Macroscopic Interferometry

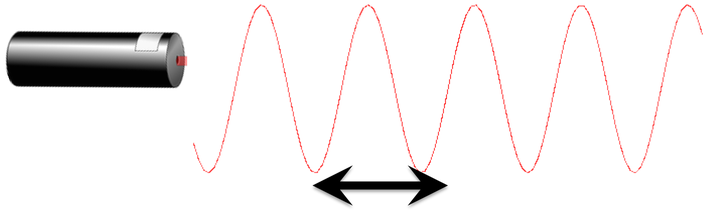
Achuta Kadambi, MIT Media Lab

Joint work with Jamie Schiel and Ramesh Raskar

Computer Vision/Graphics

Computer Vision/Graphics

Real-Life

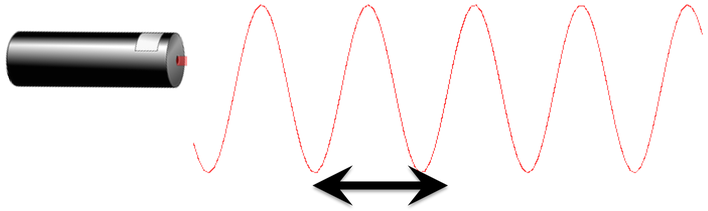


700 nanometer wavelength

Electric field only shown

Computer Vision/Graphics

Real-Life

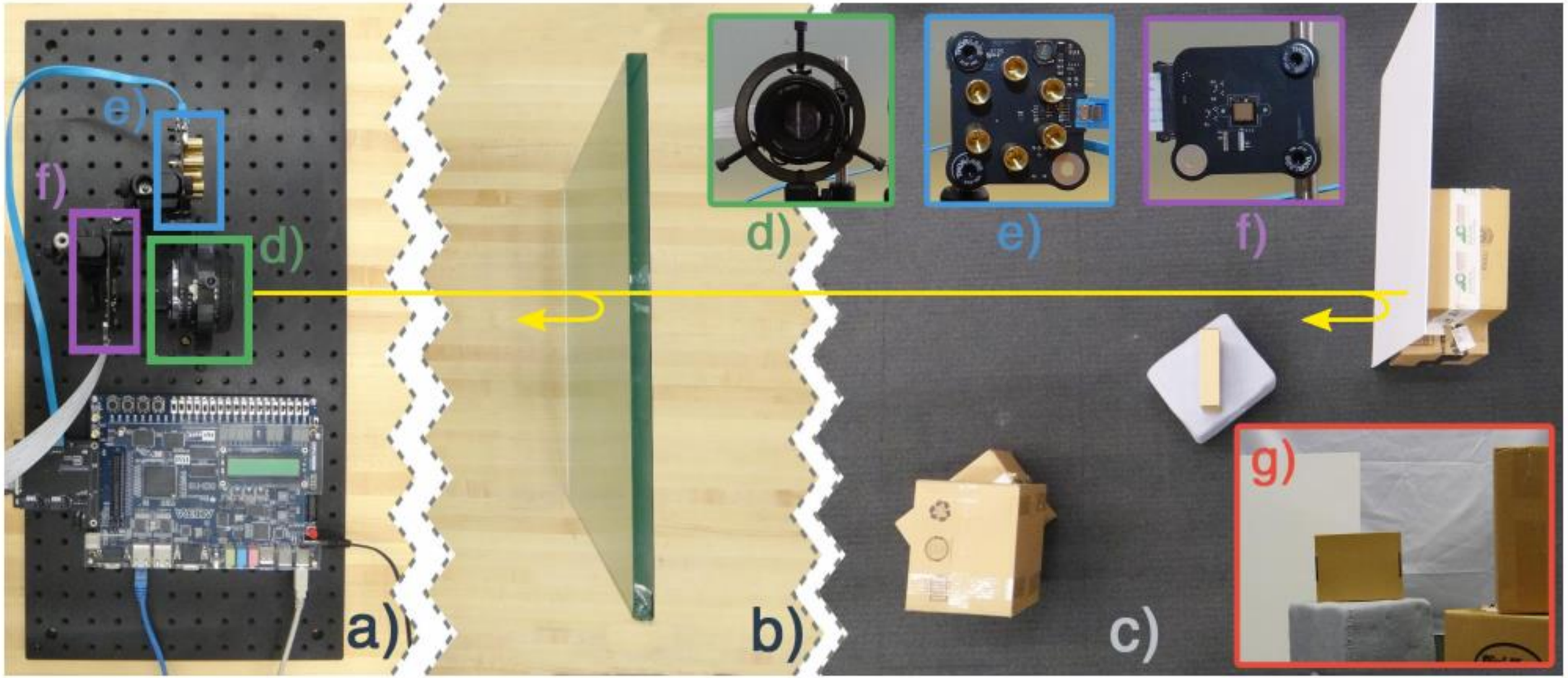


700 nanometer wavelength

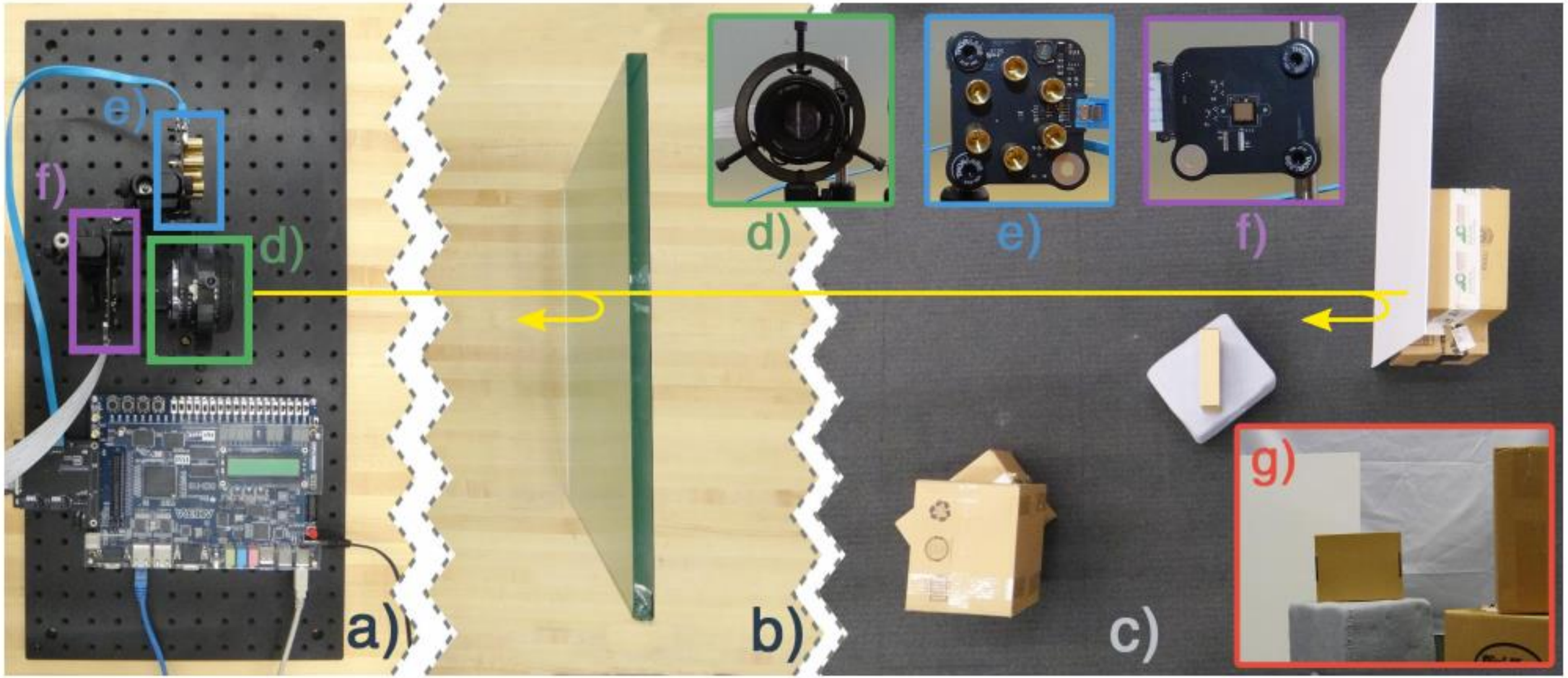
Microscopic wave phenomena → Macro scenes

Electric field only shown

Multi-depth 3D Camera

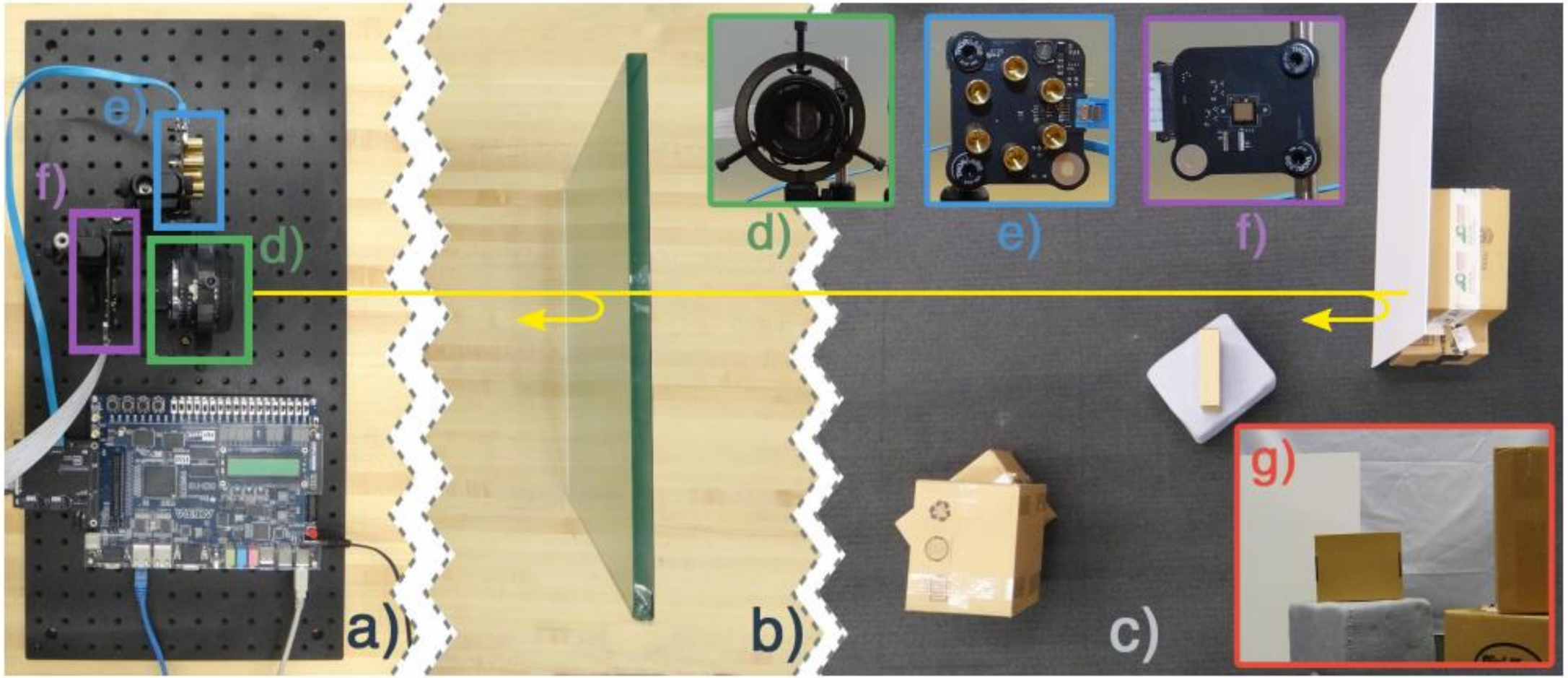


Multi-depth 3D Camera



10 meter scene

Multi-depth 3D Camera



10 meter scene

Performance competitive low SNR

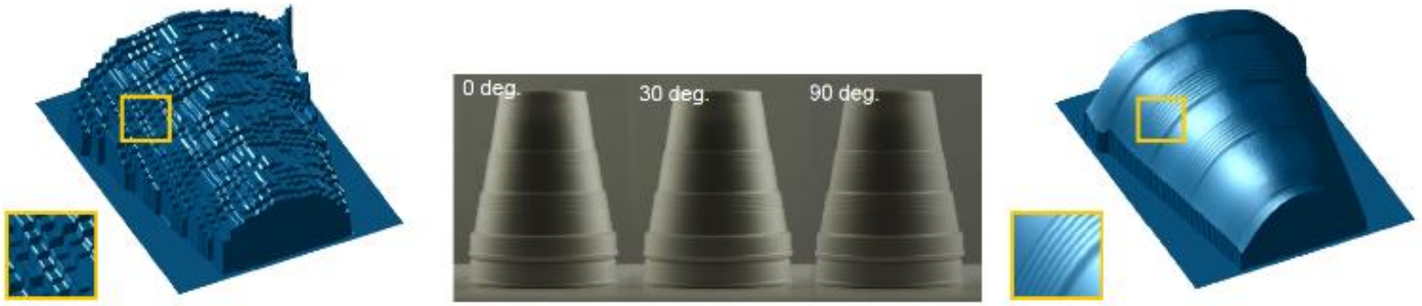
Previous Work

Polarized 3D: Depth Sensing with Polarization Cues

Achuta Kadambi[1] Vage Taamazyan[2] Boxin Shi[3] Ramesh Raskar[1]

