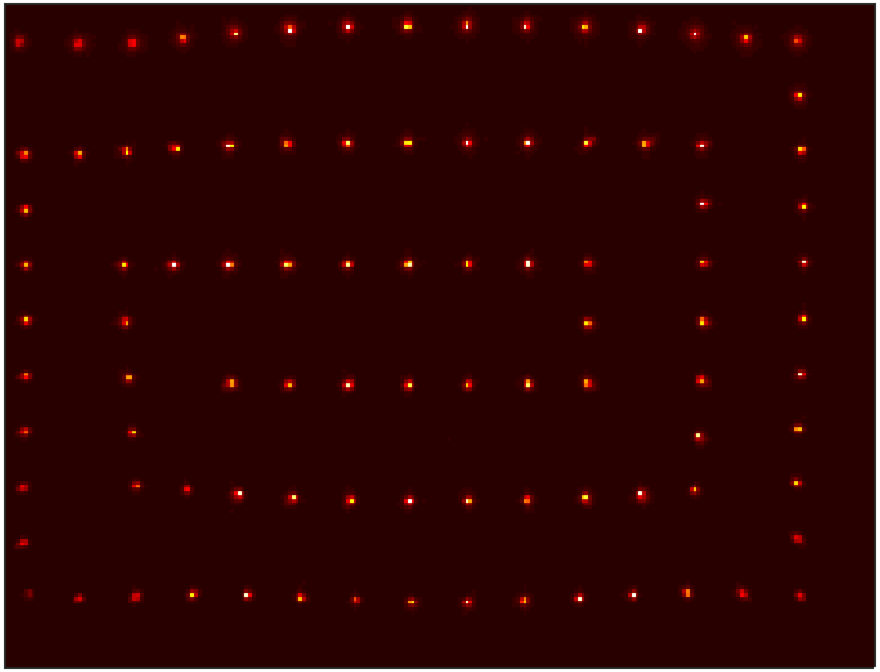
- Final data quality can best be evaluated when measuring a reference scene like a white planar surface at a known distance. This distance must to be different from that during the FPPN calibration.
- Additionally as PASS/FAIL test points, the measurement data of the calibration setups can be used for quality analysis. By upgrading the calibration boxes, additional tests may be possible (to be discussed).
- Possible test points:

Test Point	Evaluation method
image sharpness	sharpness of lens calibration pattern
imager sensitivity	brightness of lens calibration pattern alternative: additional referenced light source (tbd.)
lens distortion	limits for lens distortion results
VCSEL intensity	intensity levels (with known imager sensitivity)
distance noise	standard deviation in measurement
signal quality (optical/electrical)	limits for wiggling calibration result
pixel defects	anomalies/outliers in FPN/FPPN images
lens glare	intensity level of “dark” pixels in lens pattern image
eye-safety / VCSEL diffusor integrity	to be discussed
efficiency	normalize amplitudes by exposure time, distances, target reflectivity
beam profile	profile analysis of efficiency or plane intensity images
DME	per-pixel demodulation performance (DME = “dynamic mixing efficiency”)

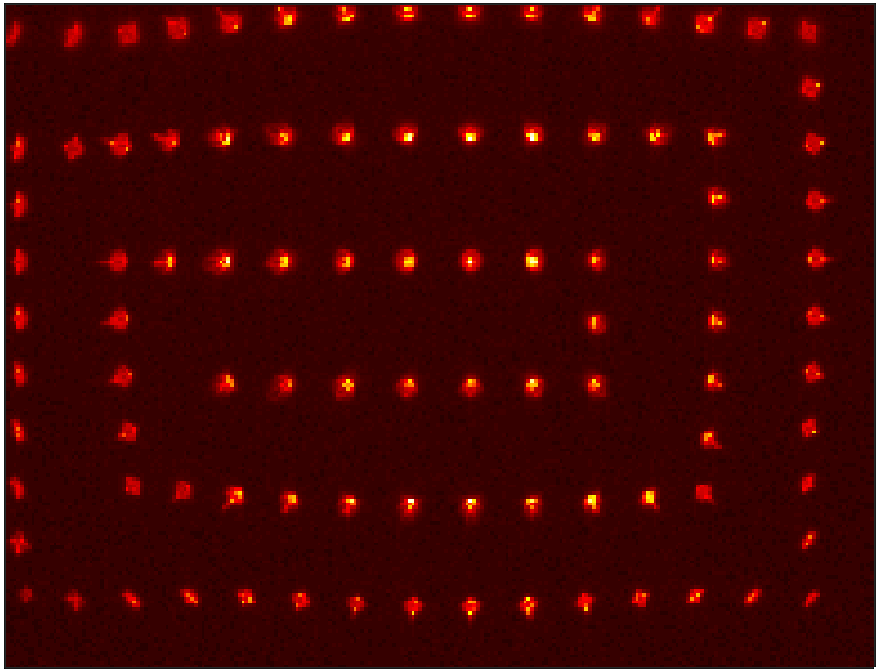
Image sharpness

- The lens focus should be ensured by well-established focusing mechanism. A reliable value can be acquired via the slanted edge modulation transfer function measurements (for sharpness “MTF50”).
- Nevertheless, during the proposed mass calibration procedure, a sharp image of a LED pattern needs to be evaluated. This can be used to single out badly unfocussed devices (e.g. by evaluating the average spot size).

