# LiDAR and Other Techniques

## Measuring Distance with Light for Automotive Industry

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# Introduction

- There is a great interest in the automotive industry to develop on-vehicle systems which make driving safer.
- In addition, motivated by market demand, a longer-term goal is development of a completely autonomous (self-driving) vehicle.

# Introduction

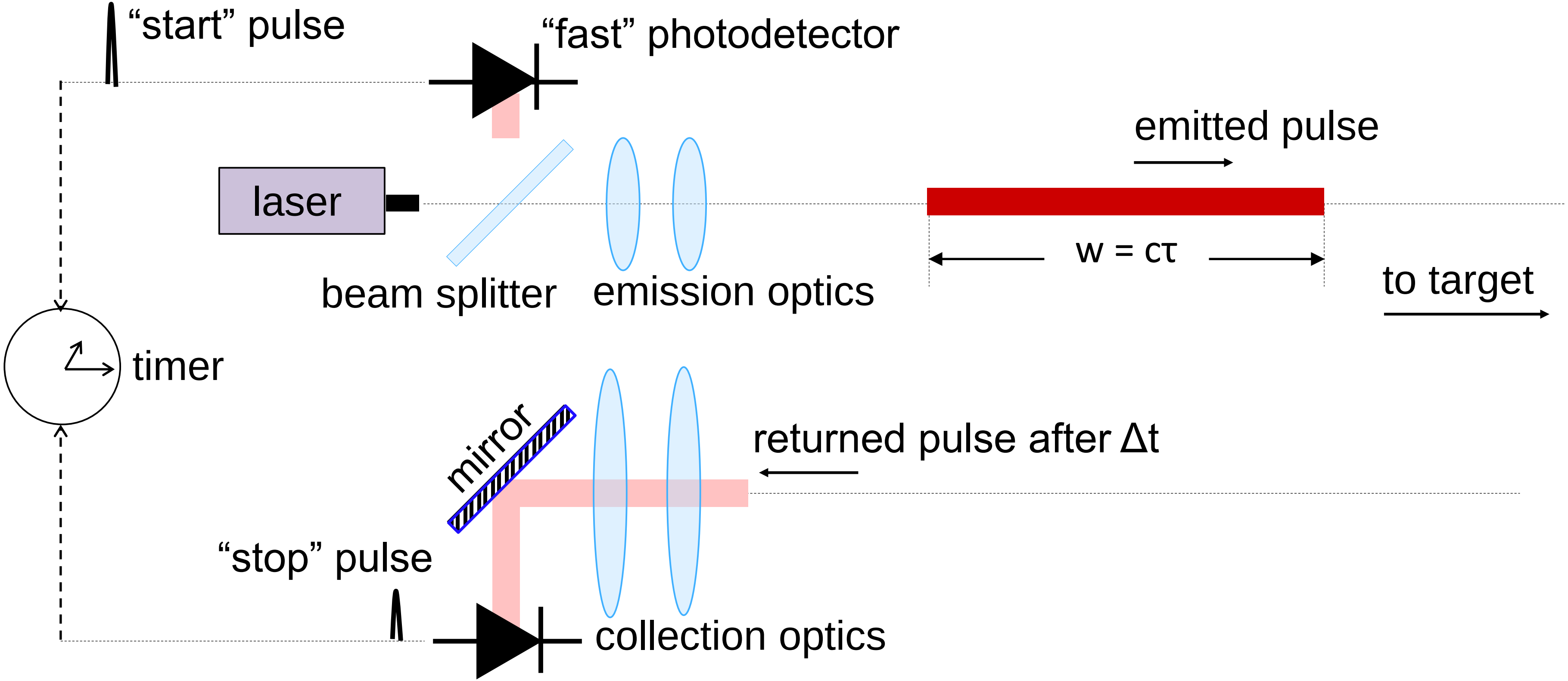
- Such a self-driving vehicle must have an ability to create a 3D map of its surroundings up to about 300 m at a video rate.

**This webinar discusses techniques and challenges of measuring distance with light for automotive applications emphasizing time-of-flight LiDAR**

# Outline

- Time of flight (Tof) LiDAR (**emphasis of this webinar**)
  - Basic concept
  - Challenges in designing ToF LiDAR
  - Types of ToF LiDAR: mechanical, flash, optical phase array
- FMCW radar (concept)
- FMCW LiDAR (heterodyne optical mixing)
- Summary and conclusions

# Basic layout of ToF LiDAR



# ToF LiDAR distance

Measure $\Delta t$

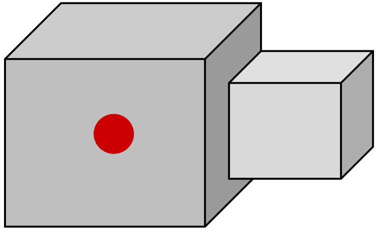
$$R = \frac{1}{2} c \Delta t$$

If $\Delta t = 0.67\ \mu s$, $R = 100$ m

or 6.7 ns per 1 m of distance

# Distance uncertainty

$$\boxed{\delta_R = \tfrac{1}{2} c \delta_{\Delta t}}$$



Laser spot small compared to the target feature

$\delta_R$ – Distance uncertainty

$\delta_{\Delta t}$ – Uncertainty in measuring $\Delta t$ (mostly due to photodetector jitter)

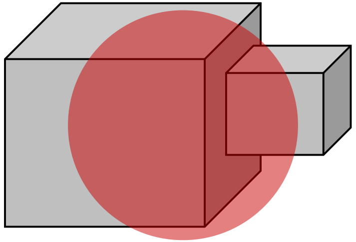
# Distance uncertainty

$$\boxed{\delta_R = \tfrac{1}{2}c\tau = \tfrac{1}{2}w}$$

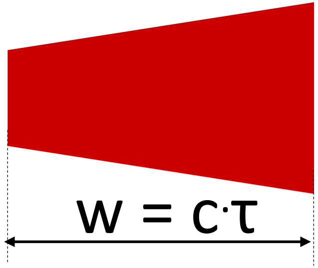
$\delta_R$ – Distance uncertainty

$\tau$ – Pulse duration

w – Pulse width ($c\tau$)

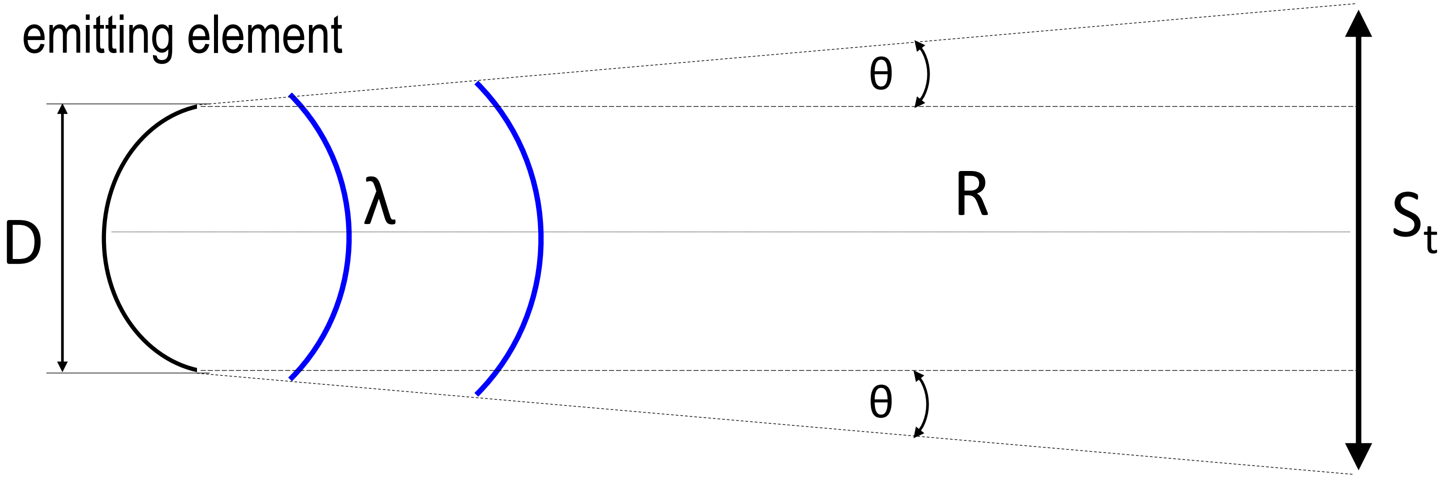


Laser spot large compared to target features



Propagating divergent pulse

# Beam Divergence



Diffraction causes beam divergence: $\theta \approx 1.22\lambda/D$

$S_t$ – Minimum resolvable transverse size at distance R

# Beam Divergence

Radar: 77 GHz –> $\lambda = 0.3$ cm.

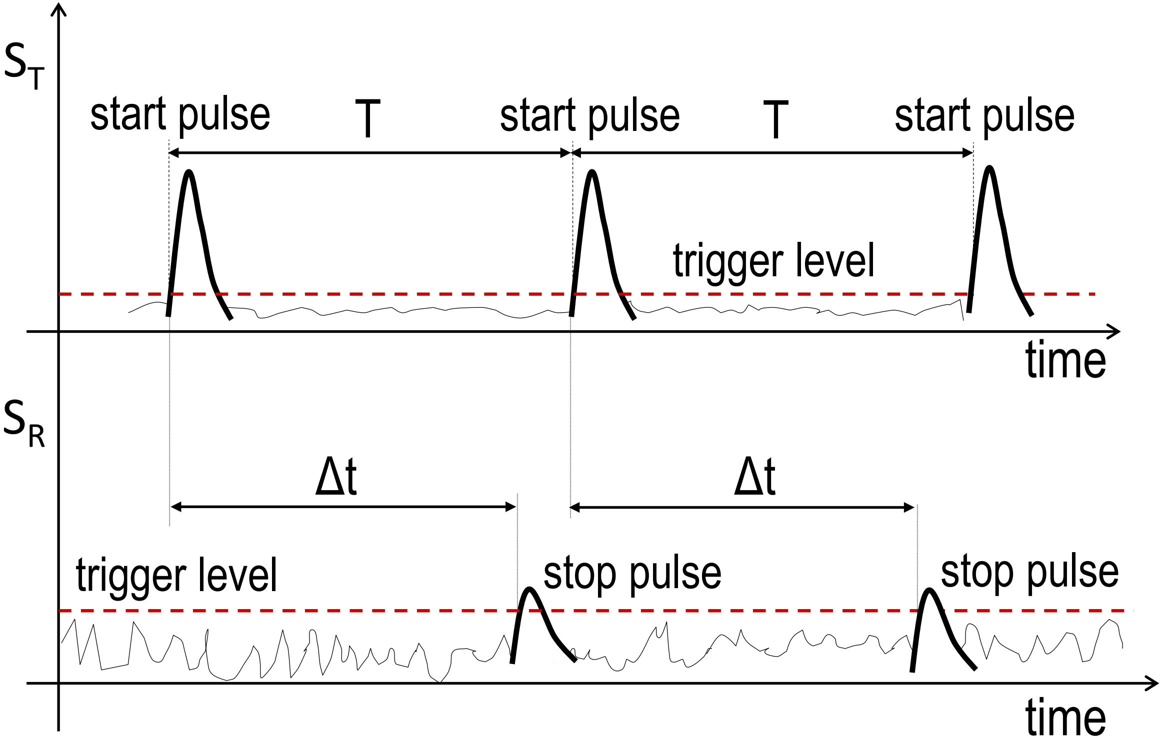
If $D = 20$ cm –> $\theta \approx 1^\circ$ –> $S_t \approx 1.8 \text{ m} + 0.2 \text{ m} = \boxed{2 \text{ m @ } R = 100 \text{ m}}$

LiDAR: 1550 nm

If $D = 5$ mm –> $\theta \approx 0.02^\circ$ –> $\boxed{S_t \approx 3.7 \text{ cm @ } R = 100 \text{ m}}$

