SH-ToF: Micro resolutiuon time-of-flight imaging with superheterodyne interferometry

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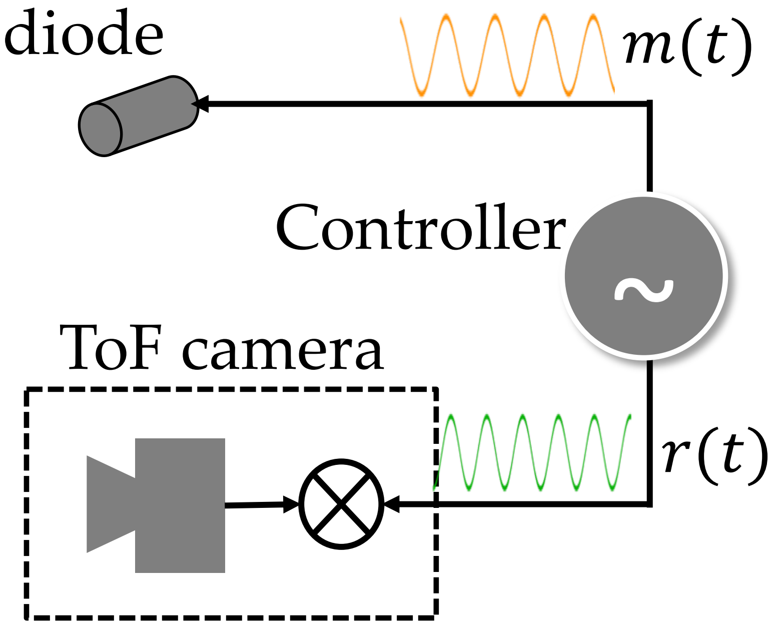
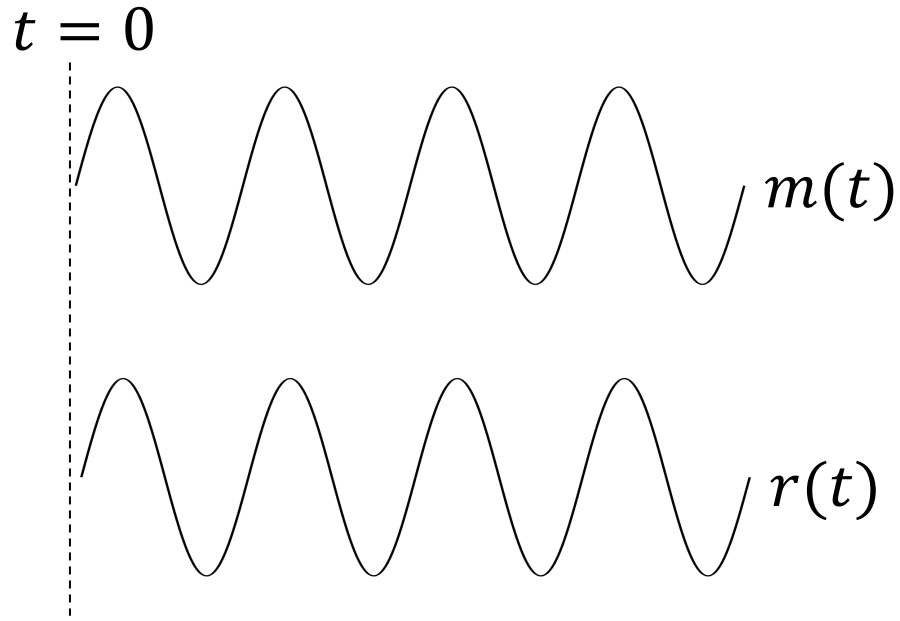
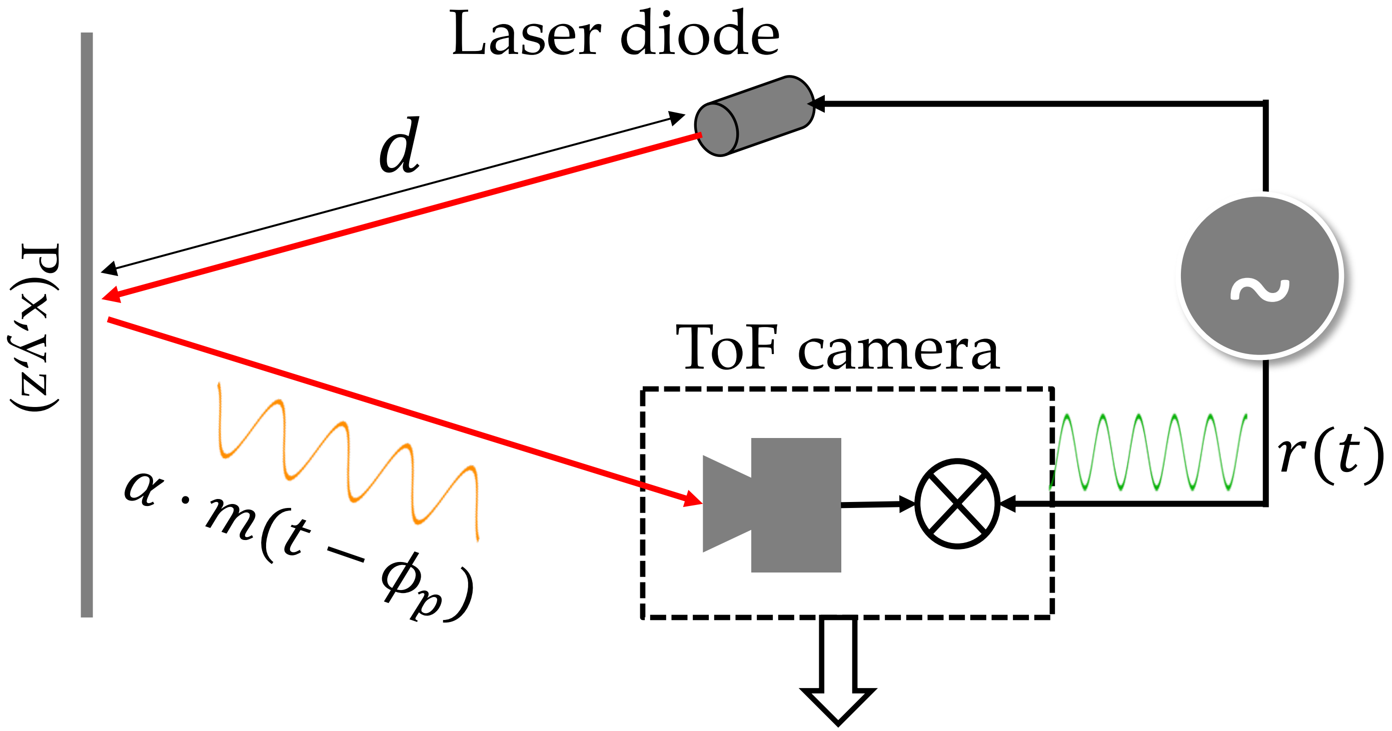
Continuous-wave time-of-flight (ToF) imaging





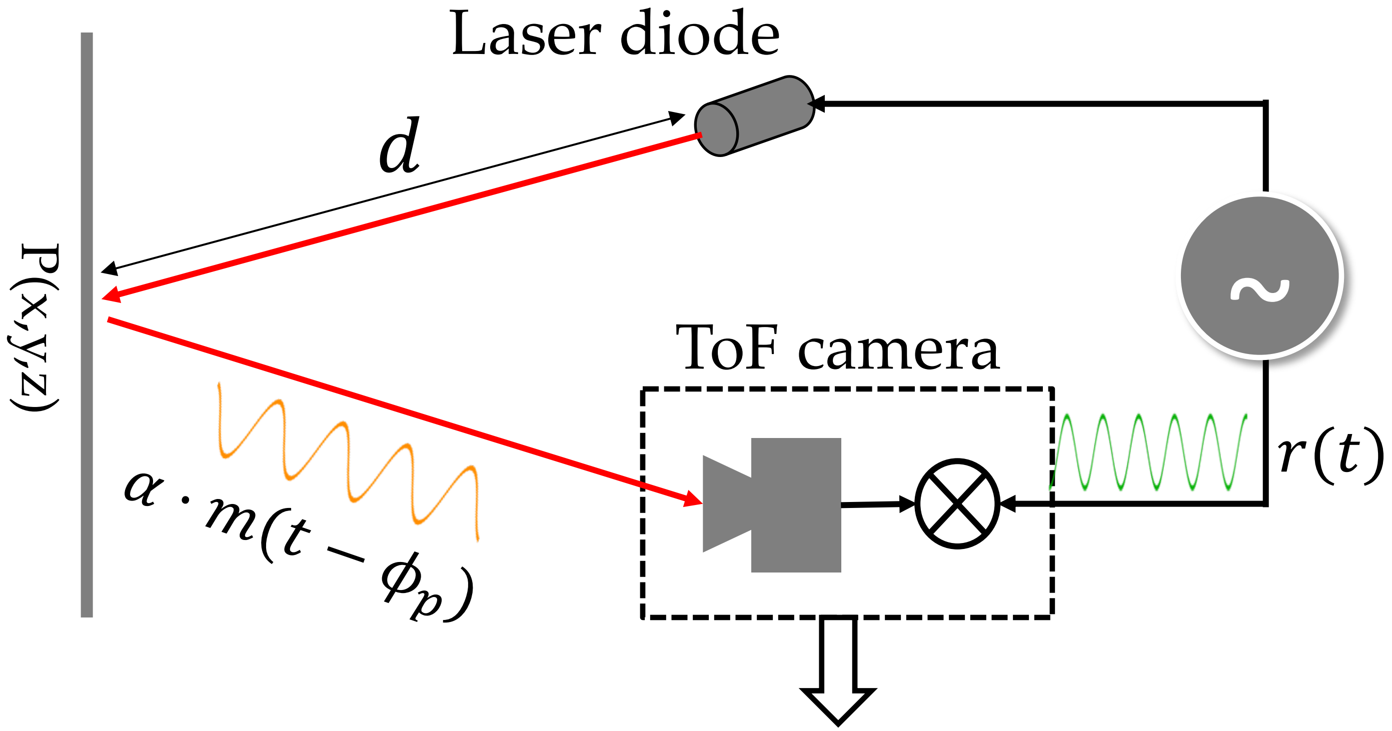
- Modulation to the amplitude of laser diode

