ESPROS Photonics Corporation

Calibration and Compensation of Time of Flight Sensors

Christof Peyer

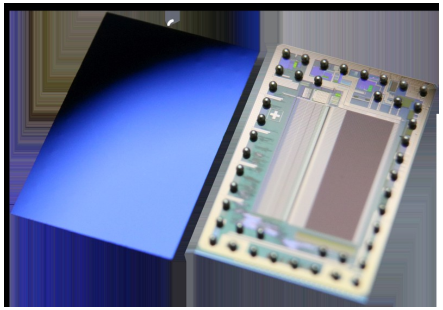
Foundation and fab vision

Foundation
- established in 2006 by Beat De Coi
- privately held corporation
- 70 million CHF initial investment
- photonics chip design and manufacturing

Locations
- Headquarters:
  - Sargans, Switzerland
- regional offices
  - Minneapolis, USA
  - Shanghai, China

Facilities
- 600m² class 1 cleanroom for backside processing
- 360m² class 100 cleanroom for testing and backend
- 80m² qualification facilities according JEDEC standards
- 60'000m² space built into solid rock for further expansion

ESPROS' offerings

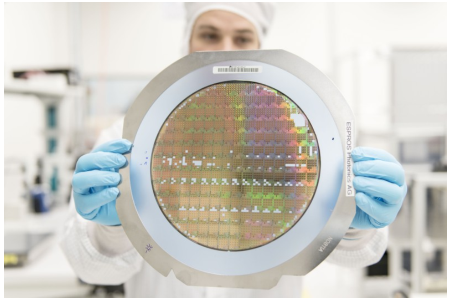


Imager Chips

TOF imagers
- 1 x 1
- 8 x 8
- 160 x 60
- 320 x 240

line imagers
- 1024 x 1

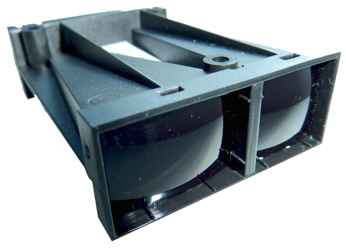
spectral sensing



ASIC and Foundry

- 150nm CMOS process
- 8” wafer size
- up to 6 metal layers
- 1 poly layer

- pixel design
- TCAD simulation
- IP building blocks
- floor planning
- tape out
- project management



Modules

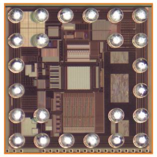
- Evalkits / Cameras

- TOFRANGE600
- TOFSCAN611
- TOFCAM635

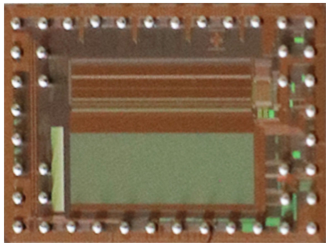
- SPM64

more to come...

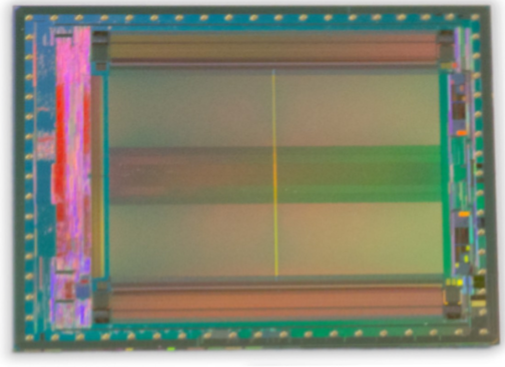
TOF Imager Product Family



epc611
8x8 pixel



epc635
160x60 pixel



epc660
320x240 pixel

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Key Business Markets

ESPROS serves high-profile customers / partners across a broad range of end-markets and specific application

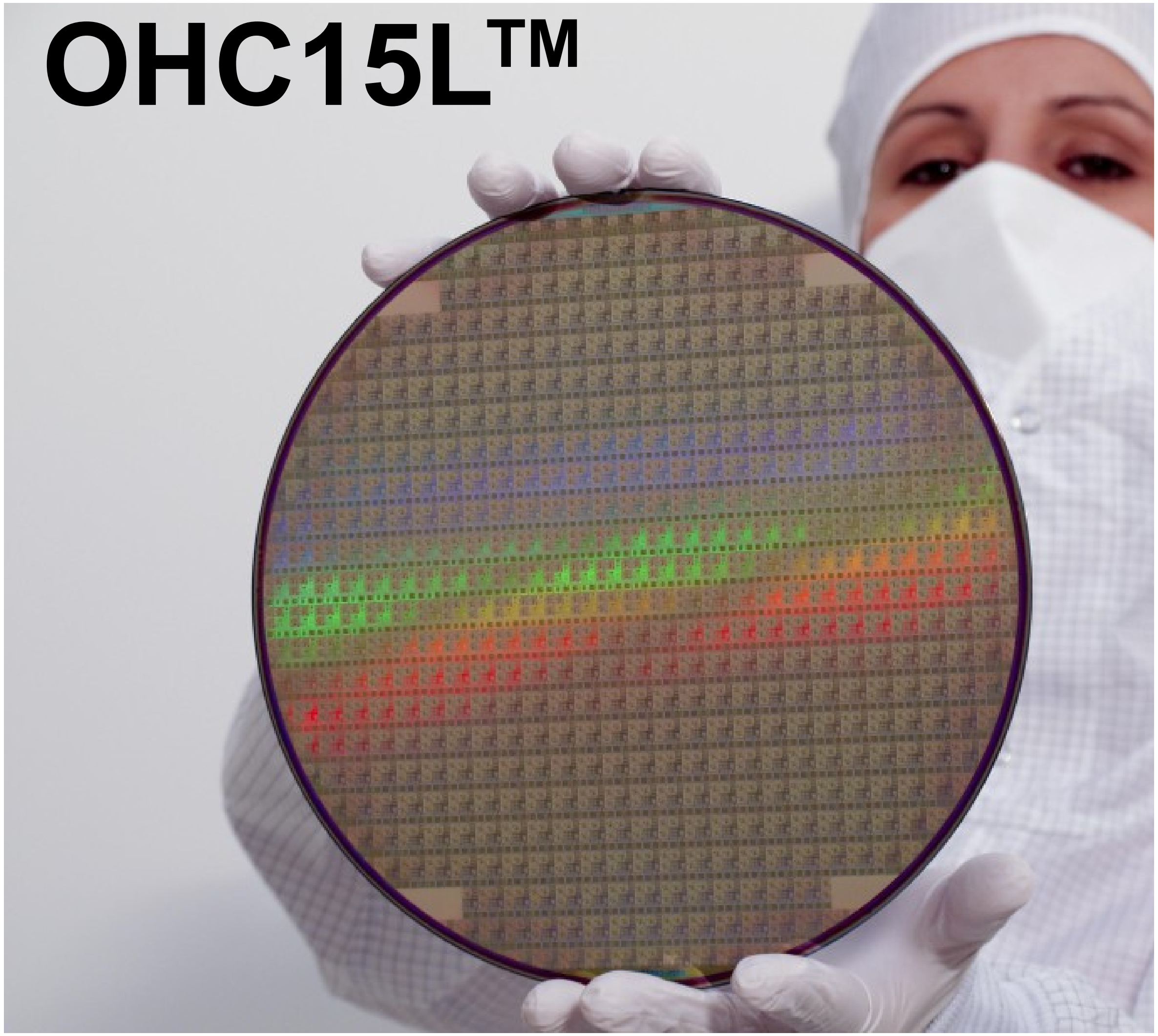
Key markets	Building Automation	Industrial	Mobile Robotics	Automotive	Consumer Electronics
Applications	• obstacle recognition • distance control • passenger approach • people counting • passenger monitoring • traffic control • people safety	• light curtain • gesture control • collision avoidance • object recognition • object dimensions • spectral sensing	• range finder • camera • SCANNING cameras • full sunlight (130kLux) • ground distance control • collision avoidance	• TOF ADAS solutions • full sunlight • mid range 30m (cwTOF) • long range >100m (pTOF) • night vision • vehicle interior monitoring • gesture control	• miniature spectral sensor • smart watch sensing • VR/AR TOF solutions • gesture control TOF
Selected active customers / partners	BIRCHER Reglomat CEDES iris parksol RTB ID SENS innovative engineering	DELTA OMRON Leica Geosystems HEXAGON SICK Sensor Intelligence. Leuze electronic the sensor people Baumer DATALOGIC	TERABEE Benewake STARSHIP marble HR HOALOHA ROBOTICS	TAKATA Valeo WAYMO BOSCH GENIUS PROS LG	SAMSUNG SAMSUNG ELECTRO-MECHANICS HUAWEI -film LG ECOVACS ROBOTICS VIAVI

ESPROS' products have successfully been deployed into several other markets like medical diagnosis, mass spectroscopy, science and research