For high-resolution 3D map, we need LiDAR

# ToF LiDAR: timing



T – repetition period

T must be > Δt

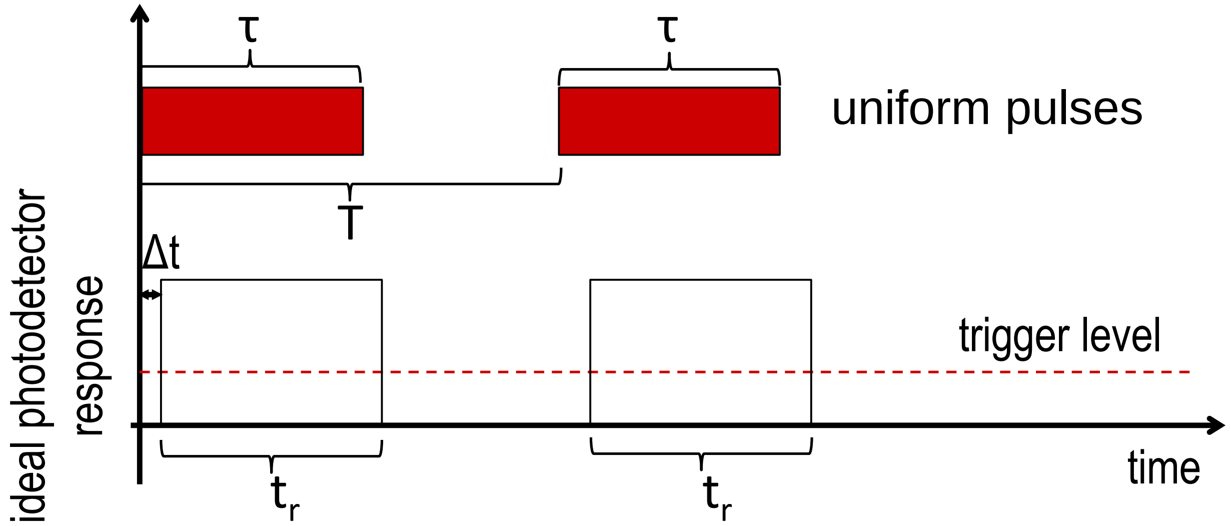
# ToF LiDAR: maximum distance

$$R_{max} = \frac{1}{2}cT = \frac{1}{2}\frac{c}{f}$$

f – Repetition frequency or sampling frequency

Photon budget imposes another limit on $R_{max}$

# ToF LiDAR: minimum distance (ideal case)



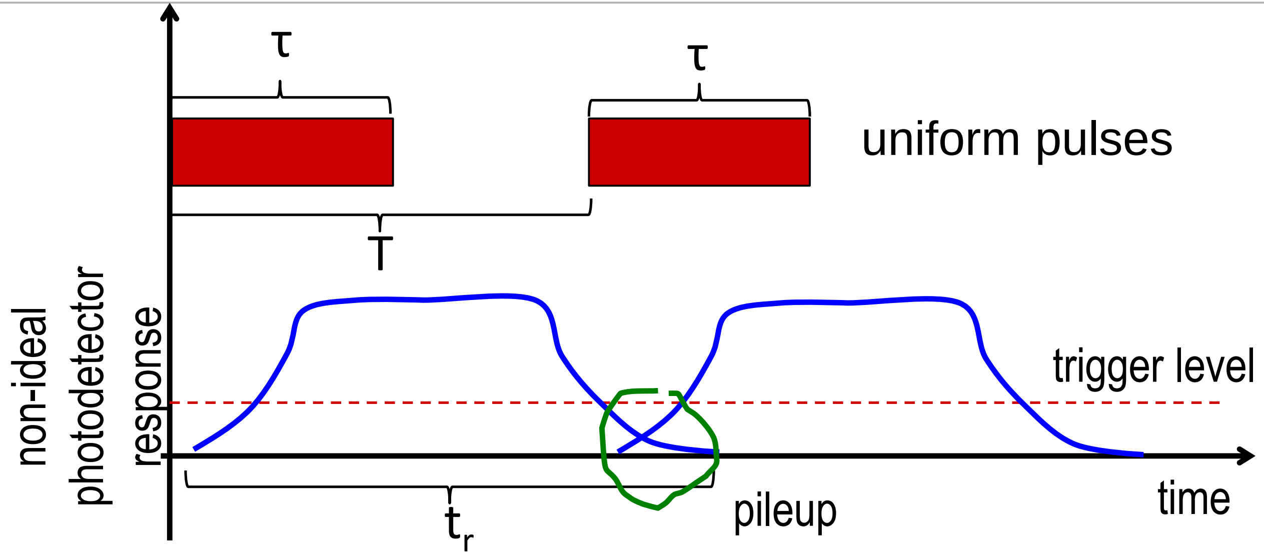
$T > \tau$

$B = \infty$

$t_r = \tau$

There is no limit on the smallest distance

# ToF LiDAR: minimum distance (realistic)



$T > \tau$

B finite

$t_r > \tau$

Signal pileup limits the smallest measurable distance

# ToF LiDAR: maximum sampling rate

$$f_{max} = 1/\Delta t_{max} = c/2R_{max}$$

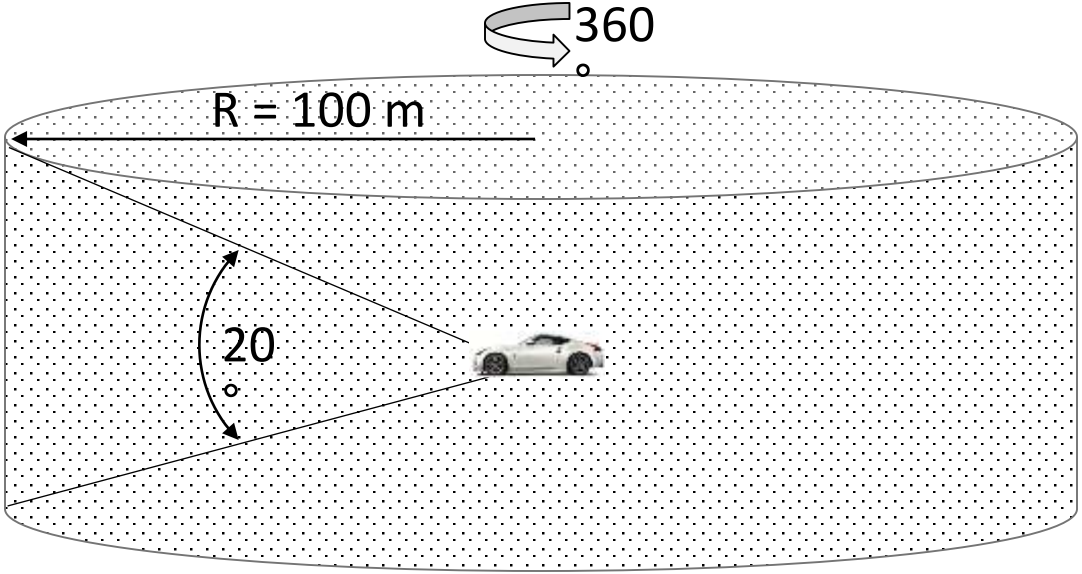
$f_{max}$ = 1.5 MHz @ R = 100 m

Larger the range, more time it takes to produce a 3D map

# ToF LiDAR: challenges

Challenges and considerations in designing ToF LiDAR

# ToF LiDAR challenges: surround view



Would like

100 m range minimum

360° azimuthal coverage

20° declination coverage

0.2° resolution (~35 cm @ 100 m)

Video rate, 20 frames/s

# ToF LiDAR challenges: sampling rate

To meet the challenge, we need $3.6 \times 10^6$ samplings/s (3.6 MHz)

Can do 1.5 MHz with one light source and photodetector @ R =100 m

**Need to compromise and/or invent different approaches**

# ToF LiDAR challenges: light source

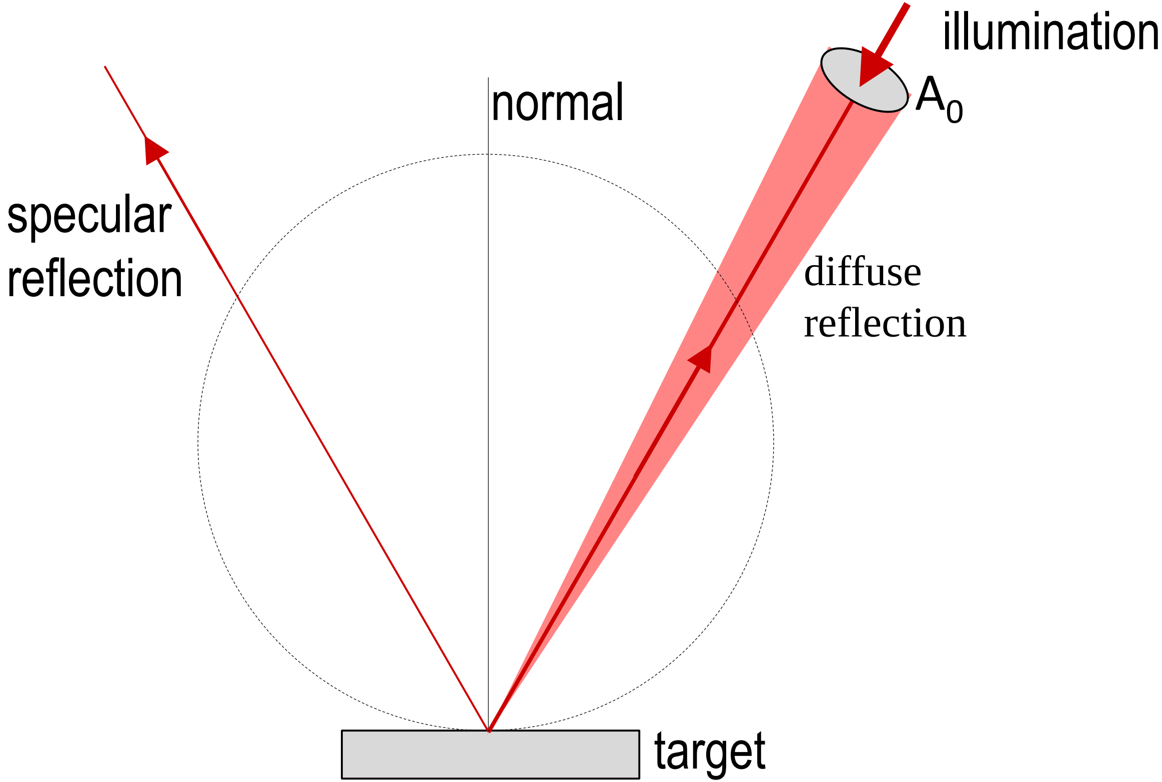
**Safe for human vision**

Short-duration pulses (can get 2 - 5 ns) at high repetition

High peak power per pulse Must comply with *admissible exposure limit (AEL)*, which is a complex function of wavelength, repetition rate, and energy per pulse.

Narrow bandwidth

# ToF LiDAR challenges: photon budget



# ToF LiDAR challenges: photon budget

$$P(R) = P_0\rho\,\frac{A_0}{\pi R^2}\,\eta_0\exp(-2\gamma R)$$

$P(R)$ – Power received

$P_0$ – Peak power transmitted

$\rho$ – Target reflectivity

$A_0$ – Aperture area of the receiver

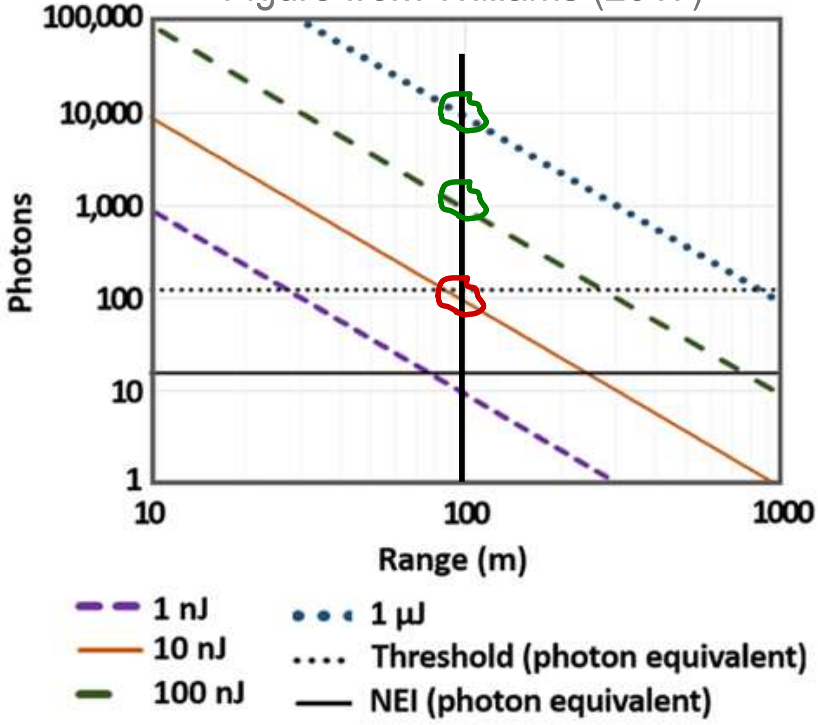
$\eta_0$ – Receiving optics transmission

$\gamma$ – Atmospheric extinction coefficient

This LiDAR equation assumes normal incidence, Lambertian reflection, flat beam profile and negligible divergence, laser spot smaller than the target, and $\gamma$ independent of R.

# ToF LiDAR challenges: photon budget

Figure from Williams (2017)



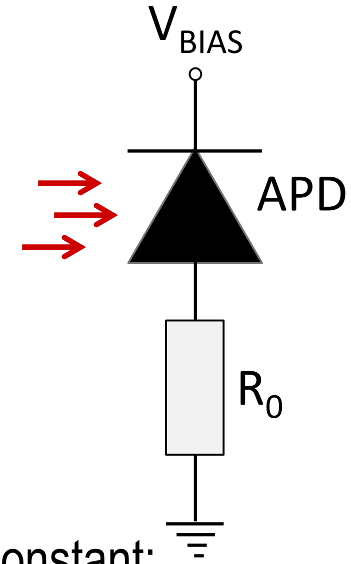
Number of photons (λ = 1550 nm) expected from a target as a function of its range using 1,10, 100, and 1000 nJ pulses.

The figure assumes target reflectivity of 30%, 70% optical efficiency, 30-mm diameter receiver, 0.5 mrad laser beam divergence, and 70% optical efficiency.