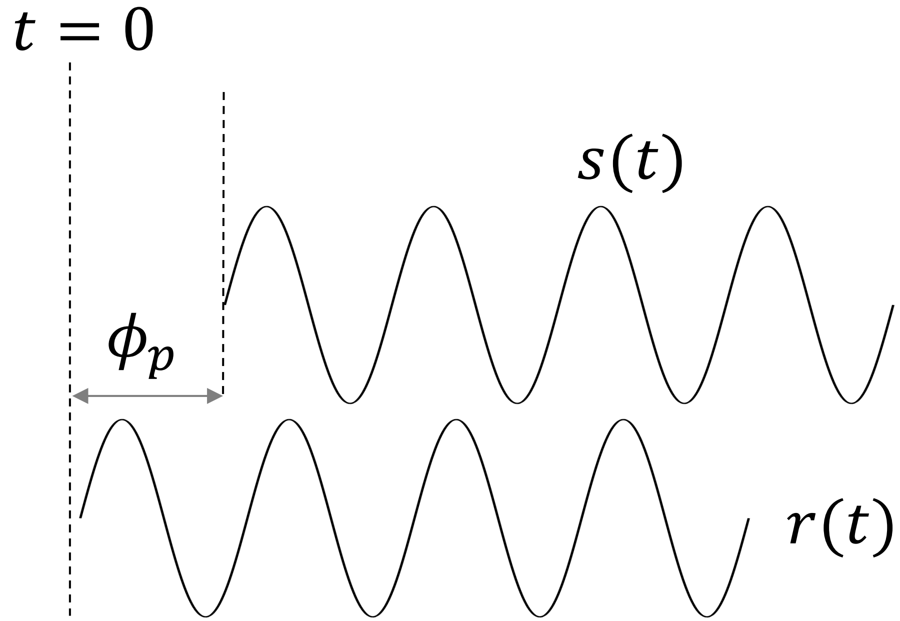
Continuous-wave ToF imaging



$$B(p) = \int_0^T \alpha \cdot m(t - \phi_p) \otimes r(t) dt$$

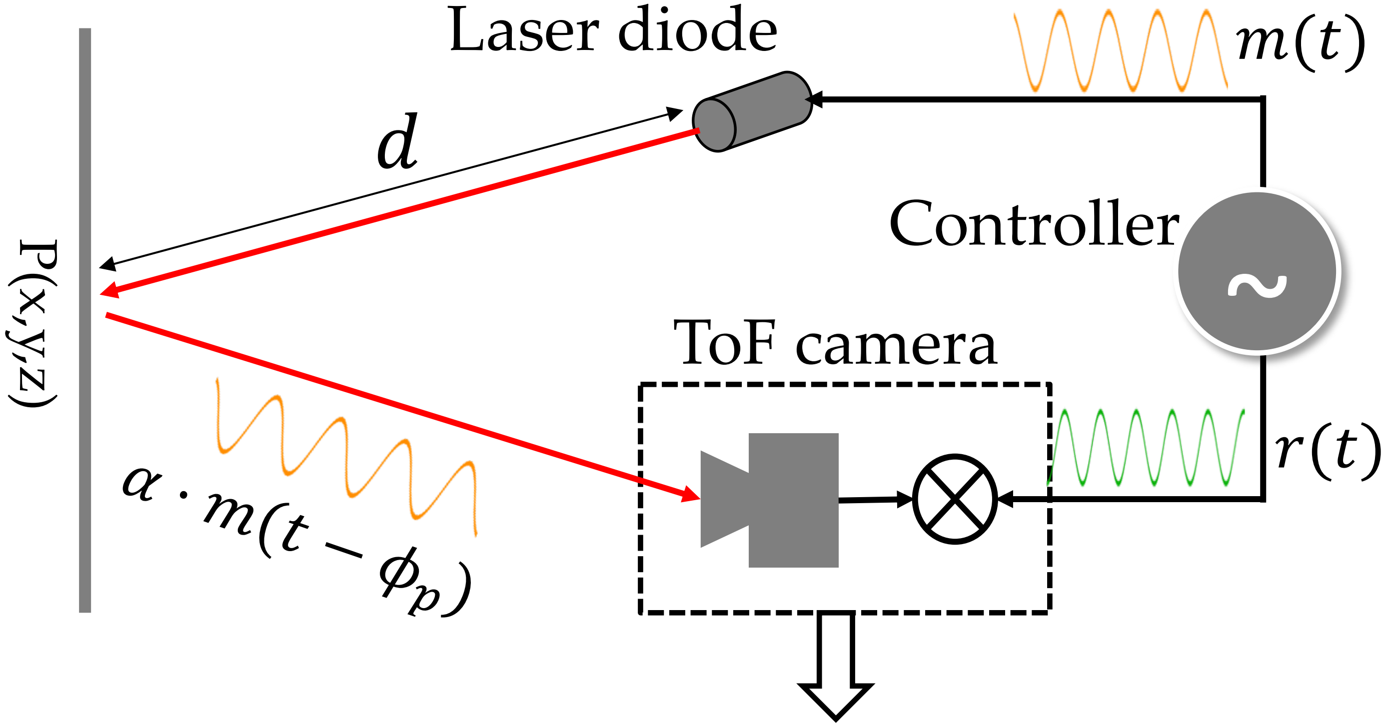
Continuous-wave ToF imaging





$$B(p) = \int_0^T \alpha \cdot m(t - \phi_p) \otimes r(t) dt$$

Continuous-wave ToF imaging



$$B(p) = \int_0^T \alpha \cdot m(t - \phi_p) \otimes r(t) dt$$

1. Introduce a constant phase in reference signal

$$B(p) = \int_0^T \alpha \cdot m(t - \phi_p) \otimes r(t - \boldsymbol{\psi}) dt$$

2. Shift phase ψ

$$\phi_p$$

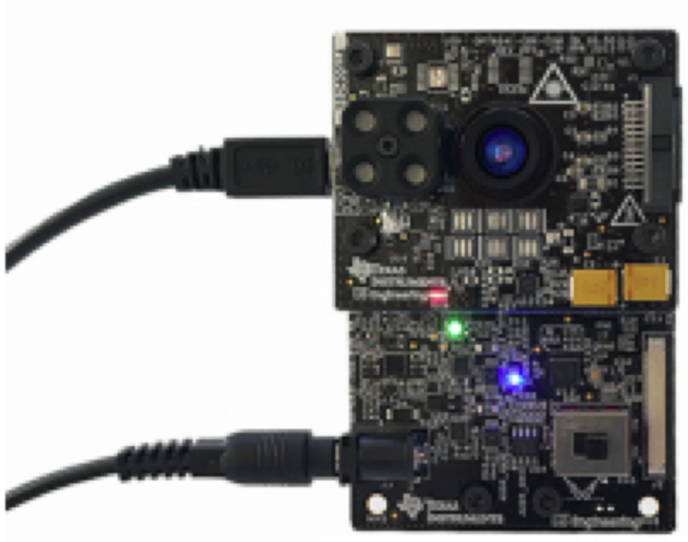
3. Depth estimation

$$d = \frac{1}{2} \cdot \frac{c}{f_t} \cdot \frac{\phi_p}{2\pi}$$

f_t: modulation frequency

PMD

Microsoft Kinect (2nd version)



Texas Instruments
OPT8241

Autonomous cars

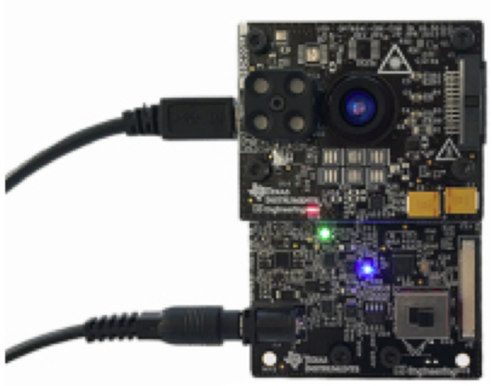
VR/AR

Robotics

HCI

Imaging with a ToF camera

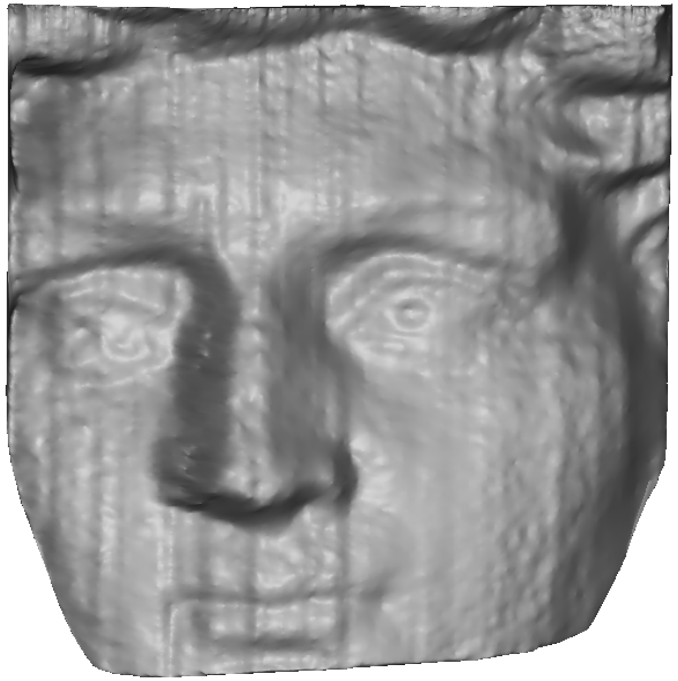
Imaging with a ToF camera



- ❑ Depth resolution: centimeters
- ❑ Miss fine details of the scanning object

Motivation

Proposed ToF imager



- Depth resolution: sub-millimeters

Depth resolution in ToF cameras

$$d = \frac{1}{2} \cdot \frac{c}{f_t} \cdot \frac{\phi_p}{2\pi}$$

$$\Delta d \propto \frac{1}{f_t}$$

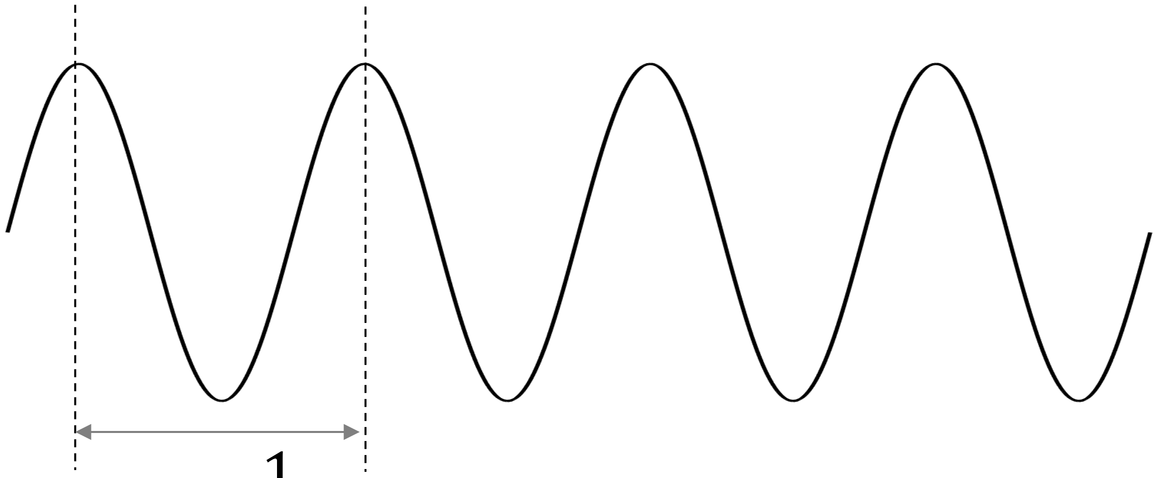
Increase modulation frequency f_t for better depth resolution Δd

Another continuous-wave ToF imaging

Light is a type of wave (electromagnetic wave)