[1]MIT Media Lab [2]Skoltech [3]SUTD

ICCV 2015, Santiago Chile



(a) Depth from Microsoft Kinect **(b)** Three Photos using a Polarizer **(c)** Polarization Enhanced Depth

ICCV15: Uses wave phenomena of polarization to enhance 3D shape

Previous Work

Polarized 3D: Depth Sensing with Polarization Cues

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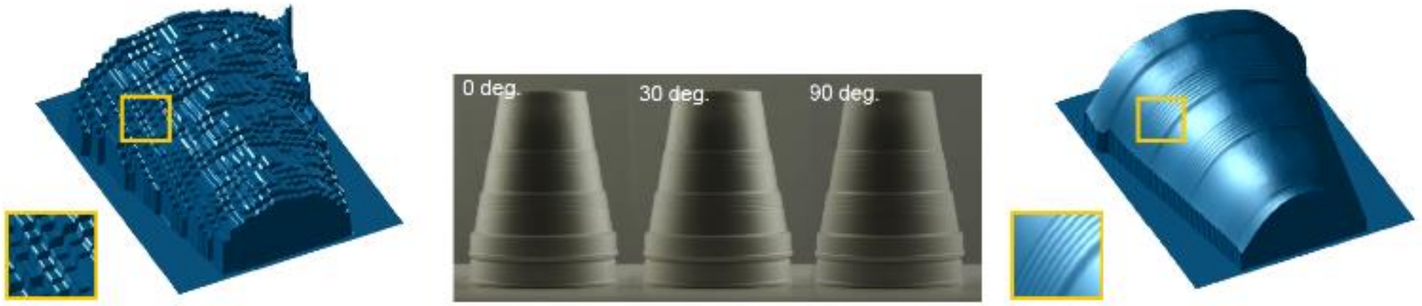
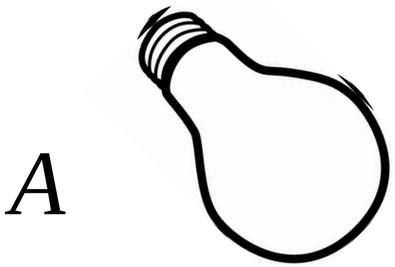
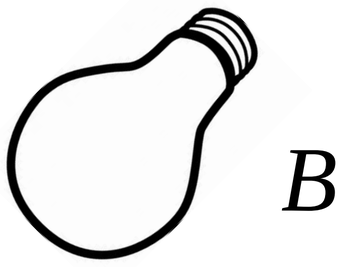


(a) Depth from Microsoft Kinect (b) Three Photos using a Polarizer (c) Polarization Enhanced Depth

ICCV15: Uses wave phenomena of polarization to enhance 3D shape

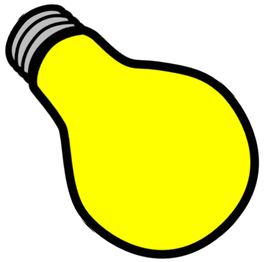
Today: Use wave phenomena to create multi-depth 3D