50-nJ 4-ns pulse (12.5 W) has: ~4 × $10^{20}$ photons @ 1550 nm

# ToF LiDAR challenges: photon budget

$$SNR(R) = \frac{P(R)S_\lambda M}{\sqrt{2eB[(P(R)+P_B)S_\lambda + I_D]FM^2 + \frac{4kTB}{R_0}}}$$



$S_\lambda$ – Detector's sensitivity

M – Detector's intrinsic gain

$I_D$ – Detector's dark current

F – Detector's excess noise factor

B – Detection bandwidth

$P_B$ – Background light optical power

e – elementary charge; k – Boltzmann constant;
T – temperature

# ToF LiDAR challenges: what wavelength?

## 1550 nm

\+ Best eye safety

\+ Lower background

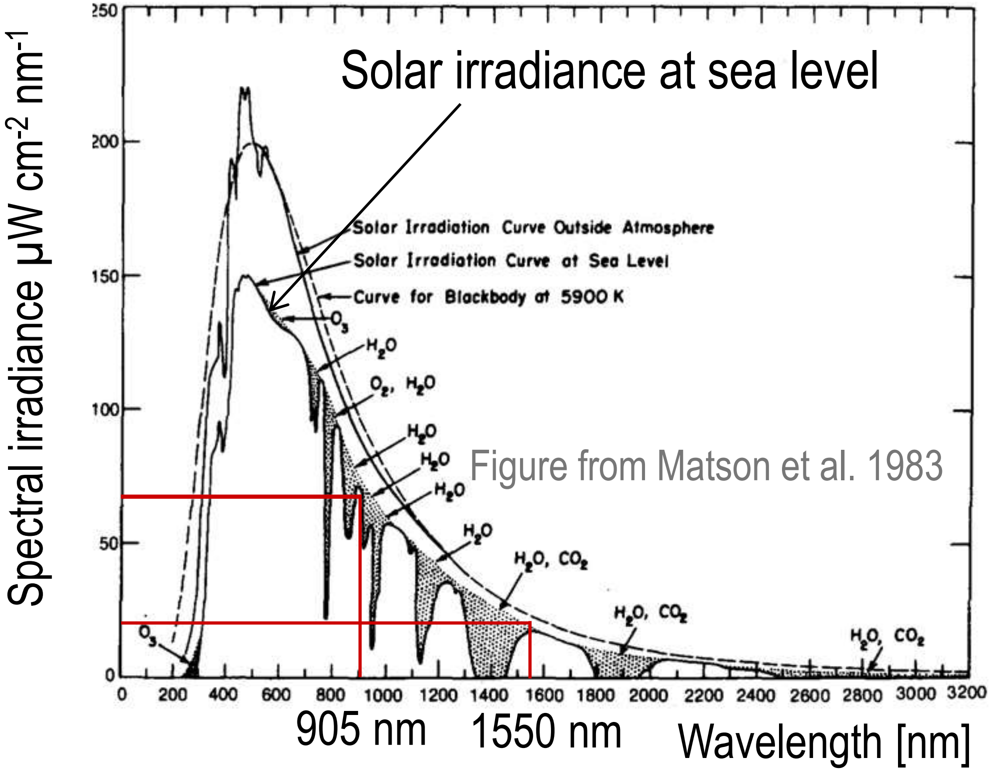
\- Requires IR (non-silicon) photodetectors

## 905 nm

\+ Better transmission in atmosphere

\+ Silicon-based photodetector

# ToF LiDAR challenges: what wavelength?

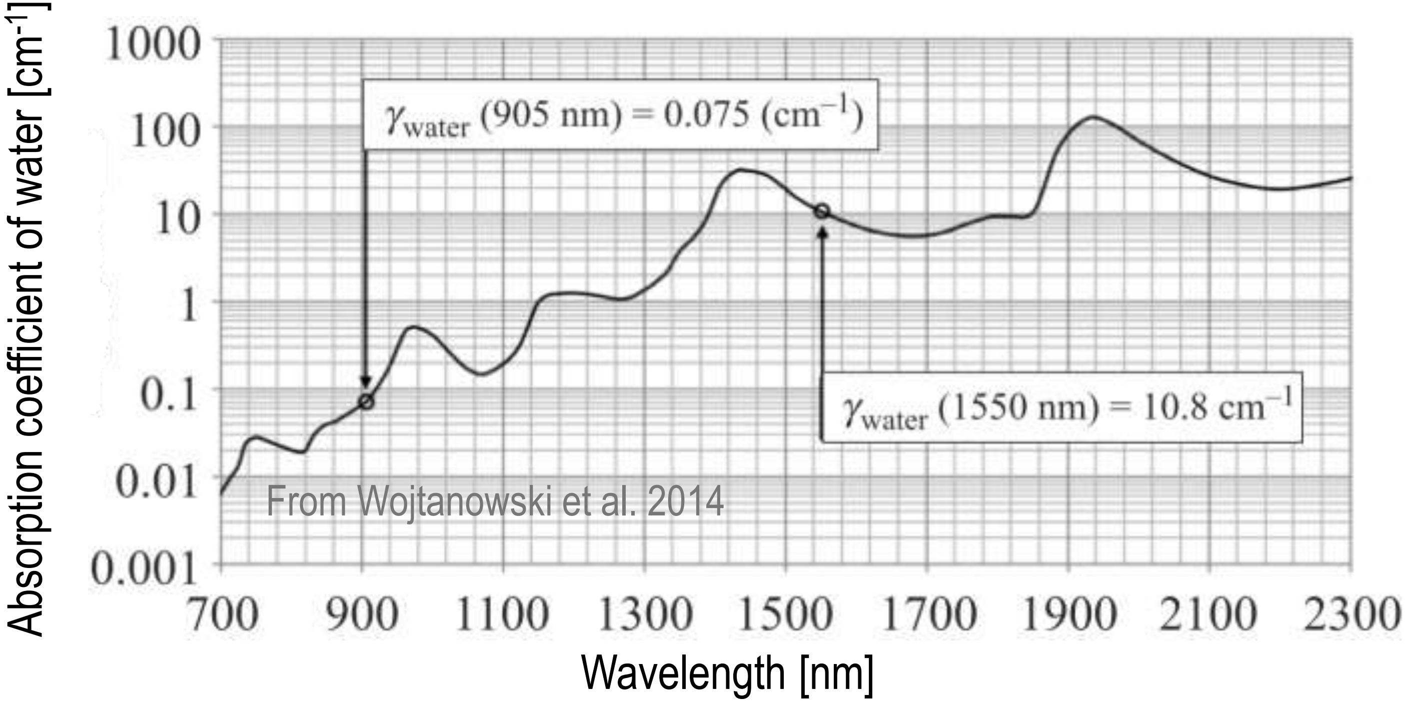


Solar irradiance at sea level

Figure from Matson et al. 1983

$P_B$ @ 1550 nm **<** $P_B$ @ 905 nm

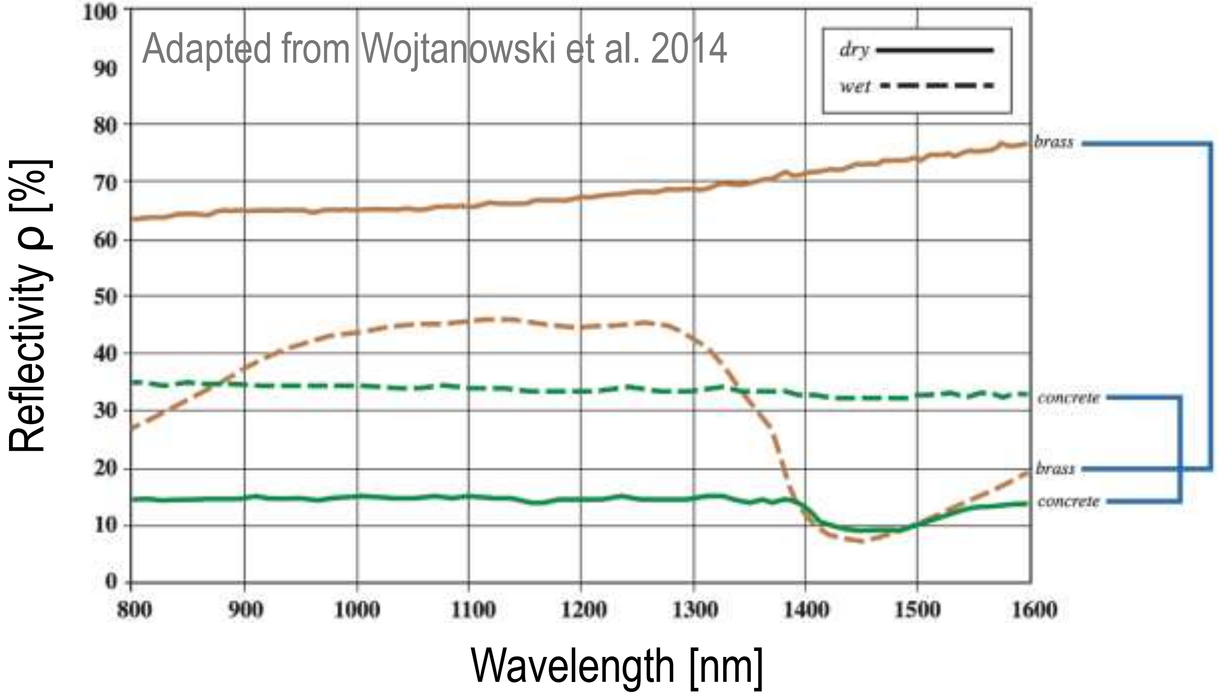
# ToF LiDAR challenges: what wavelength?



From Wojtanowski et al. 2014

$H_2O$ absorption @ 1550 nm **>** (100 × ) @ 905 nm

# 905 nm *versus* 1550 nm

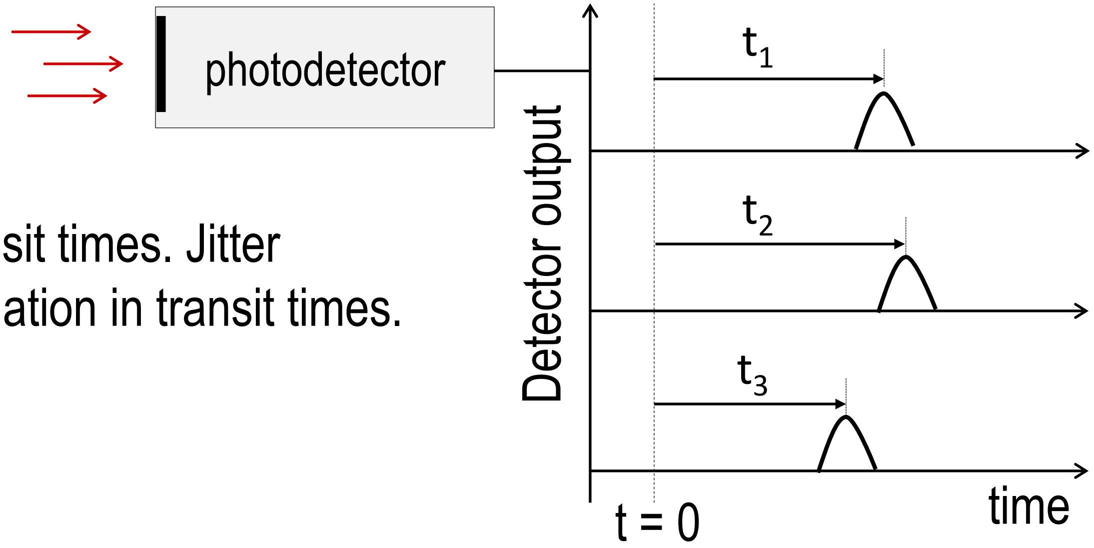


Wet surface reflects more poorly @1550 nm *versus* @ 905 nm

# ToF LiDAR challenges: photodetector

- \+ High photosensitivity
- \+ High gain
- \+ Small jitter
- \+ Small excess noise

