

# 3D Sensors



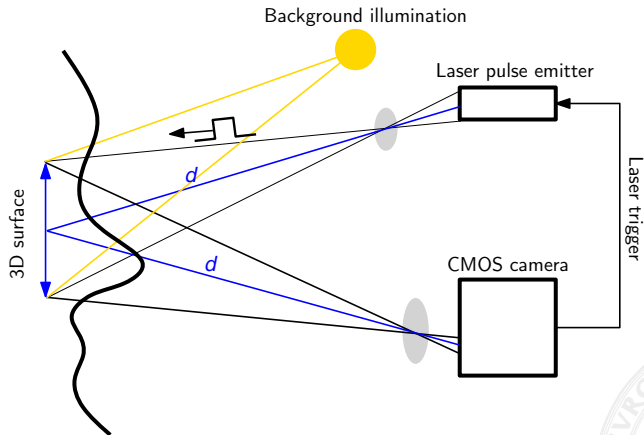
(Source: <https://www.google.com/selfdrivingcar/>)

Slide credit to Radu Horaud, <http://perception.inrialpes.fr>



# ToF Imaging

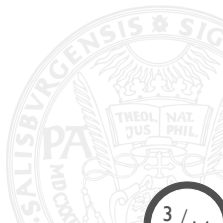
## Pulse Light Modulation – Components



# ToF Imaging

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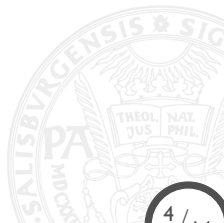
- **Emitter:** Emits short (30 to 60 [ns]) laser pulses in NIR spectrum (850 [nm] to 910 [nm])
- **Optics:** Optimizes efficiency; controls beam angle (via cylindrical lens); homogeneous distribution of laser beam (via diffusing panel)
- **CMOS Image sensor:** Captures image with a very short electronic “shutter” (30 to 120 [ns])



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## Pulse Light Modulation – Basic principle

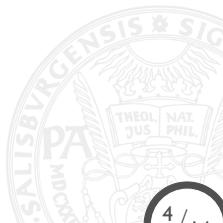
- Use light pulse(s) of short duration, generated by a laser



# ToF Imaging

## Pulse Light Modulation – Basic principle

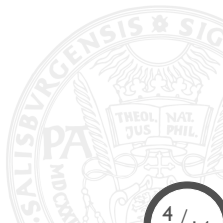
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- Distance is measured **directly from the time delay**



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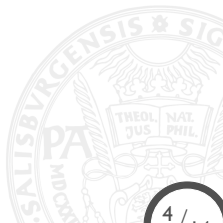
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- Emitted laser energy is low



# ToF Imaging

## Pulse Light Modulation – Basic principle

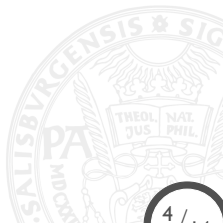
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- No phase ambiguity (as with continuous wave modulation)



# ToF Imaging

## Pulse Light Modulation – Basic principle

- Use light pulse(s) of short duration, generated by a laser
- Distance is measured **directly from the time delay**
- Emitted laser energy is low
- No phase ambiguity (as with continuous wave modulation)
- Typically used in outdoor applications (e.g., driving)



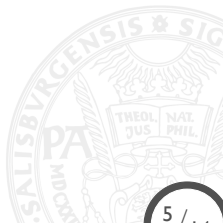


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## Pulse Light Modulation – Basic principle

**Pulse modulation** can be achieved by

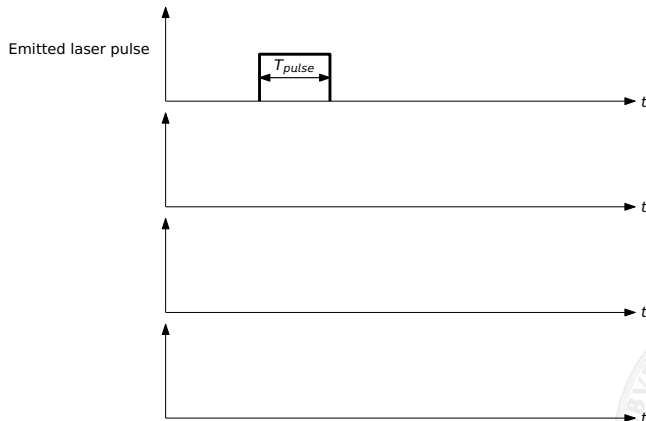
- integrating photoelectrons from the reflected light
- starting a “fast” counter at the detection of the reflection
  - Requires fast photo-detector
  - E.g., 1 [mm] accuracy requires pulse timing of  $\approx 6.6$  [ps]



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## Pulse Light Modulation – Double Short-Time Integration (DSTI)