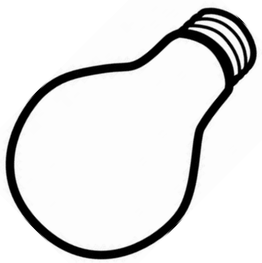




Scene

A



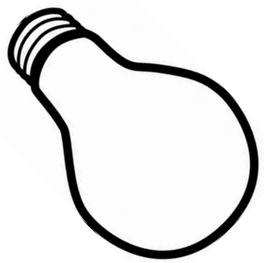


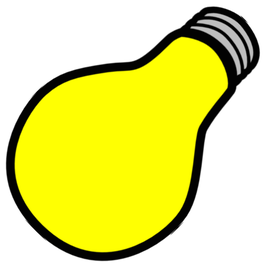
B

Scene

$$I = I_A$$

A

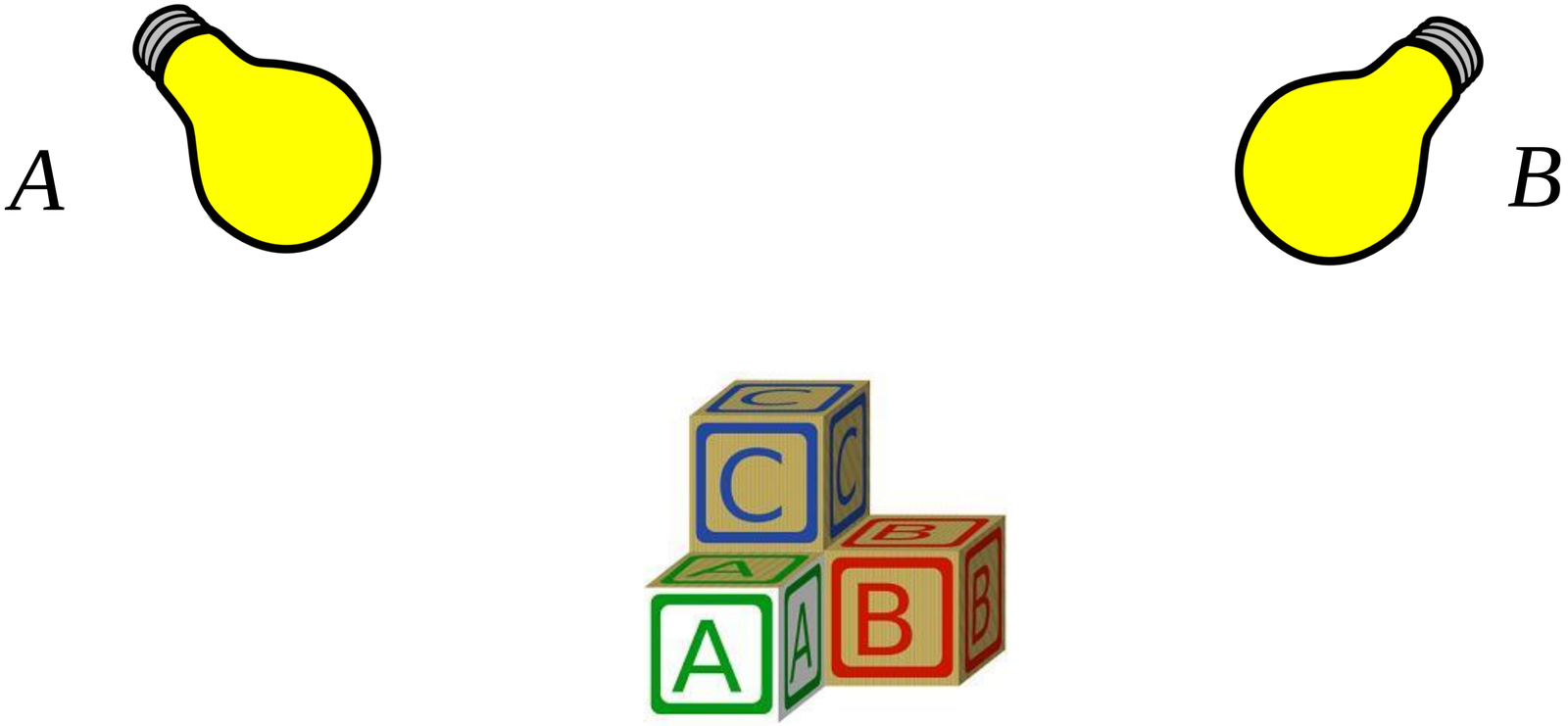




B

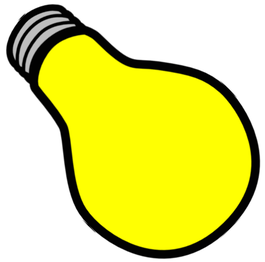
Scene

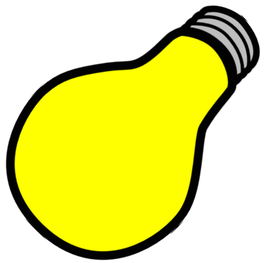
$$I = I_B$$



Scene

A

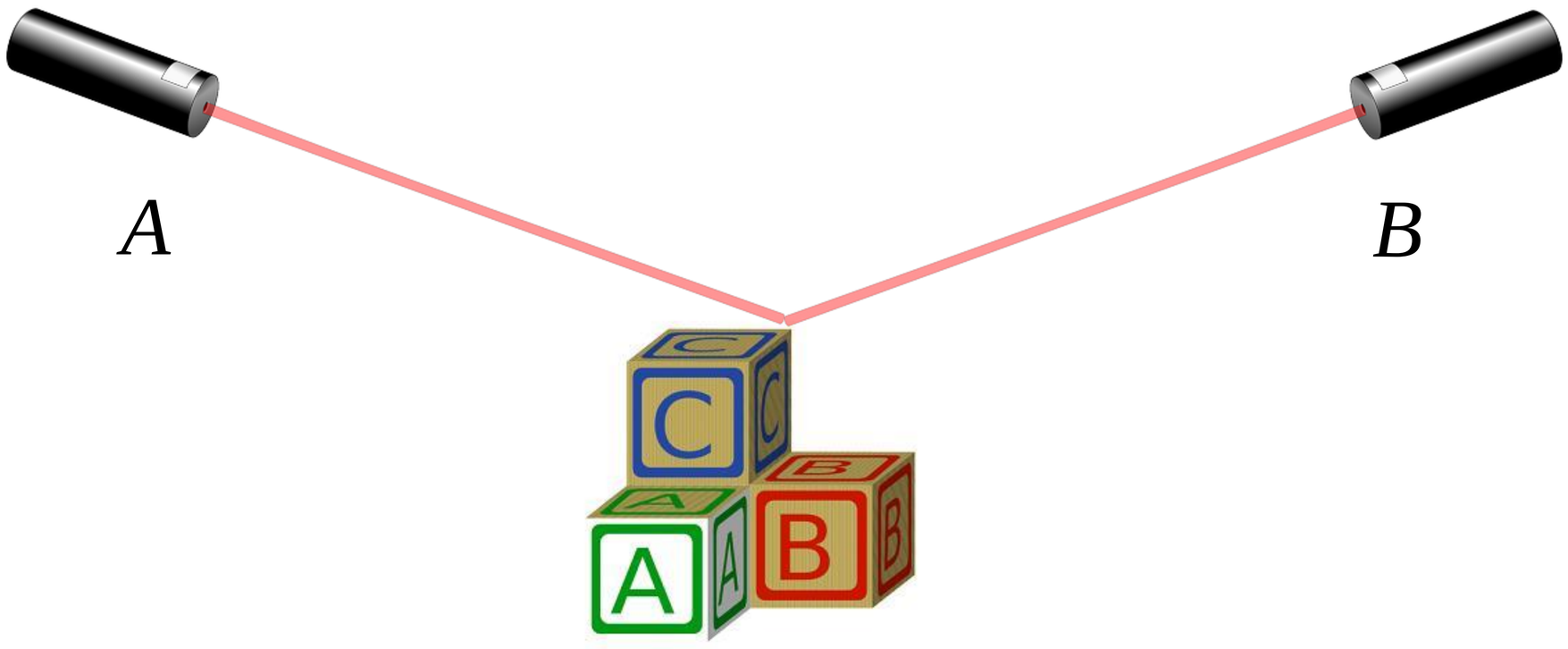




B

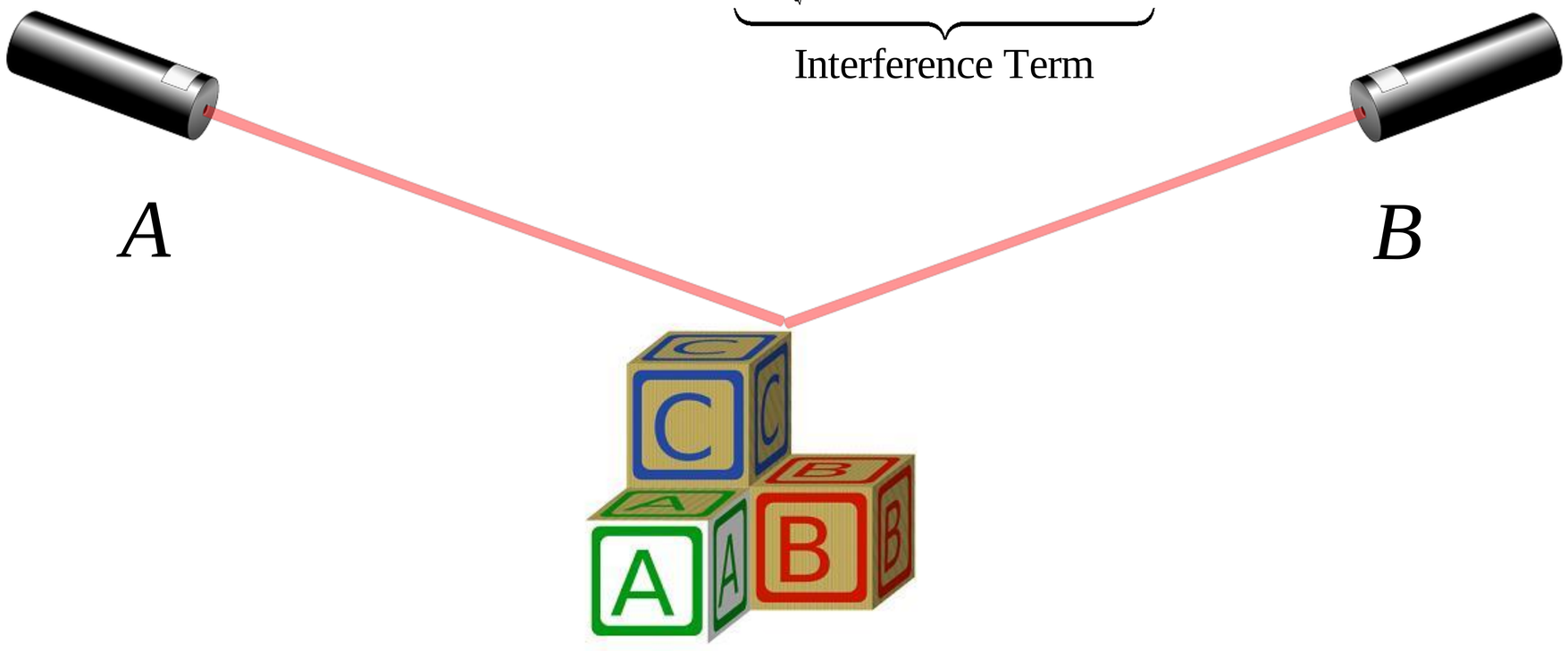
Scene

$$I = I_A + I_B$$



Scene

$$I = I_A + I_B + \underbrace{2\sqrt{I_A I_B \cos\Delta\phi}}_{\text{Interference Term}}$$



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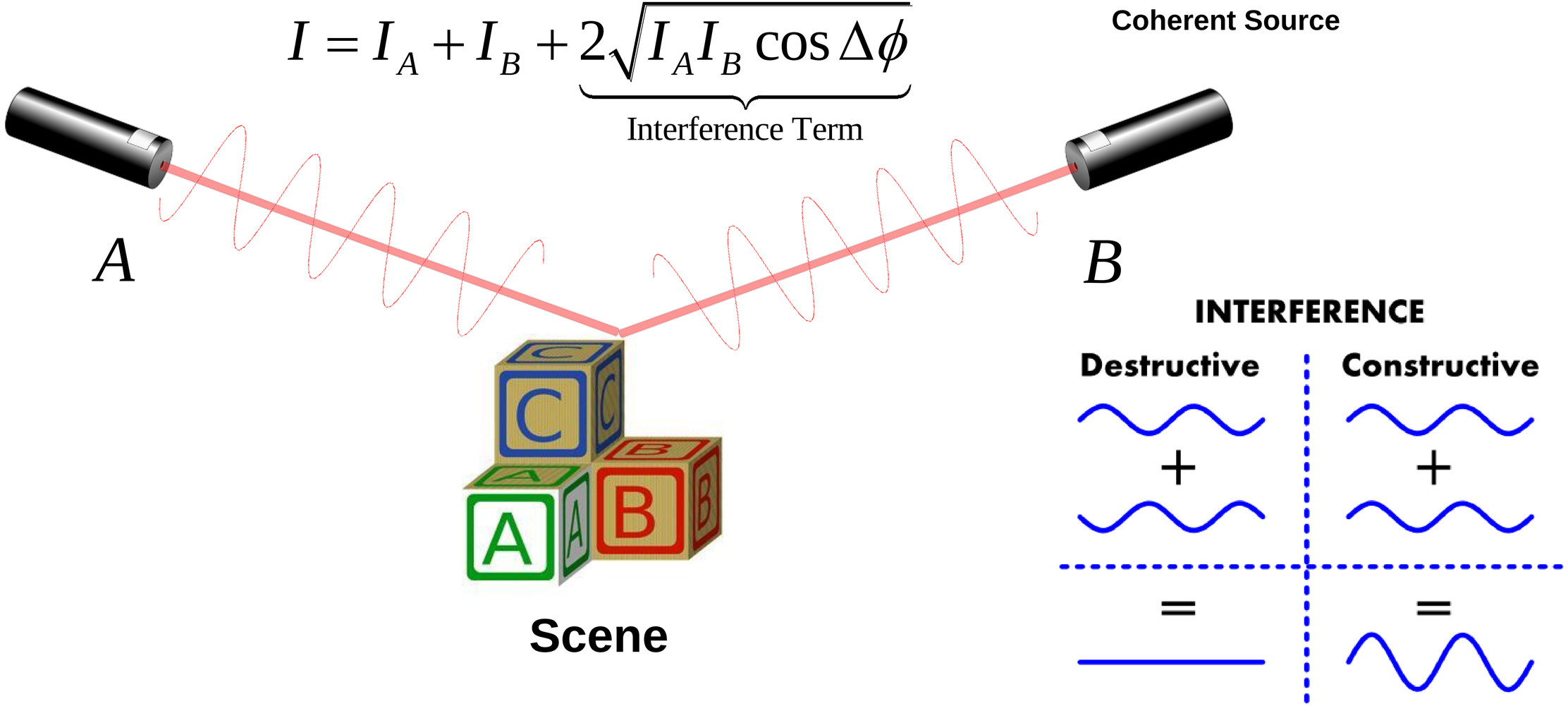


Interference graphic from sciencetalenter.dk

Interferometry

Intentionally superimposing light to get scene clues

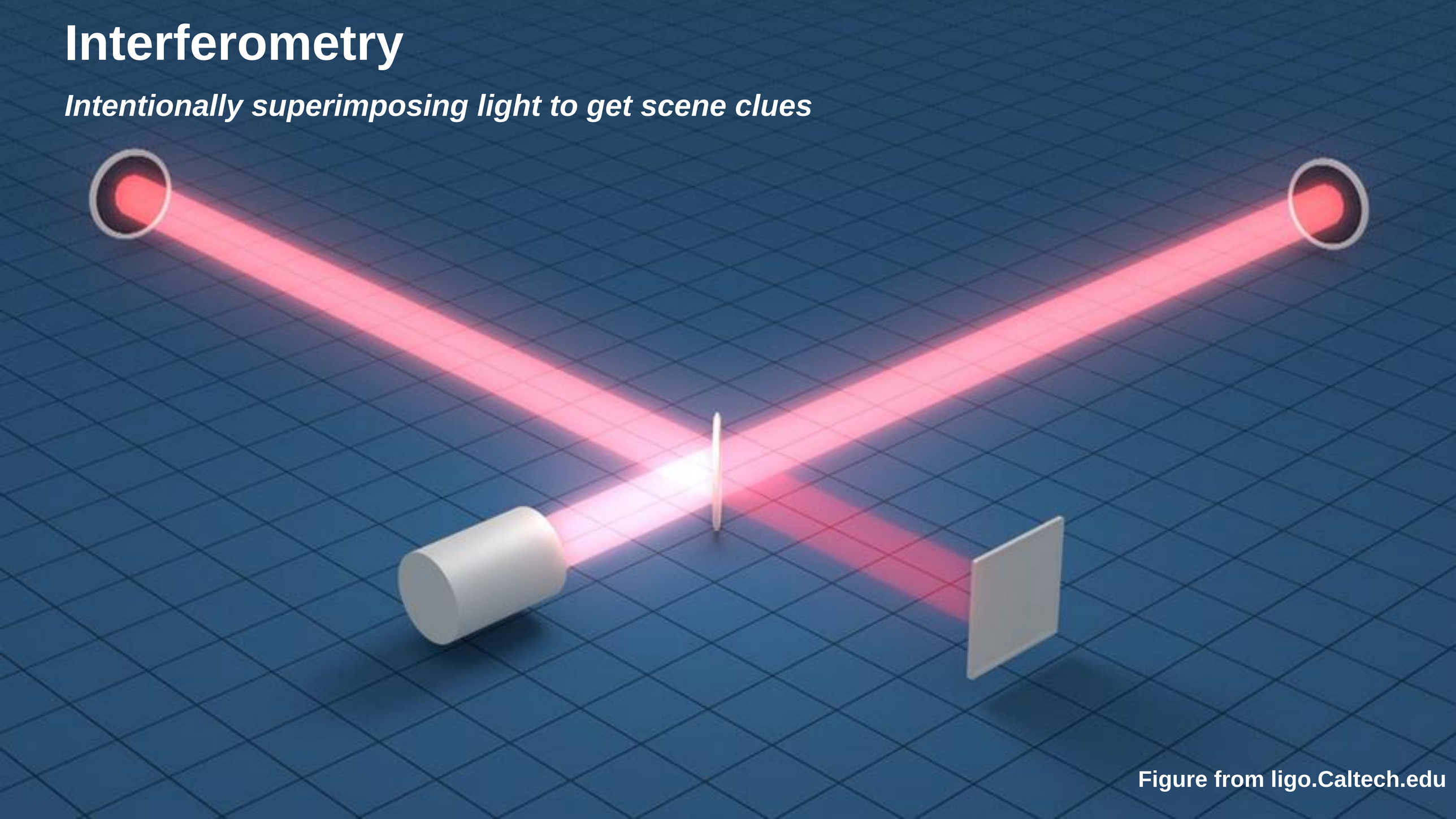
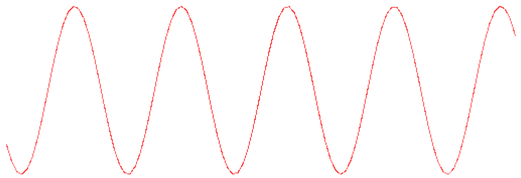


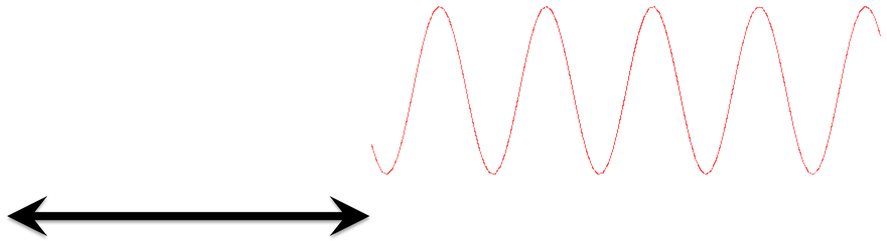
Figure from ligo.Caltech.edu

Interferometry uses a reference to probe the scene

Reference Signal



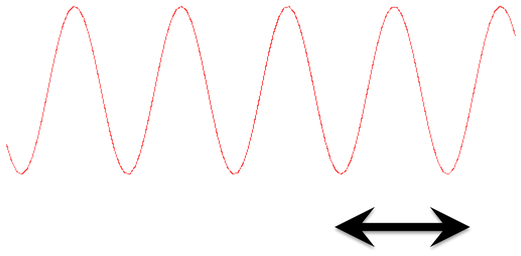
Sample Signal



Phase Delay

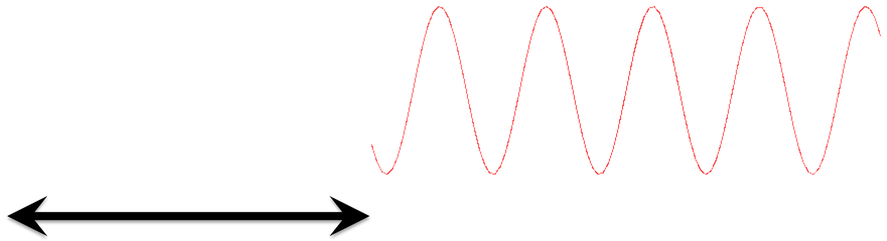
Tiny Wavelength Good for Microscopic Scenes