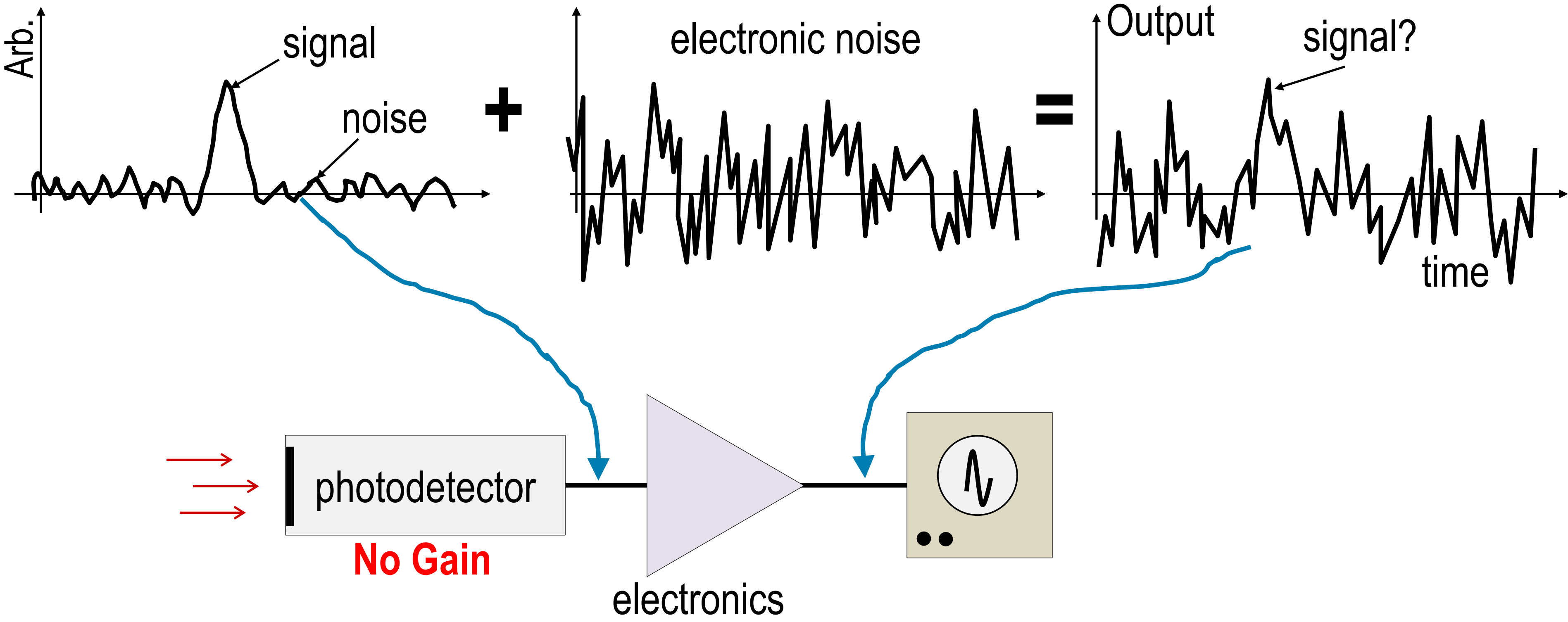
# Importance of jitter



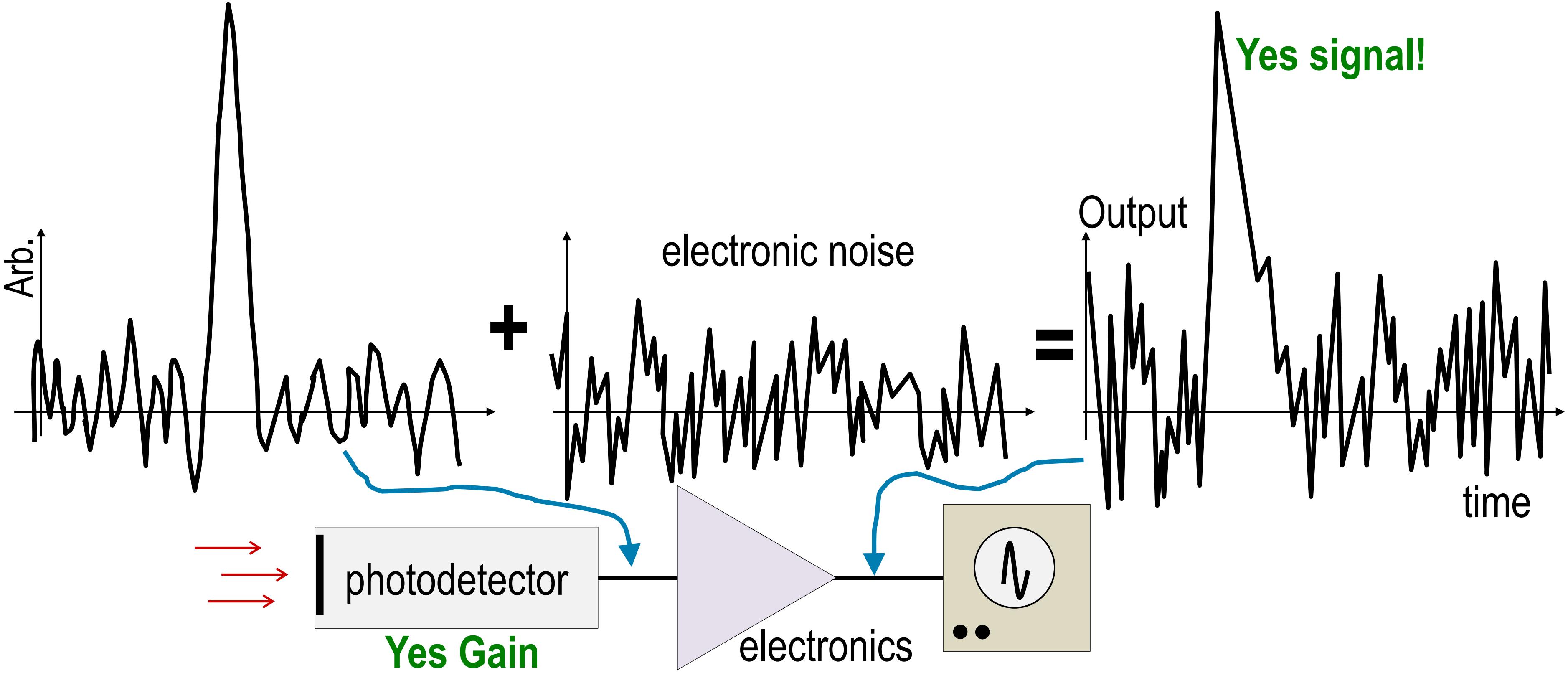
$t_1$, $t_2$, $t_3$, … transit times. Jitter represents variation in transit times.

Jitter is the main contributor to $\delta_{\Delta t}$ which affects distance resolution. 100 ps jitter implies 1.5 cm depth uncertainty.

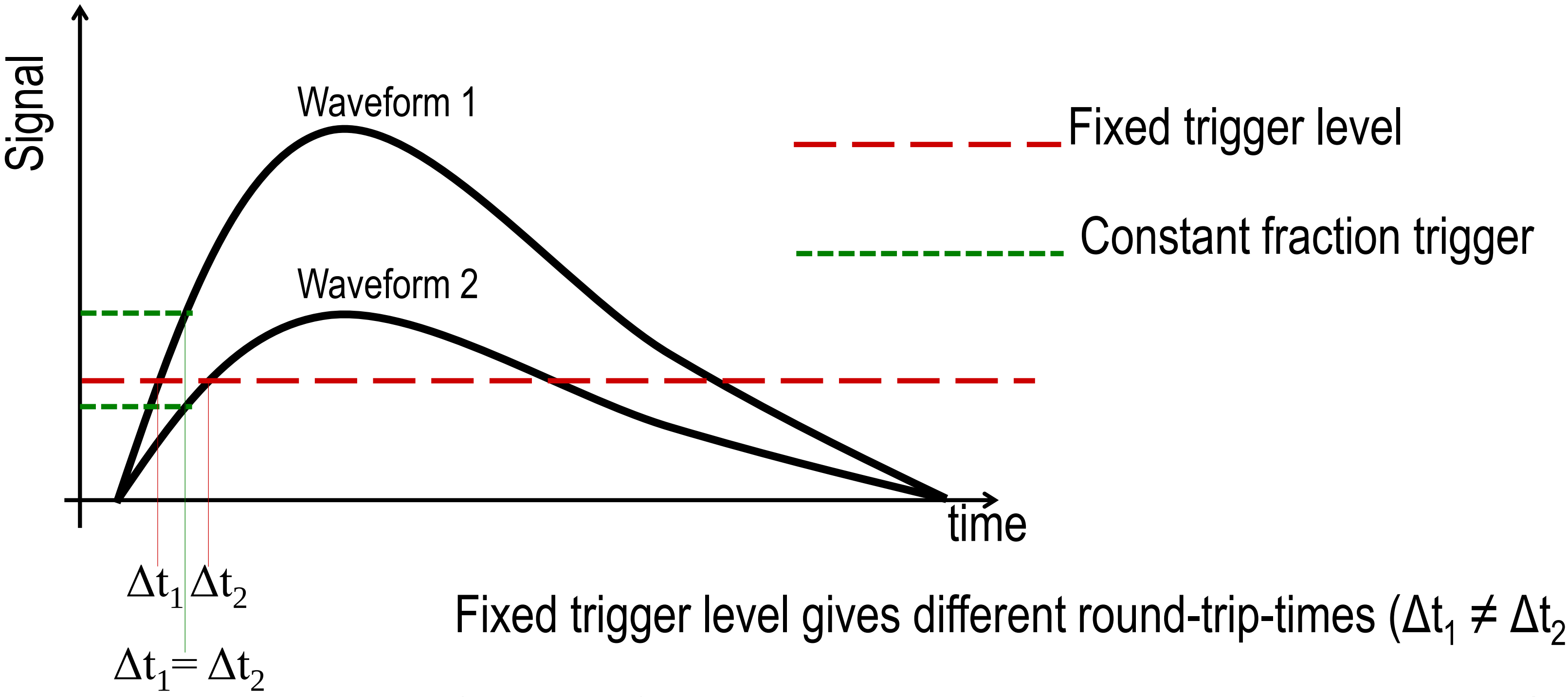
# Importance of detector gain



# Importance of detector gain



# Importance of excess noise



Fixed trigger level gives different round-trip-times ($\Delta t_1 \neq \Delta t_2$) ✖

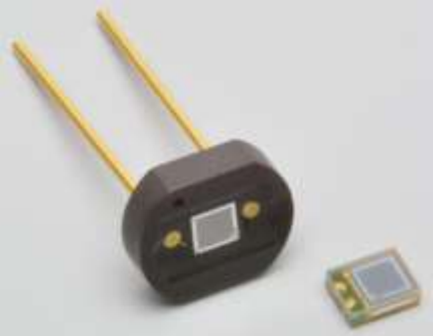
Constant-fraction trigger gives the same round-trip-times ($\Delta t_1 = \Delta t_2$) ✔

# ToF LiDAR challenges: photodetector

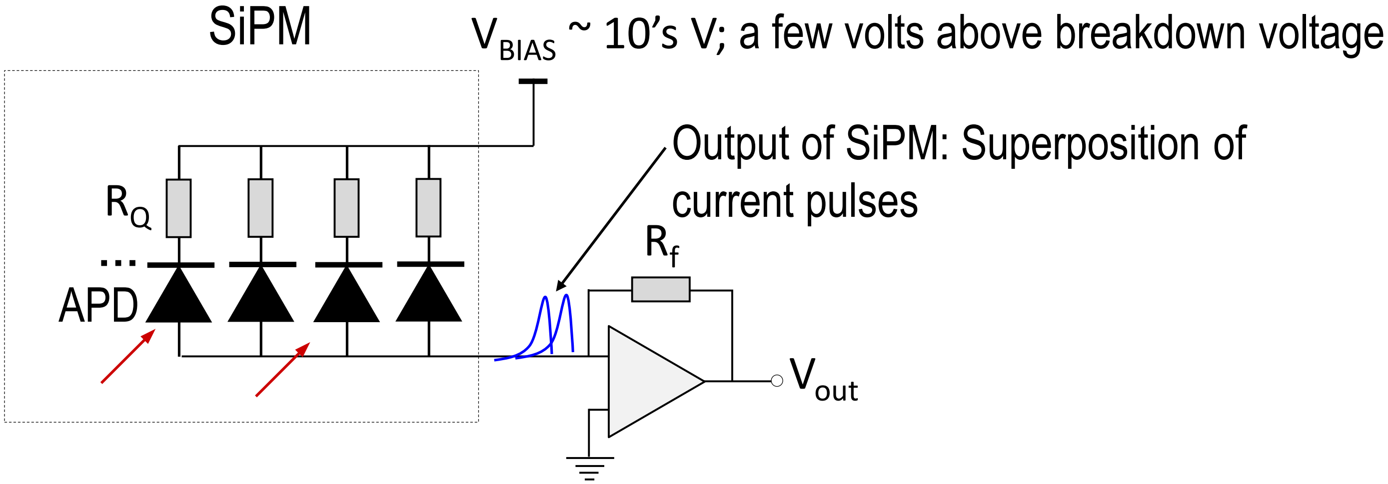
APD is the most commonly used photodetector

- ✔ Gain up to ~100 (ok, but not great)
- ✔ High quantum efficiency
- ✗ Large excess noise

Could SiPM be the detector of choice?