LED pattern: sharp



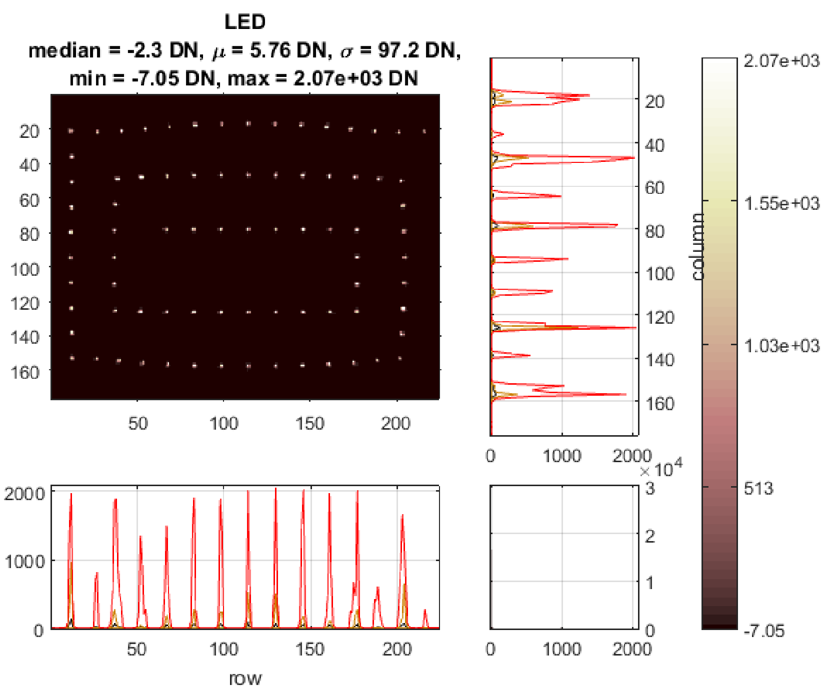
LED pattern: unsharp



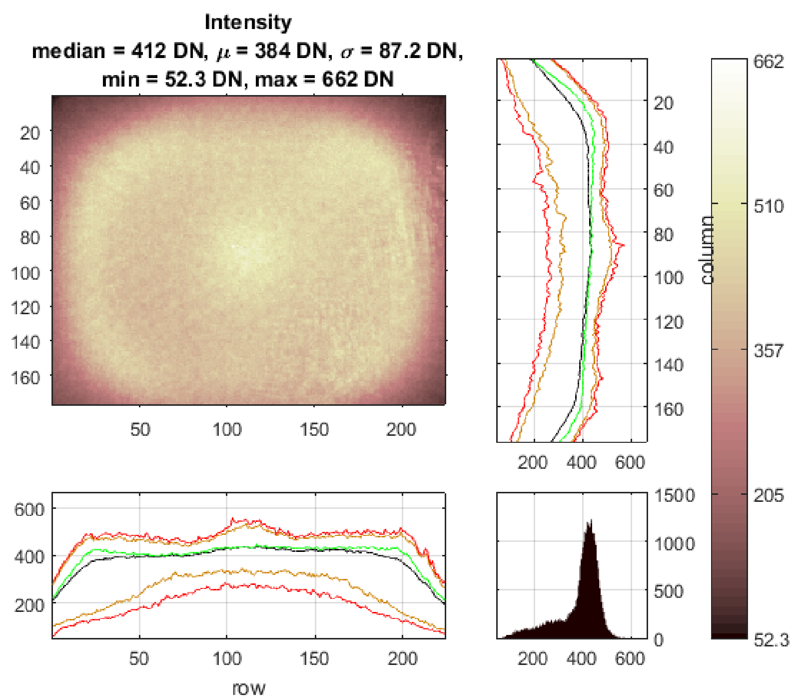
Imager sensitivity vs. VCSEL intensity

- Measuring the sensitivity (a combination of sensor and lens) can be done by measuring intensity values (gray scale) of known optical power.
- When evaluating the LED pattern, the absolute intensity values of the LEDs are impaired by aliasing. Nevertheless, setting limits here allows to single out really bad devices.
- When evaluating the Intensity values of the active illumination with a known optical output power (within reasonable limits), this also allows for thresholding bad devices.