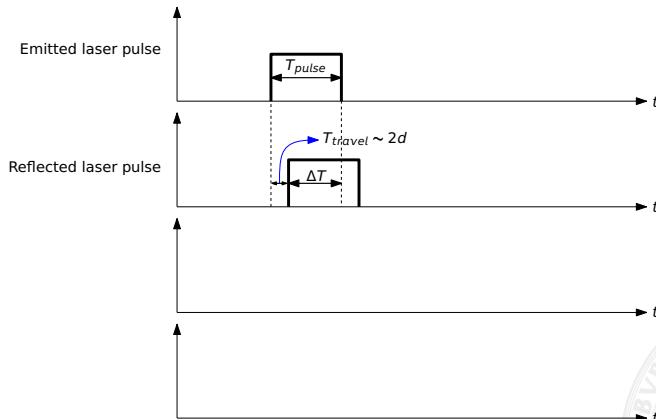
One measurement cycle:



# ToF Imaging

## Pulse Light Modulation – Double Short-Time Integration (DSTI)

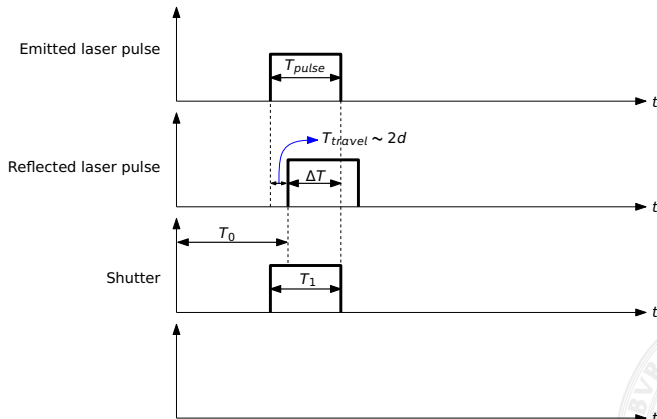
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# ToF Imaging

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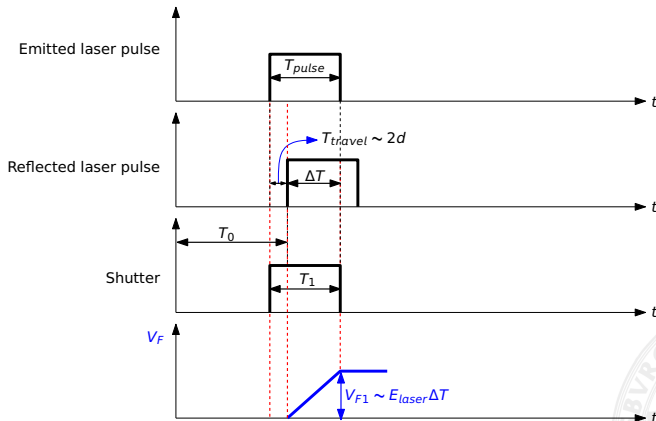
One measurement cycle:



# ToF Imaging

## Pulse Light Modulation – Double Short-Time Integration (DSTI)

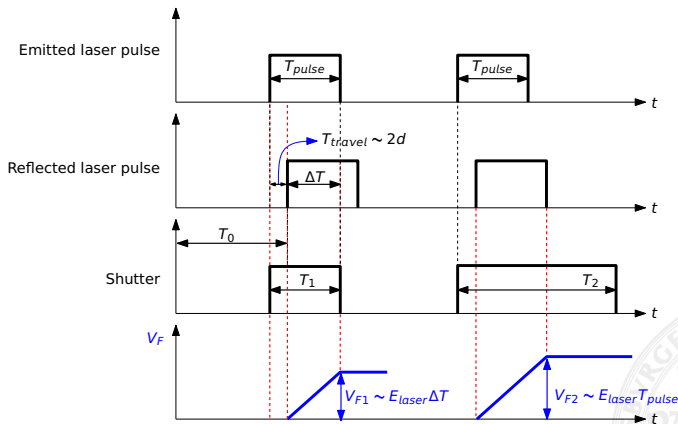
One measurement cycle:



# ToF Imaging

## Pulse Light Modulation – Double Short-Time Integration (DSTI)

One measurement cycle:

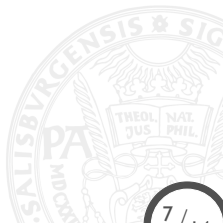


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## Pulse Light Modulation – Double Short-Time Integration (DSTI)

The **output voltage** ( $V_F$ ) is

- $\propto$  the number of photons reaching the detector
- dependent on
  - laser power
  - surface reflectance
  - background illumination



# ToF Imaging

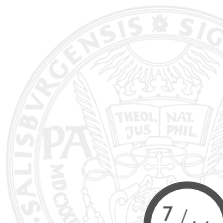
## Pulse Light Modulation – Double Short-Time Integration (DSTI)

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We have seen that, ...