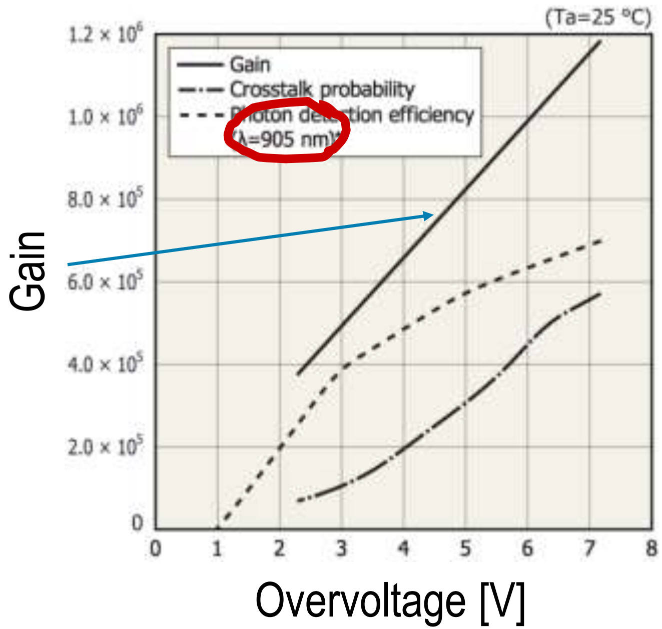


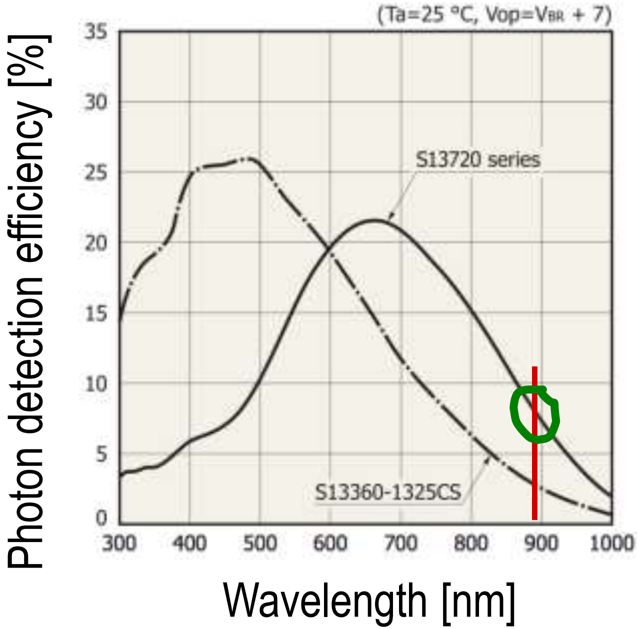
# ToF LiDAR challenges: photodetector



SiPM is an array of microcells connected in parallel. Each is a series combination of APD in Geiger mode and quenching resistor.

# SiPM

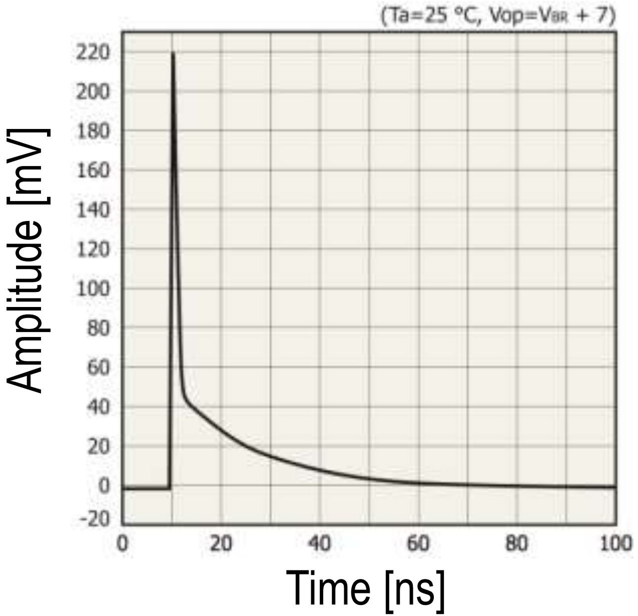




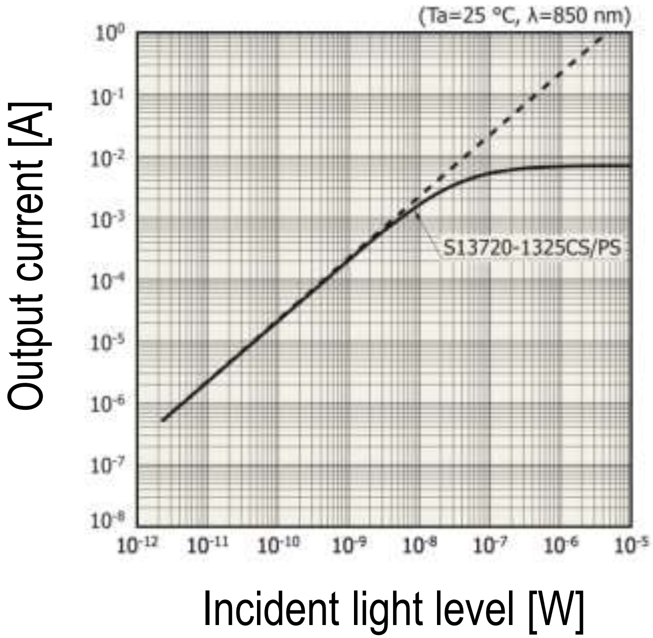
✔ Gain ($10^5$ – $10^6$) F≈1.3 ✔

✓Photosensitivity at 905 nm

# SiPM



~ Recovery time

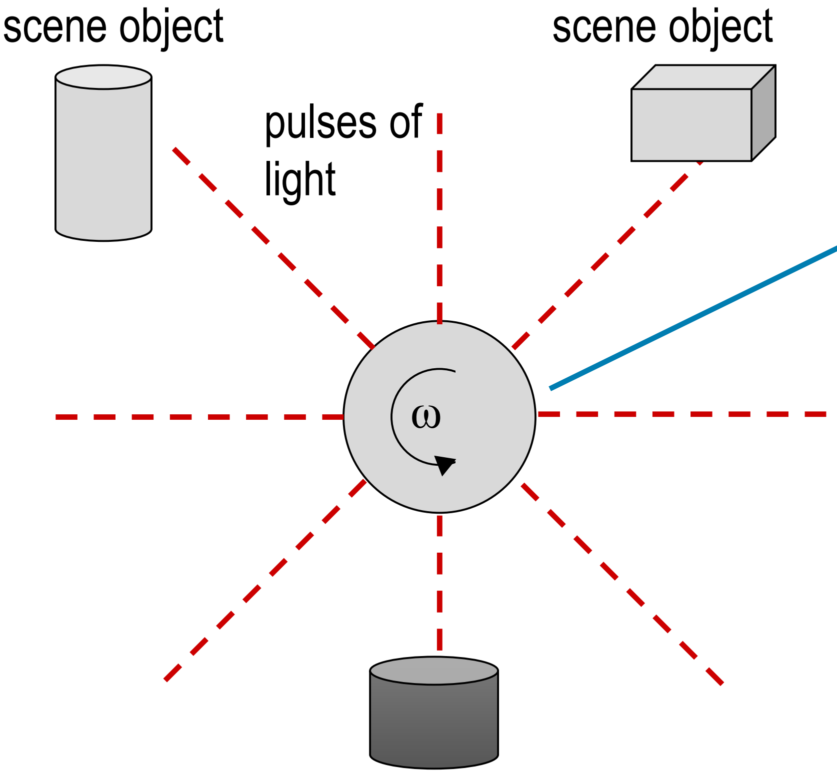


~ Linearity

# LiDAR

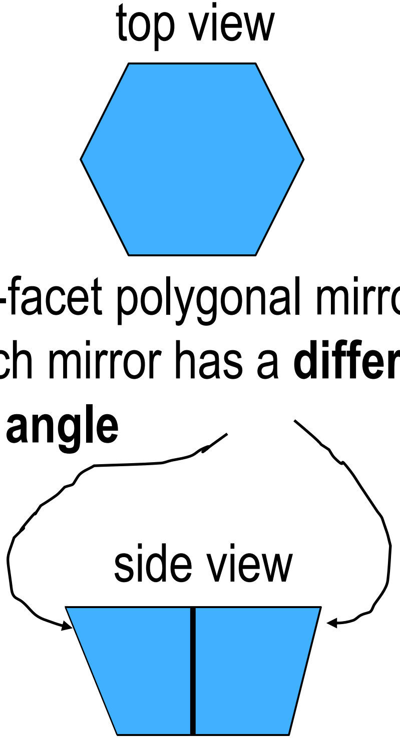
## Types of ToF LiDAR

# ToF LiDAR: Mechanical scanning

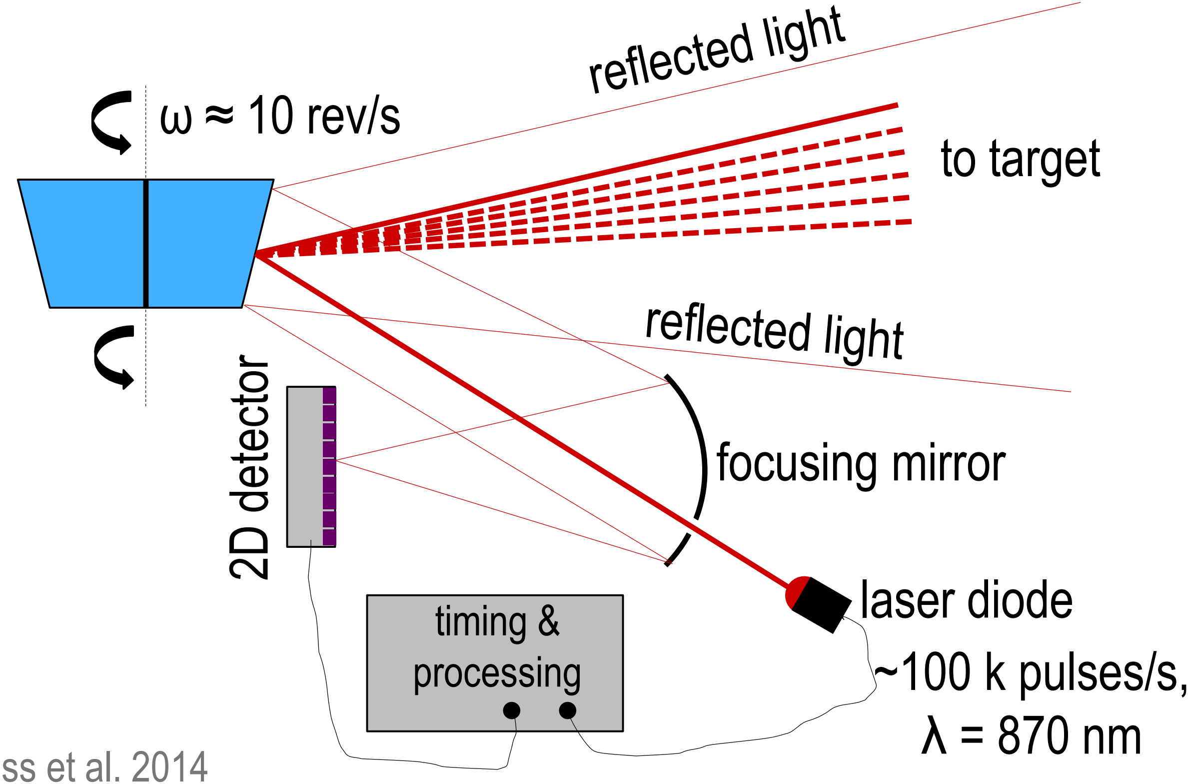


Velodyne LiDAR system: 64 channels (beams) 905 nm, 1.3 or $2.2 \times 10^6$ points per second, 5 - 20 Hz rotation, APD photo-sensors.