LED: sensitivity+aliasing

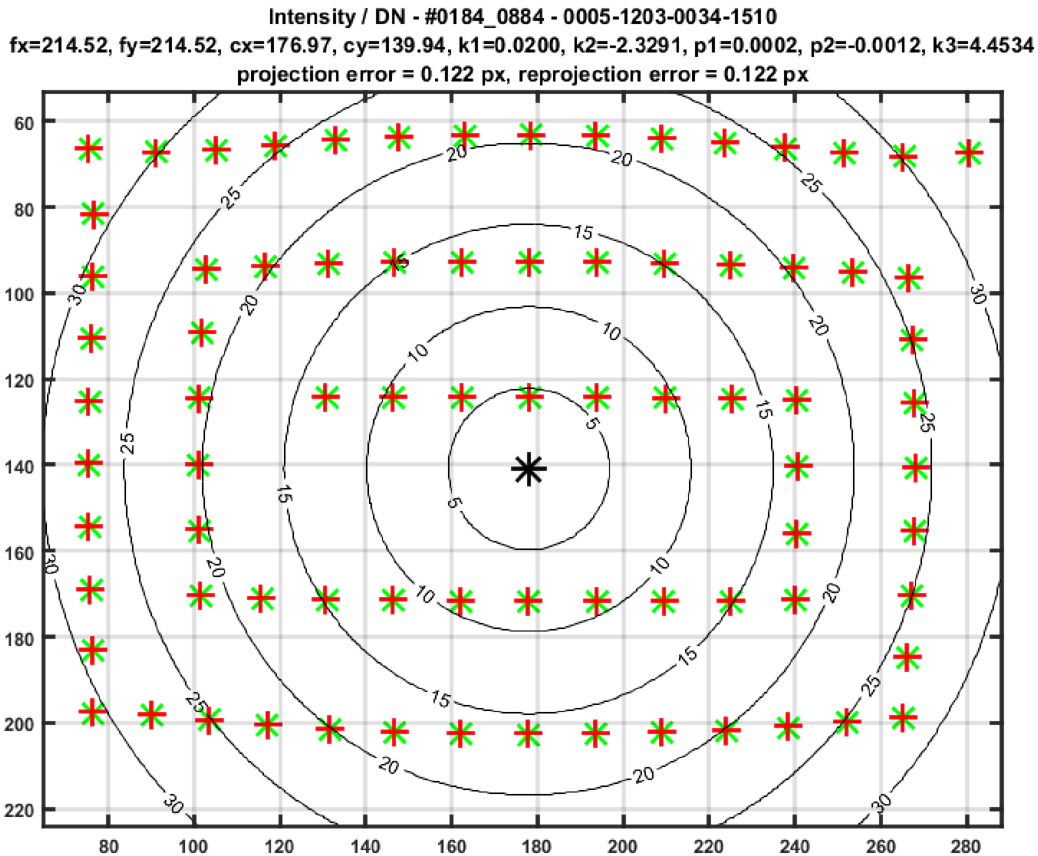


Intensity: VCSEL power + sensitivity



Lens distortion

- The lens model is fit by minimizing the detected LED positions in the image plane (green ‘x’) with the projected pixel positions from the lens model (red ‘+’). The fit quality should be used as one test point limit (“projection error”).
- The maximum deviation between ‘x’ and ‘+’ needs a limit (failed one-to-one correspondence in algorithm).
- The focal length (‘fx’ and ‘fy’) and the position of the optical axis (‘cx’ and ‘cy’) should have reasonable limits.
- The distortion limits can be set by evaluated the distortion curves



OpenCV lens model:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + t$$

$$x' = x/z$$

$$y' = y/z$$

$$x'' = x' \frac{1+k_1 r^2 + k_2 r^4 + k_3 r^6}{1+k_4 r^2 + k_5 r^4 + k_6 r^6} + 2p_1 x' y' + p_2 (r^2 + 2x'^2)$$

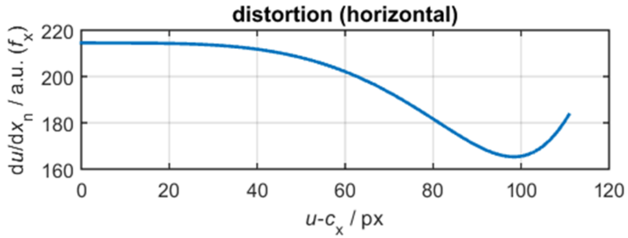
$$y'' = y' \frac{1+k_1 r^2 + k_2 r^4 + k_3 r^6}{1+k_4 r^2 + k_5 r^4 + k_6 r^6} + p_1 (r^2 + 2y'^2) + 2p_2 x' y'$$

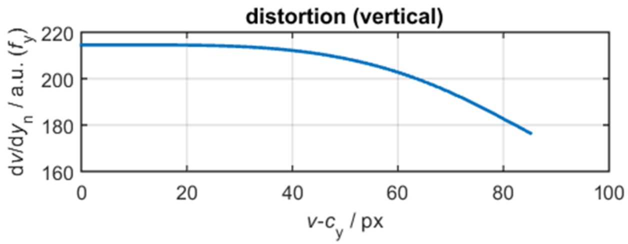
$$\text{where} \quad r^2 = x'^2 + y'^2$$

$$u = f_x * x'' + c_x$$

$$v = f_y * y'' + c_y$$

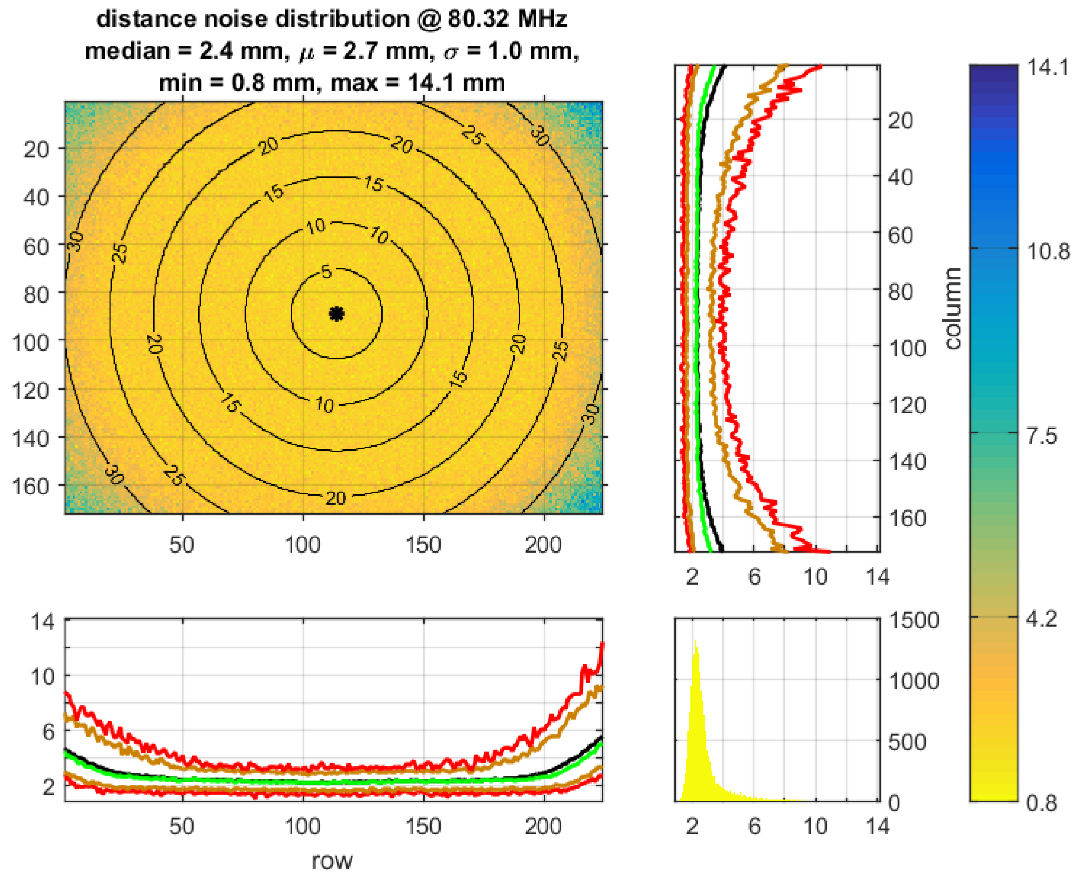
source: http://docs.opencv.org/modules/calib3d/doc/camera_calibration_and_3d_reconstruction.html