SPECIALISED IMAGING · Gpixel INC. 长光辰芯光电 · LG · ThermoFisher SCIENTIFIC

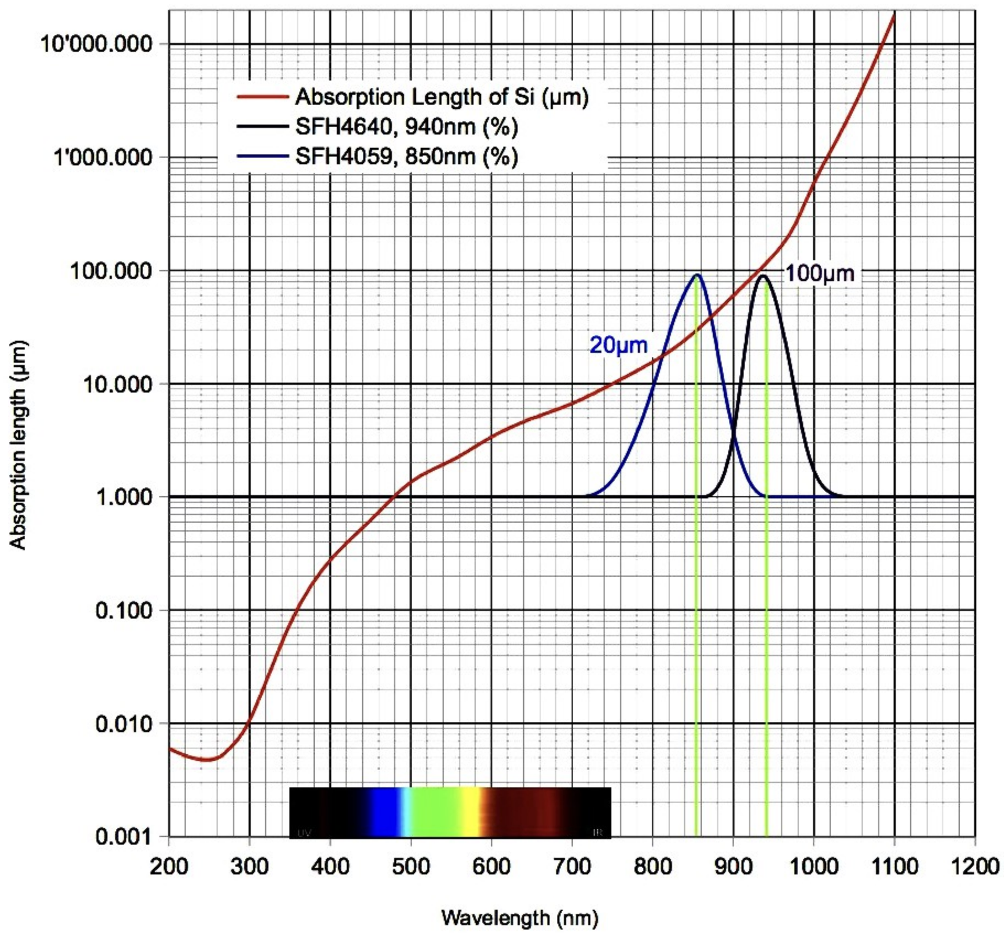
Our Technology

ESPROS imaging technology



ESPROS Technology Advantages

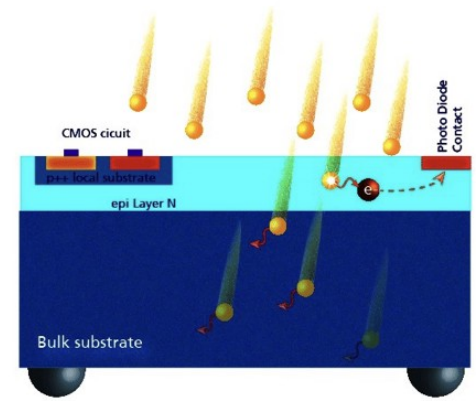
Absorption length in Silicon



CONVENTIONAL

a) thin active layer

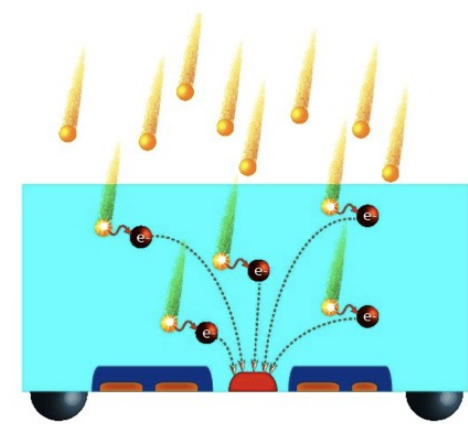
b) 20% fill factor only



ESPROS

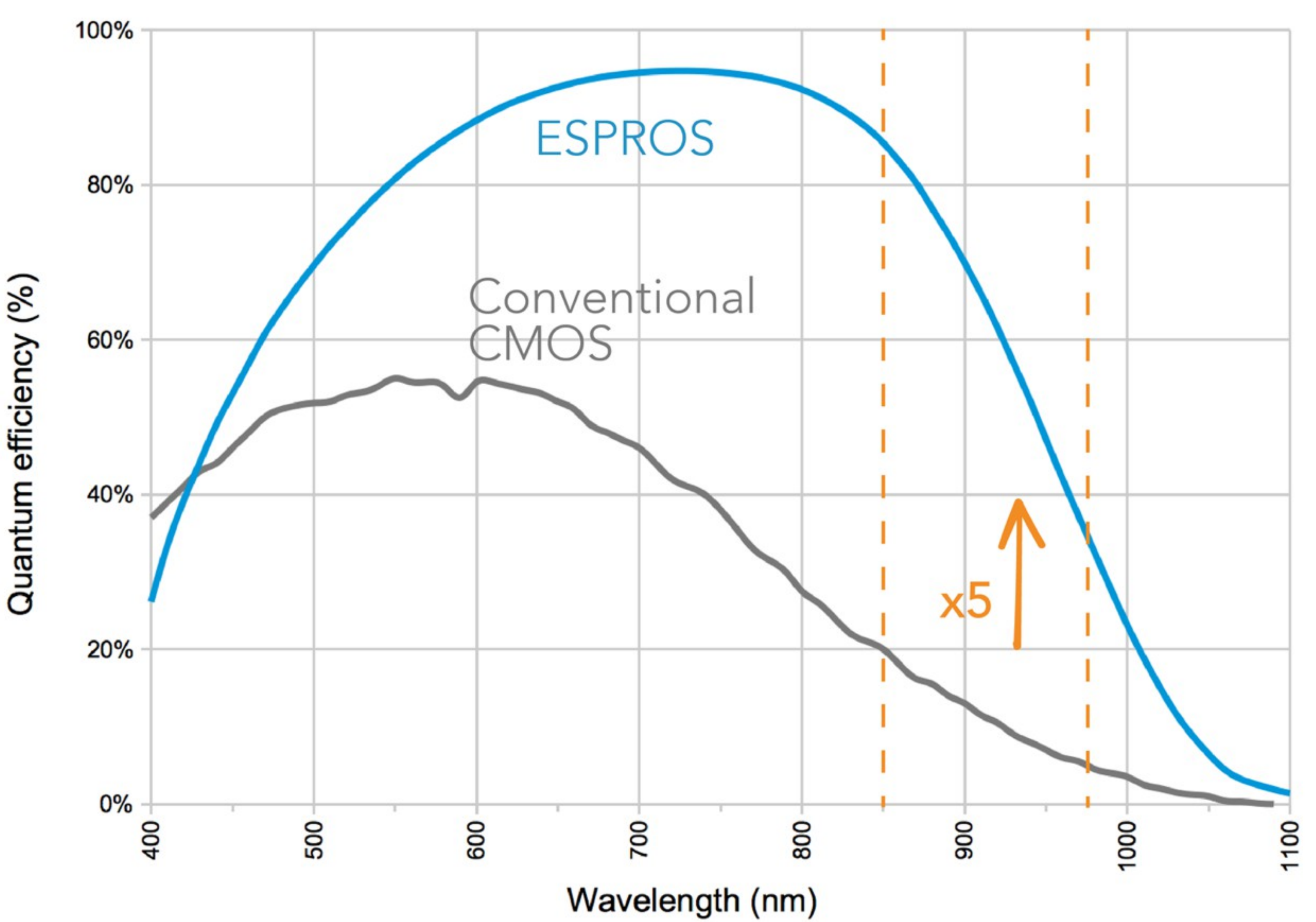
a) 50 micron absorber

b) 100% fill factor



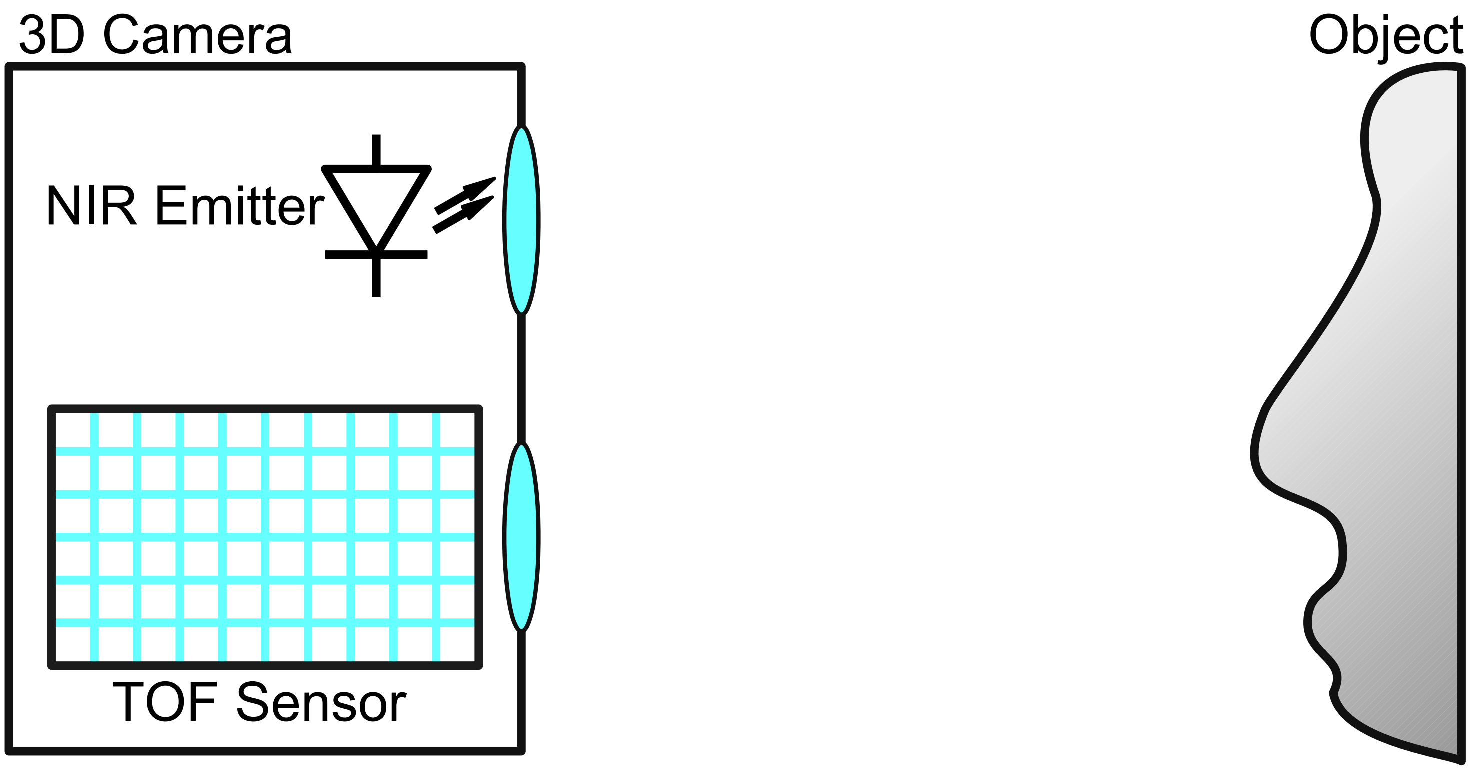
ESPROS offers a unique combination of high Quantum efficiency in near infrared (NIR) and fast charge collection and signal processing on a single substrate.