# ToF LiDAR: Rotating multi-facet mirror

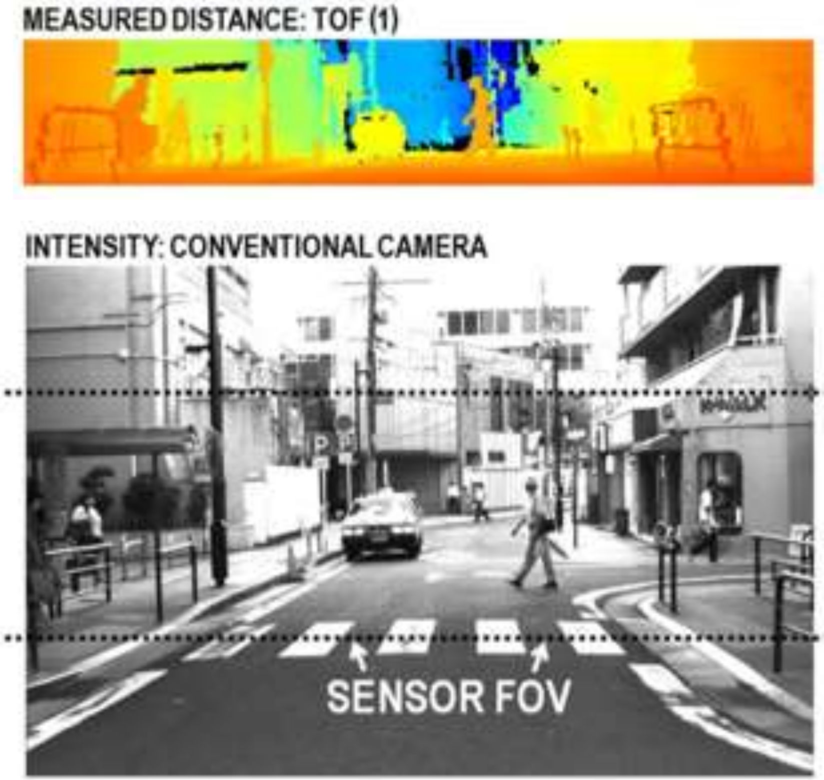


six-facet polygonal mirror; each mirror has a **different tilt angle**



Reference: Niclass et al. 2014

# ToF LiDAR: Rotating multi-facet mirror



3D map in full daylight

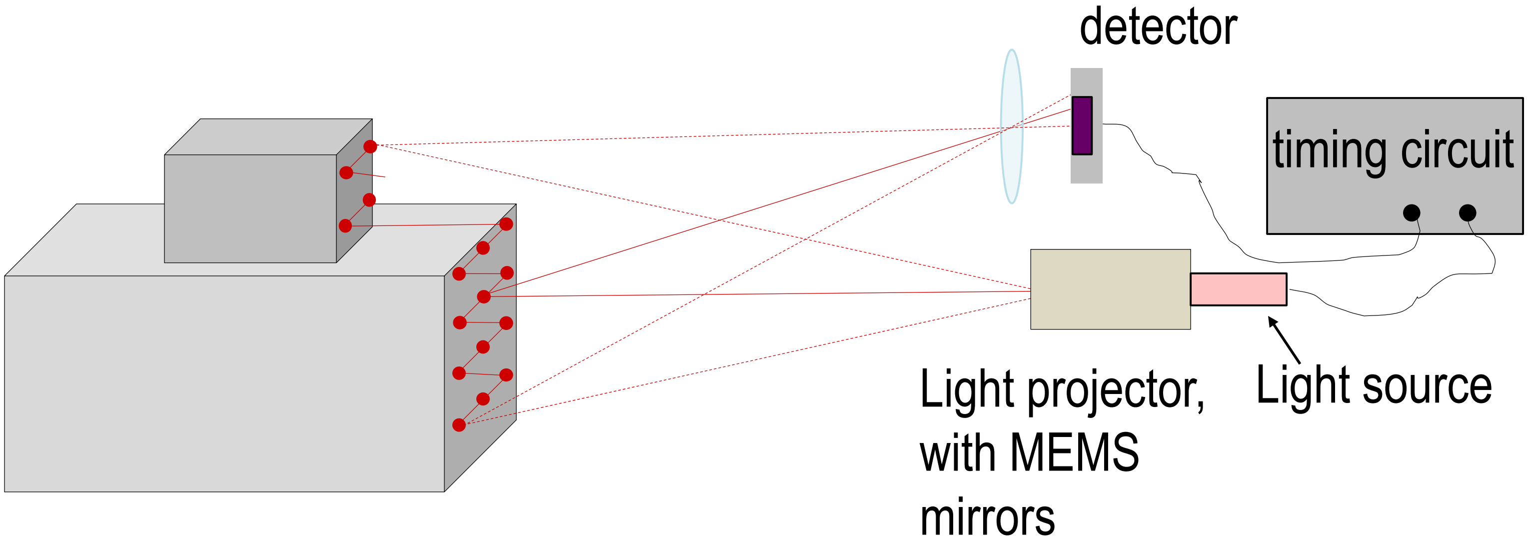
Sensor: SPAD 2D array

10 frames/s

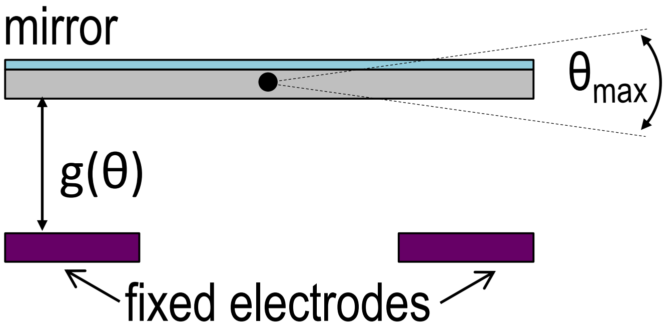
FOV: 55°×9°

Reference: Niclass et al. 2014

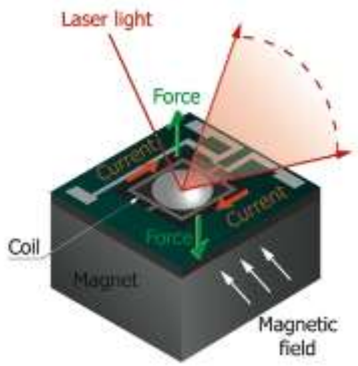
# ToF LiDAR: Scanning with MEMS mirrors



# Light projectors: MEMS mirrors



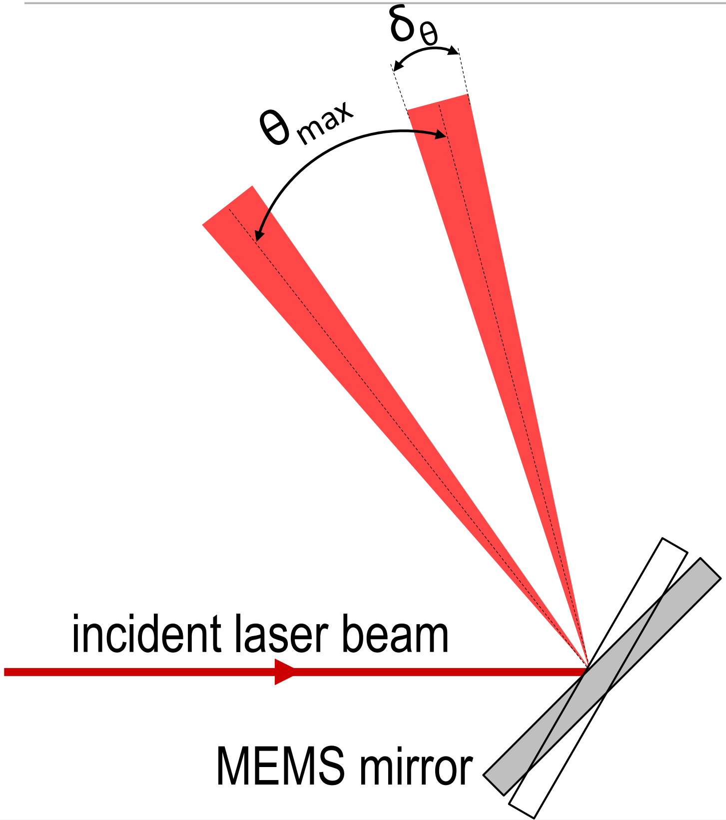
Electrostatic actuation MEMS mirror



Magnetic actuation MEMS mirror

Combining electrostatic and magnetic actuations allows 2D scanning (two axis rotation).

# Light projectors: MEMS mirrors



$\theta_{max}$ – Total scan angle

$\delta_\theta$ – Beam divergence (produced by the mirror ✖)

$N = \theta_{max}/\delta_\theta$ – Number of resolvable spots (resolution)

Reference: Patterson et el. 2004

# Light projectors: MEMS mirrors

✓ Low cost

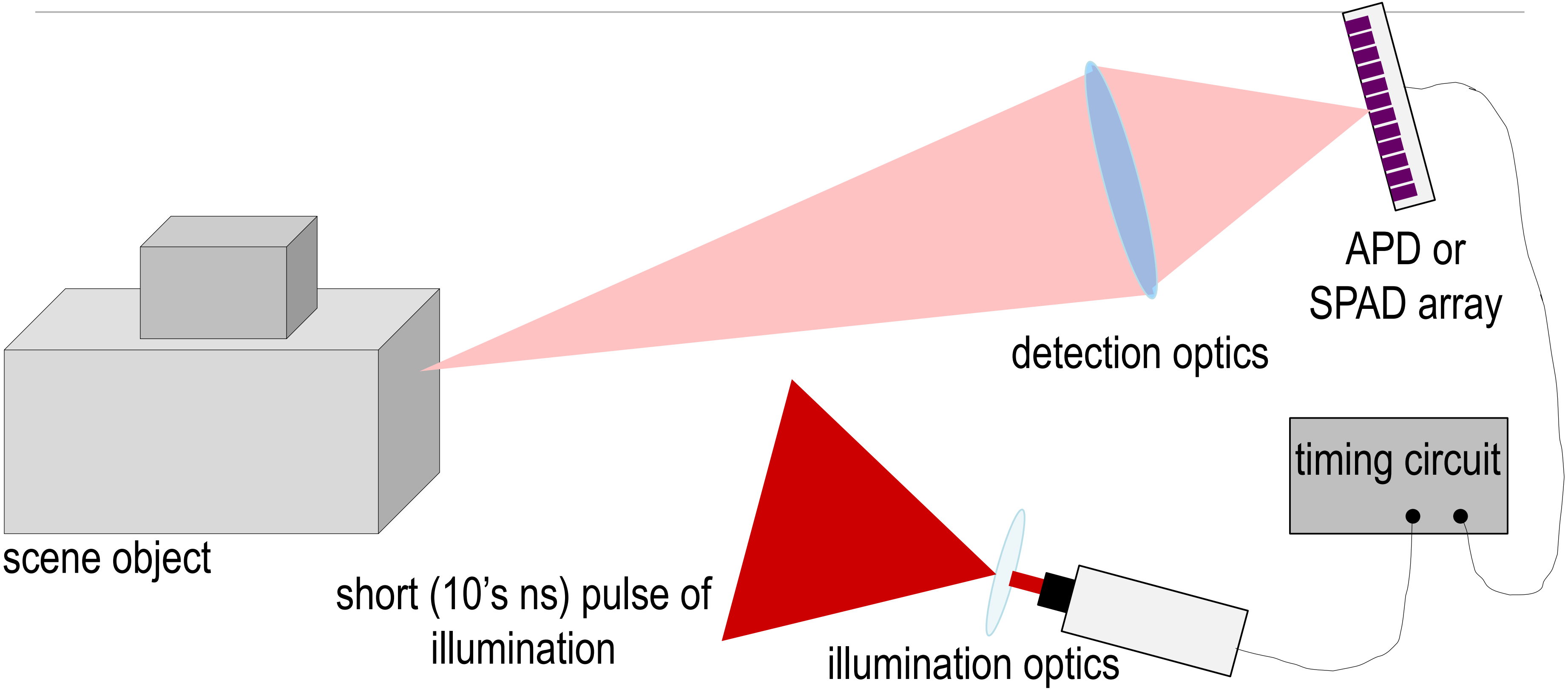
✓ Almost no moving parts

✖ Limited field of view

~ Size/frequency tradeoff

~ Frequency/beam divergence tradeoff

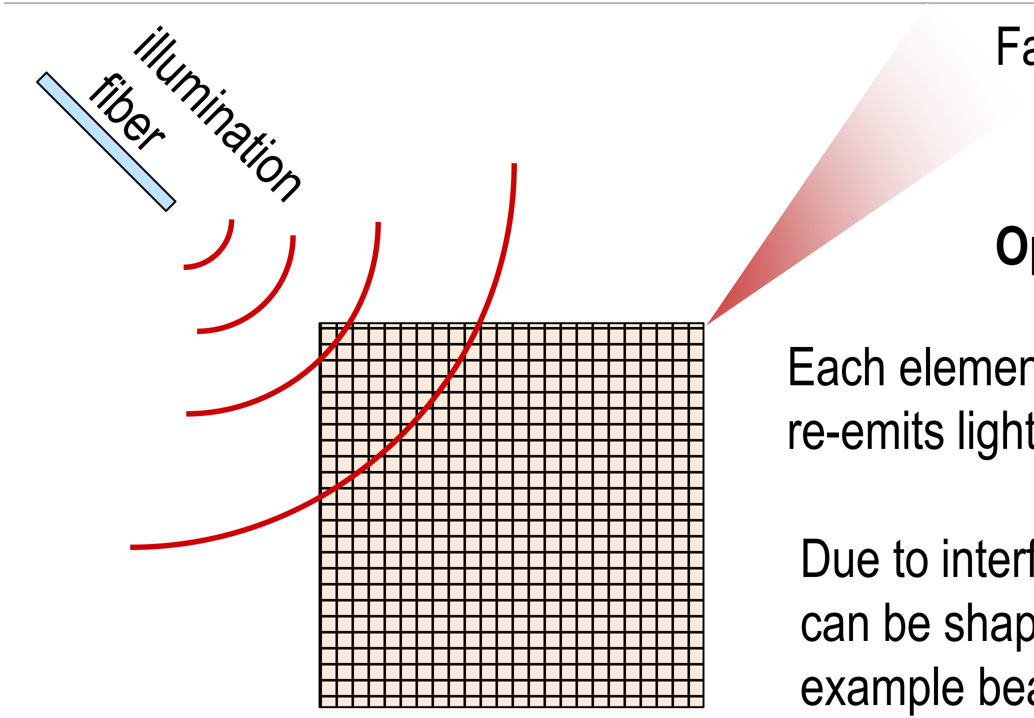
# Flash LiDAR


APD or
SPAD array
detection optics
timing circuit
scene object
short (10's ns) pulse of
illumination
illumination optics

# Flash LiDAR

- ✓ Resolution limited by the detector
- ✓ No moving parts
- ✖ Small field of view
- ✖ Starved for photons, limited range

# Optical phase array (OPA)



Far-field radiation pattern

**Optical Phased Array**

Each element (pixel, ~30 × 30 μm$^2$) receives and re-emits light with changed phase and amplitude.