$$E \cdot e^{i(2\pi\nu t)}$$

Simplified optical wave

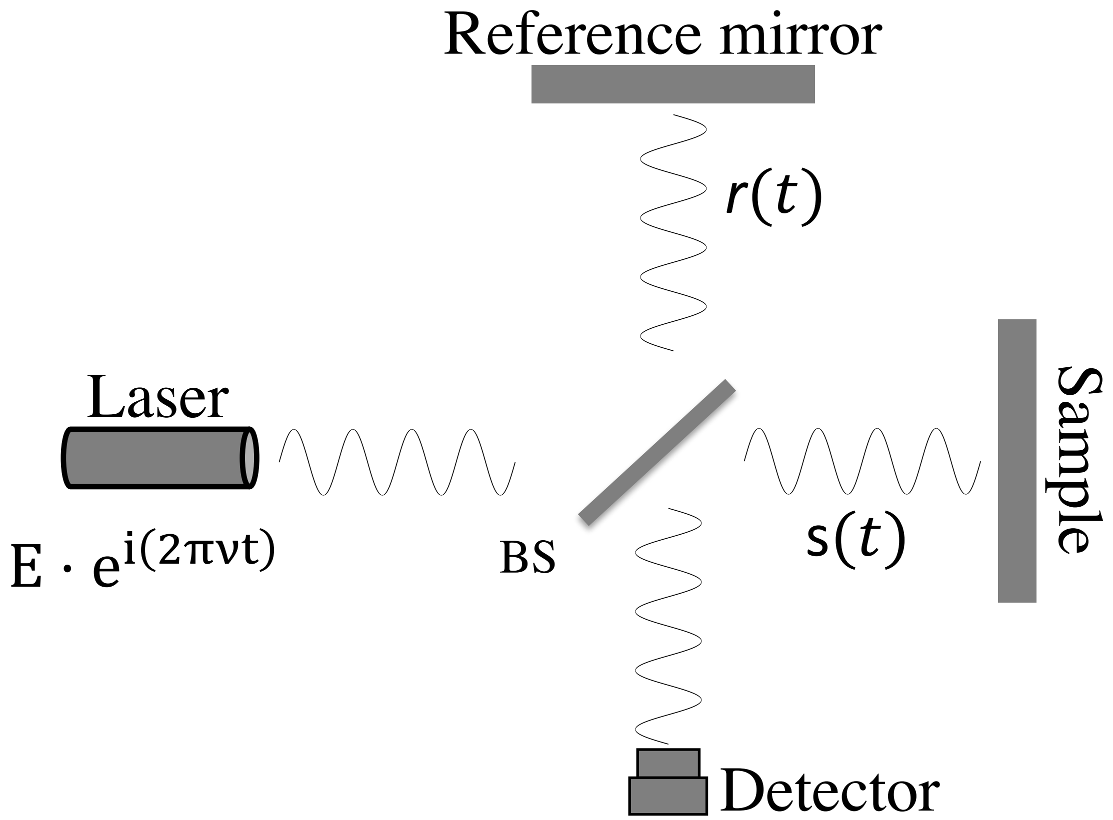


$$T = \frac{1}{\nu}$$

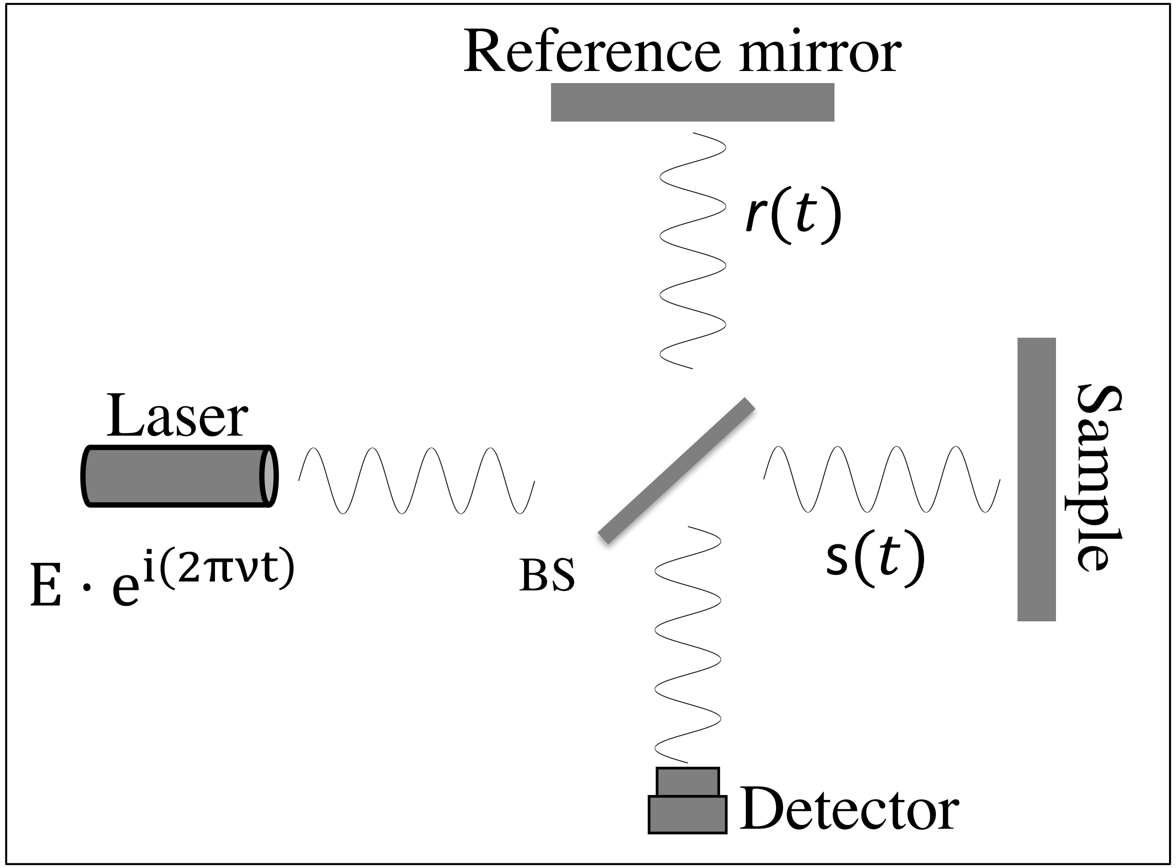
- ❑ Frequency of optical wave: ν
- ❑ 1550 nm wavelength: ν =193 THz