Quantum Efficiency

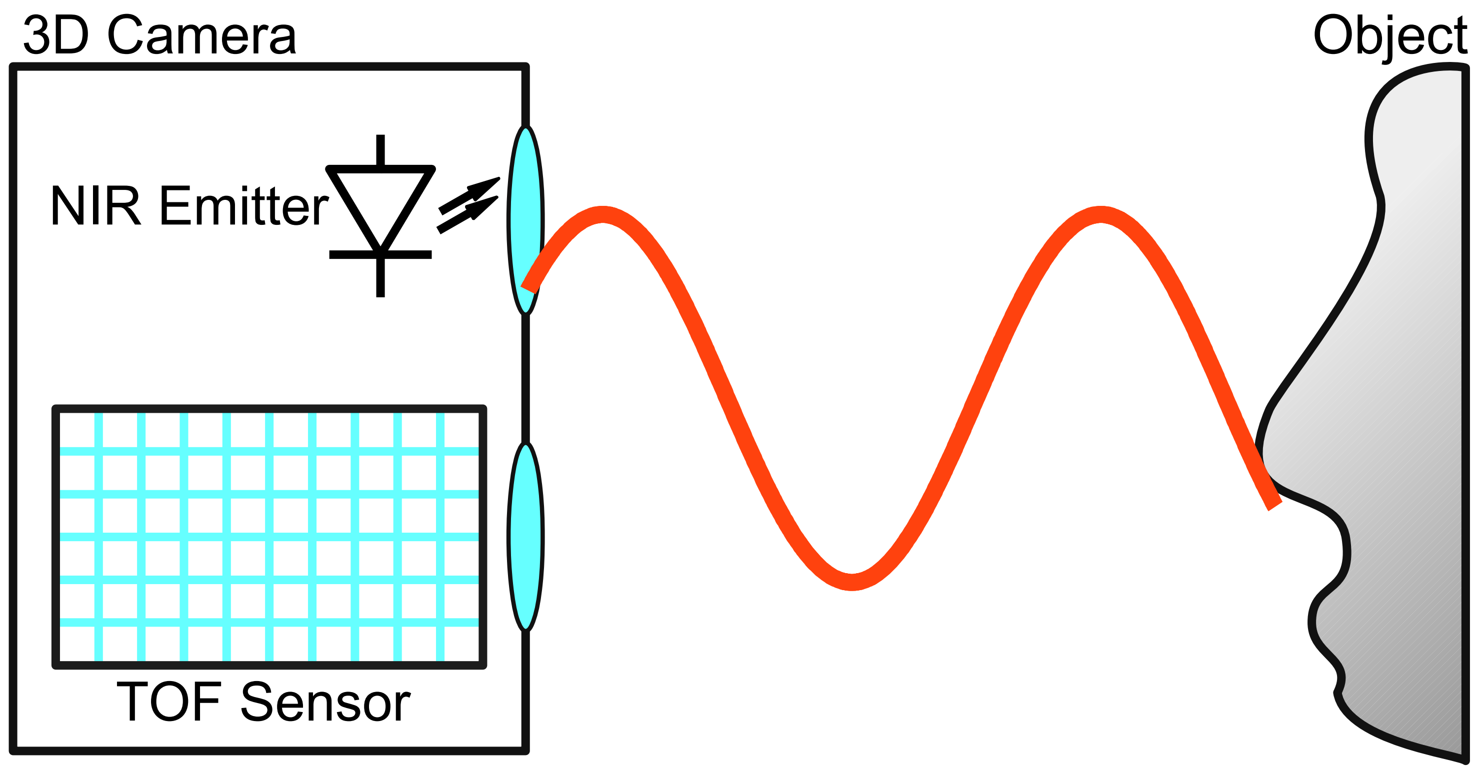


cwTOF function principle

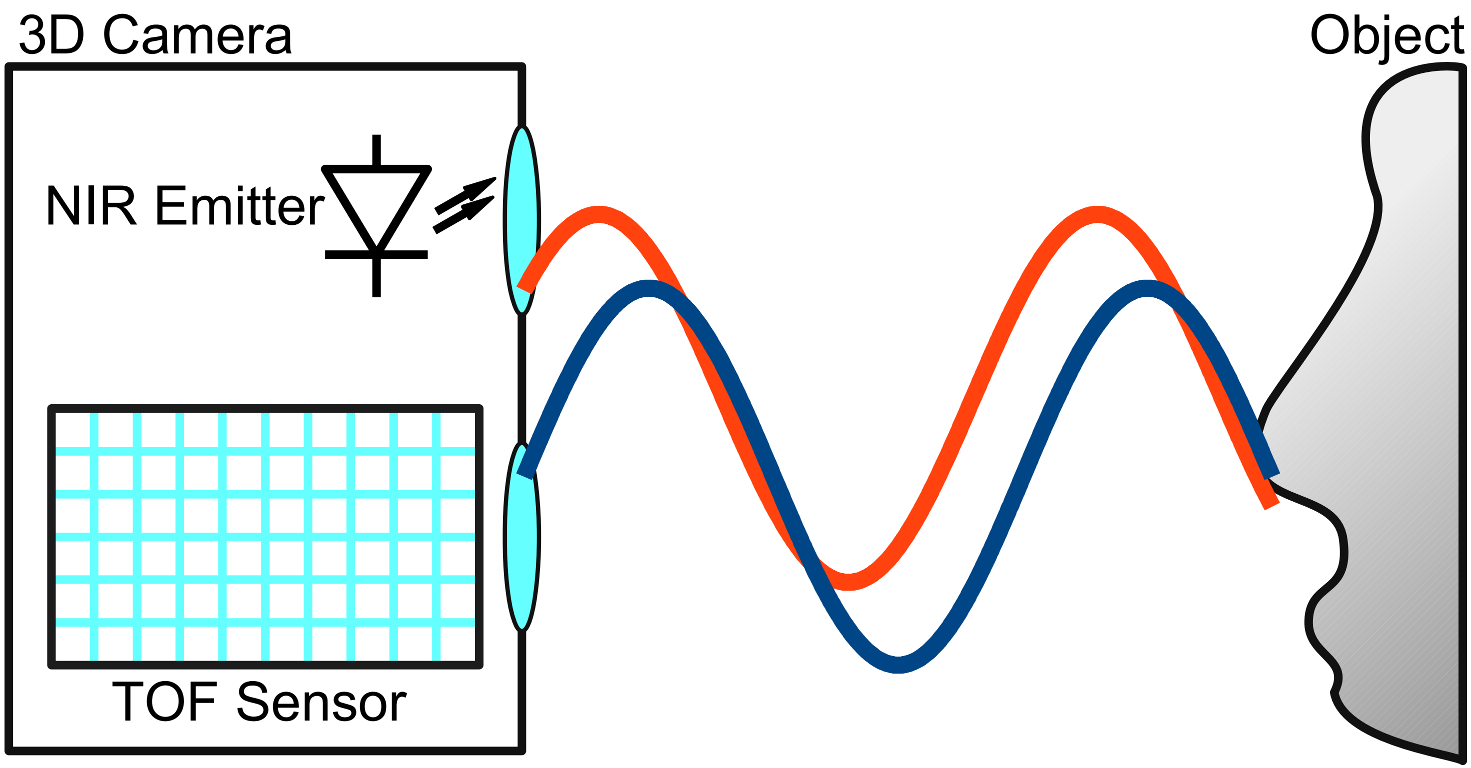
cwTOF Principle



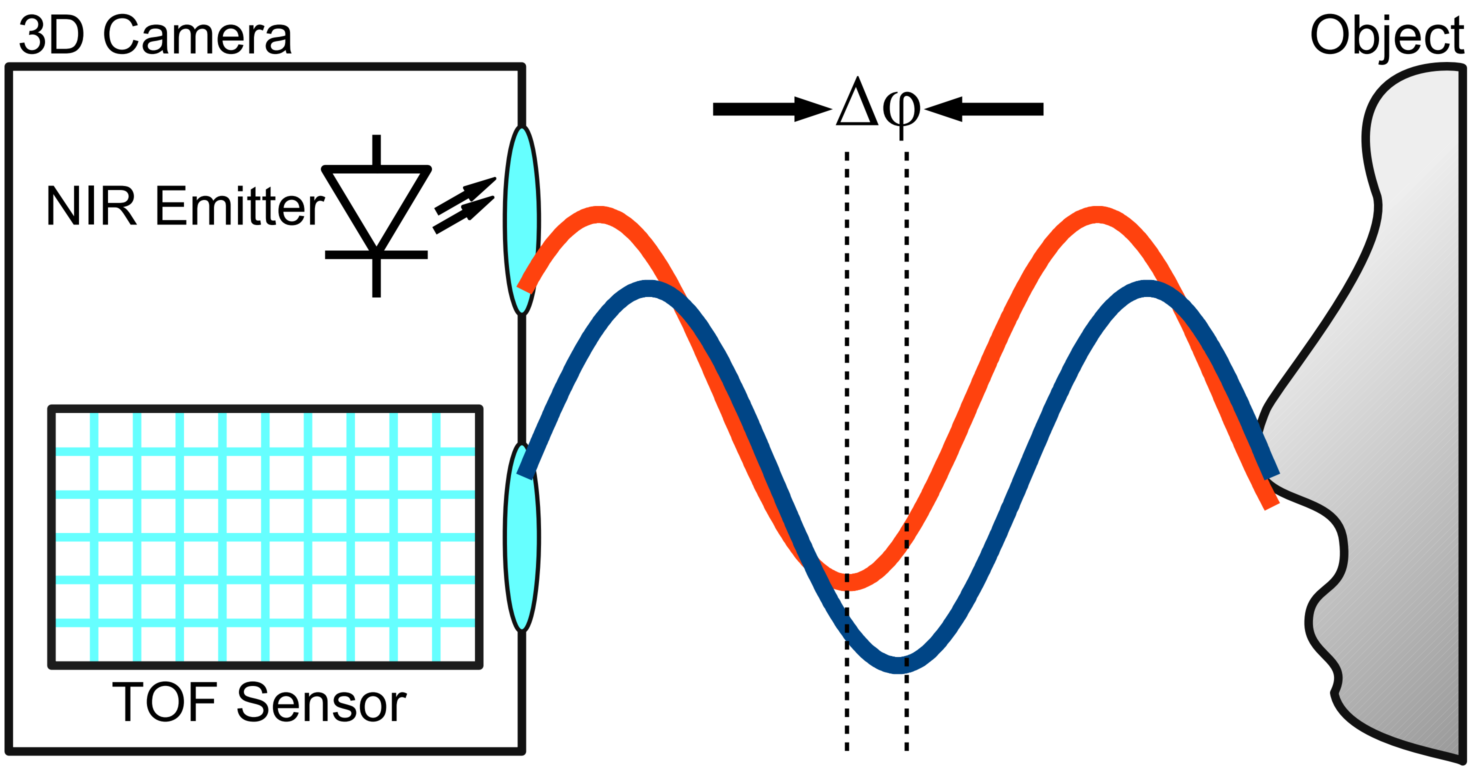
cwTOF Principle



cwTOF Principle

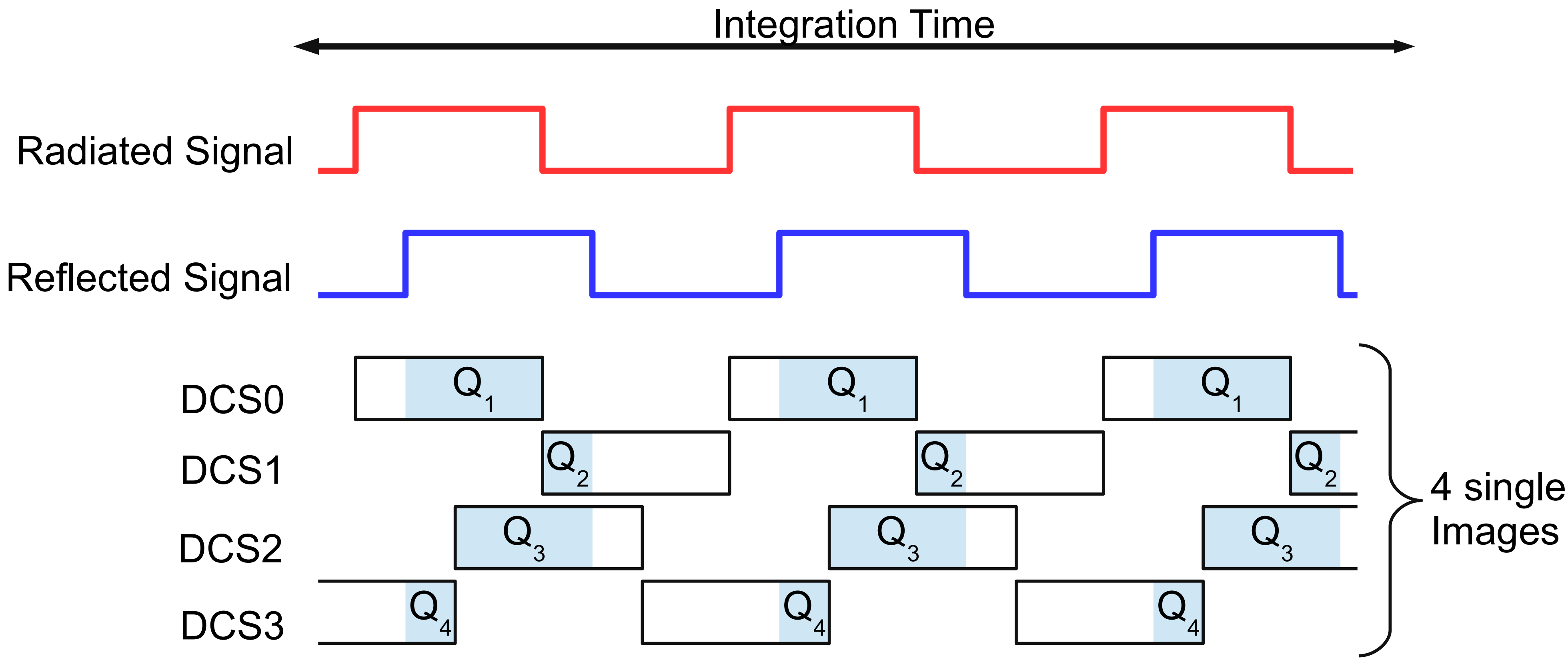


cwTOF Principle



$$Distance = \frac{c}{2} \frac{\Delta\phi}{2\pi f}$$

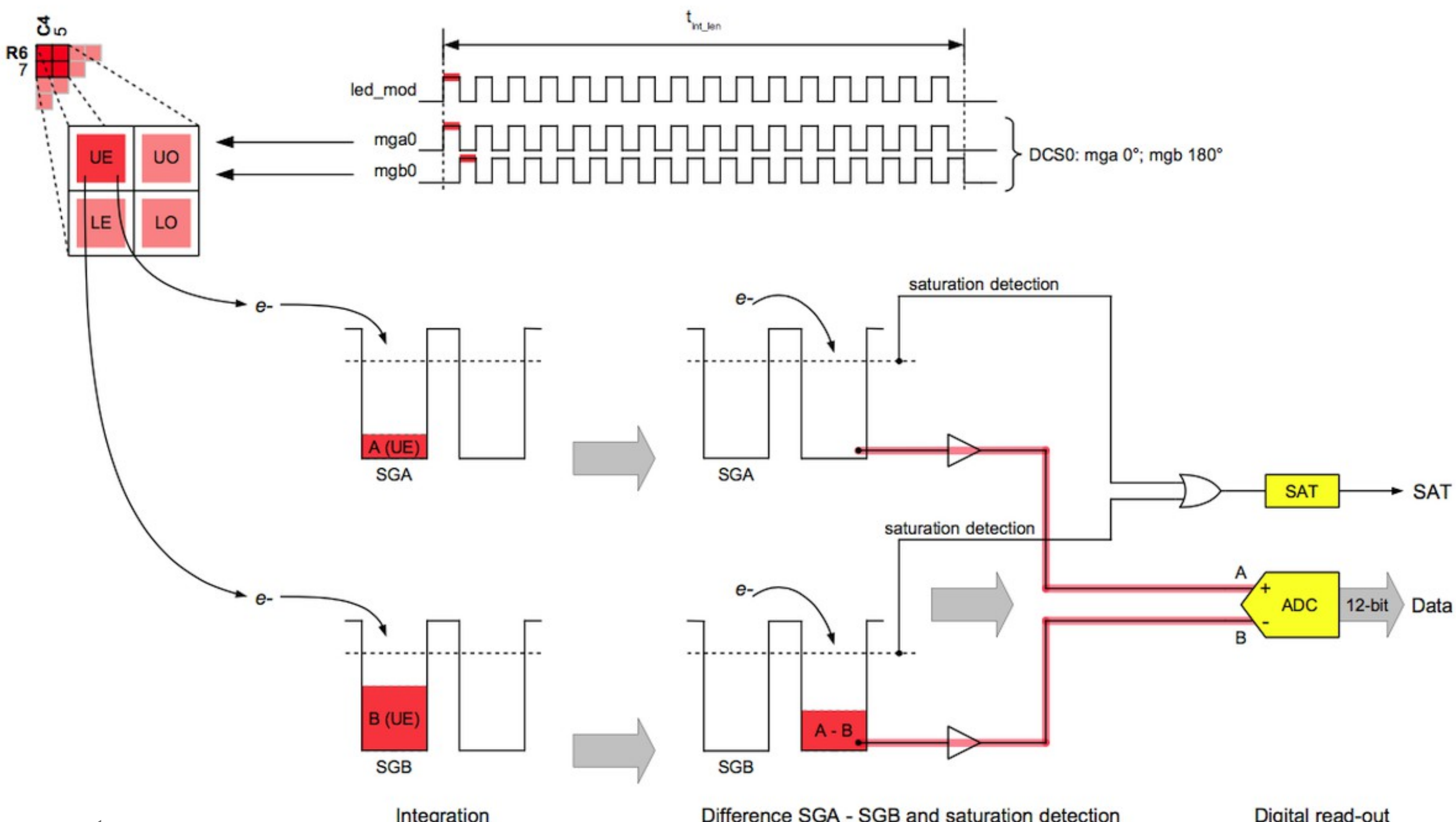
cwTOF Principle



$$\Delta\phi = arctan2\left(\frac{Q_3 - Q_4}{Q_1 - Q_2}\right) \qquad Distance = \frac{c}{2}\frac{\Delta\phi}{2\pi f}$$