Reference Signal



700 nanometer wavelength

Sample Signal



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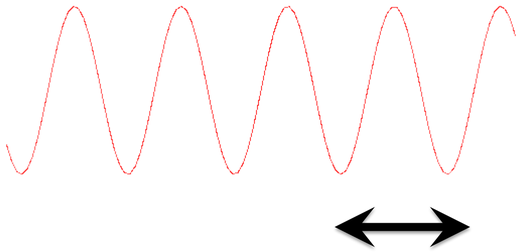
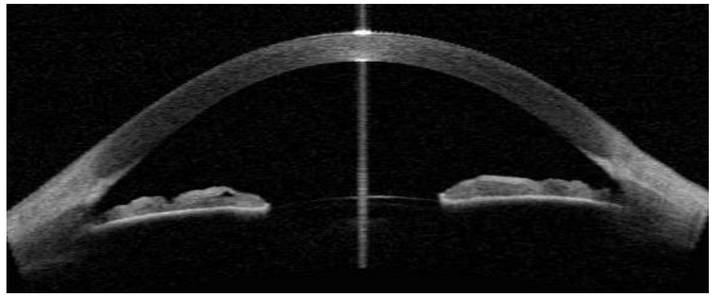
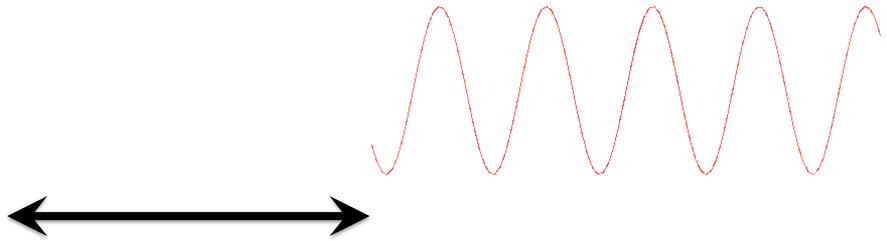


700 nanometer wavelength



Corneal OCT

Sample Signal



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Tiny Wavelength Good for Microscopic Scenes

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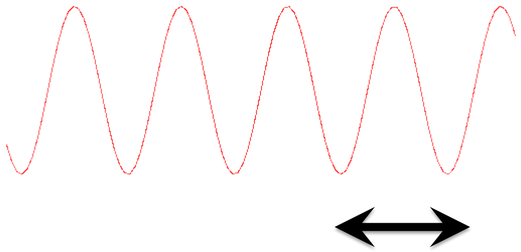

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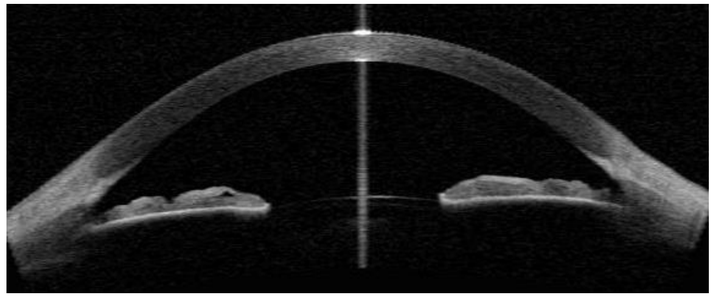

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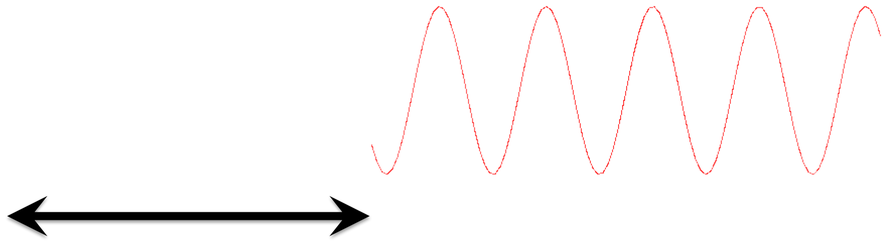
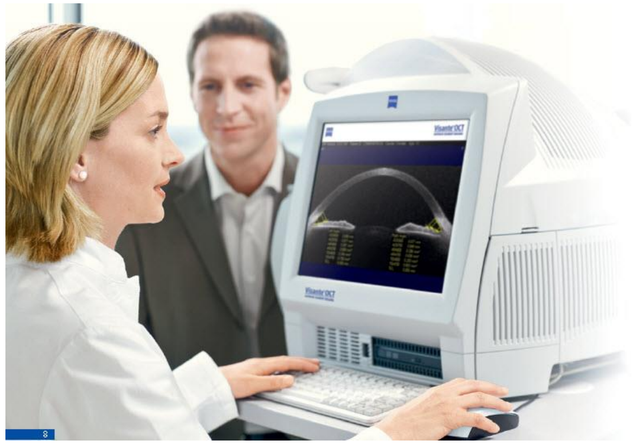
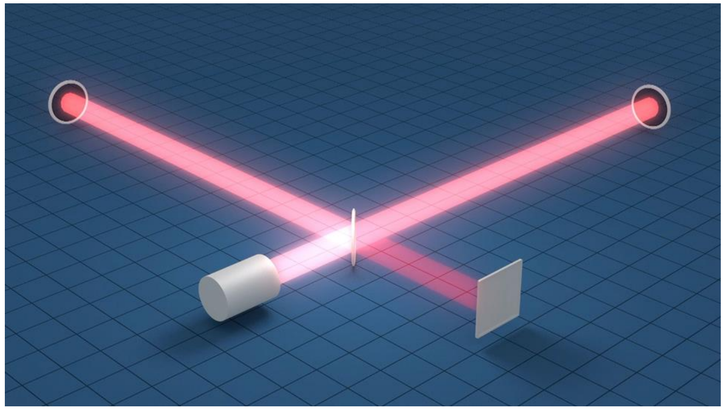


Phase Delay



Corneal OCT from Carl Zeiss Visante ®

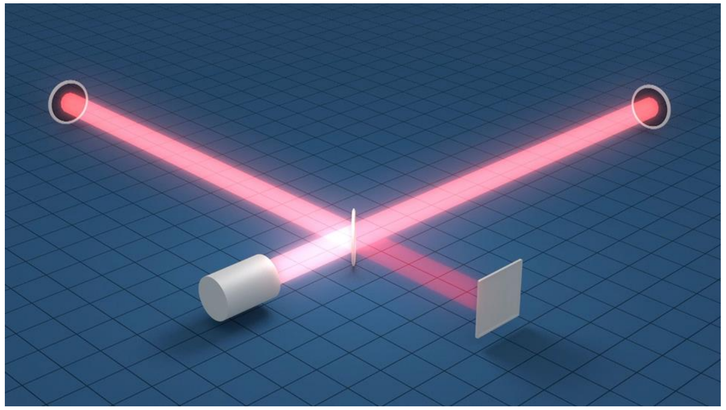
Smaller the measurement ..



LIGO Project to Detect Grav Waves

Measure sample deviations less than the size of a proton

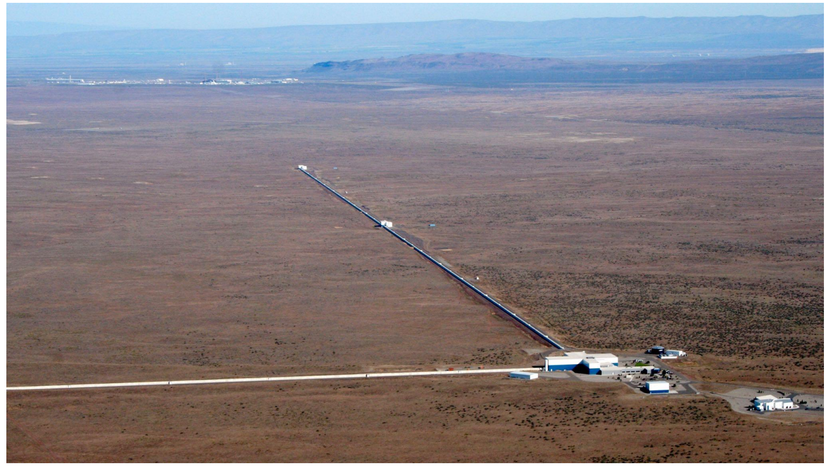
Smaller the measurement .. Bigger the instrument