- reflected pulses are shifted by  $T_{travel}$
- the shutter is synchronized with emitted pulses



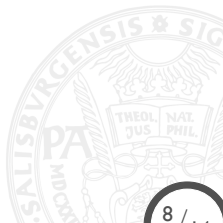


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## Pulse Light Modulation – Double Short-Time Integration (DSTI)

Two (different) shutter times are used:

1.  $T_1$  (same length as pulse time  $T_{pulse}$ )
2.  $T_2$  (longer than pulse time  $T_{pulse}$ )



# ToF Imaging

## Pulse Light Modulation – Double Short-Time Integration (DSTI)

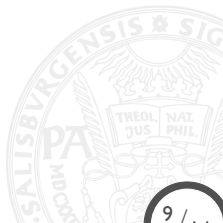
How can we compute  $\Delta T$  and eventually the distance  $d$ ?

- We know that

$$V_{F1} \propto E_{laser} \Delta T$$

and

$$V_{F2} \propto E_{laser} T_{pulse}$$



# ToF Imaging

## Pulse Light Modulation – Double Short-Time Integration (DSTI)

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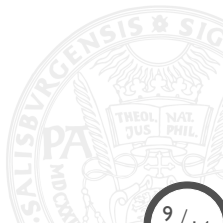
$$V_{F1} \propto E_{laser} \Delta T$$

and

$$V_{F2} \propto E_{laser} T_{pulse}$$

- We also know that  $\Delta T = T_{pulse} - T_{travel}$  and thus

$$\Delta T = \frac{V_{F1}}{V_{F2}} T_{pulse}$$



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## Pulse Light Modulation – Double Short-Time Integration (DSTI)

Finally, the distance  $d$  can be computed as

$$d = \frac{c}{2} T_{travel} = \frac{c}{2} (T_{pulse} - \Delta T) = \frac{c}{2} T_{pulse} \left( 1 - \frac{V_{F1}}{V_{F2}} \right)$$

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## Pulse Light Modulation – Maximum and minimum depth

Let's assume that the shutter opens (and thus the integration window becomes active) as the laser pulse starts.

From

$$d = \frac{c}{2}(T_{pulse} - \Delta T)$$

we see that the *maximum range* is

# ToF Imaging

## Pulse Light Modulation – Maximum and minimum depth

Let's assume that the shutter opens (and thus the integration window becomes active) as the laser pulse starts.

From

$$d = \frac{c}{2}(T_{pulse} - \Delta T)$$

we see that the *maximum range* is

$$d_{max} = \frac{c}{2} T_{pulse} \quad \text{i.e., when } T_{pulse} = T_{travel}$$

**Example:** For a **30 [ns] pulse**, we get

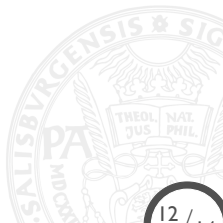
$$d_{max} = \frac{3 \times 10^8 [m/s]}{2} \cdot (30 \times 10^{-9} [s]) = 4.5 [m]$$

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Pulse Light Modulation – Maximum and minimum depth

How can we adjust max/min. depth?

I. Increase duration of  $T_{pulse}$

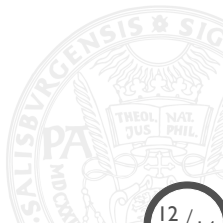


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## Pulse Light Modulation – Maximum and minimum depth

How can we adjust max/min. depth?

1. Increase duration of  $T_{pulse}$
2. Delay between pulse and opening of shutter (leading to  $d_{min} > 0$ )





# ToF Imaging

## Pulse Light Modulation – Maximum and minimum depth

How can we adjust max/min. depth?

1. Increase duration of  $T_{pulse}$
2. Delay between pulse and opening of shutter (leading to  $d_{min} > 0$ )

In case of (2), we get

$$d_{max} = \frac{c}{2}(T_{delay} + T_{pulse})$$

Thus, we generate a *blind zone*

$$d_{min} = \frac{c}{2}T_{delay}$$

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## Pulse Light Modulation – Practical considerations

**Strategy:** Repeat measurement-cycle  $n$  times and accumulate resulting voltages!

- $\Rightarrow$  increases SNR (and range accuracy) by  $\sqrt{n}$



# ToF Imaging

## Pulse Light Modulation – Practical considerations

**Strategy:** Repeat measurement-cycle  $n$  times and accumulate resulting voltages!

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**Explanation:** Say we have  $n$  i.i.d. measurements  $x_1, \dots, x_n$  (output of photodiode) with mean  $\mu$  and variance  $\sigma^2$ . We know that

$$V(\bar{x}) = V\left(\frac{x_1 + \dots + x_n}{n}\right) = \frac{\sigma^2}{n}$$

Hence, the stochastic error reduces by  $\frac{1}{\sqrt{n}}$ .



# Slide credits / Literature

Most of the material presented in this lecture is either taken from the textbook of Dal Mutto et al., online at

<http://freia.dei.unipd.it/nuovo/Papers/ToF-Kinect-book.pdf>

and the PhD thesis of O. Elkhaili [here](#).