Q_x : amount of accumulated charge in pixel

TOF Pixel Readout

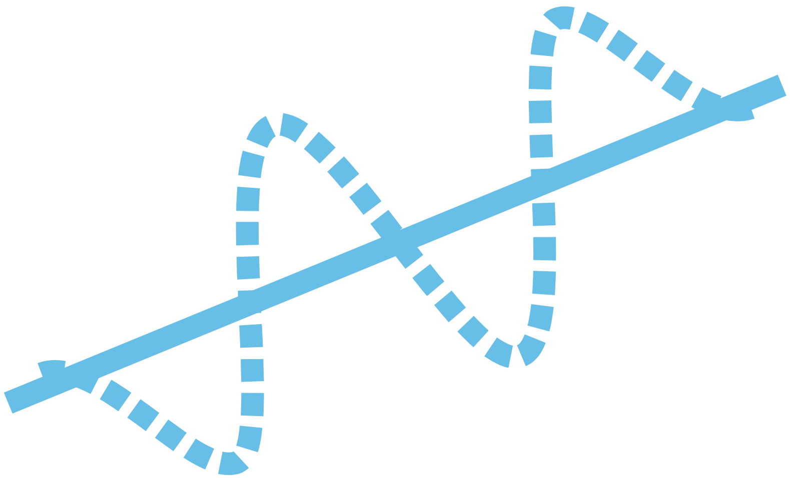


- 2 storage gates
- High full well capacity
- Differential readout
- Ambient light suppression
- High gain

Some facts

- The speed of light is 30 cm/ns.
- On-chip delay of electrical signals on tracks is 1ns/cm.
- If we want to achieve 1.5cm accuracy, we have to control all distance measurement signals on-chip in total to better than 100ps!