LIGO Project to Detect Grav Waves

Measure sample deviations less than the size of a proton

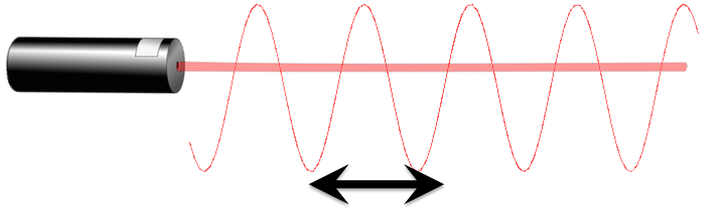
.. But kilometers in size



Vision goal: small device, large scene

Vision goal: small device, large scene

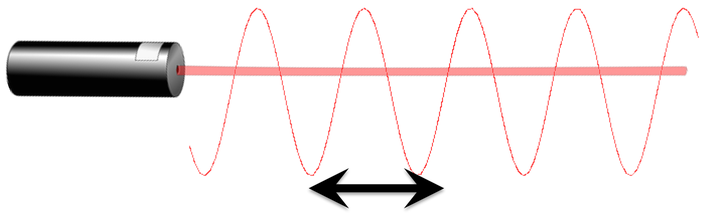
Optical Phase



700 nanometer wavelength

Vision goal: small device, large scene

Optical Phase



700 nanometer wavelength

Electronic Phase

Kinect uses electronic phase

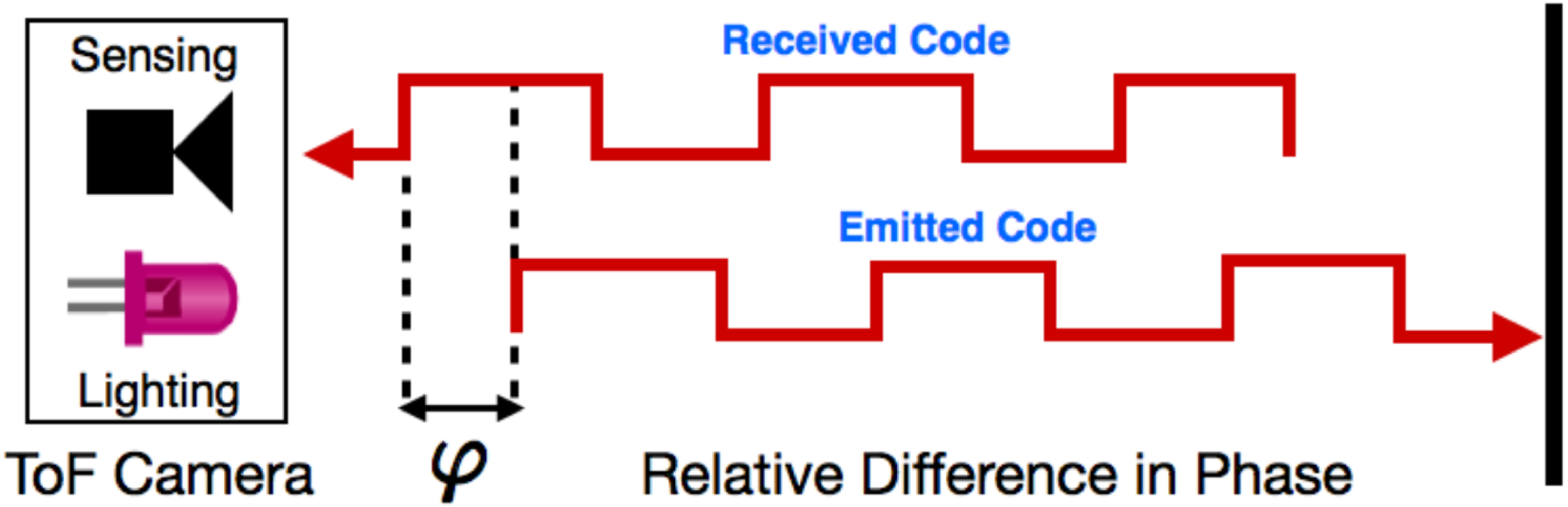
Terminology

Primal-Domain: Original Frame a Signal is Sampled In

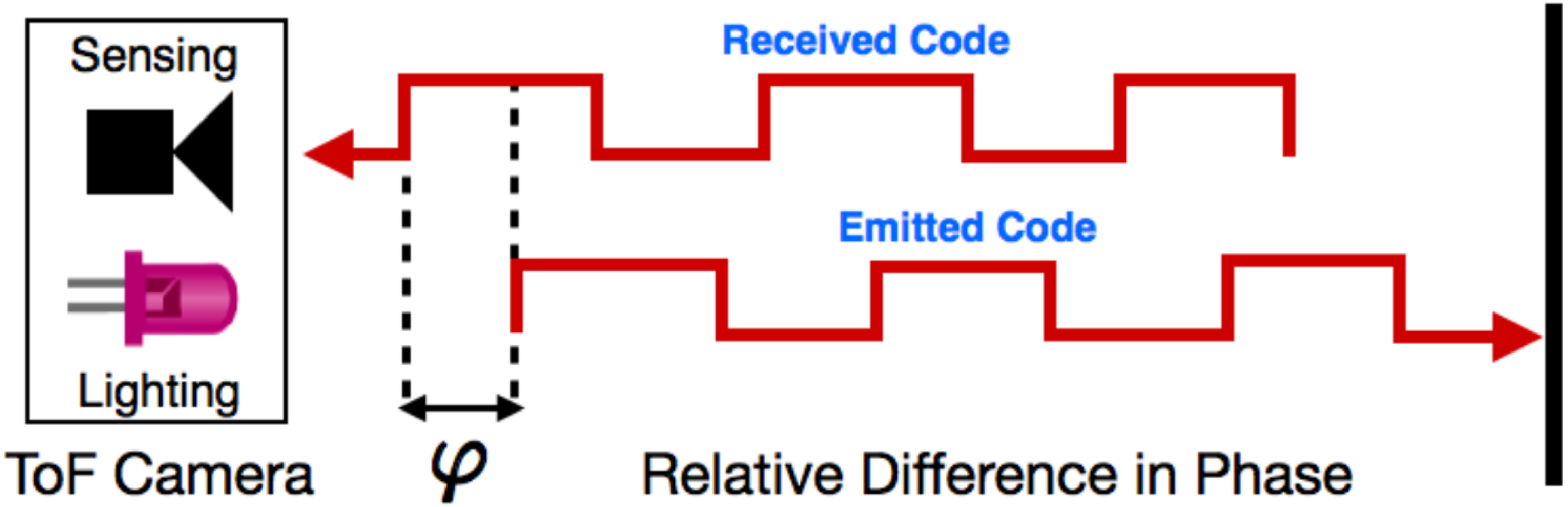
Dual-Domain: Frequency transform with respect to Primal

Phase ToF: existing Kinect-style ToF cameras

Phase ToF (Kinect)

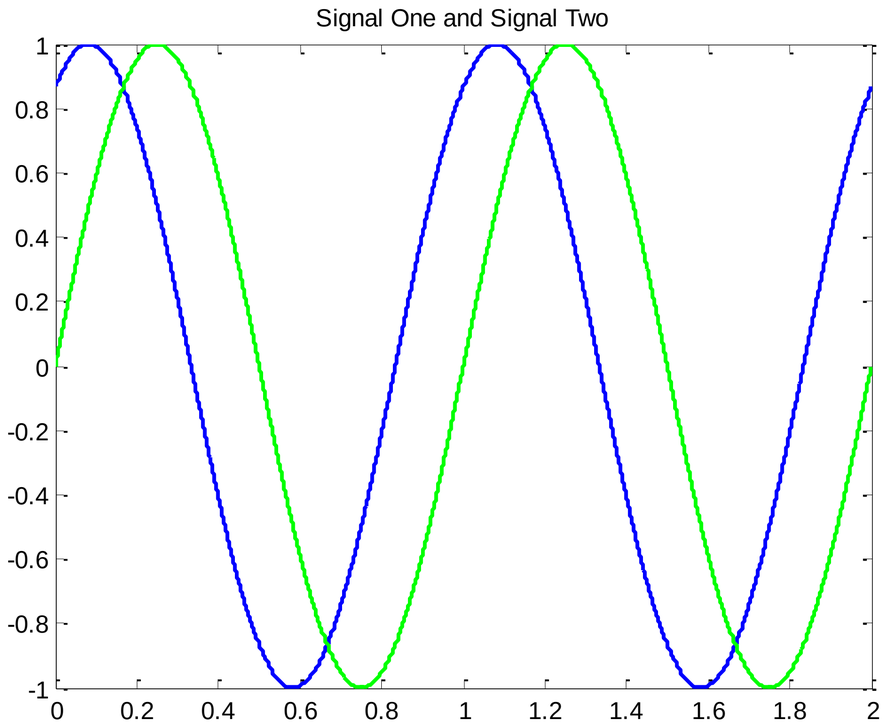


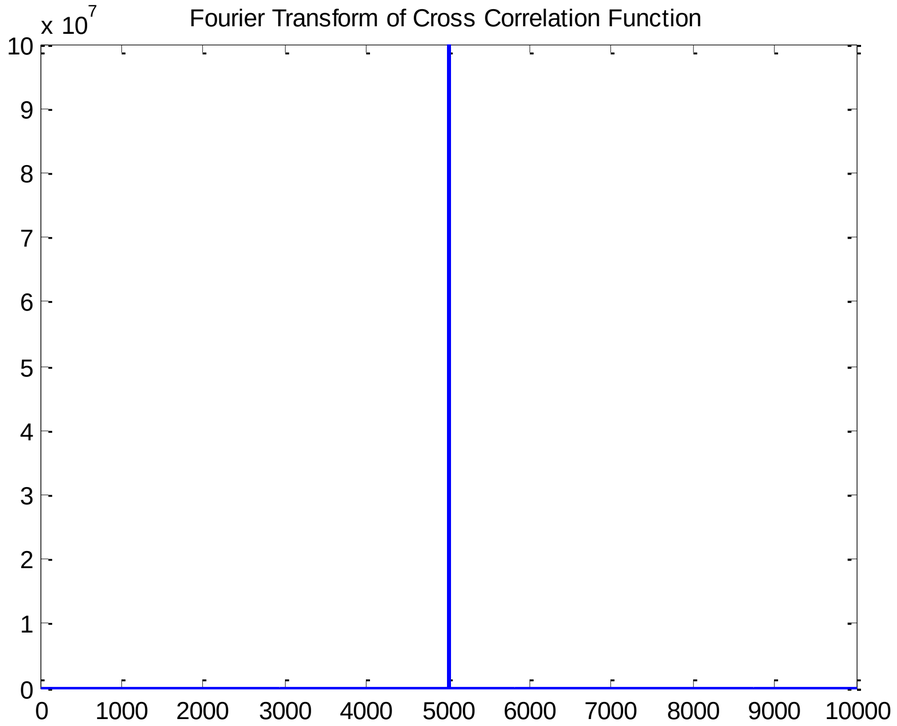
Phase ToF (Kinect)



$$z = \frac{c\varphi}{2\pi f_M}$$

How the Phase ToF (Kinect) Works






```
dt = 0.0001;
N = 20000;
t = 0:dt:(N-1)*dt;

phi1 = pi/3; phi2 = 0;
s1 = sin(2*pi*1*t + phi1);
s2 = sin(2*pi*1*t+ phi2);

xcFFT = conj( fft(s1) ) .*
fft(s2);

[~, fundamental_idx] =
max(xcFFT);

phase_difference = angle(
xcFFT(fundamental_idx) );
```

Block Diagram of Phase ToF

Phase ToF Refer.

$$r(t) = \cos(f_M t)$$

Phase ToF Sample

$$s(t) = \cos(f_M t + \varphi)$$

Primal-domain is \tau

For clarity, all constants removed

Block Diagram of Phase ToF

Phase ToF Refer.

$$r(t) = \cos(f_M t)$$

Phase ToF Sample

$$s(t) = \cos(f_M t + \varphi)$$

$\otimes$

Phase ToF Xcorr

$$c(\tau) = \cos(f_M \tau + \varphi)$$

For clarity, all constants removed

Block Diagram of Phase ToF

Phase ToF Refer.

$$r(t) = \cos(f_M t)$$

Phase ToF Sample

$$s(t) = \cos(f_M t + \varphi)$$

$\otimes$ →

Phase ToF Xcorr

$$c(\tau) = \cos(f_M \tau + \varphi)$$

→

Compute FFT wrt. τ

& Take angle of fundam.

Primal-domain is \tau

For clarity, all constants removed

Problems with Phase ToF

Multipath Interference

Reflections of two or more sine waves come back and mix

Phase Wrapping

Phase is periodic – long-range depths will wrap

Low SNR

Calculating phase requires multiple steps (prop. of errors)

Computational ToF Imaging

By count of recent papers, appears to be a hot area in comp. photo

[Godbaz et al. 2008]

[Heide and Hullin et al. 2013]

[Kadambi et al. 2013]

[Bhandari et al. 2014]

[Jayasuriya et al. 2015]

[Gkioulekas et al. 2015]

[Tsai et al. 2016]

[Su et al. 2016] -- @ Wed AM posters

[Shreshtha et al. 2016] -- @ next month's SIGGRAPH

Find more details at ICCV 2015 course:
www.media.mit.edu/~achoo/iccvtoftutorial/

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Our Contribution: change primal-domain

Changing the Primal Domain

Phase ToF Refer.

$$r(t) = \cos(f_M t)$$

Phase ToF Sample

$$s(t) = \cos(f_M t + \varphi)$$

$\otimes$ →

Phase ToF Xcorr

$$c(\tau) = \cos(f_M \tau + \varphi)$$

→

Compute FFT wrt. τ

Primal-domain is \tau

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

$$z = \frac{c\varphi}{2\pi f_M}$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

$$z = \frac{c\varphi}{2\pi f_M}$$

$$c(\tau) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

$$z = \frac{c\varphi}{2\pi f_M}$$

$$c(\tau) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M \right)$$

$$c(\tau, f_M) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

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$$z = \frac{c\varphi}{2\pi f_M}$$

$$c(\tau) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M \right)$$

$$c(\tau, f_M) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M \right)$$

$$c(\tau = 0, f_M) = \cos\left(f_M 0 + \frac{2\pi z}{c} f_M \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

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$$c(f_M) = \cos\left(\frac{2\pi z}{c} f_M \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos\left(f_M \tau + \varphi \right)$$

$$z = \frac{c\varphi}{2\pi f_M}$$

$$c(\tau) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M \right)$$

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$$c(\tau = 0, f_M) = \cos\left(f_M 0 + \frac{2\pi z}{c} f_M \right)$$