Distance noise / pixel defects

- The distance noise distribution is measures directly with the calibration box. Limits can best be applied to the center region, based on the lens viewing angles (e.g. up to 30° viewing angle for a 60° field-of-view lens).
- Pixels with too high noise (due to low amplitude) or too low (dead pixels) can be detected here by applying appropriate limits.



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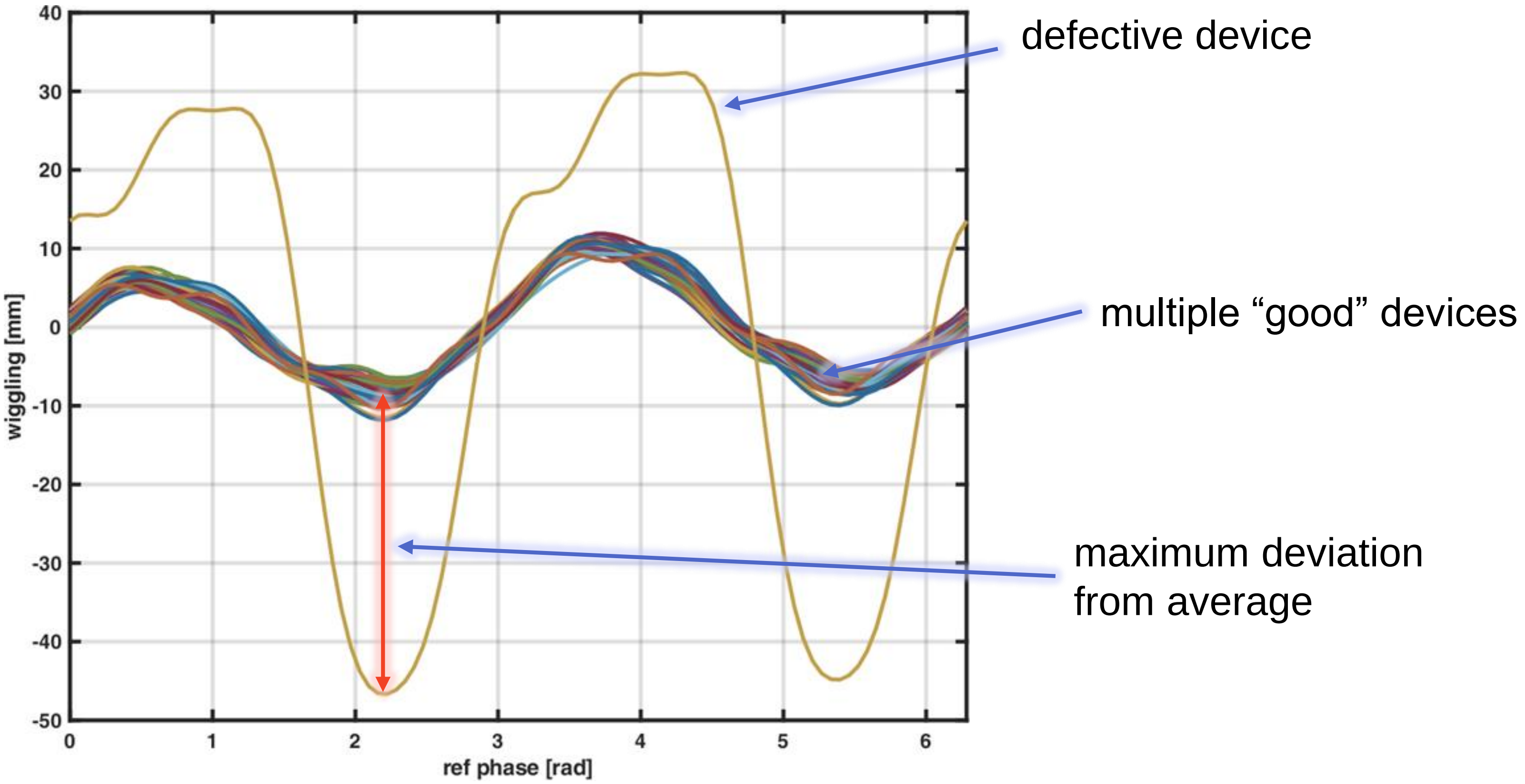
Signal quality (optical/electrical)