Error sources in TOF sensors



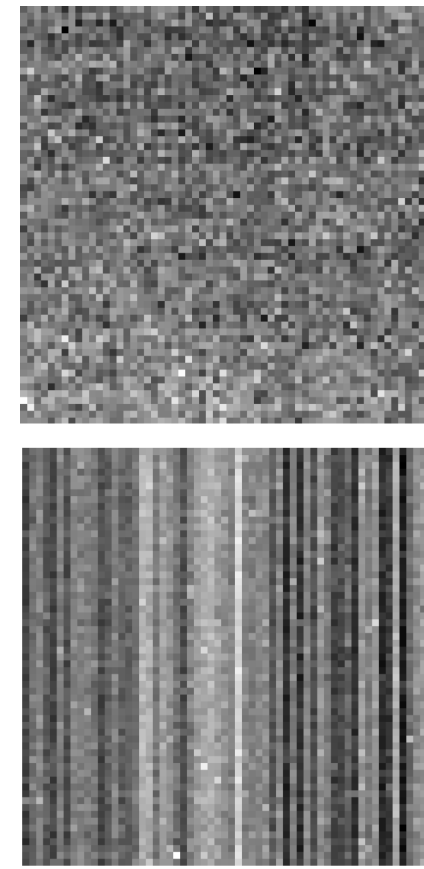
Error sources in TOF sensors

- Fixed Pattern Noise (FPN)

  two main effects:

  - Dark Signal Non-Uniformity (DSNU)
    Offset in pixel without illumination
  - Photo Response Non-Uniformity (PRNU)
    Variation of the ***gain*** how the pixel responds to light

  - Depending on architecture of sensor stripes are visible due to row and column addressing variation.
  - Differences of single column ADCs also contribute to this effect



Source: Stanford University, Lecture EE392b

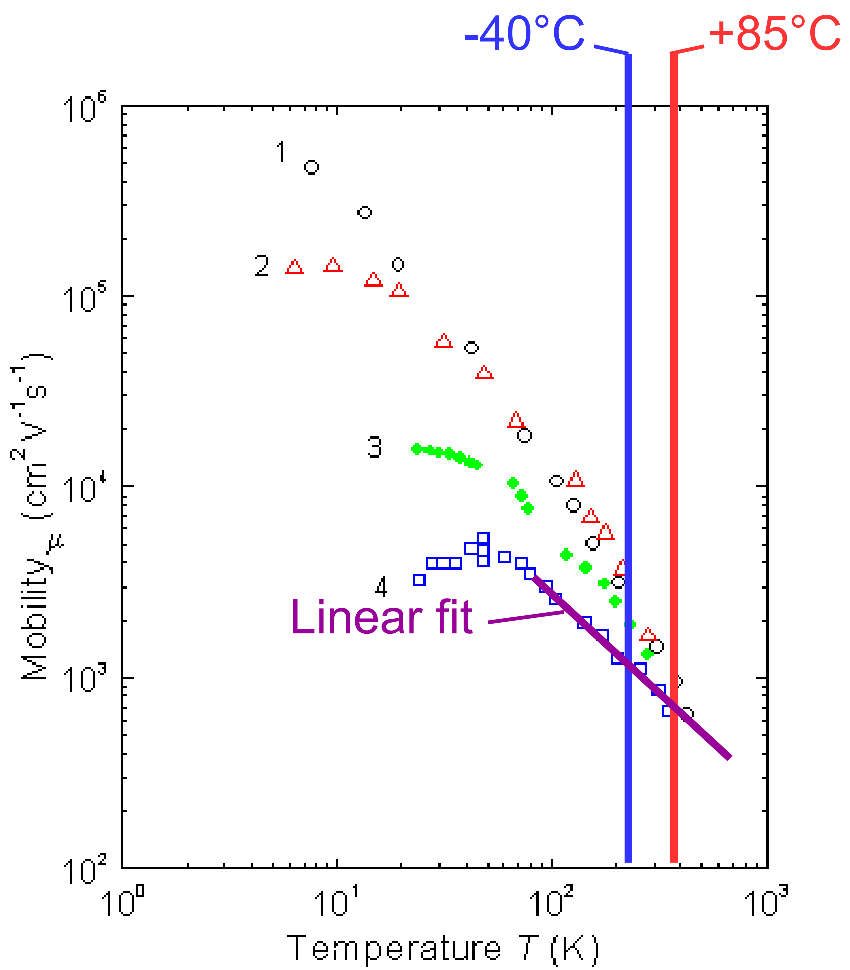
- FPN is fixed for a given sensor, but varies from sensor to sensor.

  → FPN can be corrected

Error sources in TOF sensors

- Temperature drift
  - Electron mobility decreases with rising temperature
  - Affected by temperature drift in a TOF camera system are:

Circuit	Delay [ps/K]	Distance Drift [mm/K]
Pixel	86.00	12.90
Driver	18.00	2.70
DLL Stages	4.00	0.60



Source: http://www.ioffe.ru/SVA/NSM/Semicond/Si/electric.html

- Temperature drift is a linear effect.

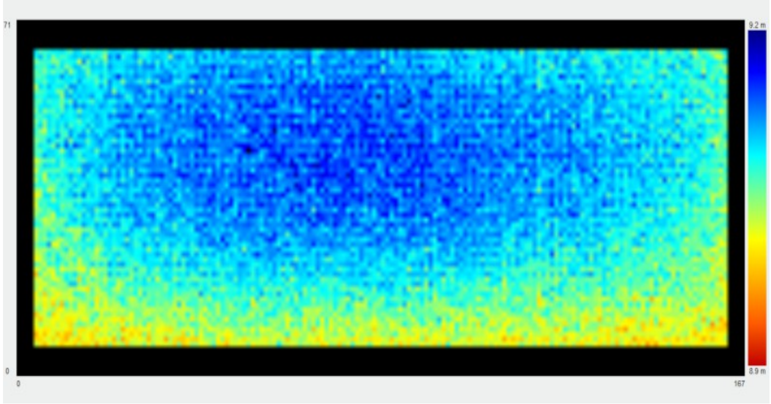
→ Temperature drift can be corrected

Error sources in TOF sensors

- Flat field error

  - TOF pixels consume significant power during demodulation due to the high demodulation frequency. Resulting in a temperature gradient with highest temperature in the center.

    This effect is heavily dependent on the thermal connection of the chip.



  - Lengths of the control signals for different pixel locations vary. Pixel closer to the modulator will report shorter distances.

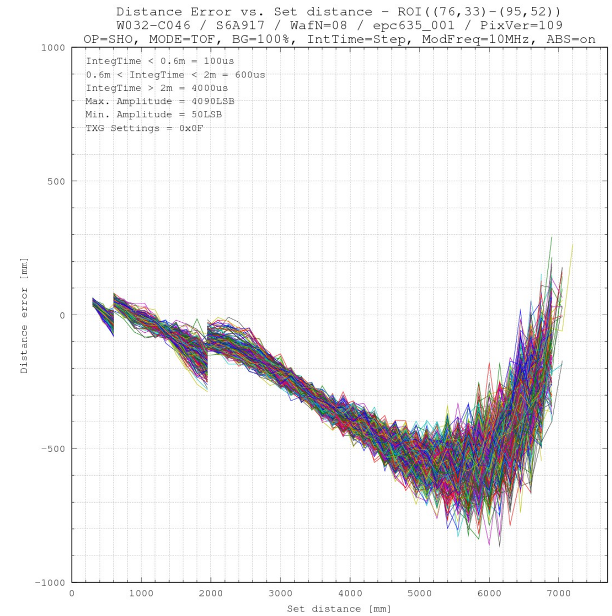
- Flat field error is fixed for a given system.

  → Flat field error can be corrected

Error sources in TOF sensors

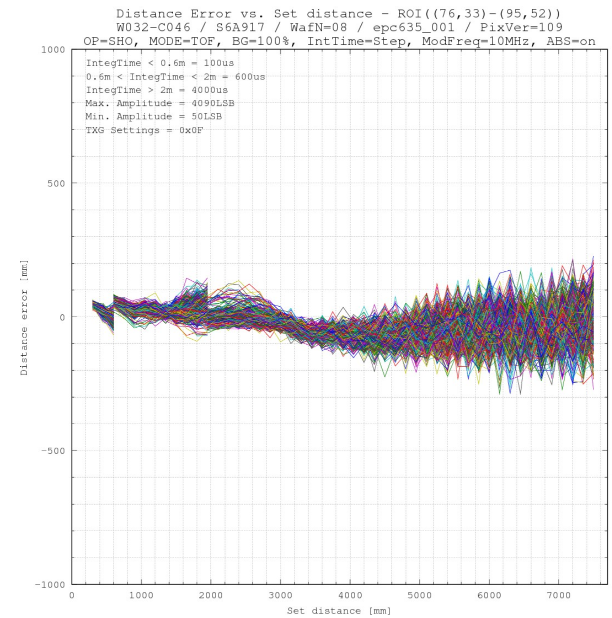
- Ambient Light
  - Increased noise due to ambient light shot noise

    → can be reduced only with more powerful illumination. No correction possible



  - Change of absolute distance due to pixel non-linearity
    - Offsets in DCS0 and DCS1

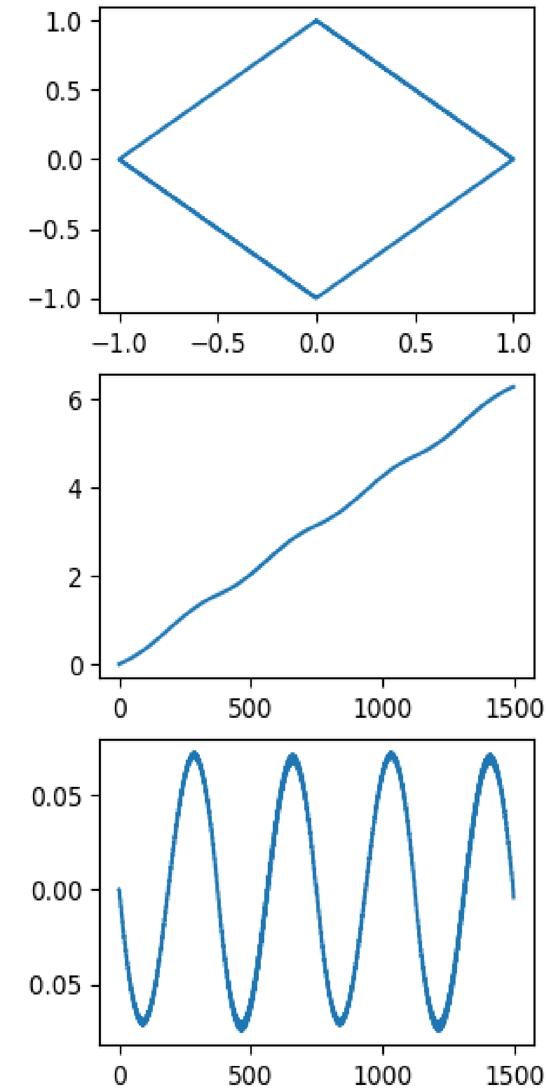
    → can be compensated by measuring ambient light and correct pixel by pixel. This is a linear effect.