Frequency ToF Xcorr

$$c(f_M) = \cos\left(\frac{2\pi z}{c} f_M \right)$$

For clarity, all constants removed

Changing the Primal Domain

Phase ToF Xcorr

$$c(\tau) = \cos(f_M \tau + \varphi)$$

$$z = \frac{c\varphi}{2\pi f_M}$$

$$c(\tau) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M\right)$$

$$c(\tau, f_M) = \cos\left(f_M \tau + \frac{2\pi z}{c} f_M\right)$$

$$c(\tau = 0, f_M) = \cos\left(f_M 0 + \frac{2\pi z}{c} f_M\right)$$

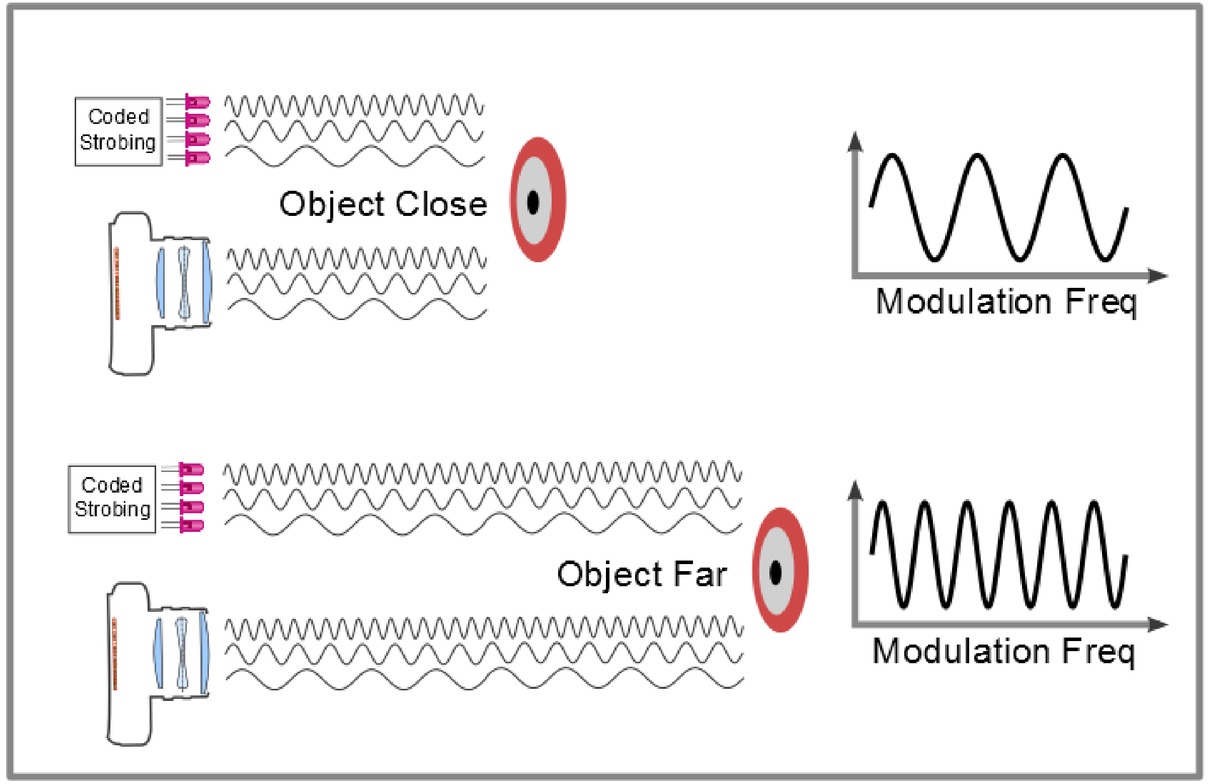
Frequency ToF Xcorr

$$c(f_M) = \cos\left(\frac{2\pi z}{c} f_M\right)$$

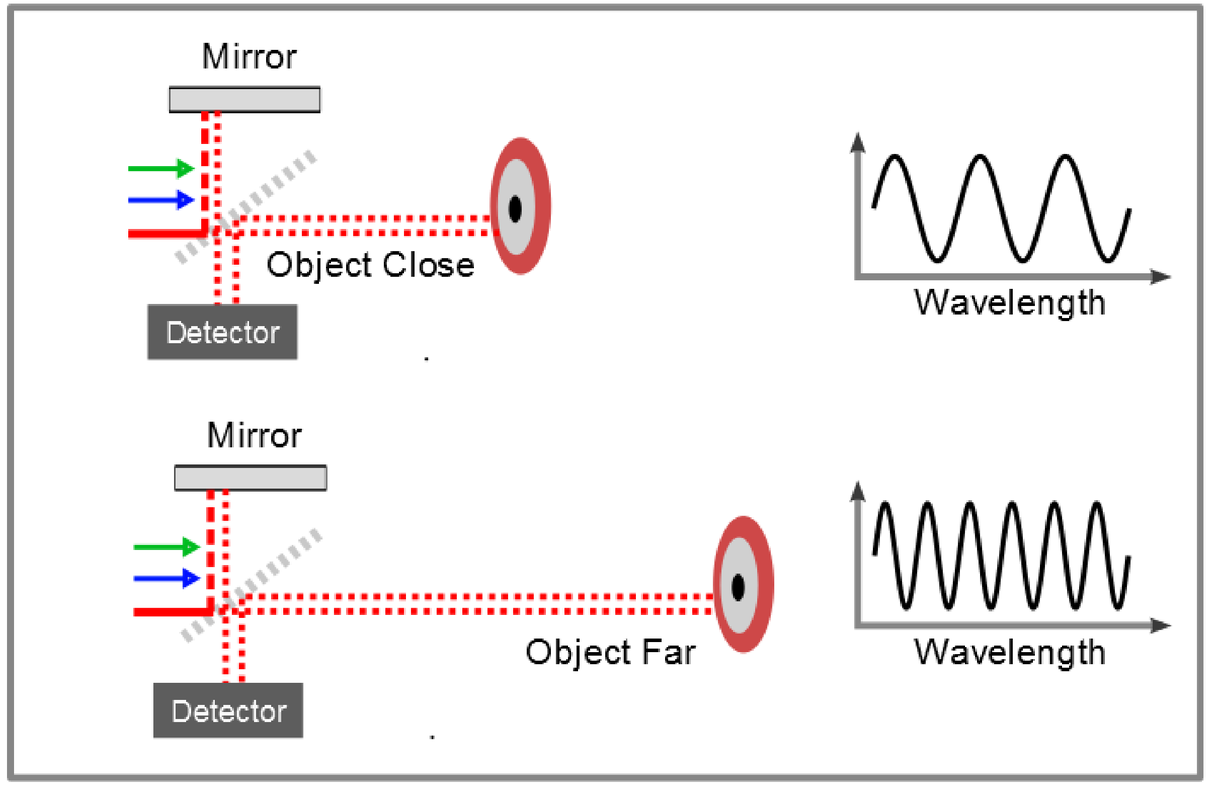
- **Primal-domain is f_M**
- **Dual-domain corresponds to pathlength.**