Due to interference, the emitted far field radiation can be shaped into variety of patterns, for example beams.

# Optical phase array (OPA)

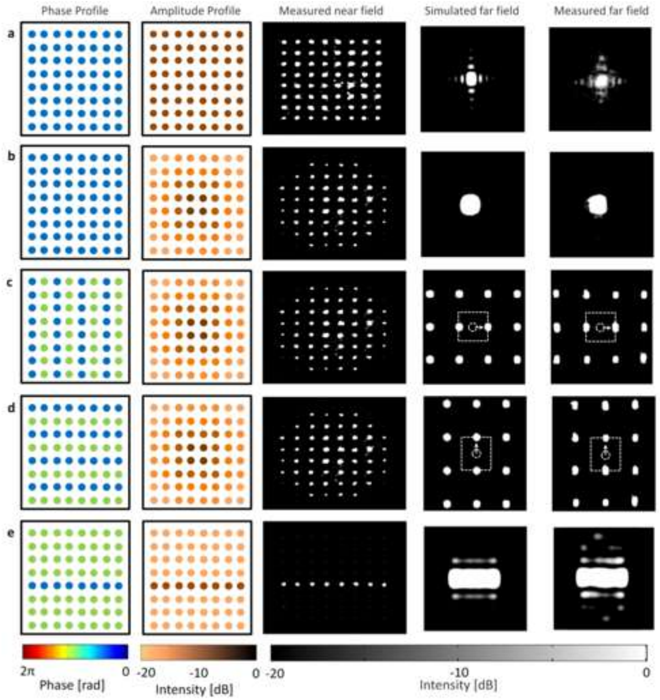


Figure from Abediasl & Hashemi 2015

- ✓ No moving parts
- ✗ Lobes and beam divergence
- ✗ Slow (due to cell tuning)

# Another approach?

Designing ToF LiDAR at reasonable cost is very challenging

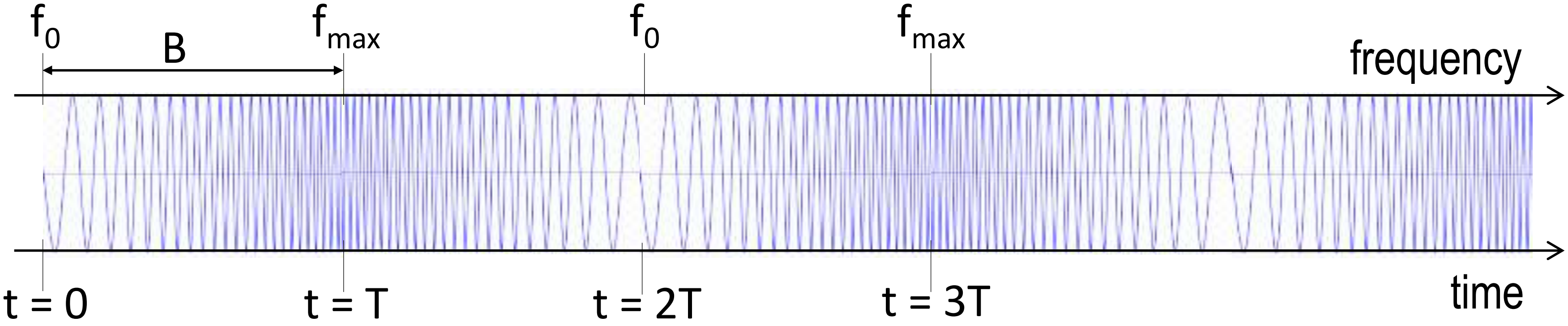
What about a different approach borrowed from radar technology?

Frequency modulated continuous wave (FMCW) LiDAR

# Advantages of FMCW LiDAR

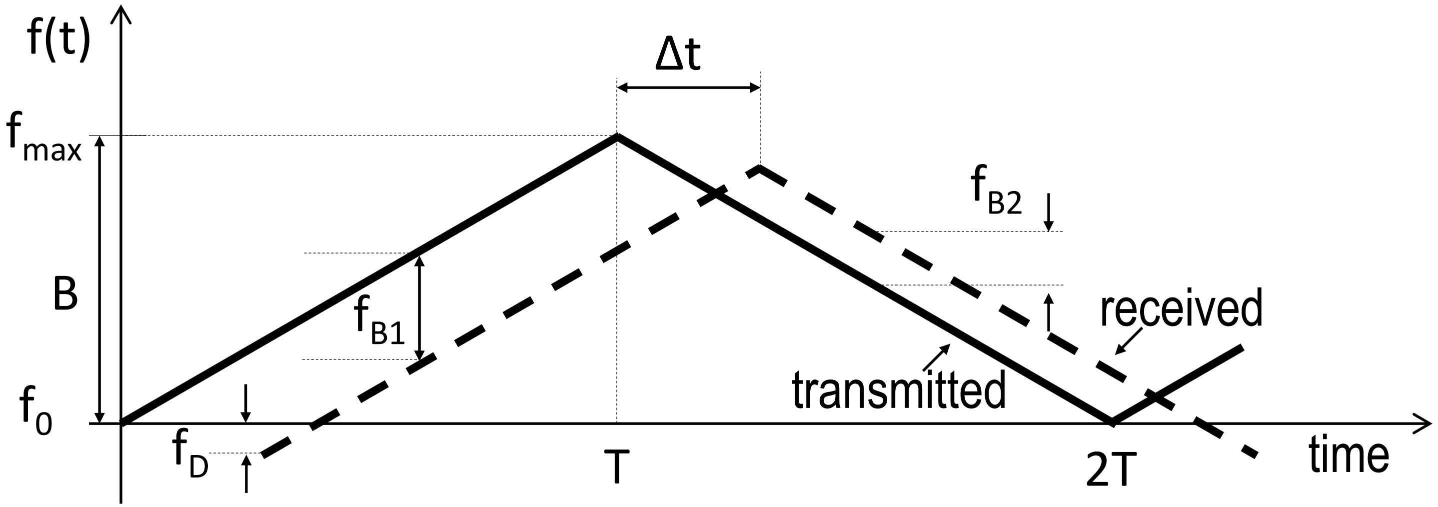
- Photon shot noise limited detection
- Immune to photon background
- Distance and velocity information in frequency domain
- Lower-bandwidth electronics

# FMCW Radar



Chirp-modulation (triangular) of frequency

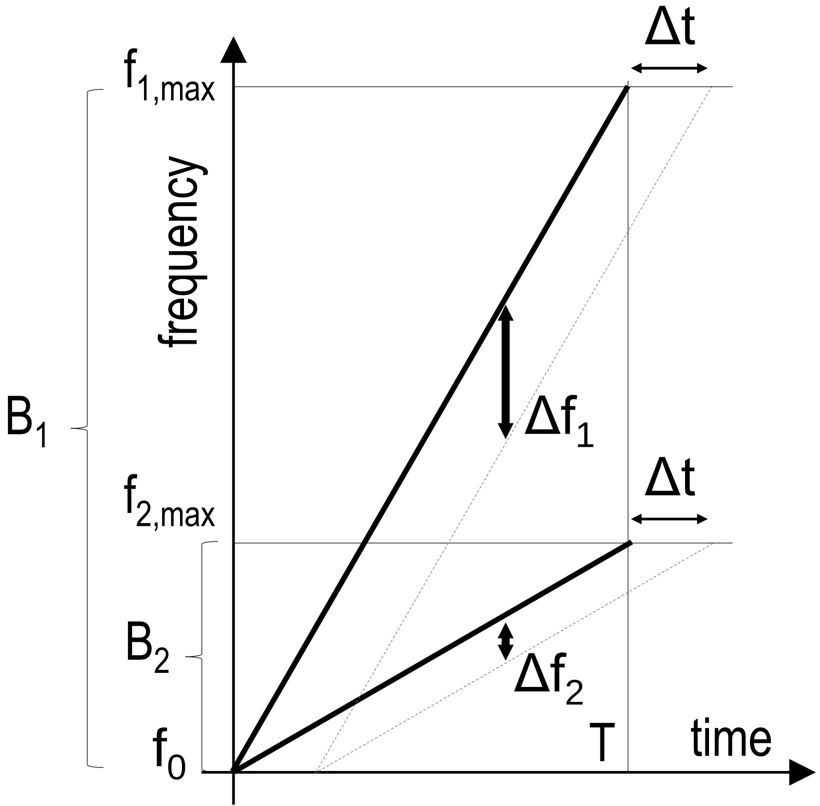
# FMCW Radar



$$f_{B1} = \frac{2BR}{cT} - \frac{2V_r}{\lambda_0}$$

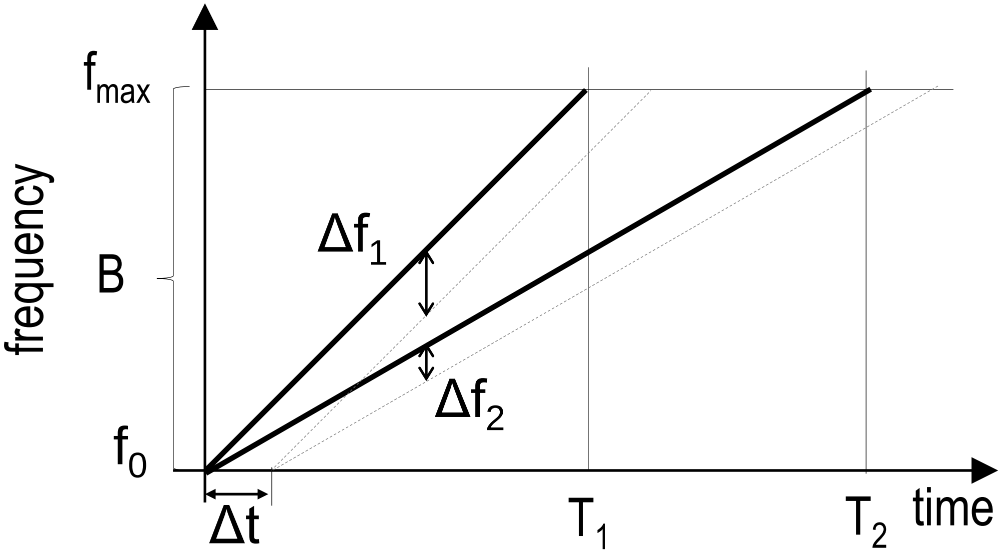
$$f_{B2} = -\frac{2BR}{cT} - \frac{2V_r}{\lambda_0}$$

# FMCW Radar



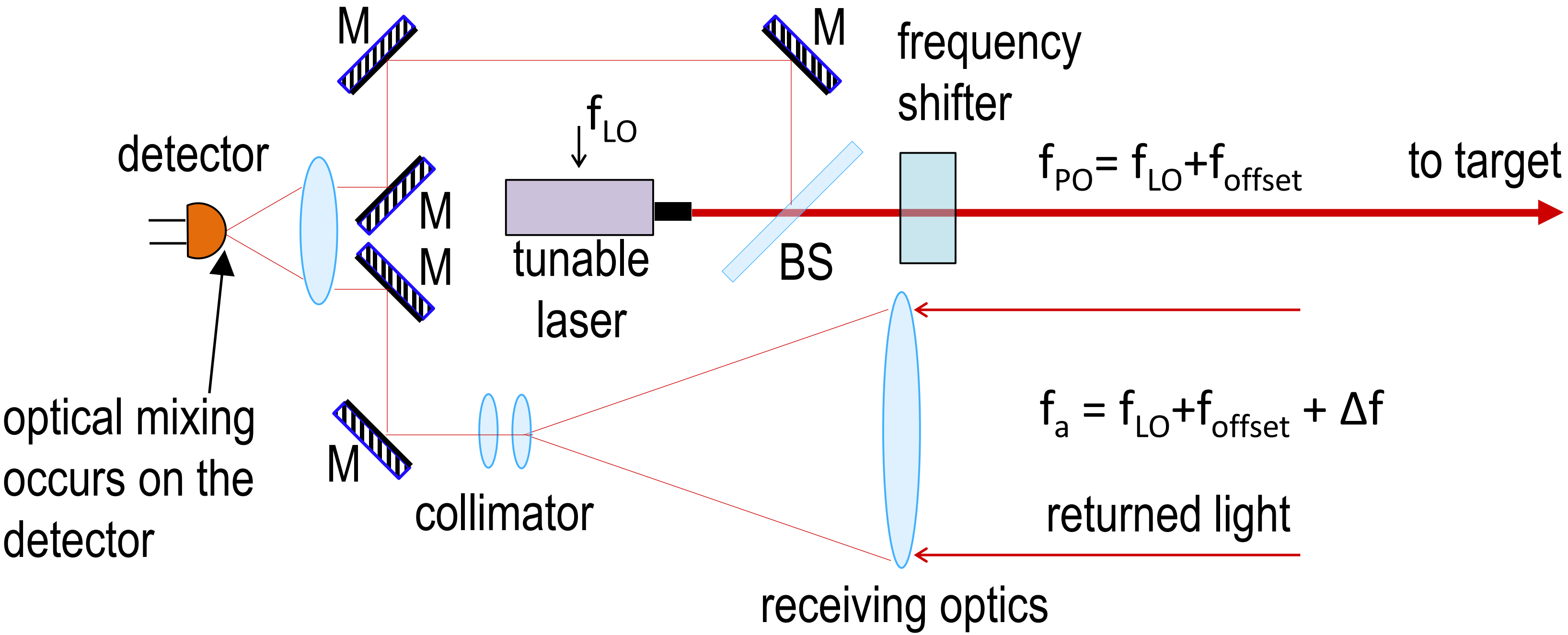
Larger bandwidth gives better distance resolution