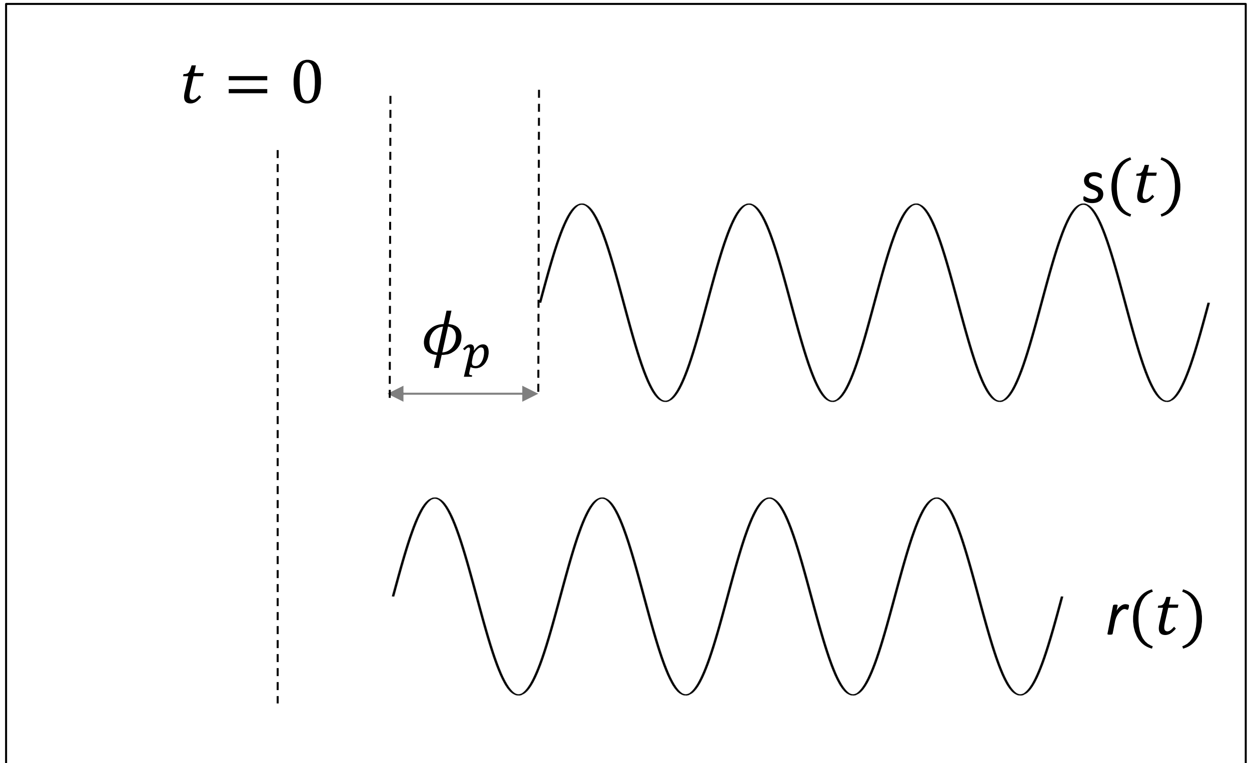
Another continuous-wave ToF imaging

Michelson Interferometry



Michelson Interferometry

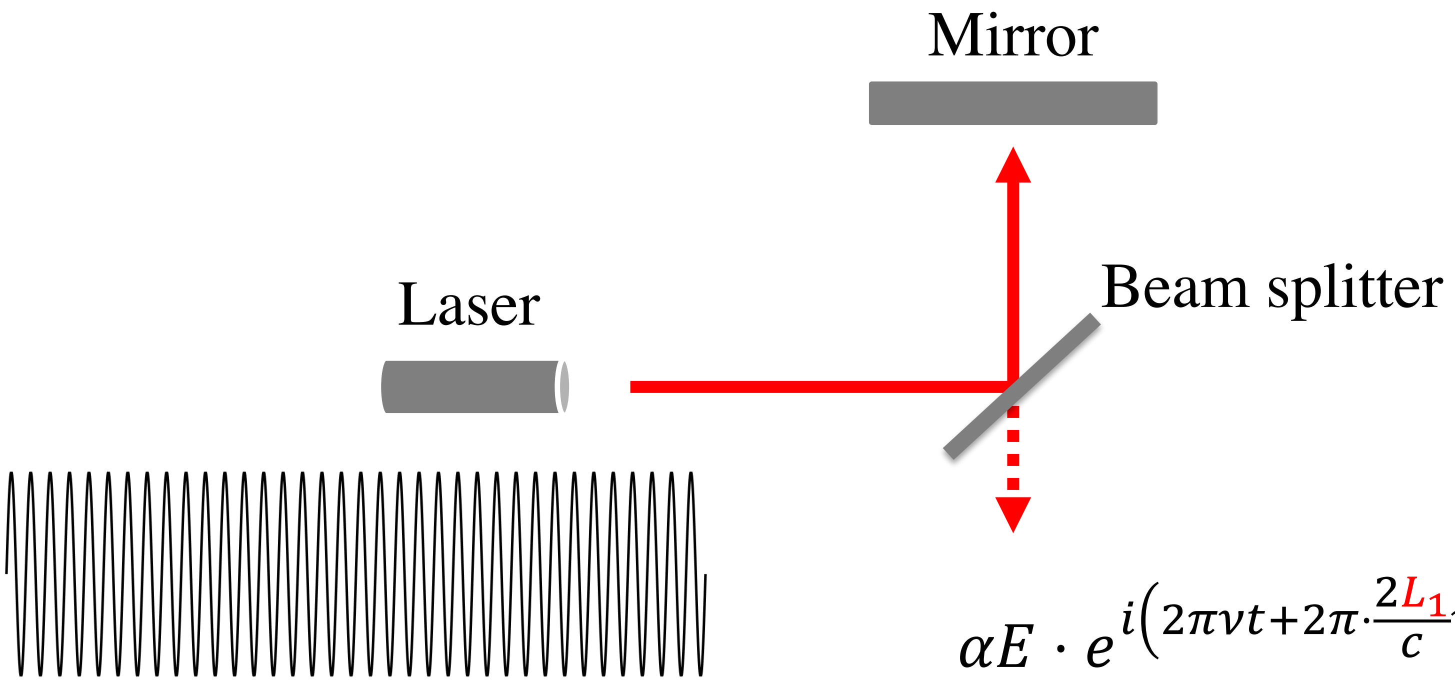




- ❑ Modulation to the phase of the light with frequency of ν

Michelson Interferometry

Reference arm

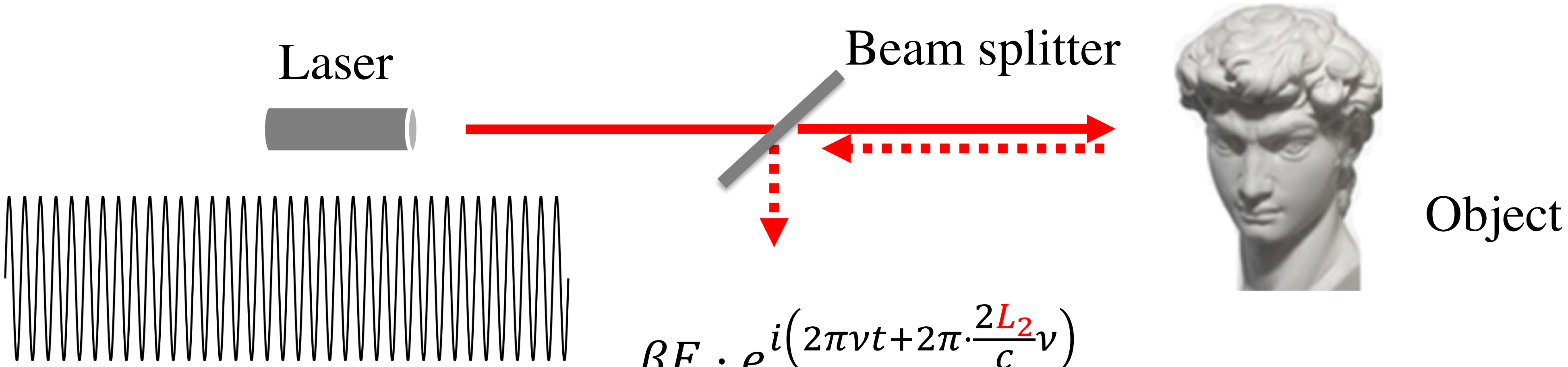


$$E \cdot e^{i(2\pi\nu t)}$$

$$\alpha E \cdot e^{i\left(2\pi\nu t + 2\pi\cdot\frac{2L_1}{c}\nu\right)}$$

Michelson Interferometry

Sample arm

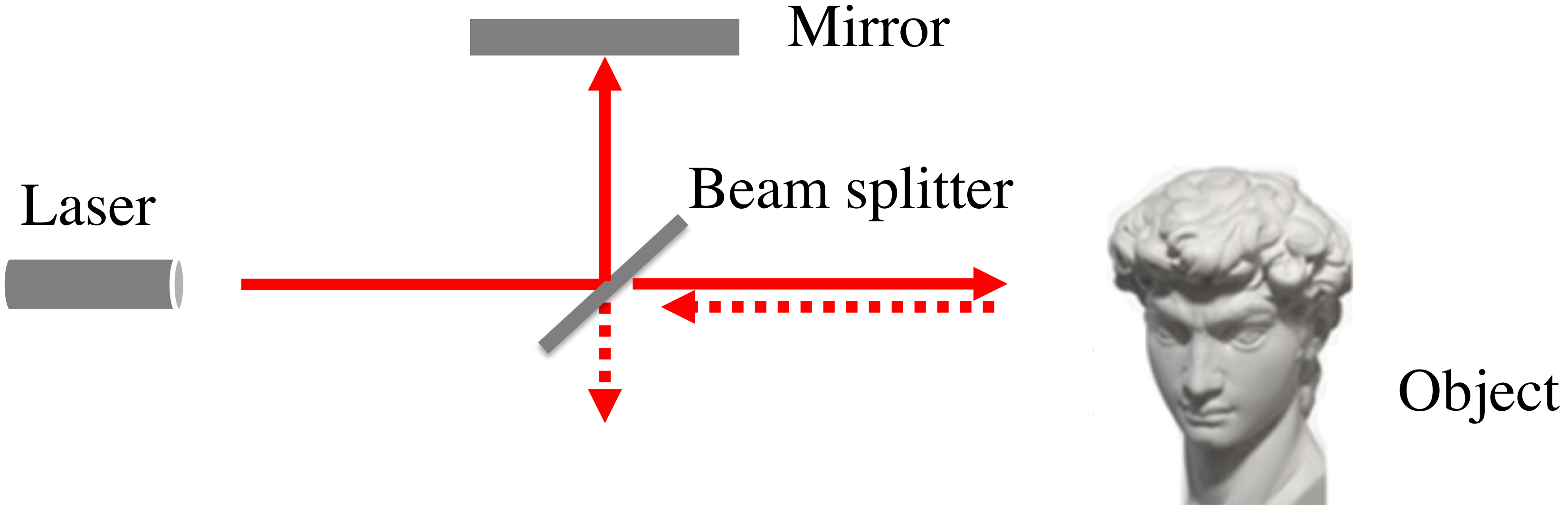


$$\beta E \cdot e^{i\left(2\pi\nu t + 2\pi \cdot \frac{2L_2}{c}\nu\right)}$$

$$E \cdot \cos(2\pi\nu t)$$

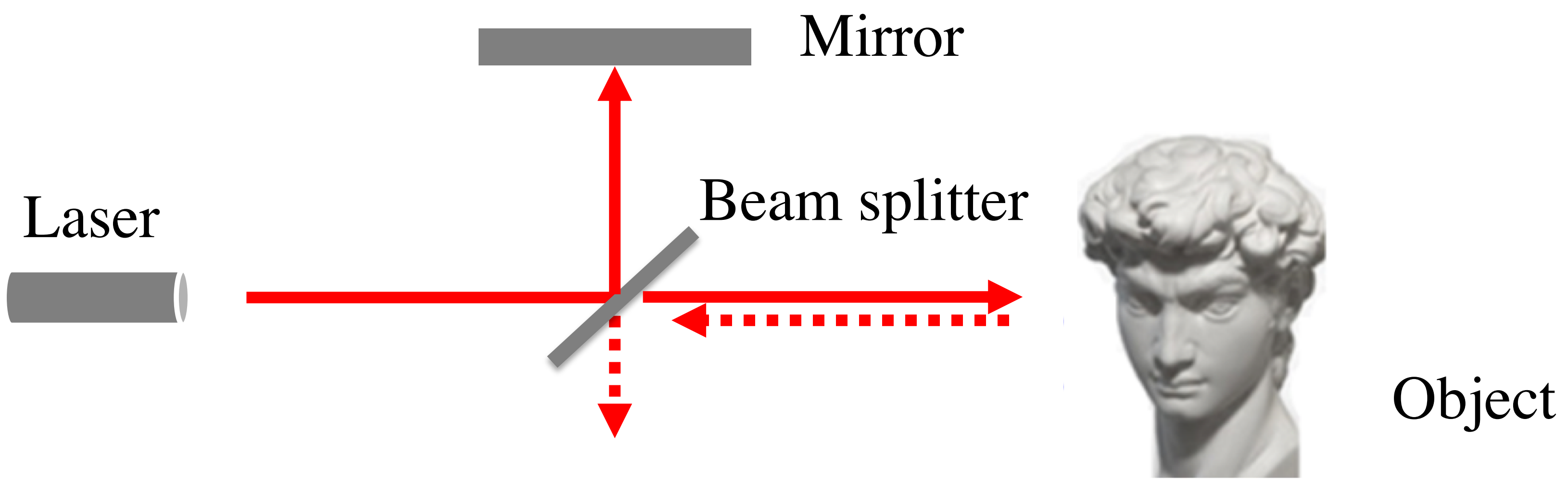
Michelson Interferometry

Reference signal + Sample signal



$$I = \left\| \alpha E \cdot e^{i\left(2\pi\nu t + 2\pi \cdot \frac{2L_1}{c}\nu\right)} + \beta E \cdot e^{i\left(2\pi\nu t + 2\pi \cdot \frac{2L_2}{c}\nu\right)} \right\|^2$$

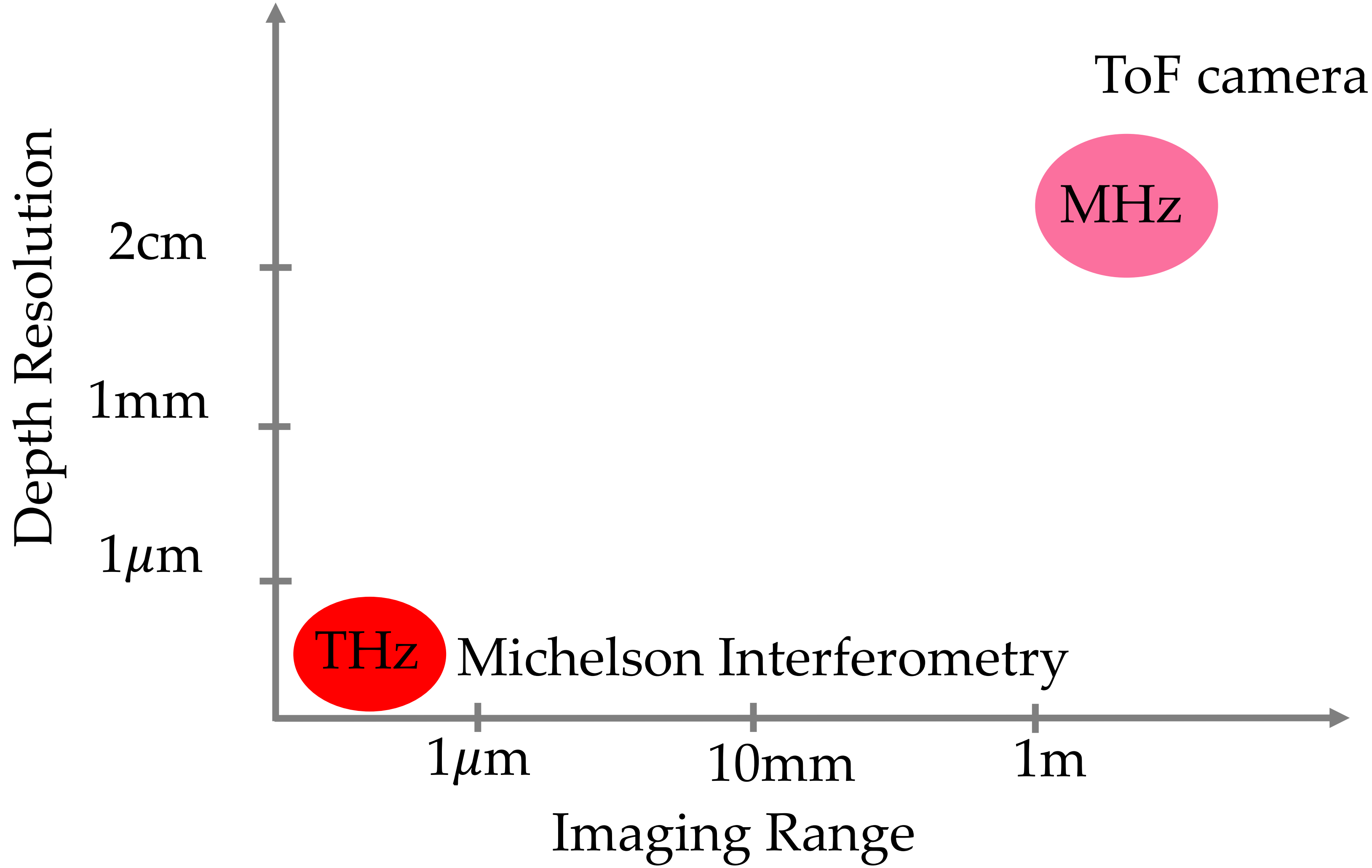
Michelson Interferometry



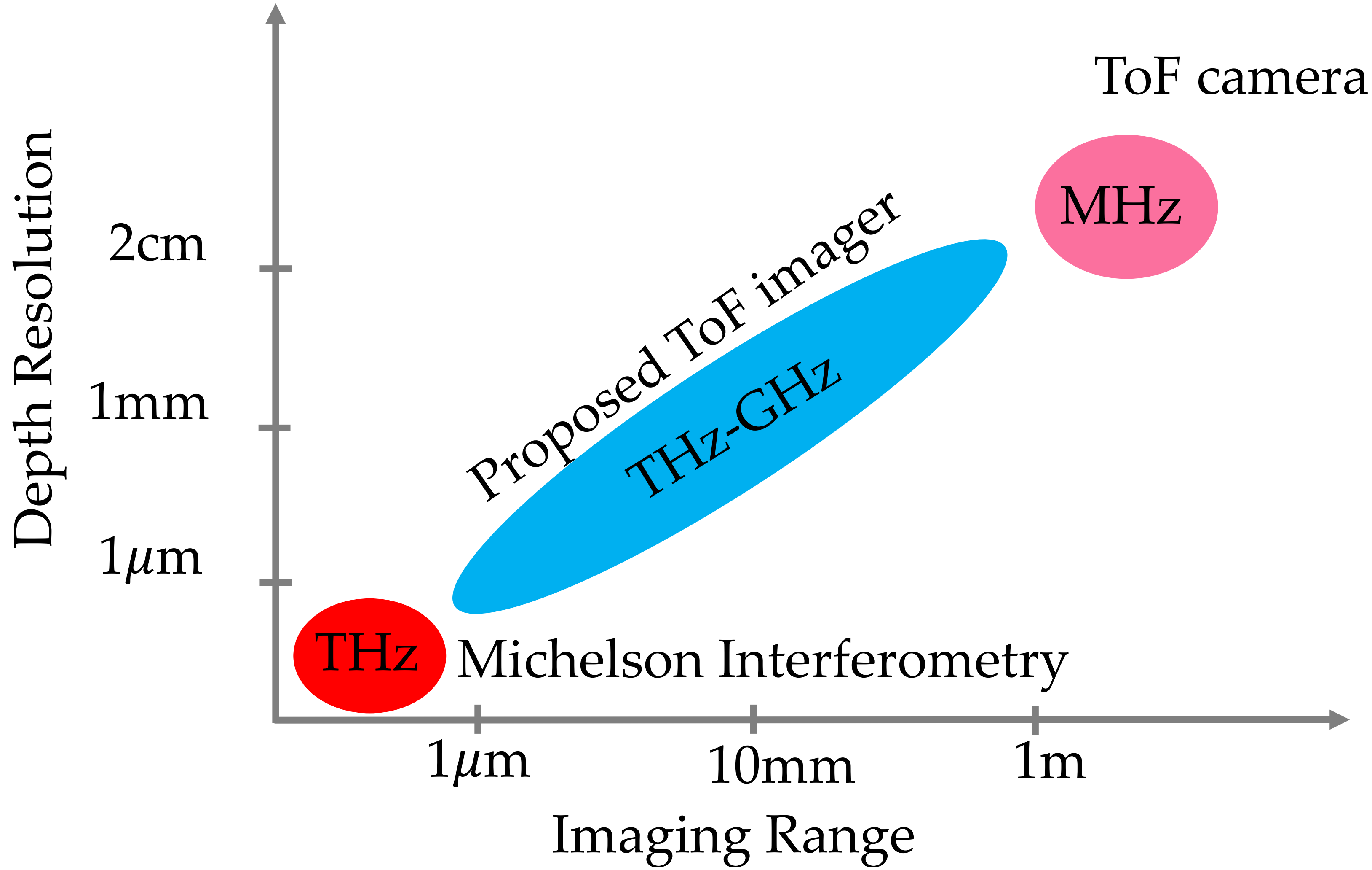
$$I = \gamma \cos\left(2\pi \cdot \frac{2(L_1 - L_2) \cdot \nu}{c}\right)$$