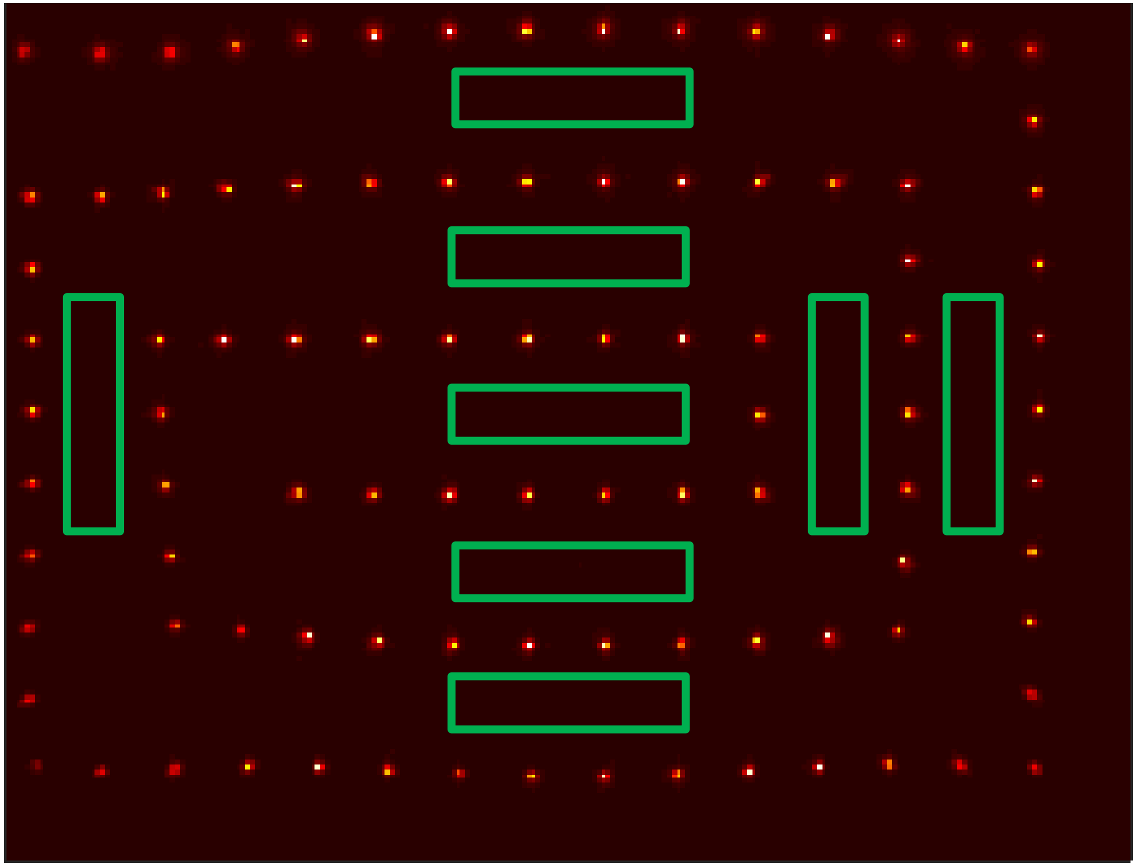
- Most sensitive to deviations in the optical or electrical modulation signals is the wiggling. A maximum wiggling deviation from the data of a golden device or averaged values of multiple devices can be used.



c o n f i d e n t i a l

Lens glare

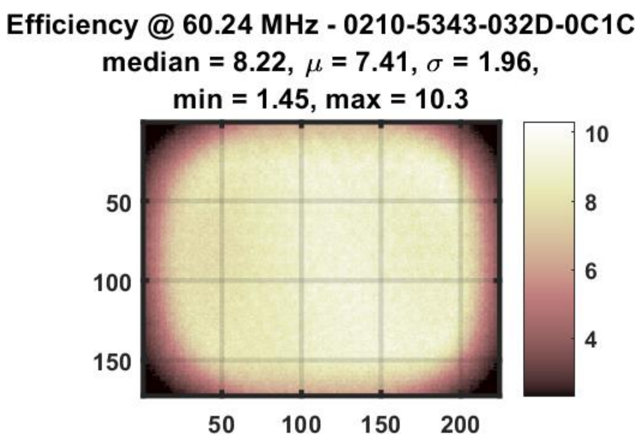
- Lens glare has a direct impact on ToF data quality and must be avoided. A test point value can be determined by analyzing the averaged “black level” from the LED measurements (green marked):



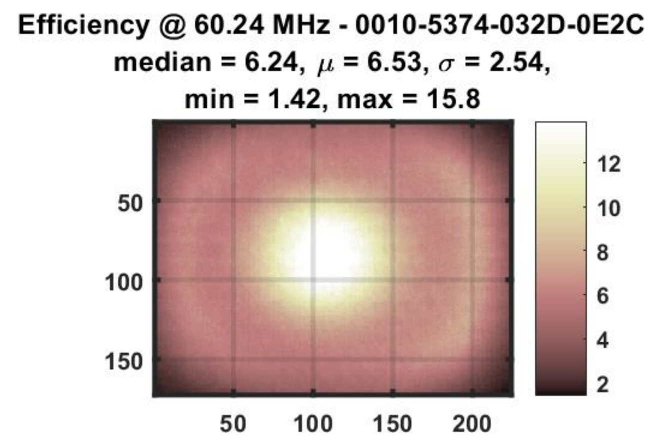
Efficiency

- The “efficiency” describes a per-pixel, frequency dependent value of the signal strength per exposure time
- wiggling-free amplitude, normalized by
  - exposure time in µs
  - squared radial distance in m
  - cosine of incident angle (assuming Lambertian reflectance)
  - reflectivity of target surface
- The mean of all valid pixels can be used as a performance value
- The standard deviation of all valid pixels can be used to indicate the homogeneity of the illumination
- The resulting pixel matrix may also be used for beam profile analysis