# FMCW Radar



Shorter T gives better resolution

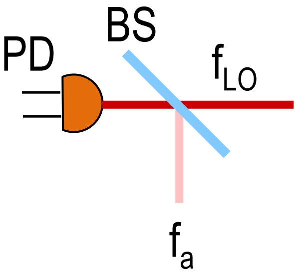
# FMCW LiDAR (heterodyne optical mixing)



# FMCW LiDAR (heterodyne optical mixing)

$$|E_{tot}|^2 = |E_a + E_{LO}|^2 = |A_a\cos(2\pi f_a t + \phi_a) + A_{LO}\cos(2\pi f_{LO} t + \phi_{LO})|^2$$

$$|E_{tot}|^2 = |E_a|^2 + |E_{LO}|^2 + \mathbf{A_a A_{LO}\cos[2\pi(f_a - f_{LO})t + (\phi_a - \phi_{LO})]}$$



$$P_{sig} = P_a + P_{LO} + 2\sqrt{P_a P_{LO}}\cos[2\pi(f_a - f_{LO})t + (\phi_a - \phi_{LO})]$$

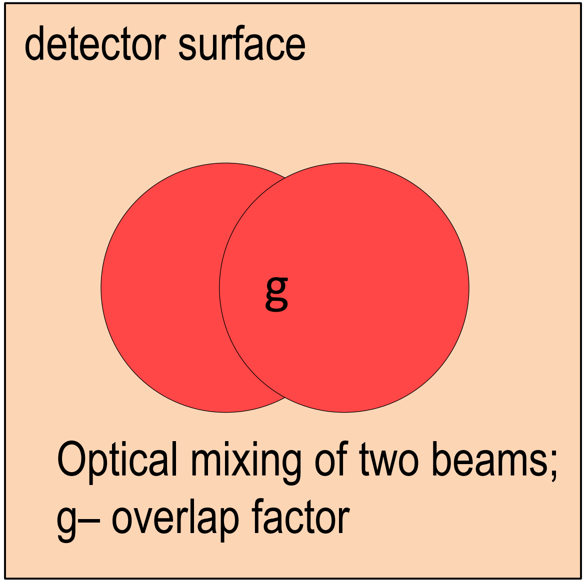
$$i_{sig} = \frac{\eta e P_{sig}}{hf} = i_a + i_{LO} + \boxed{\boxed{2\sqrt{i_a i_{LO}}}\cos[2\pi\boxed{(f_a - f_{LO})}t + (\phi_a - \phi_{LO})]}$$

**amplification!** measure this

$$f_a - f_{LO} = \Delta f + f_{offset}$$

We get Δf, and thus R and $V_R$

# Coherent detection



Optical mixing of two beams;
g– overlap factor

For maximum signal:

- the beams must overlap (ideally g = 1)
- wavefronts must have the same shape
- polarization is the same
- spatial coherence

# Coherent detection

$$\frac{S}{N} = \frac{i^2}{(i_{SN})^2} \approx \frac{g\eta P_s}{2hfB}$$

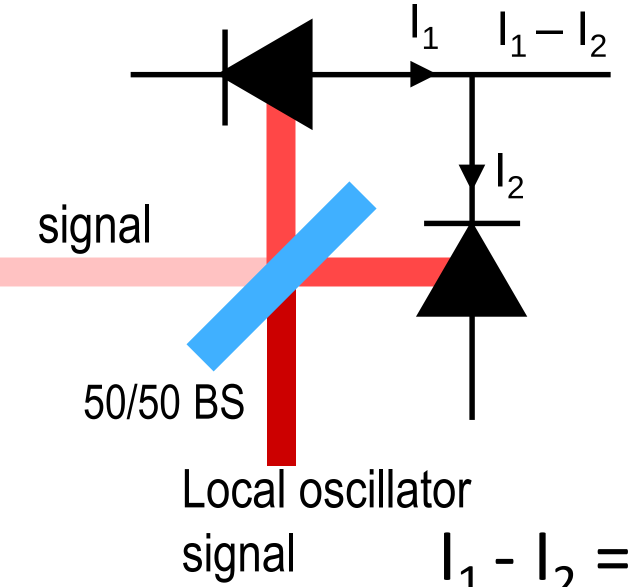
g – overlap factor; η – photodetector quantum efficiency; B – detection bandwidth

By making $P_{LO}$ large enough, one can make the detection photon-shot noise limited.

Photodiode can be used for the photodetection.

# Balanced detection

Excess noise of LO (through the DC part) can reduce S/N. Remedy: use balanced detection.



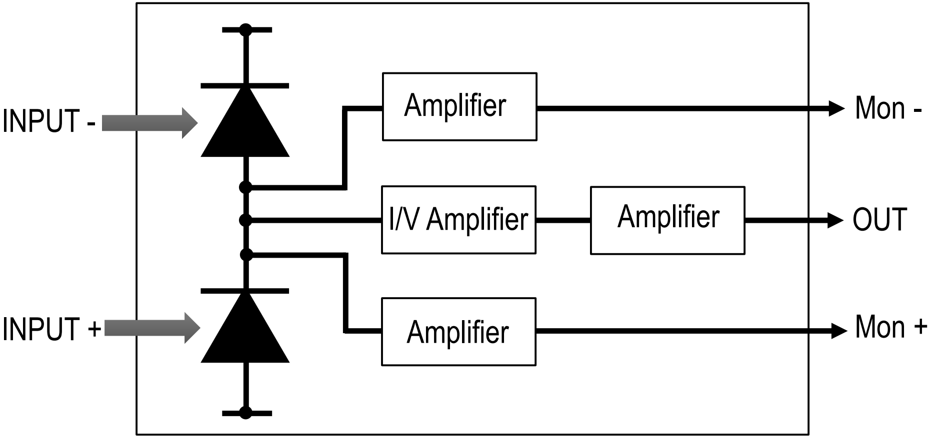
$$I_1 = (\eta e/hf)[½P_{lo} + ½P_s + (P_sP_{lo})^{½}\sin(\Delta\omega t + \phi)]$$

$$I_2 = (\eta e/hf)[½P_{lo} + ½P_s - (P_sP_{lo})^{½}\sin(\Delta\omega t + \phi)]$$

+/- are due to π/2 shifts when light reflects from the BS

$$I_1 - I_2 = 2(\eta e/hf)(P_sP_{lo})^{½}\sin(\Delta\omega t + \phi)$$

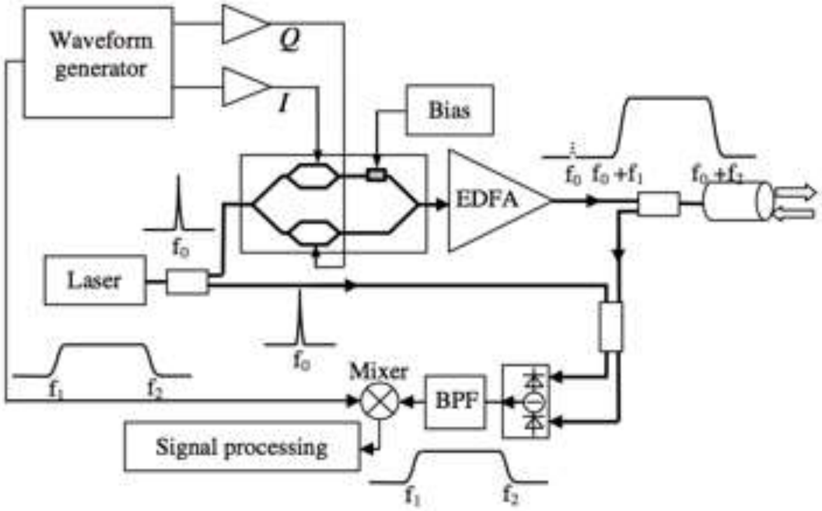
# Balanced photodiodes by Hamamatsu

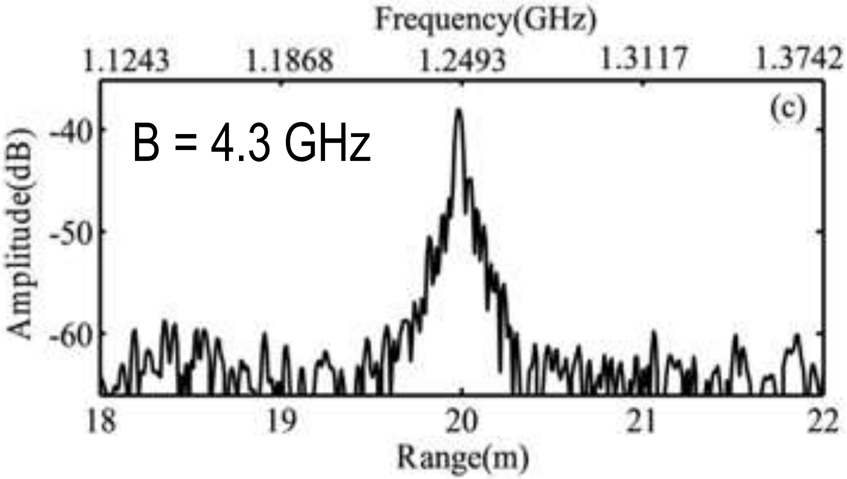


Balanced photodiode module offered by Hamamatsu

Hamamatsu also offers matched bare photodiodes

# Coherent detection: working example





B = 4.3 GHz

λ = 1549.54 nm

Gao & Hui 2012

# Is there a perfect LiDAR?

| LiDAR System | Range | Reliability | Cost | Size | Systems per car |
|---|---|---|---|---|---|
| Mechanical | Long | Good | Mid. to high | Bulky | 1 |
| MEMS based | Medium to long | Good | Low | Compact | 1 – 4 or more |
| Flash | Short | Very good | Low | Compact | 1 – 4 or more |
| Optical Phase Array | Advantages: solid state design with no moving parts<br>Disadvantages: loss of light that restricts the range | | | | |
| FMCW | Advantages: immune to background, photon shot noise detection<br>Disadvantages: data processing intensive, still requires beam steering | | | | |

Not yet…

# Summary & Conclusions

- Some form of LiDAR is likely to be needed on self-driving car
- ToF LiDAR is very challenging to design
  - Beam steering and photodetection are the most outstanding challenges
- There is a growing interest in FMCW LiDAR with optical mixing
- There is no default LiDAR design yet; work in progress

# Upcoming Webinar (January 2018)

**Silicon Photomultiplier: Operation, Performance, & Optimal Applications**

Presenter: Slawomir Piatek

Host: Laser Focus World

Wednesday, January 10, 2018

# Visit Booth #521 & Presentations at PW18

**Development of an InGaAs SPAD 2D array for Flash LIDAR**

Presentation by Takashi Baba, January 29, 2018 (11:00 AM - 11:30 AM)

**Development of an InGaAs MPPC for NIR photon counting applications**

Presentation by Takashi Baba, January 30, 2018 (5:50 PM - 6:10 PM)

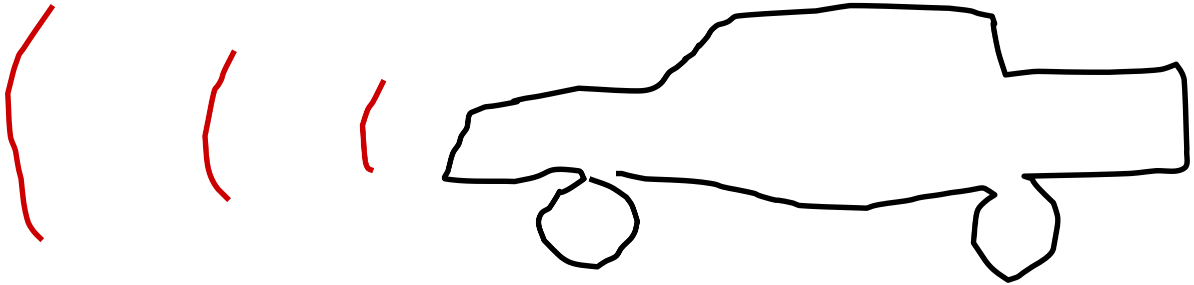
**Photodetectors, Raman Spectroscopy, and SiPMs versus PMTs**

One-day Workshop with Slawomir Piatek, January 31, 2018 (8:30 AM - 5:30 PM) – Free Registration Needed

**Development of a Silicon hybrid SPAD 1D array for LIDAR and spectrometers**

Poster session with Shunsuke Adachi, January 31, 2018 (6:00 PM - 8:00 PM)

# Thank you for listening!



- Speaker Contact – Slawomir Piatek (spiatek@physics.rutgers.edu)
- LiDAR Inquires to Hamamatsu – Jake Li (jli@Hamamatsu.com)