$$z = \frac{1}{2} \cdot \frac{c}{\nu} \cdot \frac{\phi}{2\pi}$$

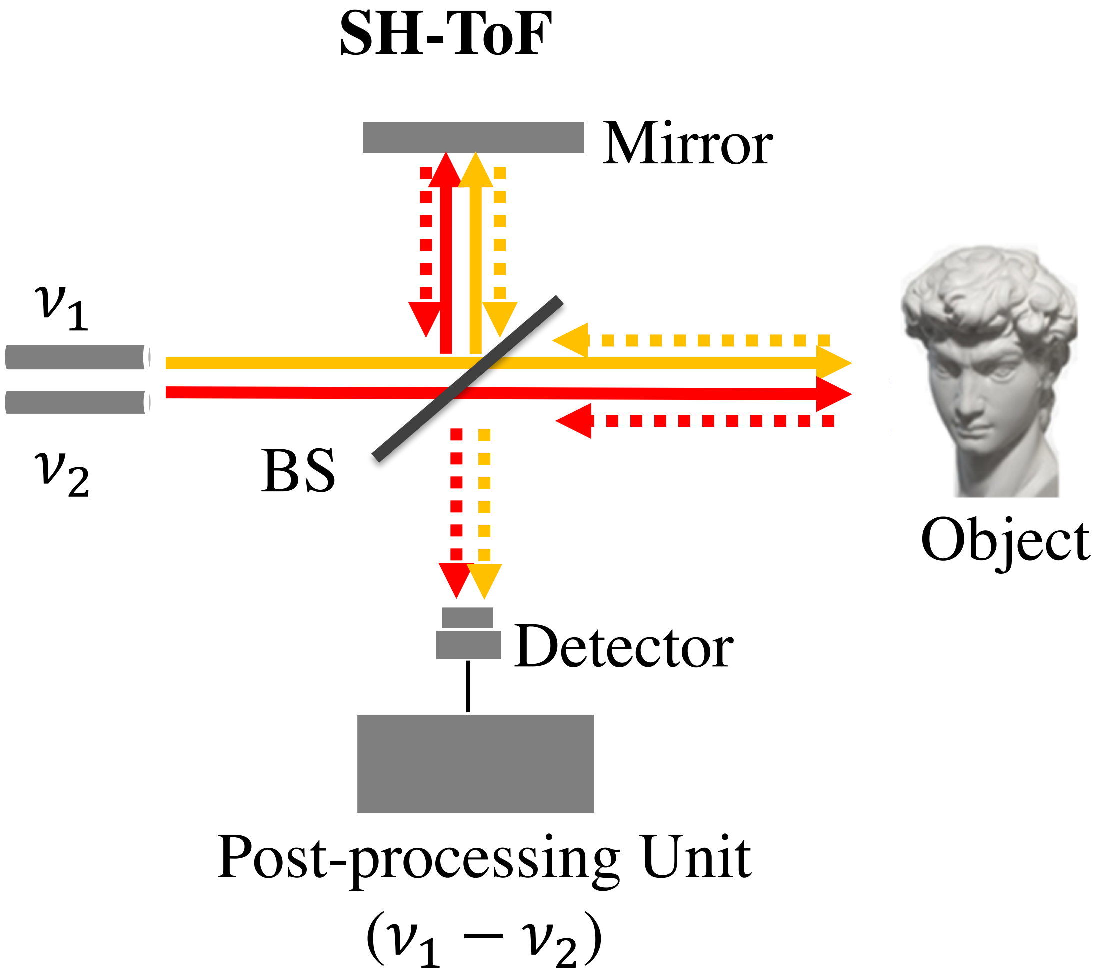
Michelson Interferometry vs ToF camera



Scope of the proposed ToF imager

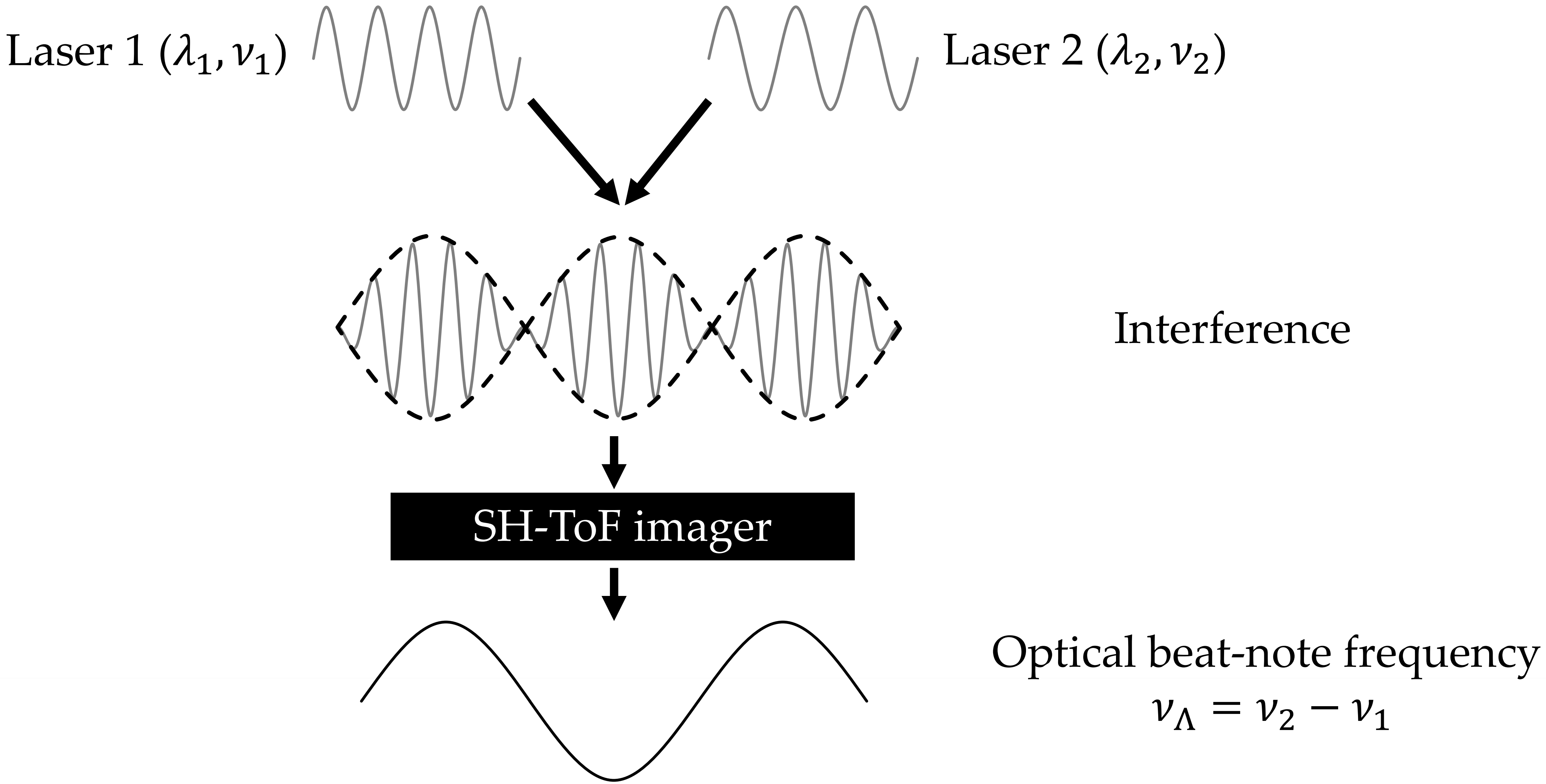


Proposed continuous-wave ToF imaging



- ❑ ToF imaging based on interferometry
- ❑ Two lasers with close wavelengths

Proposed continuous-wave ToF imaging



Comparison

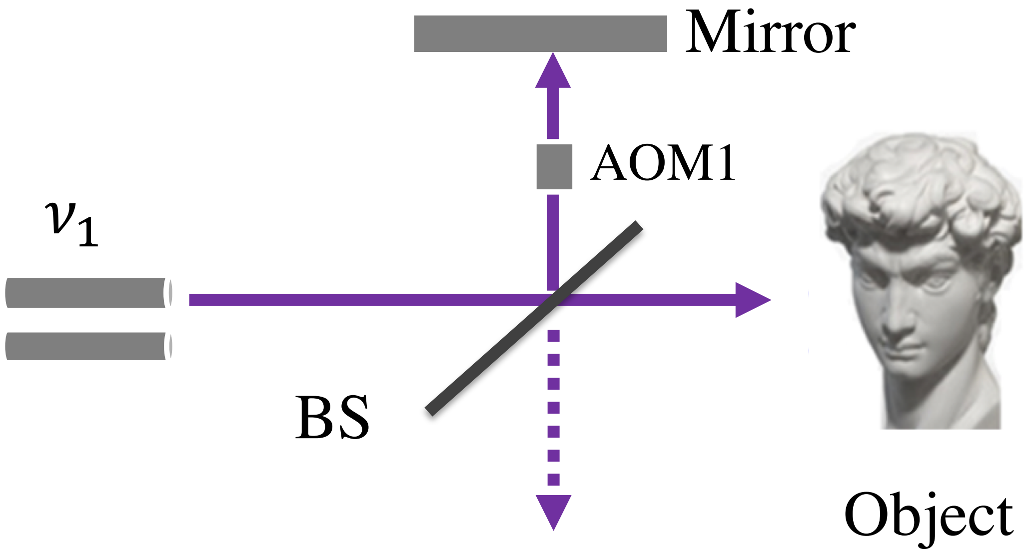
MI	SH-ToF	ToF camera
$z = \frac{1}{2} \cdot \frac{c}{\boldsymbol{\nu}} \cdot \frac{\phi}{2\pi}$	$z = \frac{1}{2} \cdot \frac{c}{(\boldsymbol{\nu_1} - \boldsymbol{\nu_2})} \cdot \frac{\phi}{2\pi}$	$z = \frac{1}{2} \cdot \frac{c}{\boldsymbol{f_t}} \cdot \frac{\phi}{2\pi}$
100 THz	**1 THz ~ 1 GHz**	**100 MHz**

Contributions

- SH-ToF framework
- Tunability of modulation frequency
- 3D scanning of optical rough objects

Principle of SH-ToF

Laser 1



f_{m1}: modulation frequency to AOM 1

AOM: acousto-optic modulator

L: optical path difference (OPD) between reference and sample arms

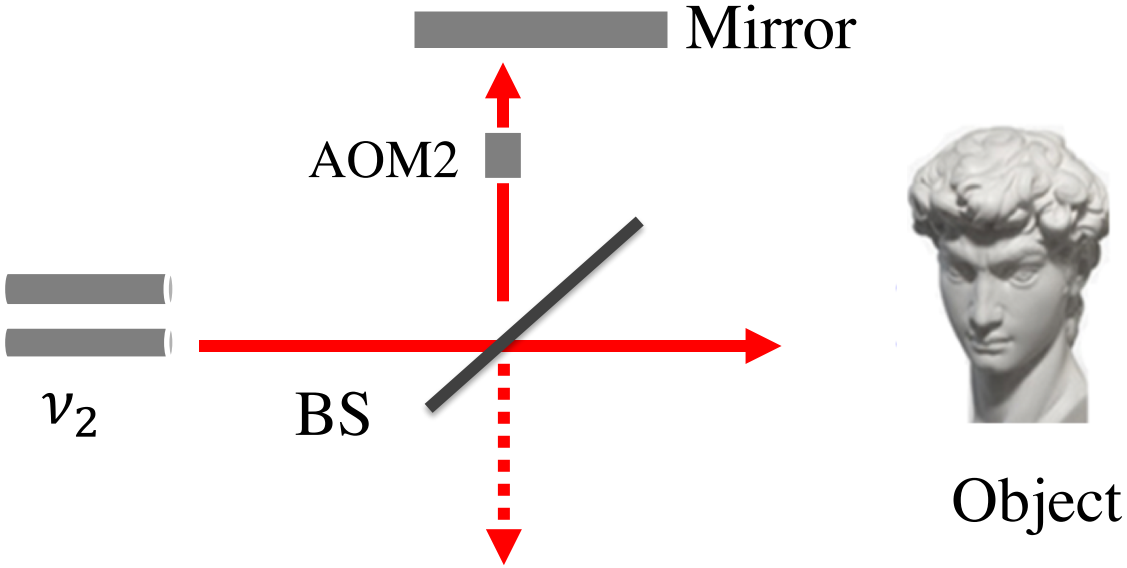
$\nu_1 + f_{m1}$
ν_1

$$I_{\lambda_1}(t) = cos\left(\frac{4\pi L}{c} \cdot \nu_1 - 2\pi f_{m1} t\right)$$

Principle of SH-ToF

Laser 2

f_{m2}: Modulation frequency to AOM 2



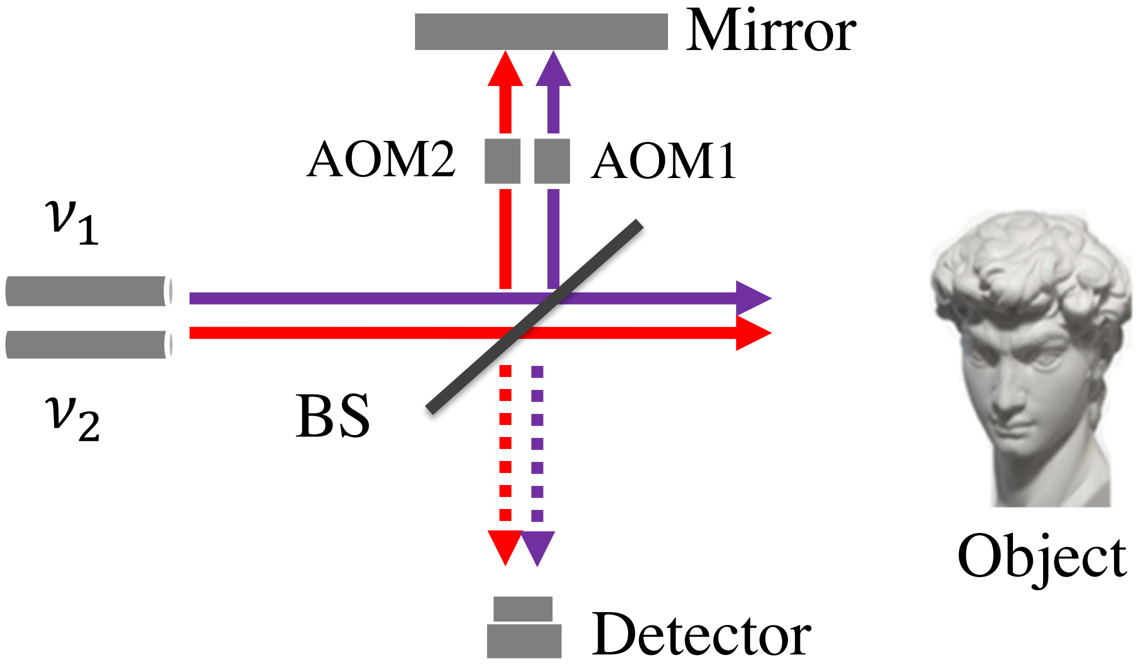
$\nu_2 + f_{m2}$

ν_2

$$I_{\lambda_2}(t) = cos\left(\frac{4\pi L}{c} \cdot \nu_2 - 2\pi f_{m2} t\right)$$

Principle of SH-ToF

Laser 1+2



$\nu_1 + f_{m1}$

ν_1

$\nu_2 + f_{m2}$

ν_2

$$I(t) = cos\left(\frac{4\pi L}{c} \cdot \nu_1 - 2\pi f_{m1} t\right) + cos\left(\frac{4\pi L}{c} \cdot \nu_2 - 2\pi f_{m2} t\right)$$