good VCSEL beam



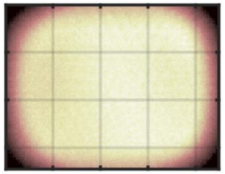
bad VCSEL beam

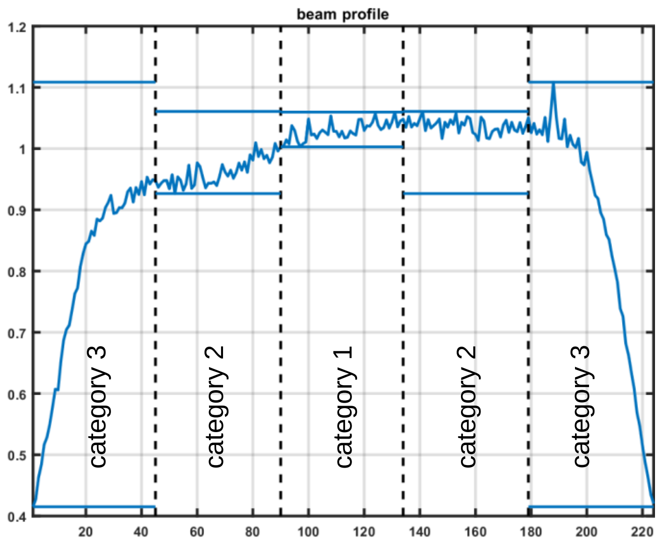


Beam profile calculation

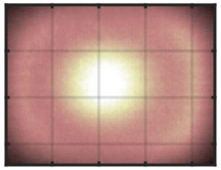
- The beam profile analysis is sensitive to the typical VCSEL diffusor error of increased light output in the central beam. The implemented procedure to get key values for pass/fail limits is:
  - take the maximum values of all valid pixels per column of a efficiency image to get a beam profile
  - divide the profile into five equal sections
  - categorize the five sections into three regions:
    - central region (category 1)
    - mid region (category 2)
    - outer region (category 3)
  - normalize the profile by the average value of category 2
  - apply pass fail limits to the minimum and maximum off all three categories (→ 6 values with limits)

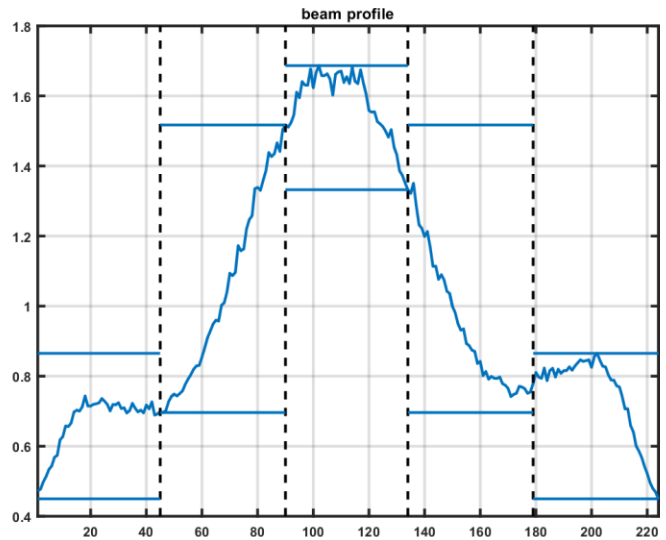
good VCSEL beam





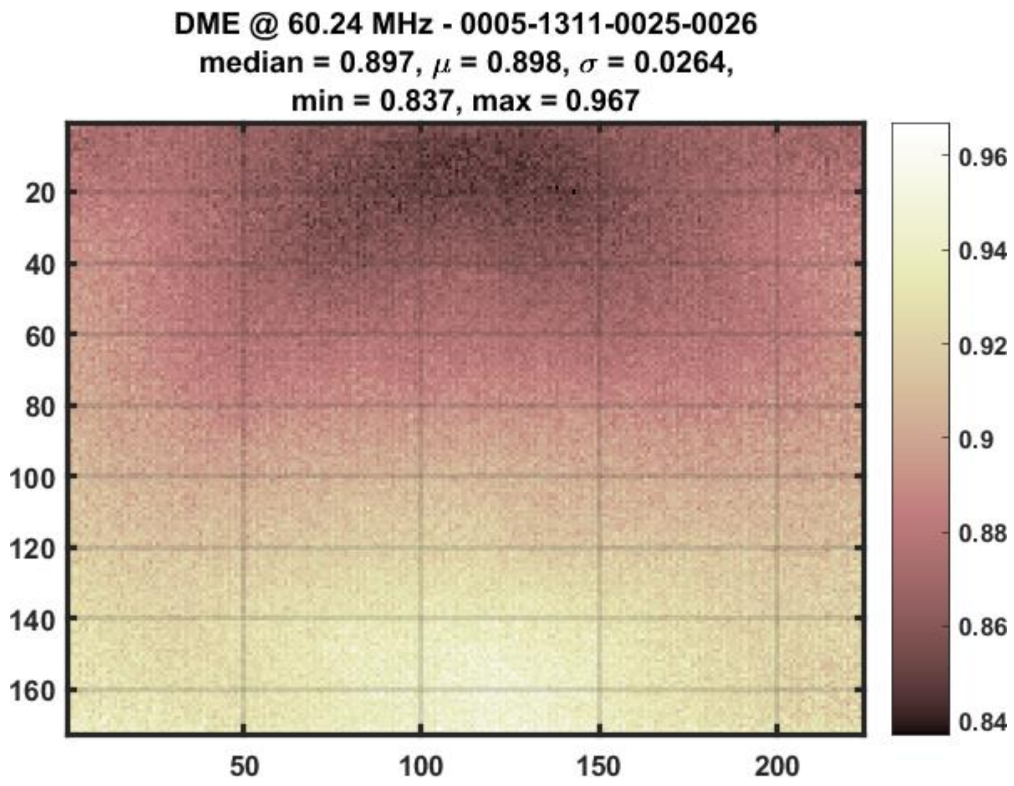
bad VCSEL beam





Dynamic mixing efficiency

- Dynamic mixing efficiency (DME) is defined as AC contrast (modulated pixels) over DC contrast (unmodulated pixels). The contrast is a quality measure of the time-of-flight technology. (For a deeper explanation of contrast see ToF basics.)
- A high DME indicates a good time-of-flight performance. Strong variations within the pixel matrix are an indicator for sensor errors or defect pixels.