Error sources in TOF sensors

- Demodulation
  - Modulation and demodulation are rectangular functions
  - Demodulation is a trigonometric function (atan)

  → **4th order harmonics**

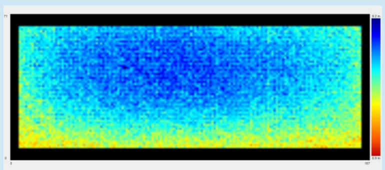
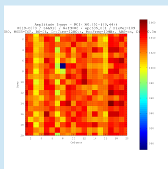
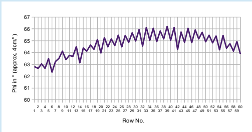
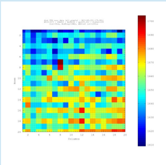
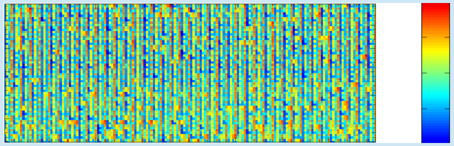
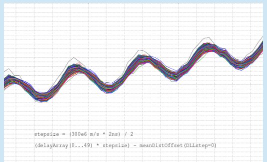


- Demodulation error is fixed for a given system and modulation frequency.

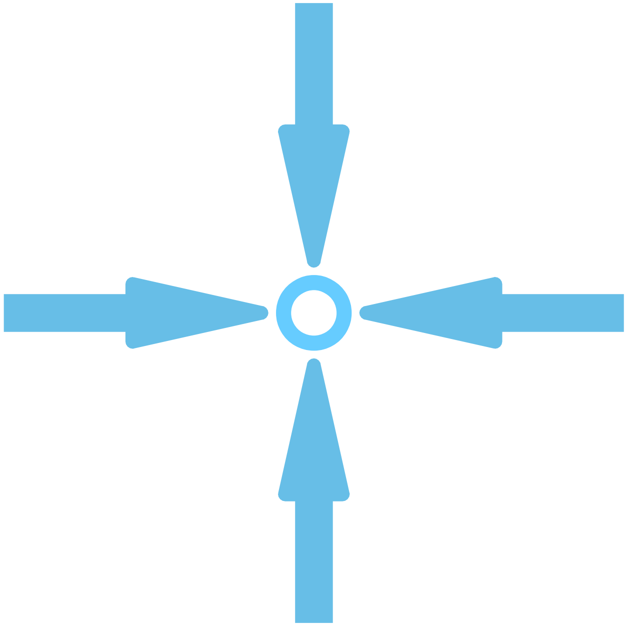
  → Demodulation error can be corrected

Summary Error Sources: DRNU

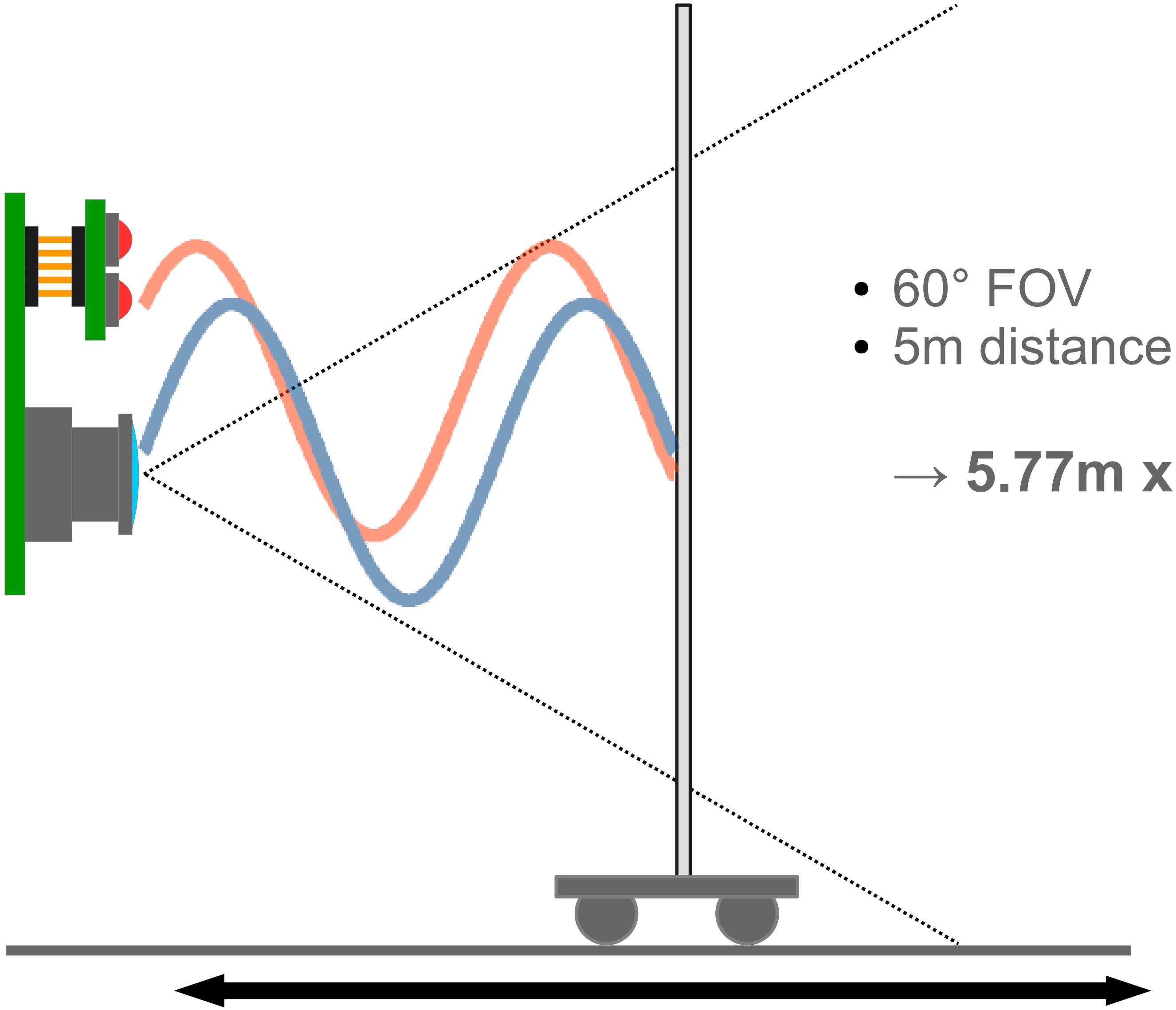
DRNU: **D**istance **R**esponse **N**on-**U**niformity

	Flat field error (physics)
 	Column ADC differences (chip design)
	Row addressing differences (chip design)
	Pixel fix pattern noise (manufacturing process)
	4th order harmonics (demodulation algorithm)