Principle of SH-ToF

$$I(t) = cos\left(\frac{4\pi L}{c} \cdot v_1 - 2\pi f_{m1} t\right) + cos\left(\frac{4\pi L}{c} \cdot v_2 - 2\pi f_{m2} t\right)$$

I(t)²

$$S(t) = \left\{cos\left(\frac{4\pi L}{c} \cdot v_1 - 2\pi f_{m1} t\right) + cos\left(\frac{4\pi L}{c} \cdot v_2 - 2\pi f_{m2} t\right)\right\}^2$$

Principle of SH-ToF

$$I(t) = cos\left(\frac{4\pi L}{c}\cdot v_1 - 2\pi f_{m1}t\right) + cos\left(\frac{4\pi L}{c}\cdot v_2 - 2\pi f_{m2}t\right)$$

$I(t)^2$

$$S(t) = \left\{cos\left(\frac{4\pi L}{c}\cdot v_1 - 2\pi f_{m1}t\right) + cos\left(\frac{4\pi L}{c}\cdot v_2 - 2\pi f_{m2}t\right)\right\}^2$$

bandpass

$$B(t) = cos\left(\frac{4\pi L}{c}(v_1 - v_2) - 2\pi(f_{m1} - f_{m2})t\right)$$

Principle of SH-ToF

$$I(t) = cos\left(\frac{4\pi L}{c} \cdot \nu_1 - 2\pi f_{m1} t\right) + cos\left(\frac{4\pi L}{c} \cdot \nu_2 - 2\pi f_{m2} t\right)$$

I(t)²

$$S(t) = \left\{cos\left(\frac{4\pi L}{c} \cdot \nu_1 - 2\pi f_{m1} t\right) + cos\left(\frac{4\pi L}{c} \cdot \nu_2 - 2\pi f_{m2} t\right)\right\}^2$$

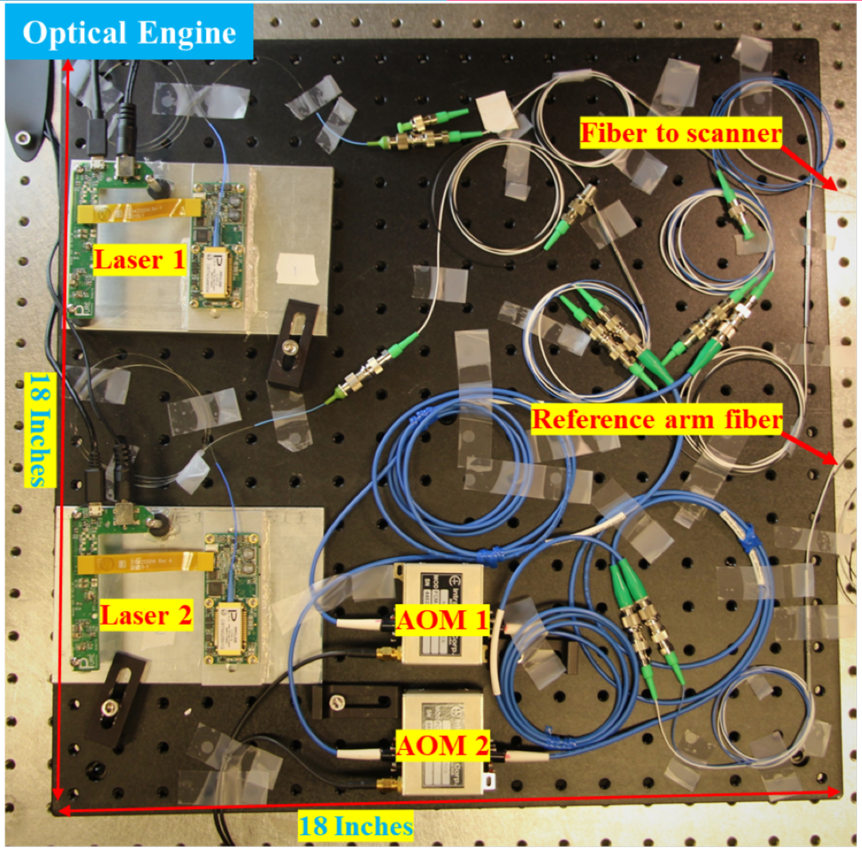
bandpass

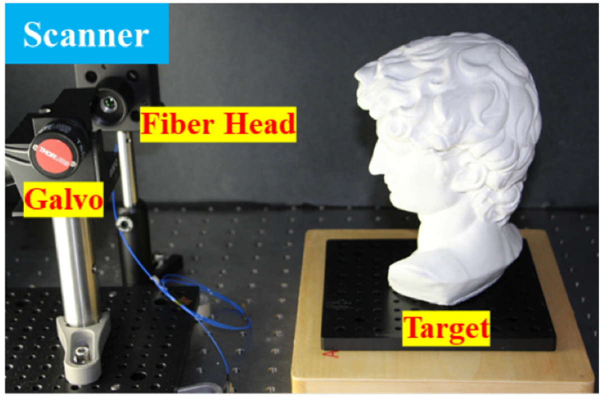
$$B(t) = cos\left(\frac{4\pi L}{c}(\nu_1 - \nu_2) - 2\pi(f_{m1} - f_{m2})t\right)$$

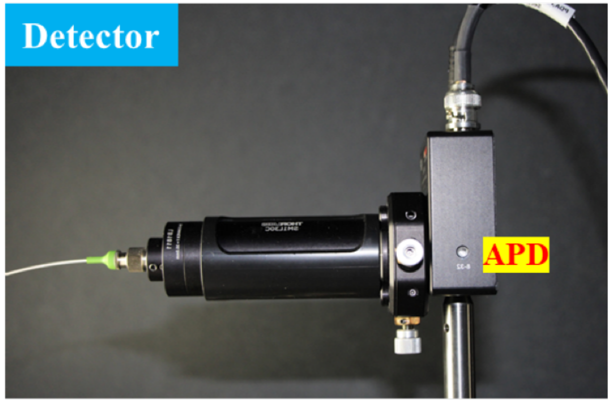
Depth estimation

$$L = \frac{1}{2} \cdot \frac{c}{\nu_1 - \nu_2} \cdot \frac{\Phi(L)}{2\pi}$$

Prototype



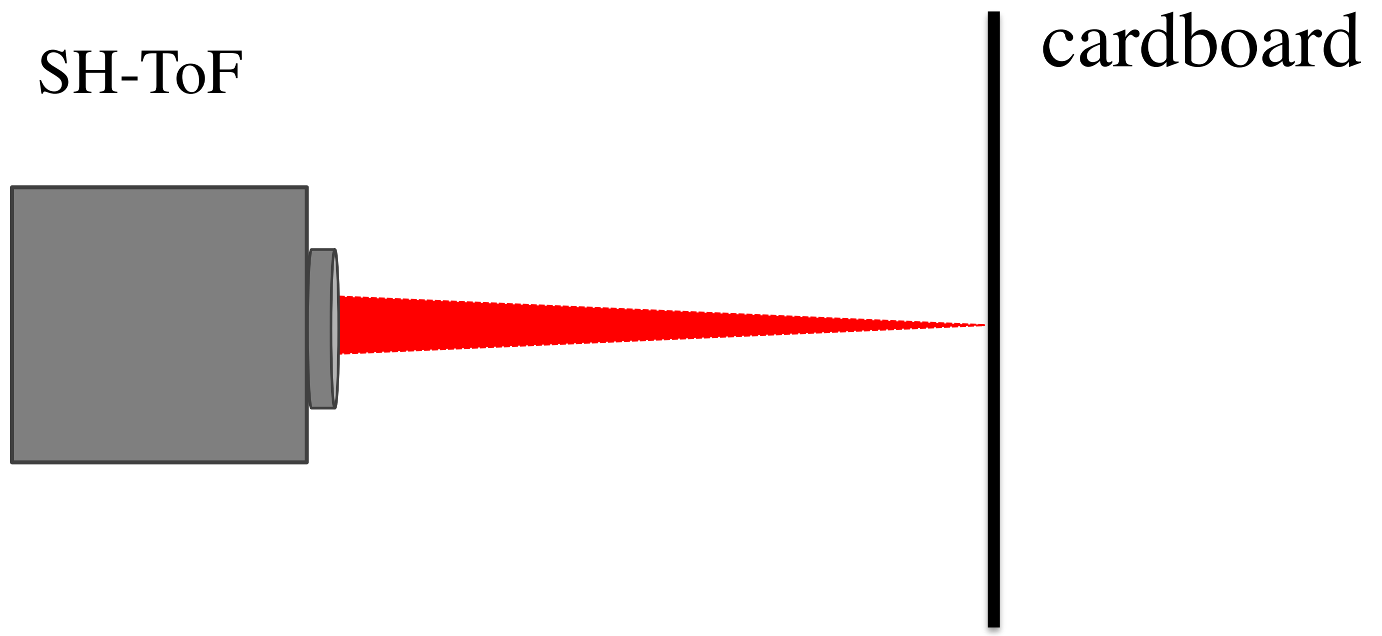




- Tunable lasers with center wavelengths of 1550nm
- AOM frequencies: 40 MHz and 40.1MHz

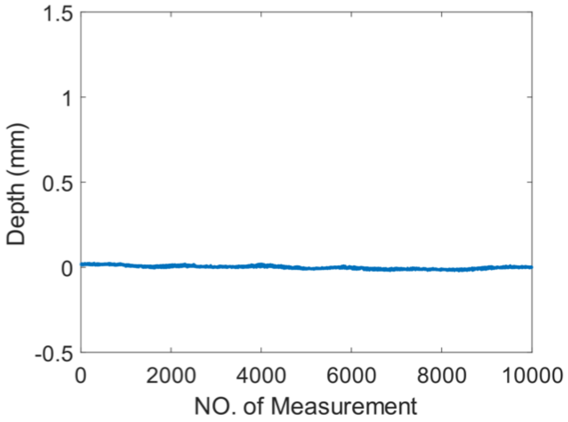
Upper bound performance

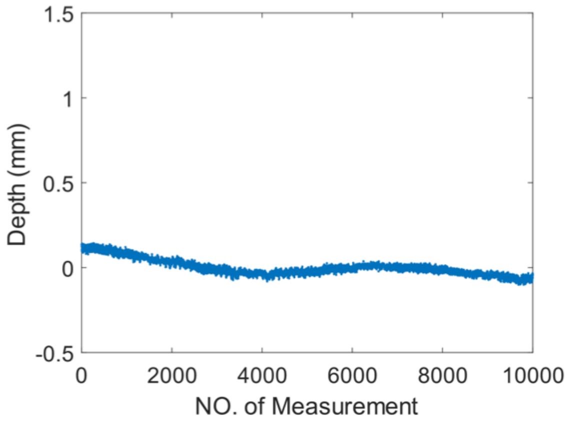
Experimental setup

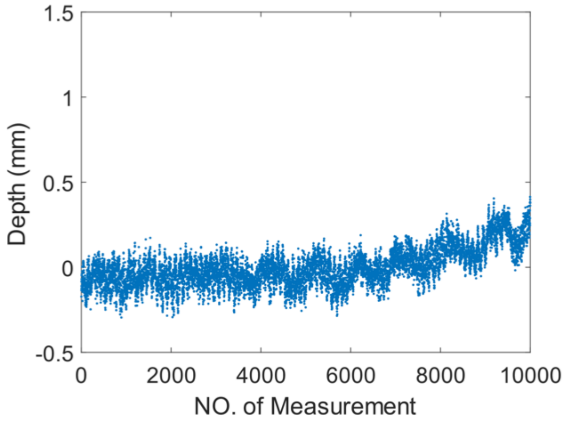


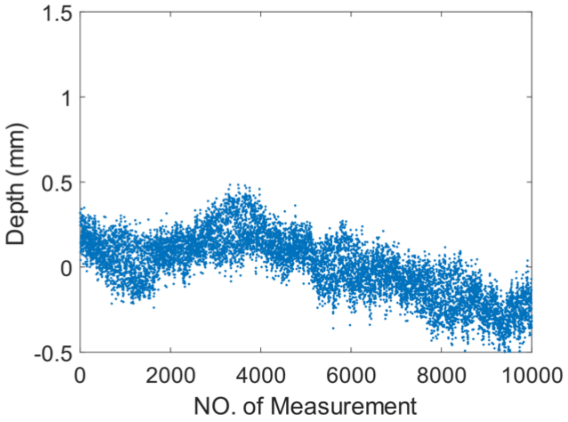
- Laser beam is fixed and focused on a point
- Repeat measurements for 10000 times