For clarity, all constants removed

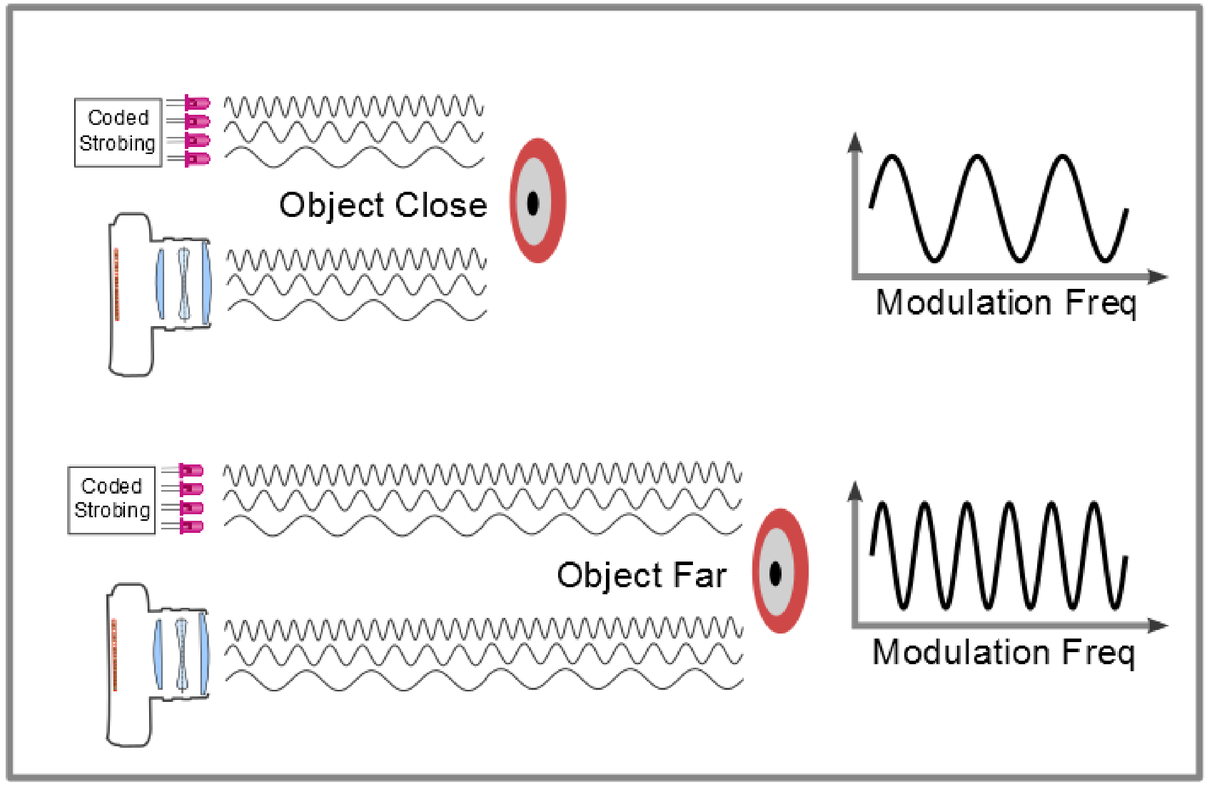
Frequency-Domain Time of Flight



Frequency-Domain Optical Coherence Tomography

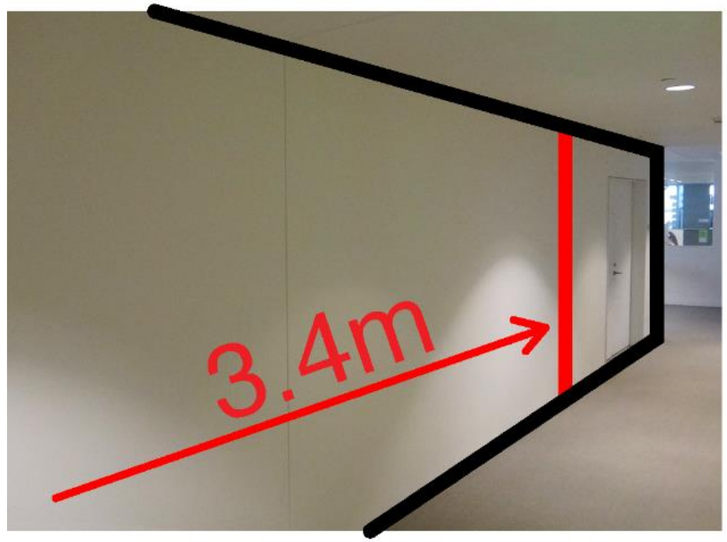


Frequency-Domain Time of Flight



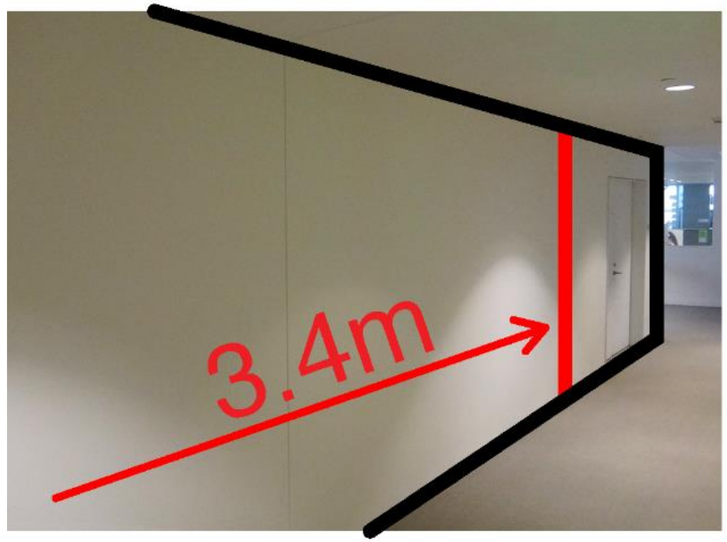
Macroscopic Scenes

Long-range scene

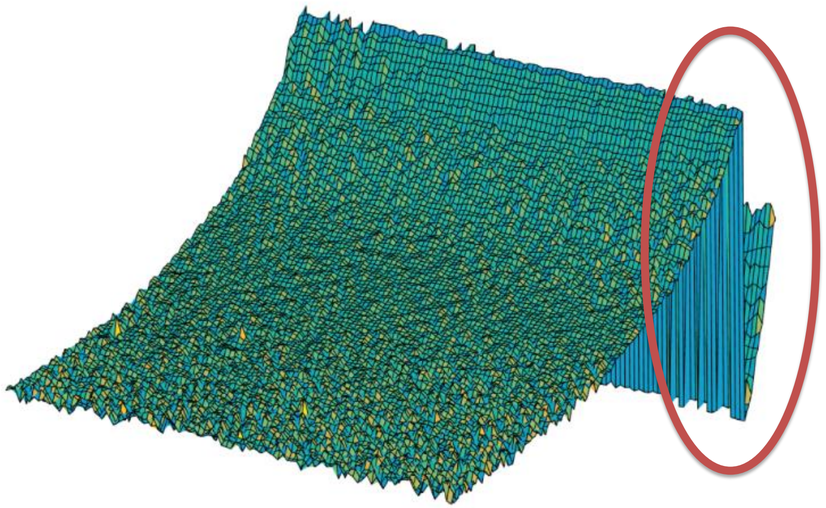


Macroscopic Scenes

Long-range scene

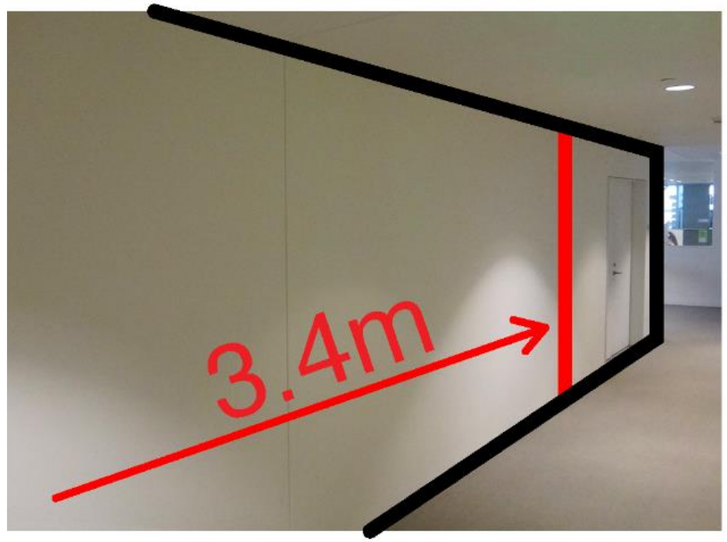


Phase ToF

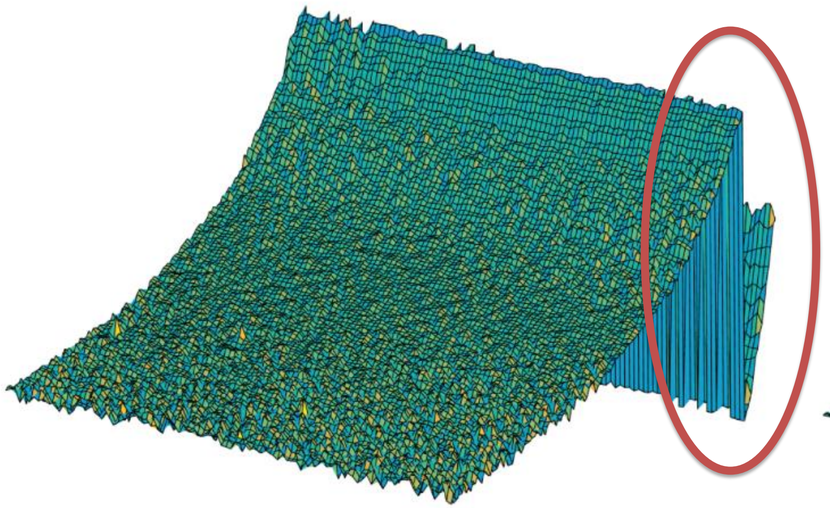


Macroscopic Scenes

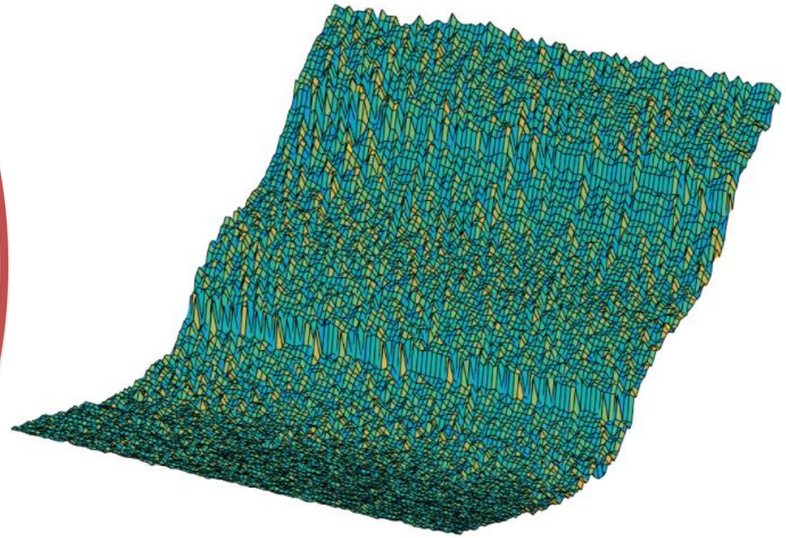
Long-range scene



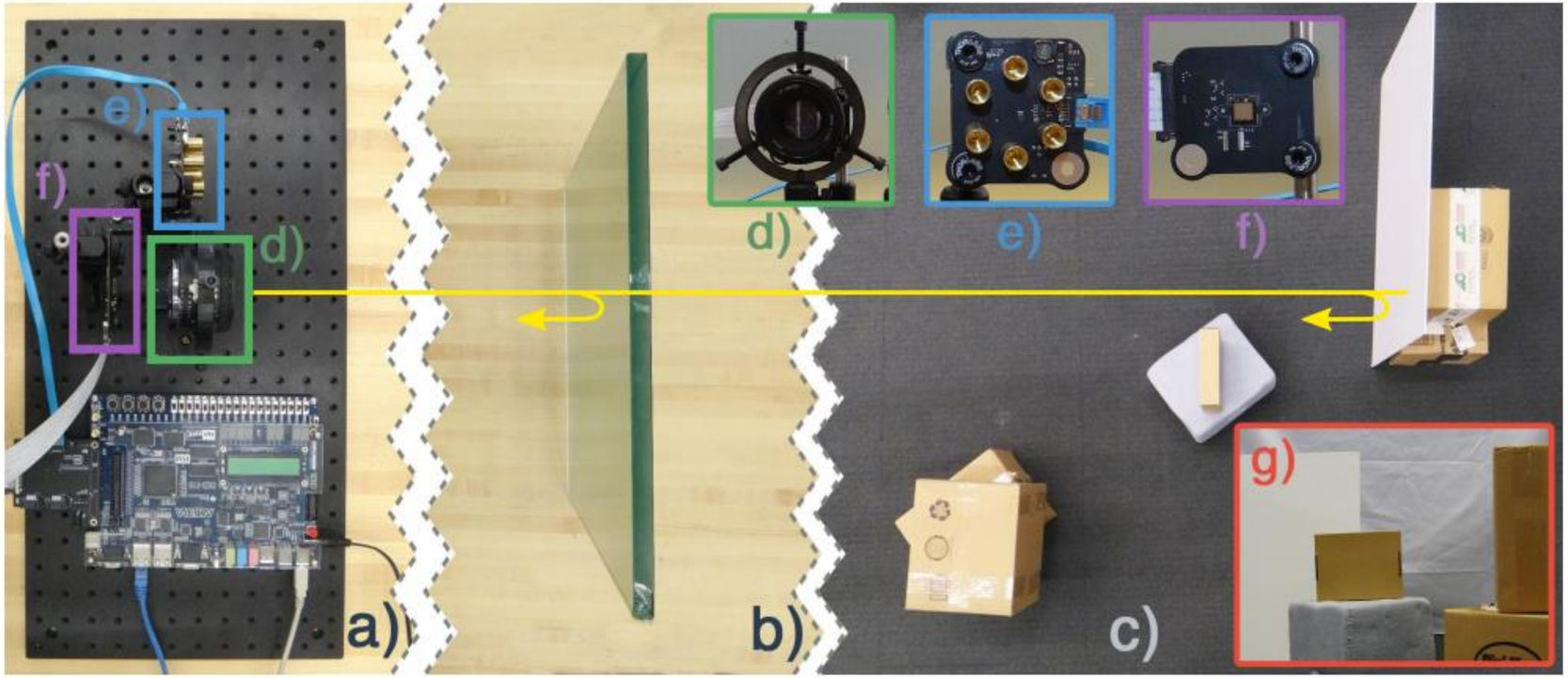
Phase ToF



Frequency-Domain ToF

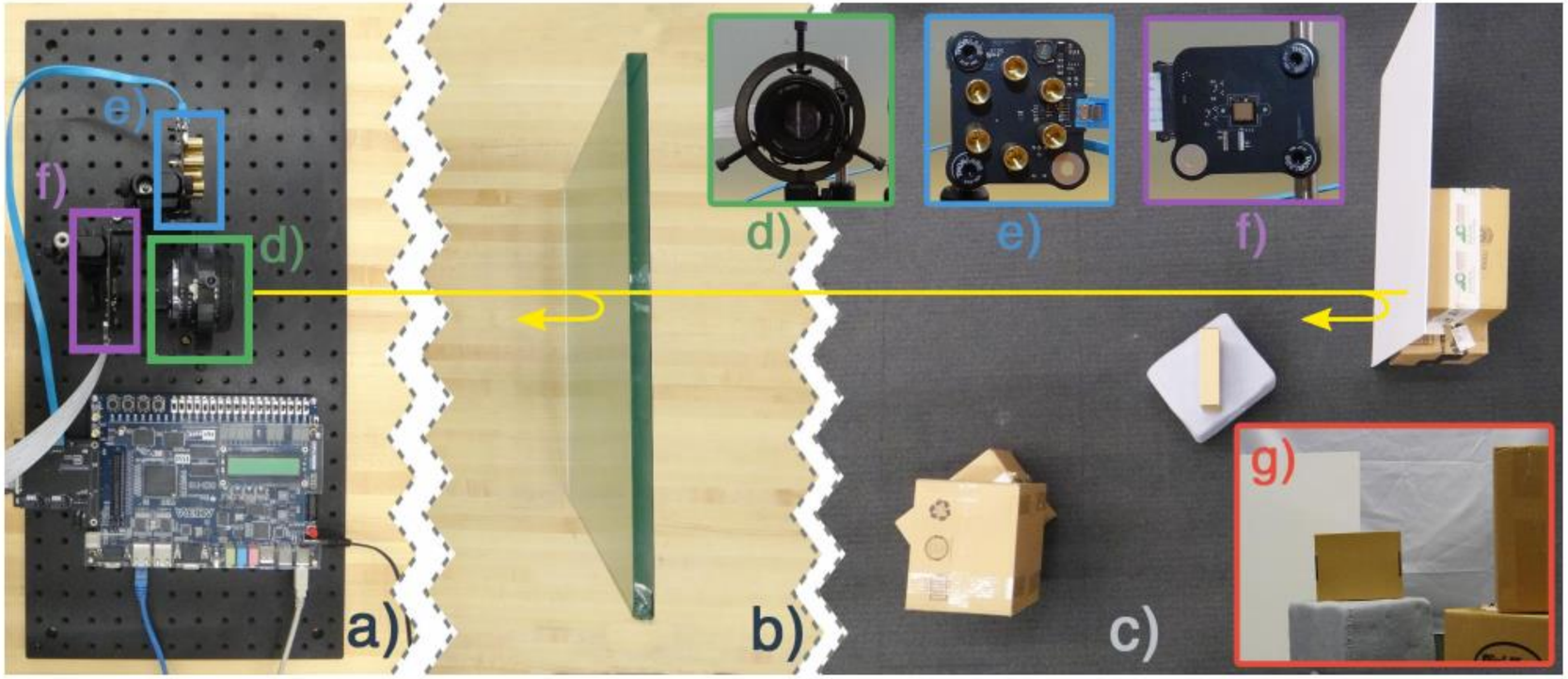


Multi-depth 3D Camera



Need only 4 frequencies to recover both reflections

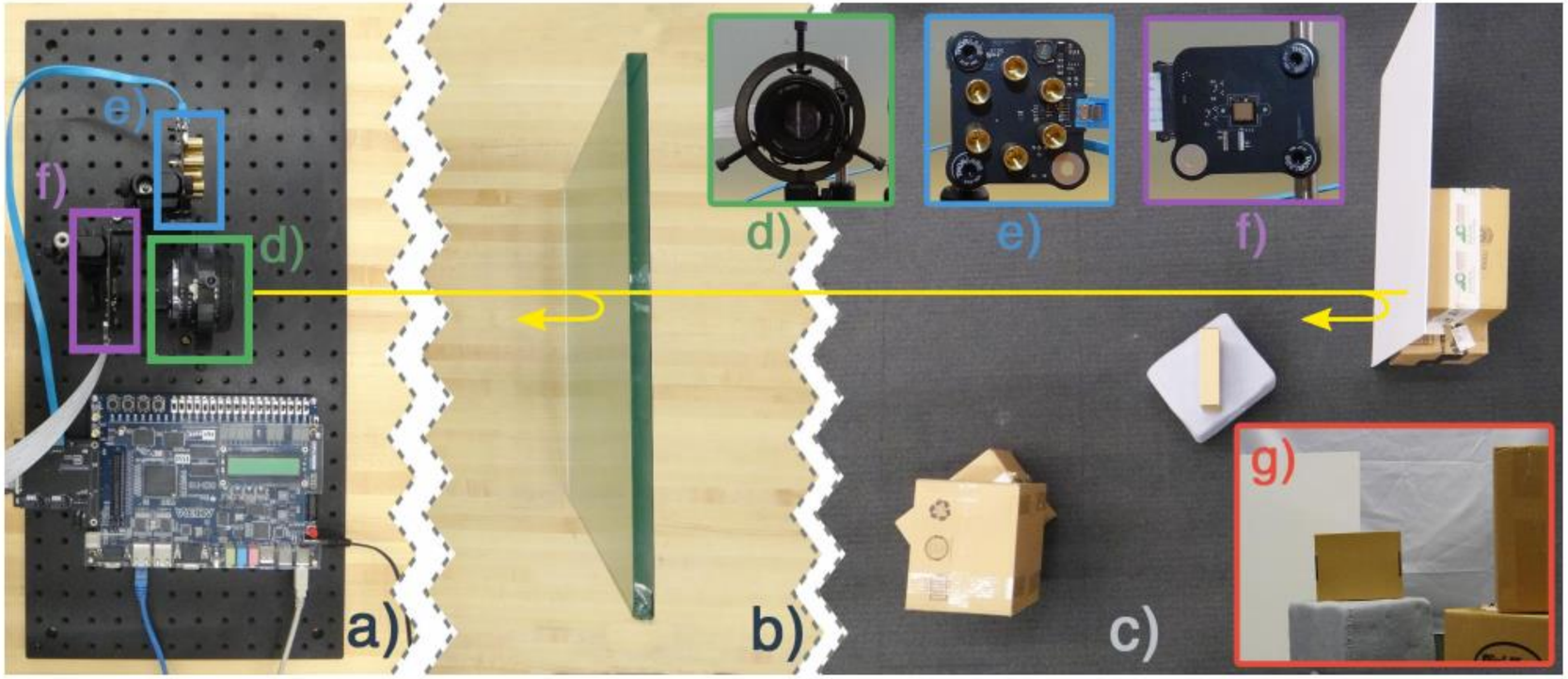
Multi-depth 3D Camera



Phase ToF Depth

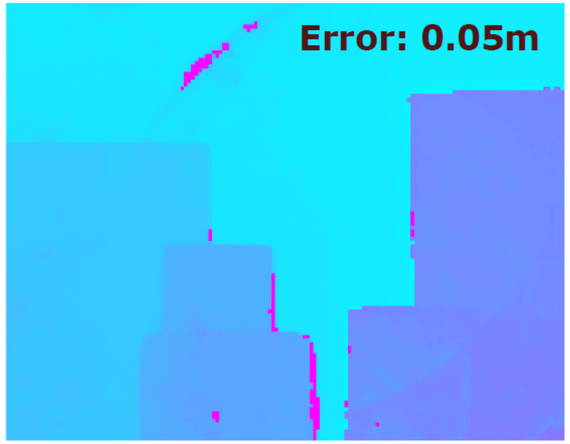
Need only 4 frequencies to recover both reflections