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Camera calibration

Customer support

Calibration requirements for customers

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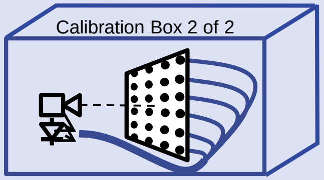
For a full calibration procedure, a customer needs:

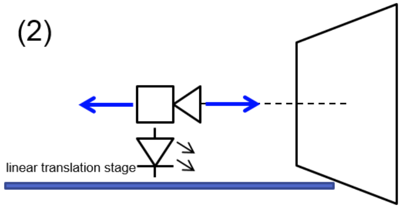
1) Calibration boxes:

- FPPN/lens target, mounted in a rigid frame
- Fiber bundle and target, mounted in a rigid frame
- verification box for a basic evaluation of the resulting data quality



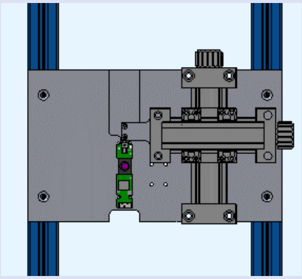
2) Linear translation stage:

- Automated precise positioning against a planar, matte and homogeneous surface
- Minimum length: one unambiguous range of the lowest modulation frequency (e.g. 2.5 m @ 60 MHz)
- Shielded from sunlight / other infrared light sources
- used to bring up golden samples (→ fiber box one-time calibration) and to fully characterize the depth performance



3) Camera trays / module test sockets:

- Box #1 tray/socket:
  - Socket lateral position needs to be adjustable
  - Alignment has to be possible (e.g. dummy module with plumb bob)
  - Free field-of-view for lens and active illumination (VCSEL/LED)
- Box #2 tray/socket:
  - Free field-of-view for lens
  - Light from active illumination (VCSEL/LED) needs to be guided into optical fiber bundle
  - No stray-light: Light, that is not coupled light into needs to be 100% shielded.
- Linear translation stage:
  - Free field-of-view for lens and active illumination (VCSEL/LED)



4) Software

- Data acquisition and processing software to produce calibration data, compatible with the pmd processing chain

Calibration requirements: pmd deliverables

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1) Calibration boxes:

- CAD design data, schematics, list of materials
- detailed documentation
- supplier recommendation
- support by design reviews

2) Linear translation stage:

- supplier recommendation
- requirements documentation

3) Camera trays / module test sockets:

- CAD reference design data
- support by design reviews (in particular of the VCSEL coupling, the fiber bundle and of the tray)

4) Software

- Matlab source code for data acquisition and processing software to produce calibration data which is compatible with the pmd processing chain
- data acquisition based on Royale API with FPGA framegrabber
  → customer needs to bring up an own framegrabber including own API