cwTOF Calibration and Compensation



cwTOF Calibration and Compensation

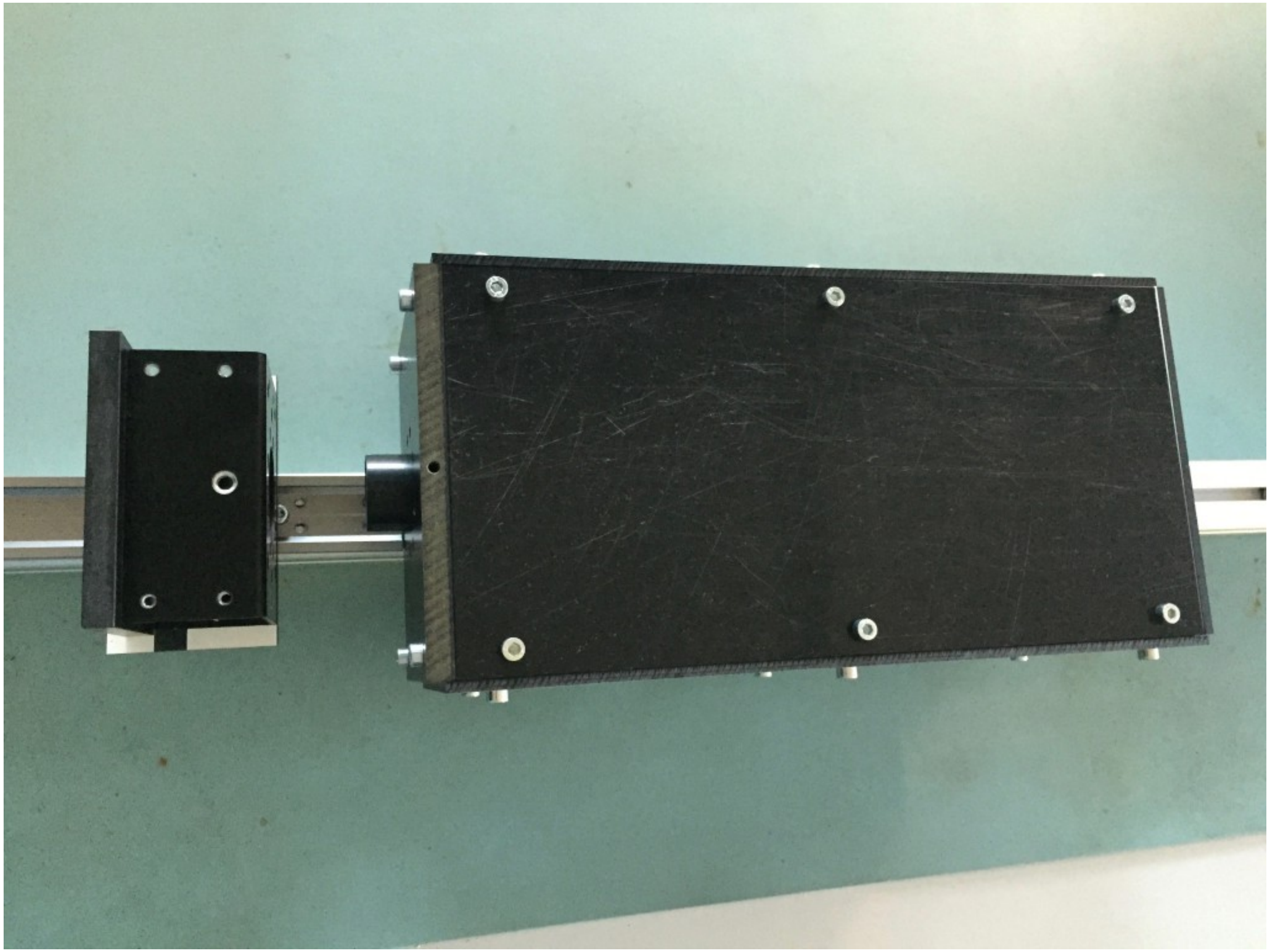


- 60° FOV
- 5m distance

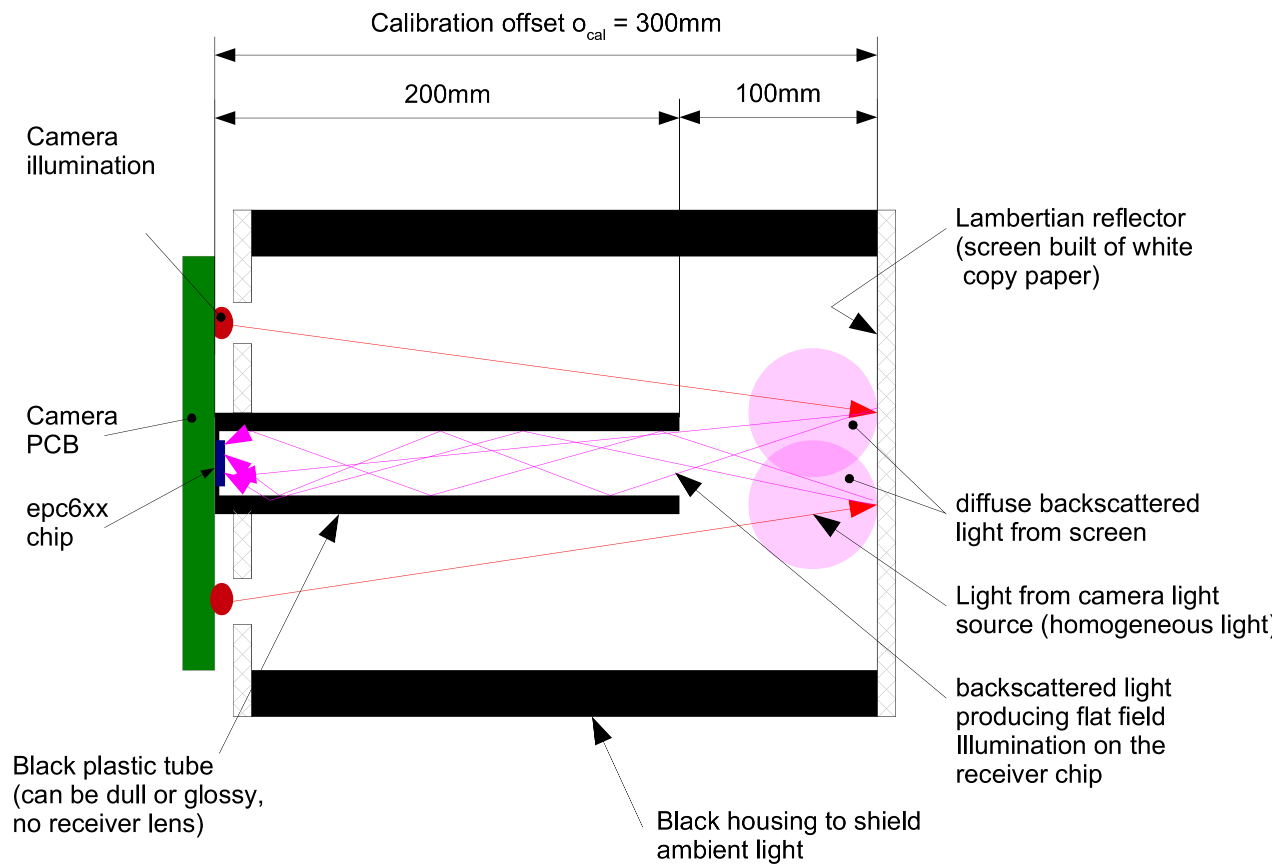
→ **5.77m x 4.33m Target!**

Camera Calibration

A simple box can be used for camera calibration!



Camera Calibration



- Conditions:
  - No lens on imager chip for good flat field illumination
  - TOF amplitude shall be in a range of 1000 to 1500 DN
  - Temperature stable environment. Chip temperature must not change more than ±0.5K during calibration.

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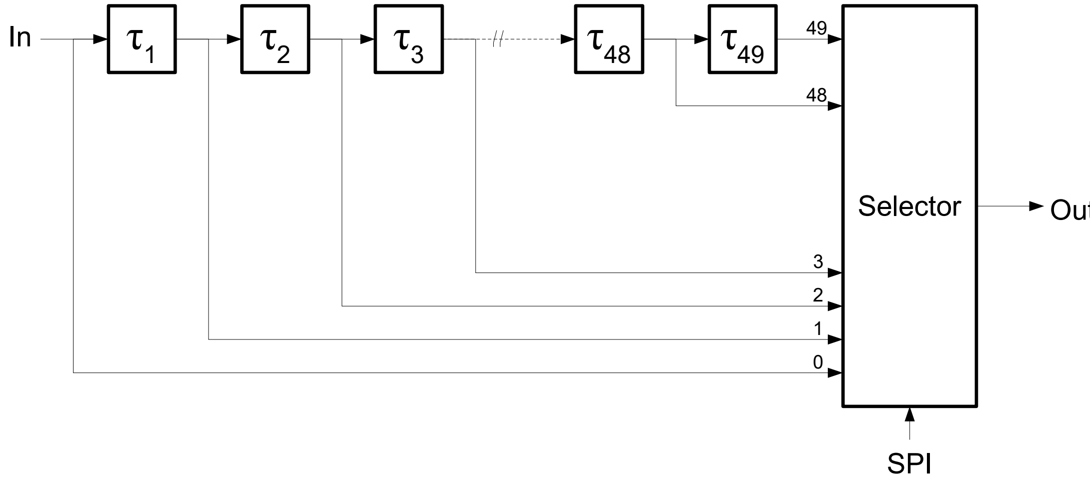
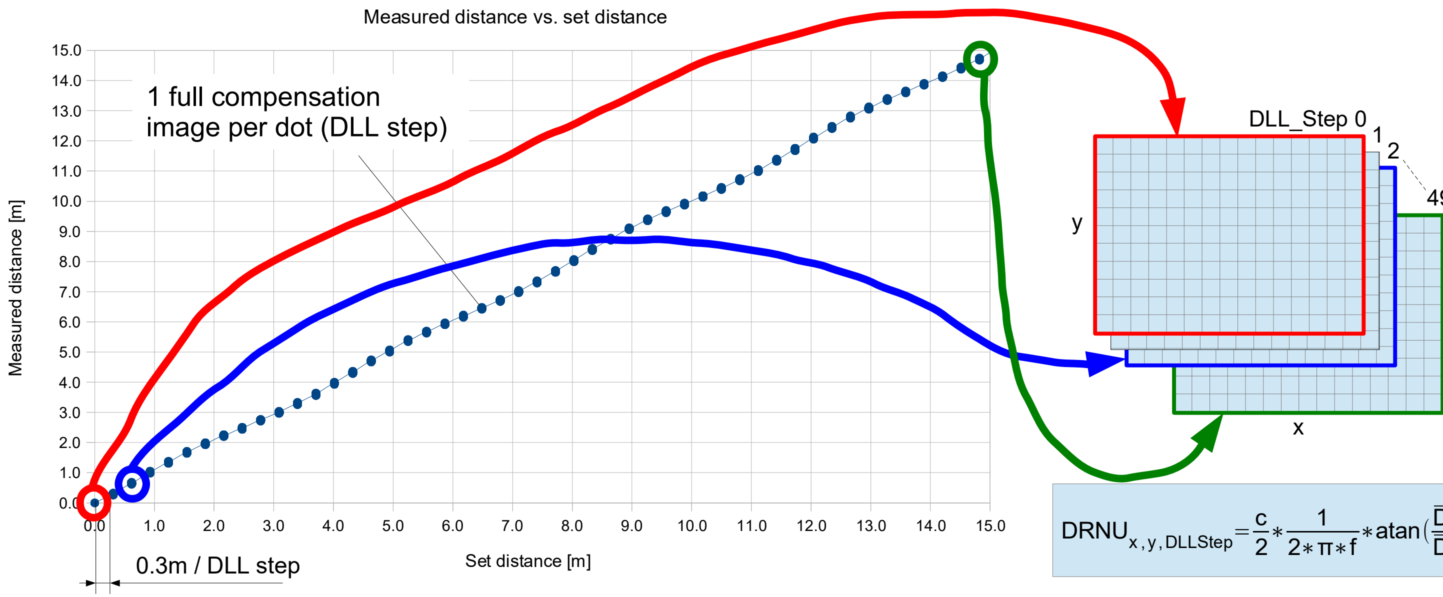
Camera Calibration: Use of the DLL



- The DLL unit allows to delay the LED/LD in 49 steps of approx. 2ns.
- One step represents a virtual distance shift of approx. 30cm to the screen in the calibration box
- Since we create a flat field illumination, all pixels of the imager chip “see” the object in the same virtual distance and with the same signal strength
- The signal strength remains the same if we change the virtual distance

Camera Calibration: LUT per DLL Step

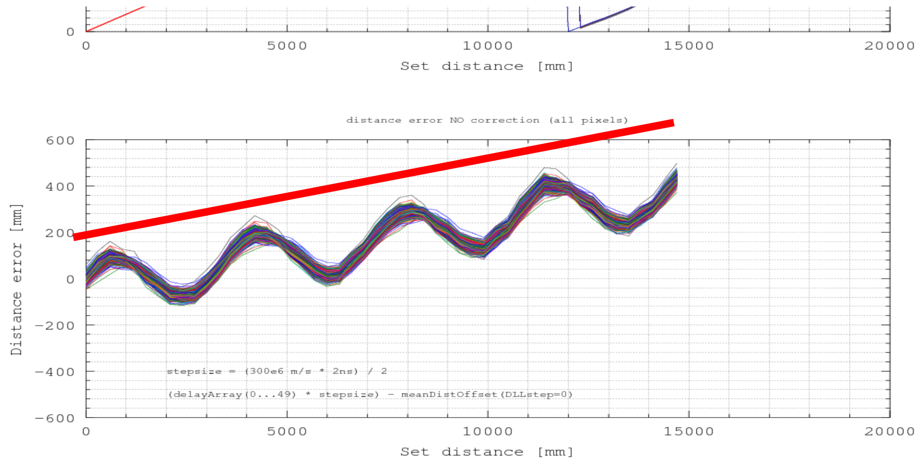


$$DRNU_{x,y,DLLStep} = \frac{c}{2} * \frac{1}{2*\pi*f} * atan\left(\frac{DCS3 - DCS1}{DCS2 - DCS0}\right) - n*d_{DLL} - o_{zero}$$

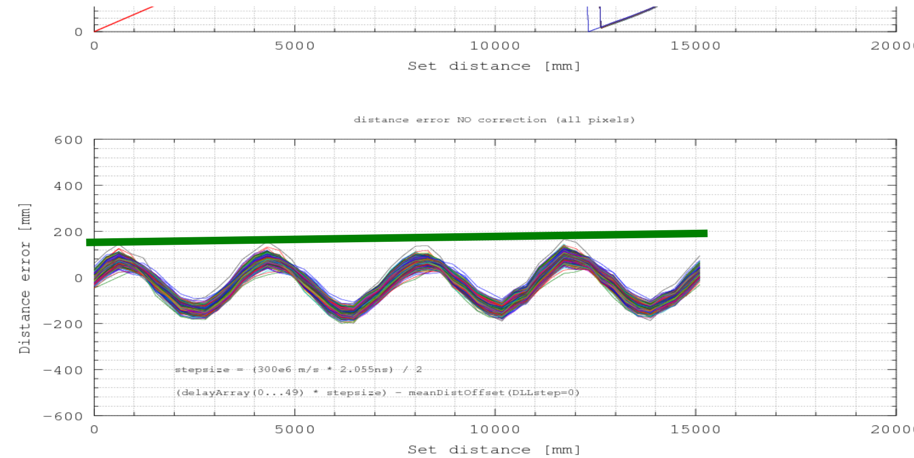
Go step by step from 0 to 49 DLL steps:

1. For each DLL step setting take the average of 100 TOF images by acquiring 4 DCS per pixel.
2. Calculate the distance per pixel from the DCS values. The result is a signed integer value.
3. Subtract this TOF distance from the ”set” distance given by the number of DLL steps used.
4. Store the result into an array DRNU_LUT(x,y,DLL_Step). This is the calibration array which will be used during runtime for compensation.