Upper bound performance







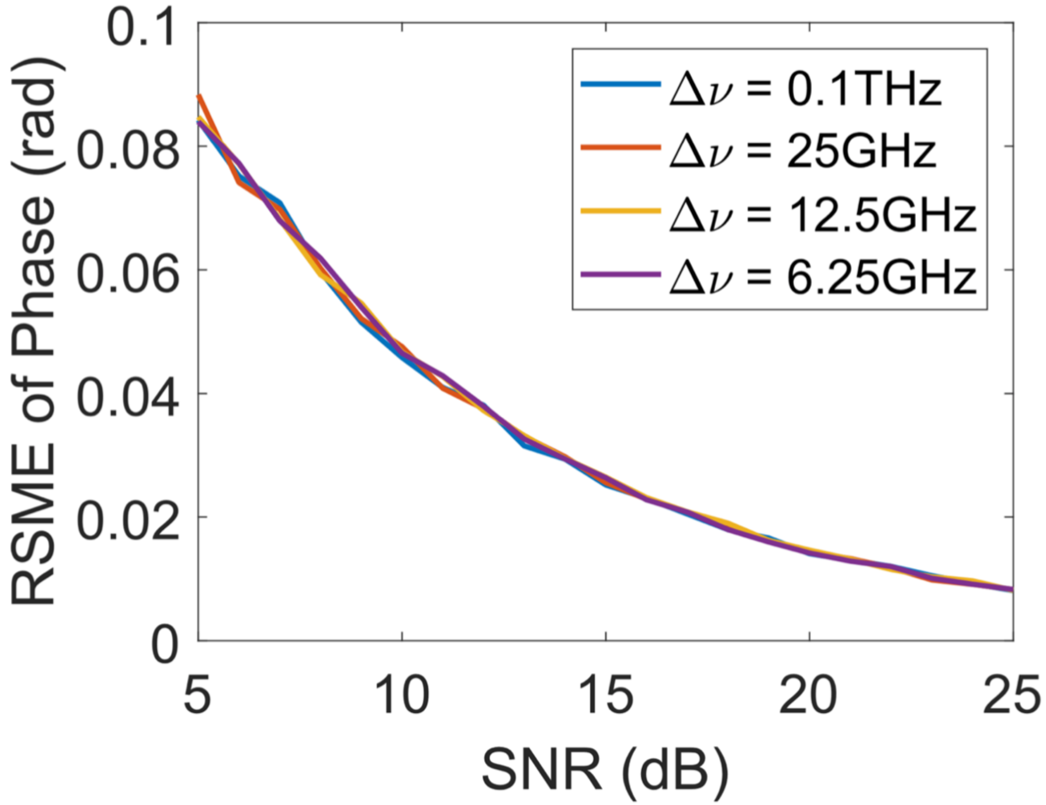


$\Delta\nu$[GHz]	**100**	**25**	**12.5**	**6.25**
Λ[mm]	3	12	24	48
$\delta\Phi$[rad]	0.041	0.049	0.059	0.047
δz[mm]	0.009	0.047	0.114	0.179

comp photo lab

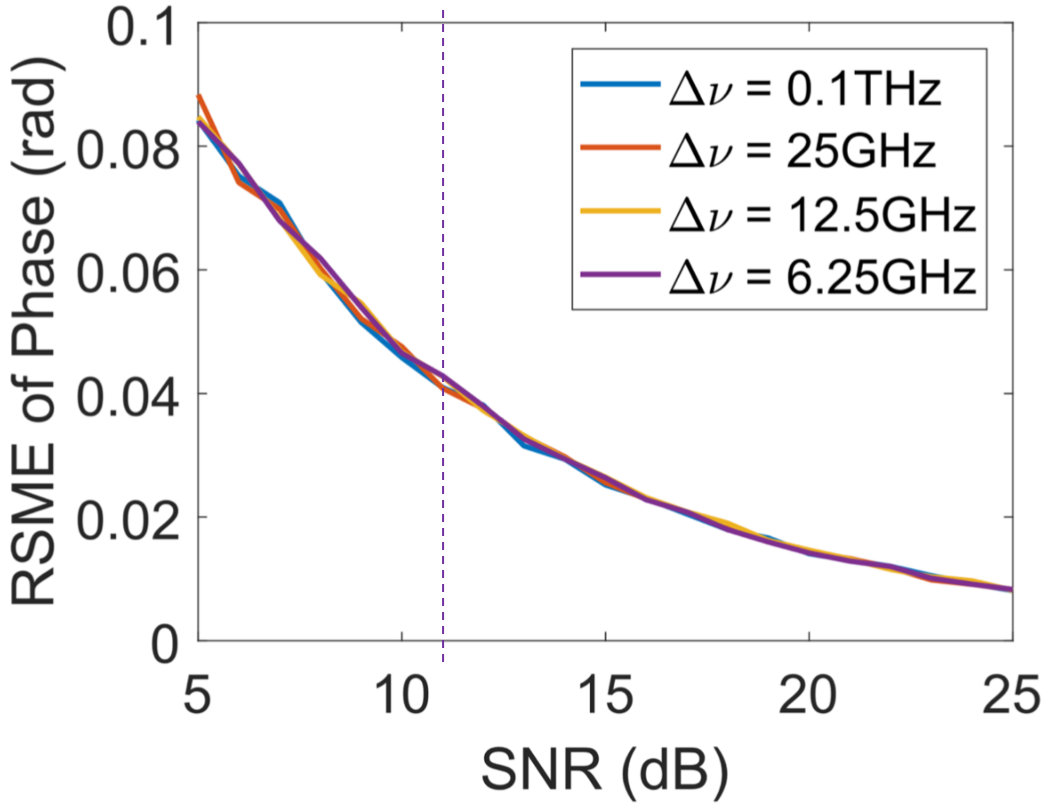
Upper bound performance (simulation)

- ❑ Simulator based on our physical setup
- ❑ Phase error with different SNRs



Upper bound performance (simulation)

- ❑ Simulator based on our physical setup
- ❑ Phase error with different SNRs
- ❑ SNR≈ 11dB in our prototype

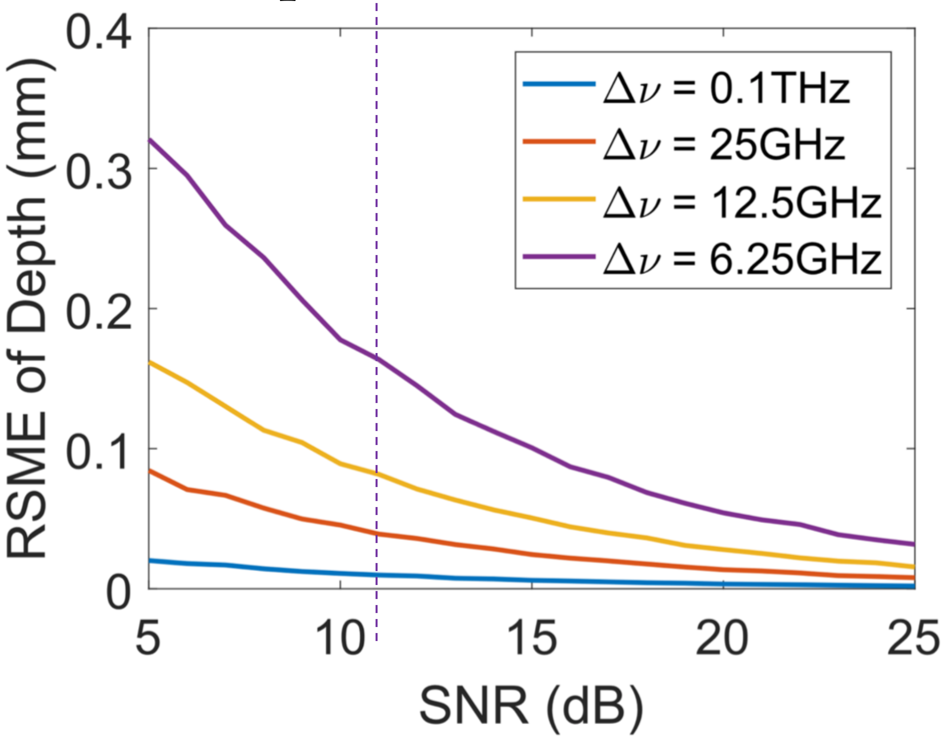


$\Delta\nu$[GHz]	**100**	**25**	**12.5**	**6.25**
$\delta\Phi$[rad]	0.041	0.049	0.059	0.047

Quantify the prototype

$$L = \frac{1}{2} \cdot \frac{c}{\nu_1 - \nu_2} \cdot \frac{\Phi(L)}{2\pi}$$

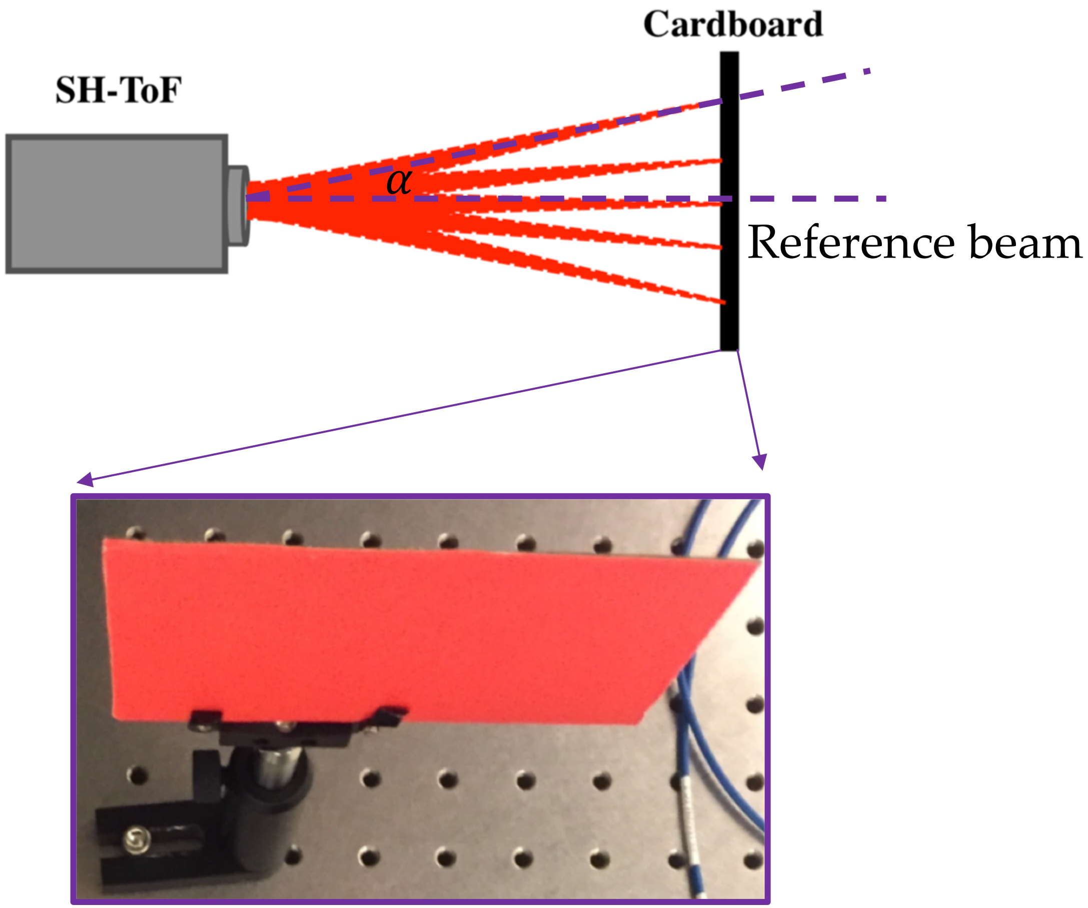
RSME of depth VS SNR (Simulation)



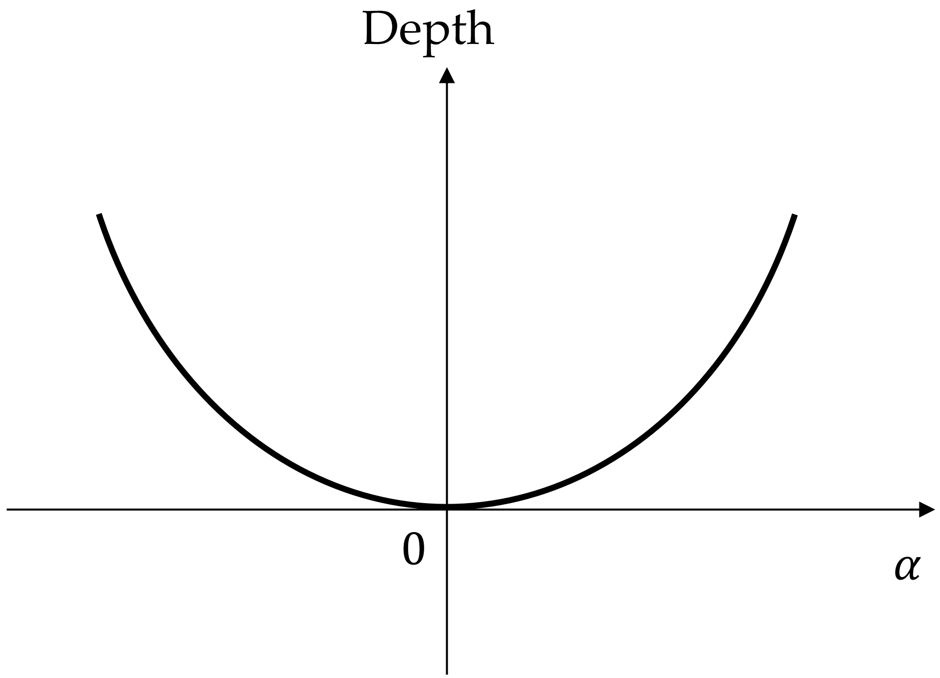
$\Delta\nu$[GHz]	**100**	**25**	**12.5**	**6.25**
δz[mm]	0.009	0.047	0.114	0.179