5) Documentation

- Step-by-step user guide for data acquisition and software

Series Calibration Workflow

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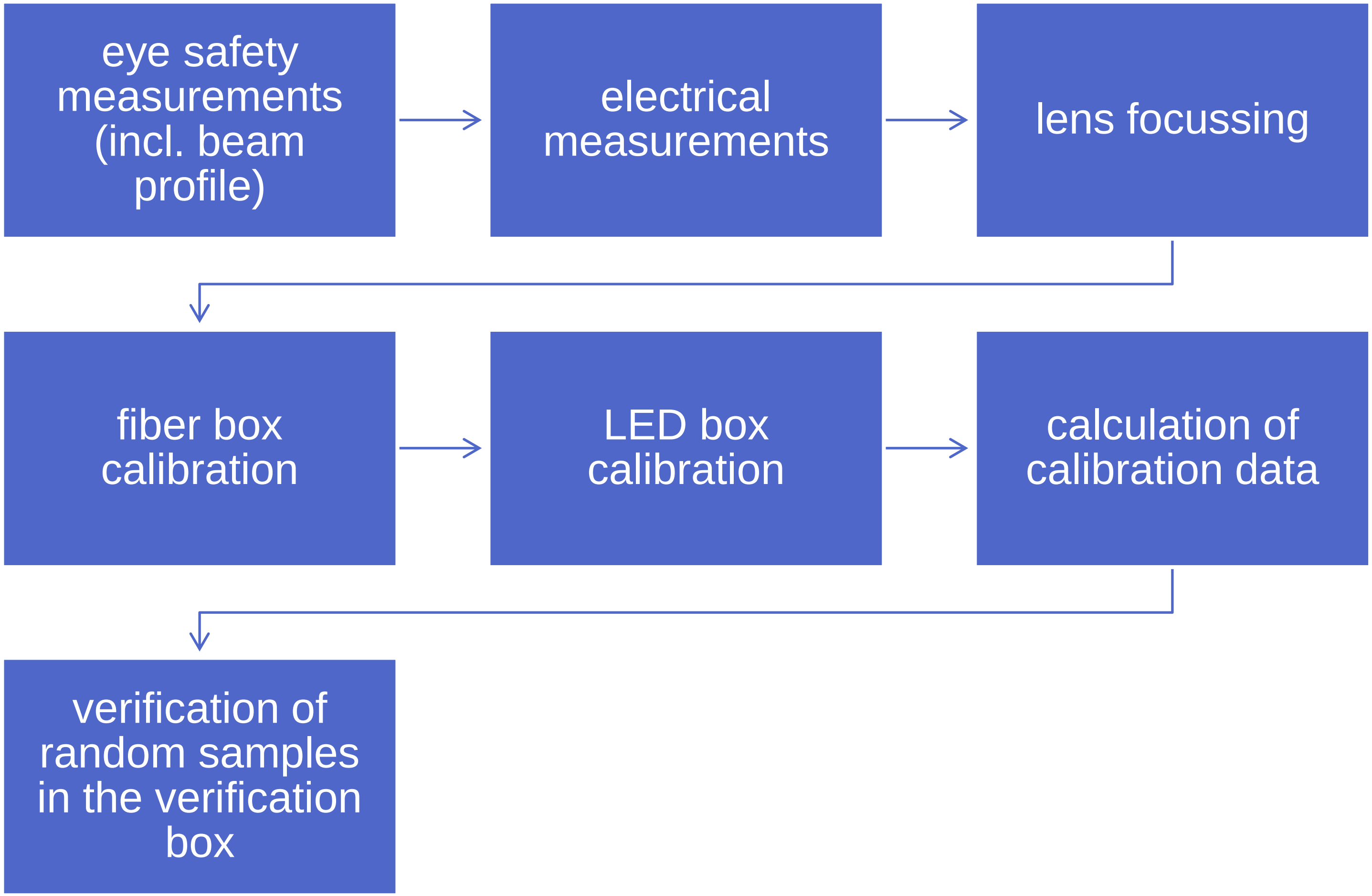
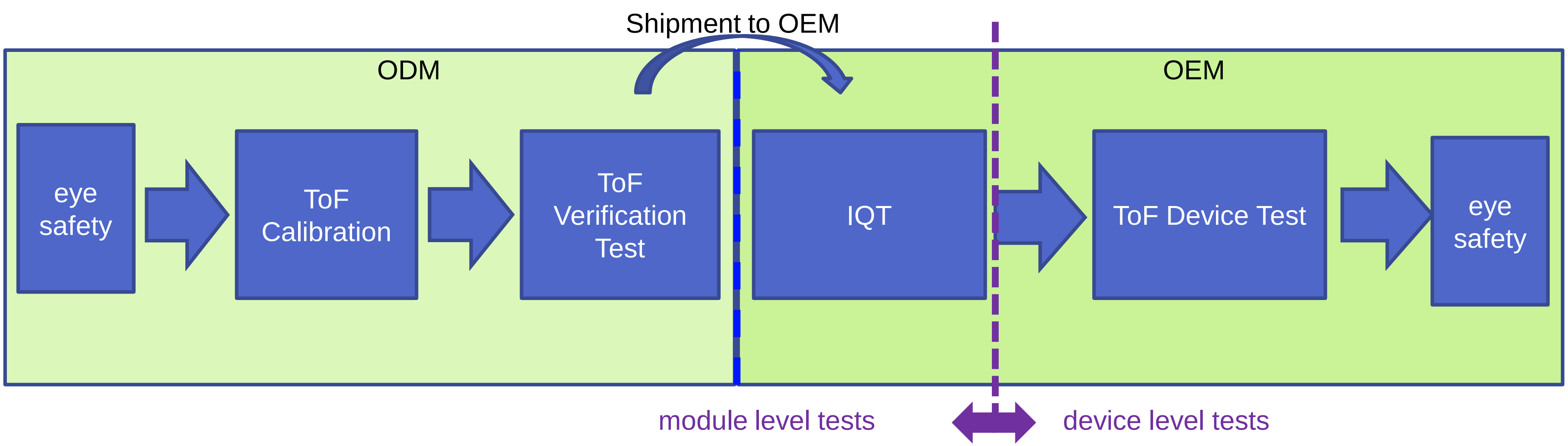


Test discussion

- **ODM**
  - **mandatory: eye and skin safety**
  - performance is tested to a significant extent during ToF calibration already
  - ToF Verification Test (module level): performance verification (random samples, distance unequal to calibration distance)
  - Highly recommended: LTS to verify performance for few random samples and to bring up golden samples
  - Highly recommended: setup to reproduce test results reported by OEM (setup can be LTS)
- **OEM**
  - **mandatory: eye and skin safety**
  - Optional: IQT on module level, i.e. test of functionality before device integration
  - ToF Device Test at OEM with complete device in the verification box
  - Performance plausibility check at a single distance
  - Highly recommended: LTS for comprehensive performance evaluation (random samples)
- **pmd**
  - support ODM and OEM regarding test implementation (HW and SW)



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Automatic eye-safety measurement setup

Steps during eye-safety measurements

1. Mount the module in front of the integrating sphere
   - Dedicated mount
   - Framegrabber to start up the module

2. Test of current monitor average criteria
   - Trigger of average criteria by increase of integration time
   - Load of imager configuration with increased integration time to trigger the average current monitor
   - Integrating sphere will show that optical output is at around zero if average criteria was triggered

3. Power cycle to reset the current monitor to enable VCSEL functionality after average criteria shutdown

4. Start measurement script to determine average optical power with standard configuration (Tango use-case test)
   - Optical average power measured with integrating sphere
   - Calculation of peak optical power with duty cycle which is fixed at around 25%

5. Test of current monitor average criteria
   - Load of imager configuration to trigger the peak criteria by setting the duty cycle to 100% during integration
   - Integrating sphere detects if VCSEL is switched off which means that average criteria is OK

6. Results are stored into test report /GUI with pass/fail visualisation
   - Software has to be done by ODM
   - pmd can support with implementation proposals