Camera Calibration: DRNU_LUT Result



t_{DLL_n} too high (2.00ns):
Increasing slope



t_{DLL_n} correct (2.055ns):
Horizontal slope

--> Check that the DRNU_LUT looks like in the right image <--

Runtime Compensation: Global Procedure

Step #1	Calculate ambient light compensation on DCS0 and DCS1 pixel by pixel
Step #2	Calculate the raw distance
Step #3	Calculate compensated distances by using DRNU_LUT and interpolation
Step #4	Apply Formula to remove temperature drift
Step #5	Add absolute distance offset

Step #1 Ambient Light

- DCS0 and DCS1 have to be compensated
- DCS2 and DCS3 are not affected
- k is a global correction value

$$DCS0/1_{x,y,BGComp} = DCS0/1_{x,y} - \frac{BG_{x,y} * k}{\sqrt{t_{int}}}$$

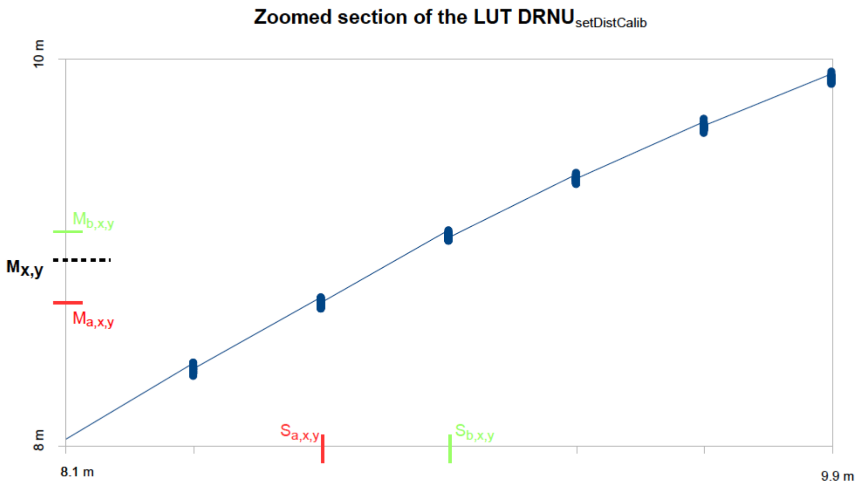
Step #2: Raw distance calculation

- Use the well known formula:

$$D_{Raw\,x,y} = \frac{c}{2} * \frac{1}{2 * \pi * f} * \operatorname{atan}\left(\frac{DCS3_{x,y} - DCS1_{x,y,BGComp}}{DCS2_{x,y} - DCS0_{x,y,BGComp}}\right)$$

Step #3: DRNU Error Compensation

- Determine the indices for the DRNU_LUT:




```
for ( I = 0,1,..,49 )
        Ma,x,y = DRNUCalib x,y, n[ i ]
        Mb,x,y = DRNUCalib x,y, n[ i +1 ]
        if (( Draw x,y >= Ma,x,y ) AND ( Draw x,y < Mb,x,y ))
                Sa,x,y = i * dDLL
                Sb,x,y = Sa,x,y  + dDLL
                dCamOffset, x,y = calc Formula
        end if
end for
```

- Calculate DRNU values for compensation:

$$DRNU_{Calib\ x,y,n} = DRNU_{x,y,n} + d_{DLL} * n + o_{zero}$$

- Calculate the compensated distance:

$$d_{CamOffset,x,y} = \frac{(S_{b,x,y} - S_{a,x,y})}{(M_{b,x,y} - M_{a,x,y})} * (D_{Raw\ x,y} - M_{a,x,y}) + S_{a,x,y} - o_{zero}$$

Step #4: Temperature Compensation

- During the acquisition with a grayscale image for ambient light compensation, the current temperature T_{ACT} can be obtained.
- Use the following formula to calculate a temperature compensated distance:

$$d_{x,y,Comp} = d_{CamOffset,x,y} - (T_{ACT} - T_{CAL}) * (TC_{Pix} + TC_{OD} + n * TC_{DLLn})$$

- Temperature coefficients:

TC_{Pix}	86ps/K	12.9mm/K
TC_{OD}	18ps/K	2.7mm/K
TC_{DLLn}	4ps/K * n	0.6mm/K * n

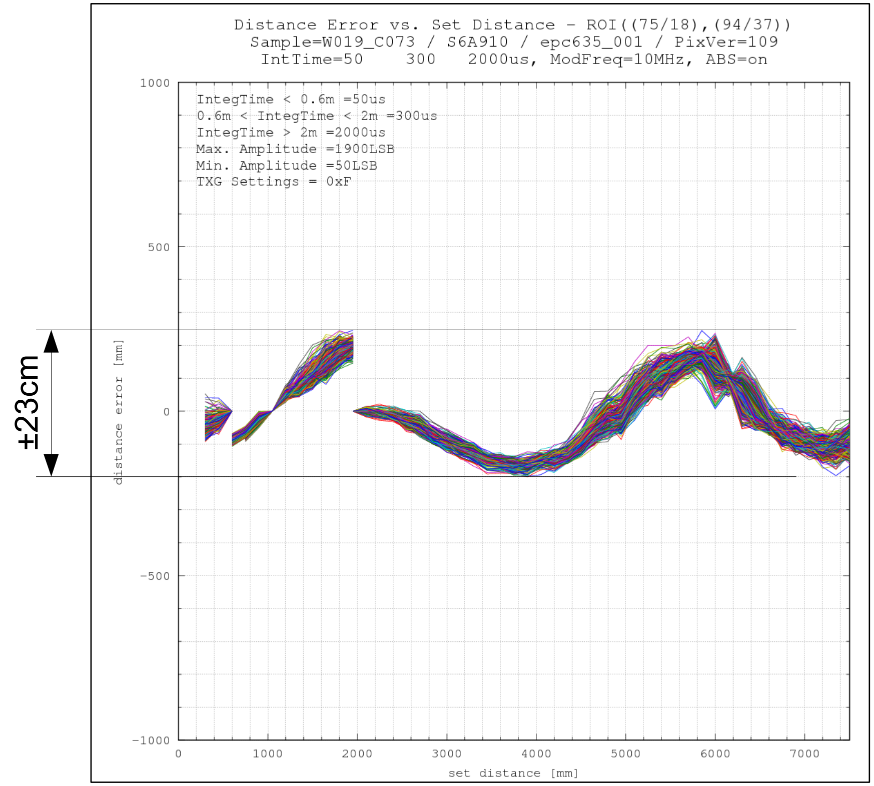
Runtime Compensation: Step #5: Absolute Distance calibration

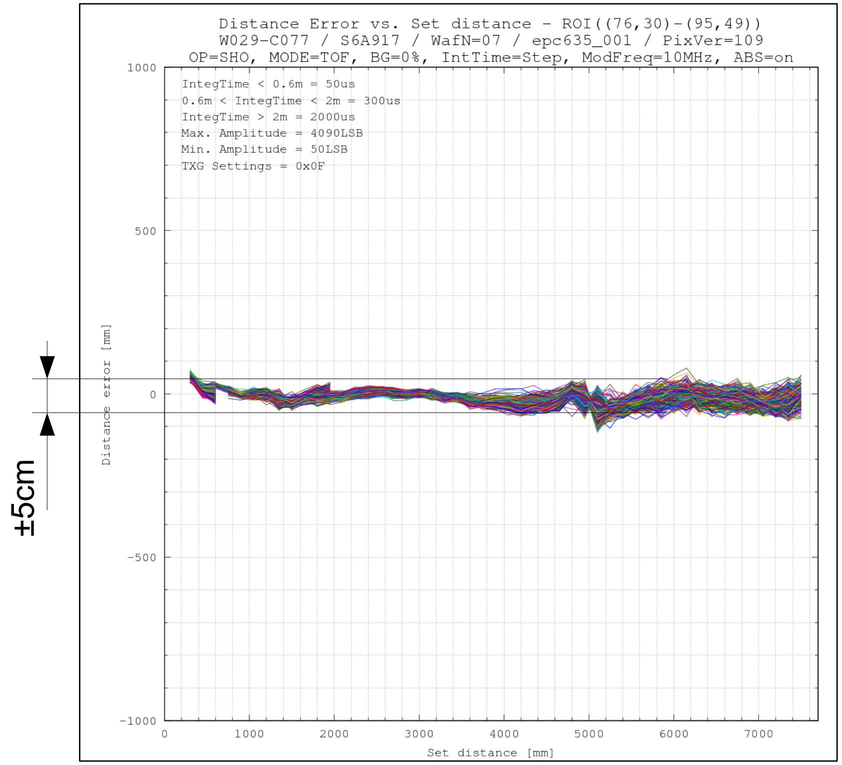
- Attach the receiver lens to the camera
- Point with the camera to a white target in a distance of e.g. 1m
- Read the distance of the center pixel(s) to the target
- Calculate the difference between the set distance and the measured distance. The result is o_{Cal} which eliminated the global camera offset:

$$d_{x,y} = d_{x,y,Comp} + O_{cal}$$

- o_{cal} is a global value and valid for all pixel

Effect of Calibration and Compensation





Results:

Parameter	Uncalibrated and not compensated	Calibrated and compensated
Absolute distance error	±23cm	±5cm
Temperature drift at low TOF amplitude ΔT=40K	60cm	5cm
Drift due to strong ambient light	100cm	10cm

Conclusion

- There are no perfect imagers. Fast TOF imagers are affected even more.
- The purpose of these slides is to present a way, how distance errors can be reduced. However, they cannot fully eliminated!
- More detailed information is available in AN10.

Thank you!

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