Performance with scanning and Tunability

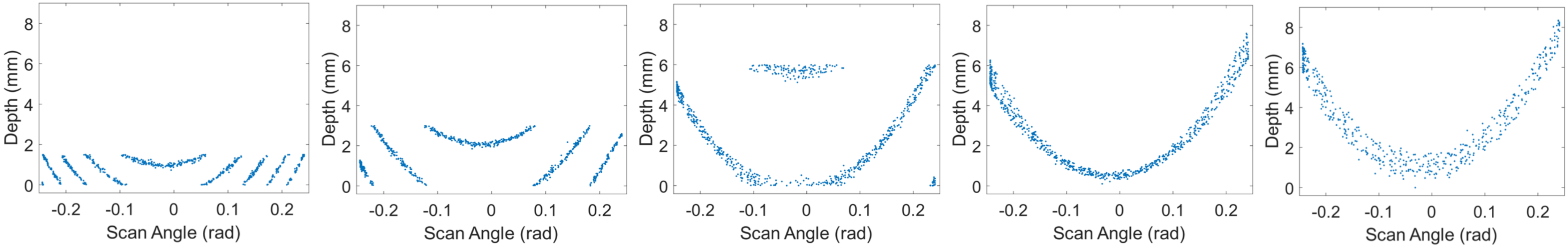
Line-scanning setup



Depth map at different scanning angles

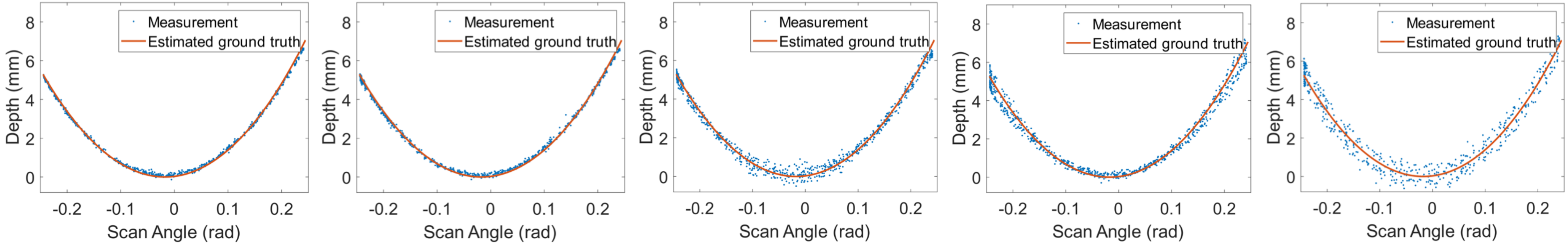


Performance with scanning and Tunability



$\Delta\nu$[GHz]	**100**	**50**	**25**	**12.5**	**6.25**

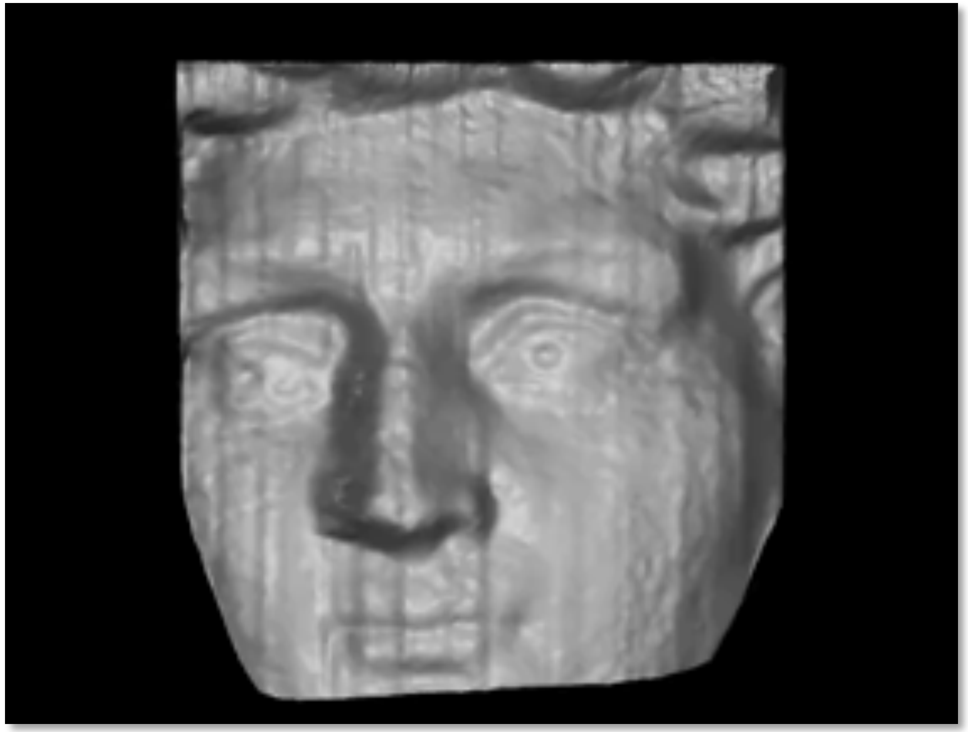
Performance with scanning and Tunability



$\Delta\nu$[GHz]	**100**	**50**	**25**	**12.5**	**6.25**
δz[mm]	0.070	0.093	0.221	0.274	0.437

3D scanning

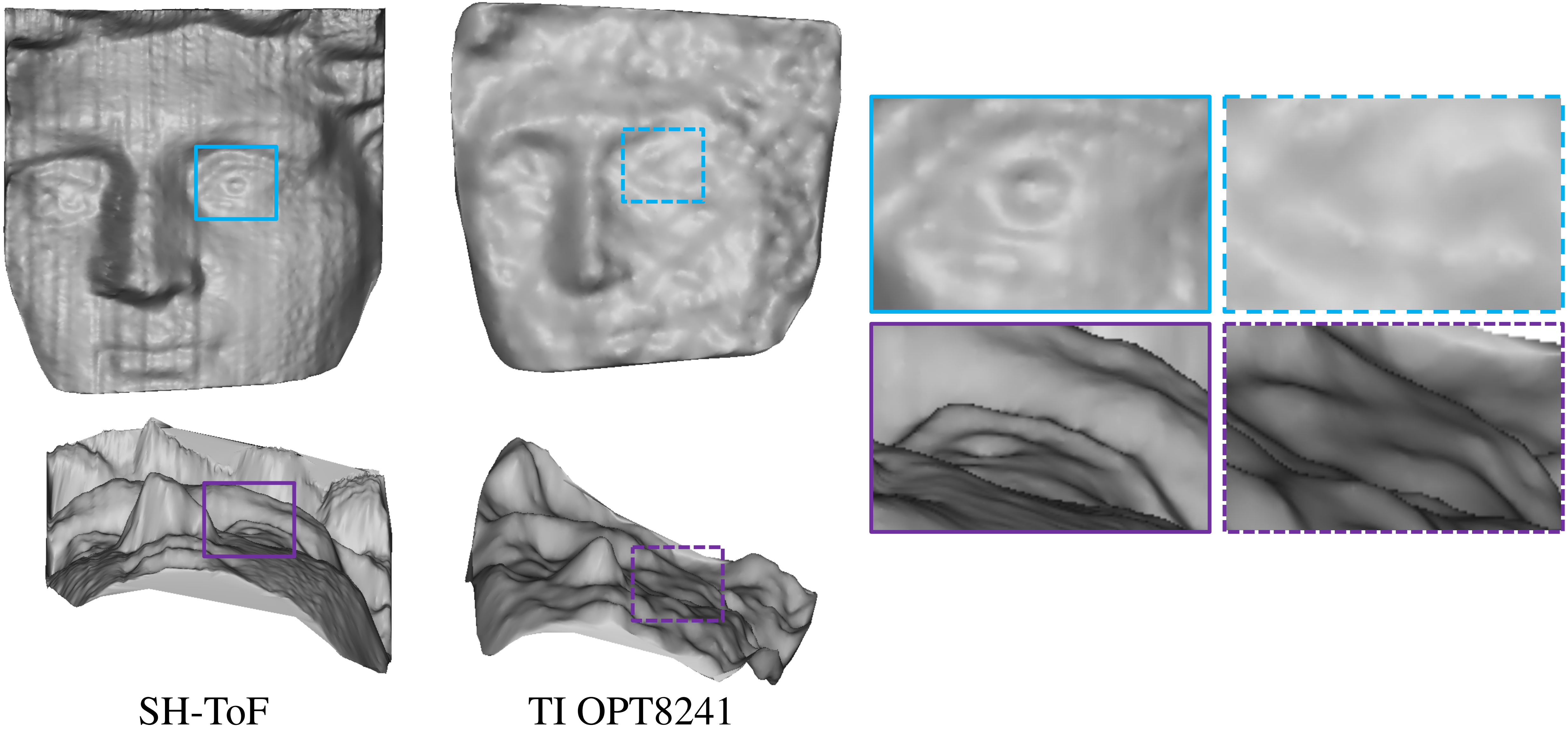
Photo of the bust



SH-ToF scanning

- Modulation frequency: 6.25 GHz (Λ = 48 mm)

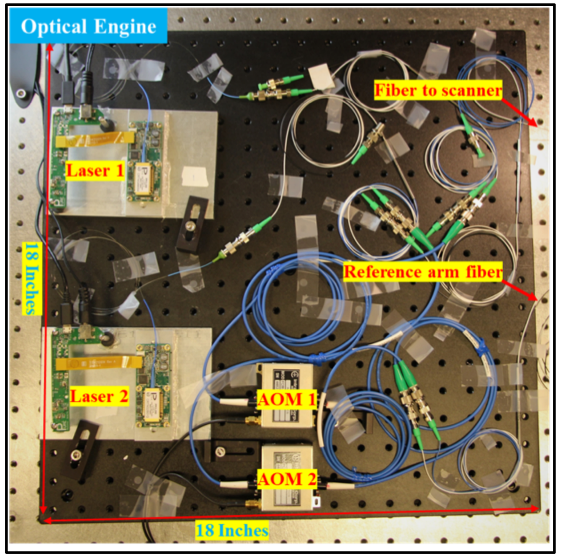
3D scanning

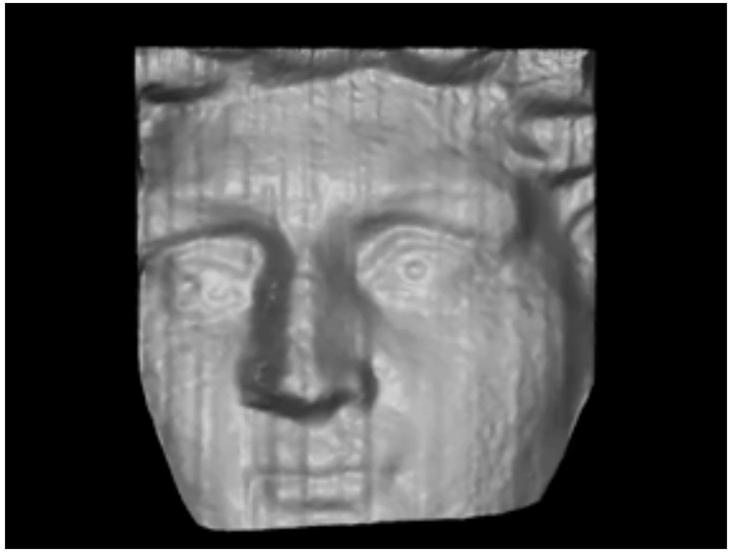


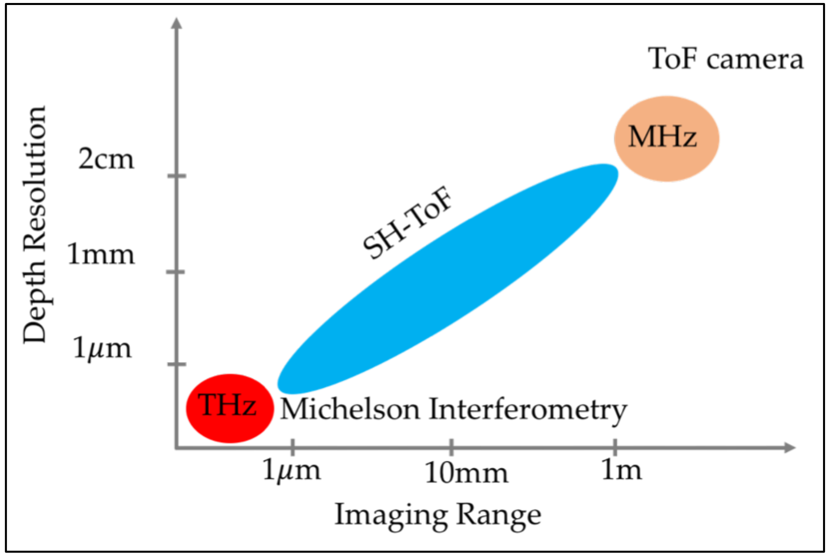
Limitations and future work

- Low time efficiency due to raster scanning
  - Focal-plane SH-ToF
- Looking around corner with SH-ToF
  - DARPA REVEAL project

Summary







- SH-ToF framework
- Prototype to demo micro resolution
- Flexibility between imaging range and resolution

Thank you!