Multi-depth 3D Camera



Phase ToF Depth

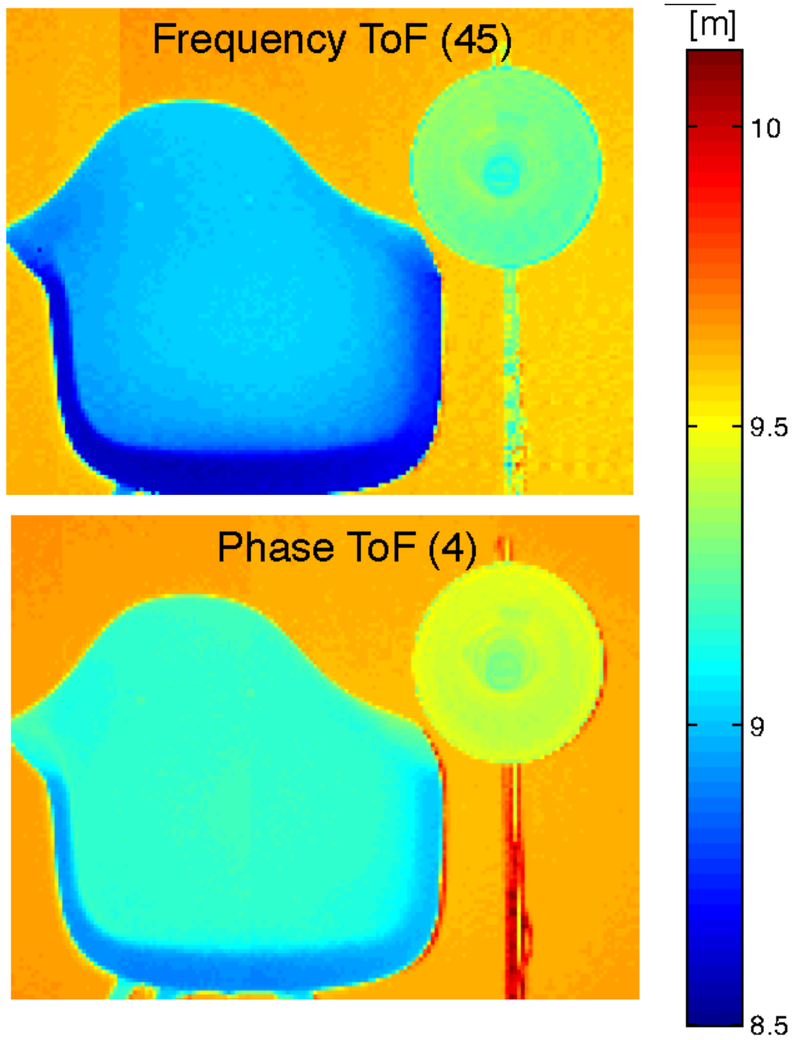
Frequency ToF Depth



Need only 4 frequencies to recover both reflections

Resolving Multipath Interference

Scene



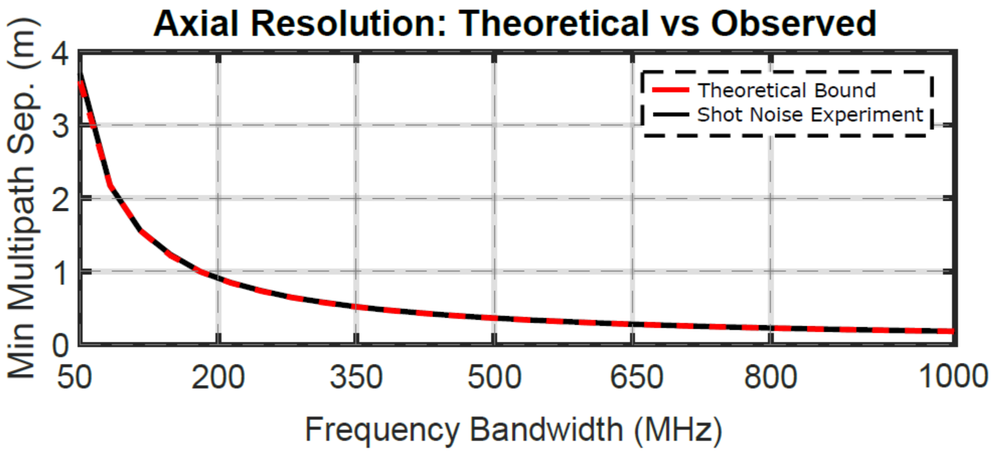
Method	Multi-path error [m]	Single-path error [m]	Overall error [m]
4-FD-ToF	0.319	0.044	0.187
45-FD-ToF	**0.153**	0.020	**0.090**
Phase ToF	0.347	**0.016**	0.191
Bhandari	0.279	0.018	0.145

How close can the reflections be?

Proposition 1: *Multi-path interference can be resolved in Frequency-Domain ToF if the optical path-length between any two reflections is less than:*

$$\Delta z \approx 0.6c/\Delta f_{\mathrm{M}}.$$

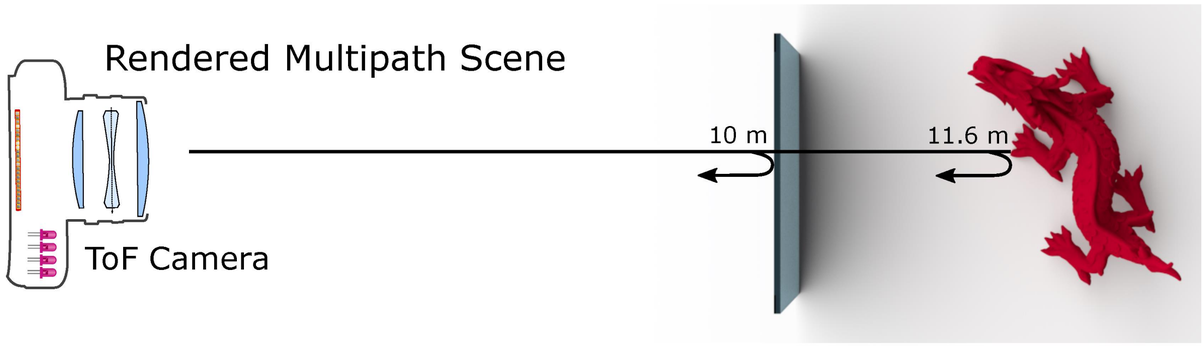
How close can the reflections be?

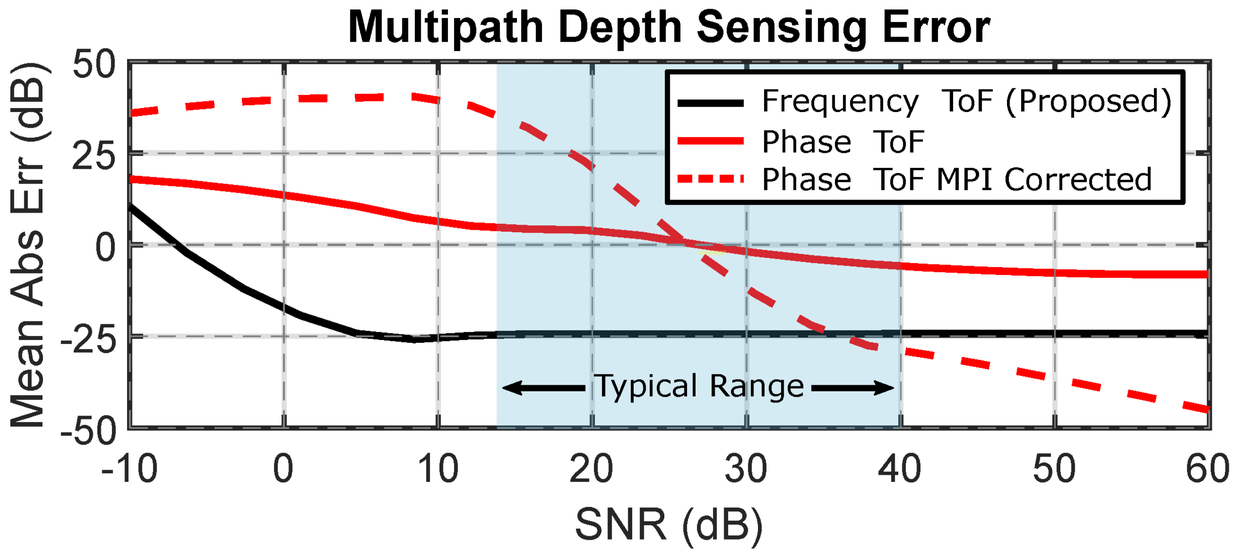


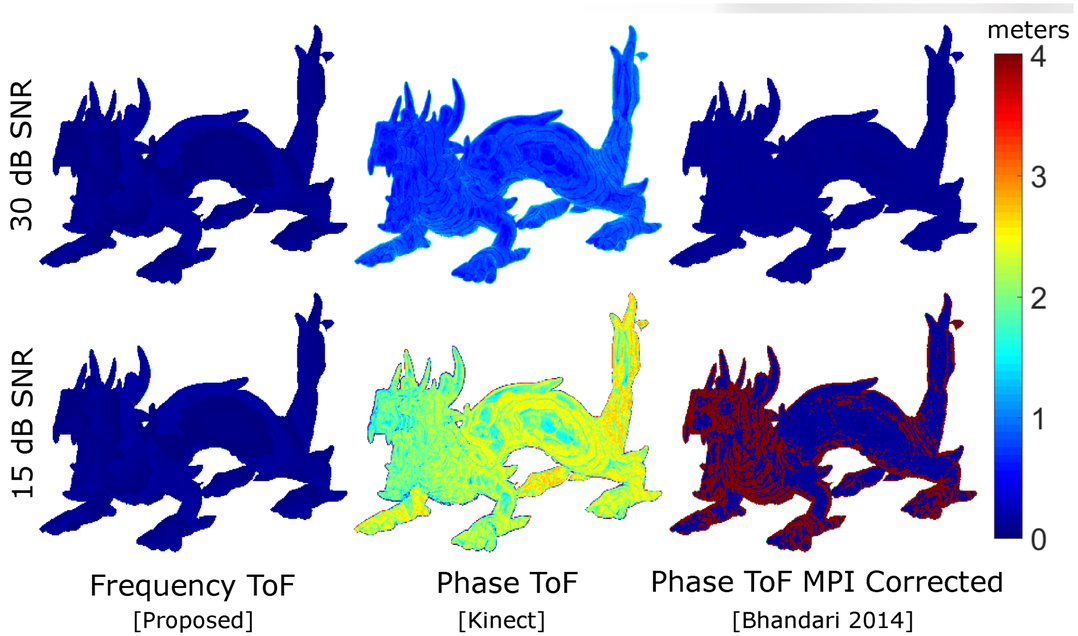
Proposition 1: *Multi-path interference can be resolved in Frequency-Domain ToF if the optical path-length between any two reflections is less than:*

$$\Delta z \approx 0.6c/\Delta f_{\mathrm{M}}.$$

Analyzing multipath estimation in low SNR



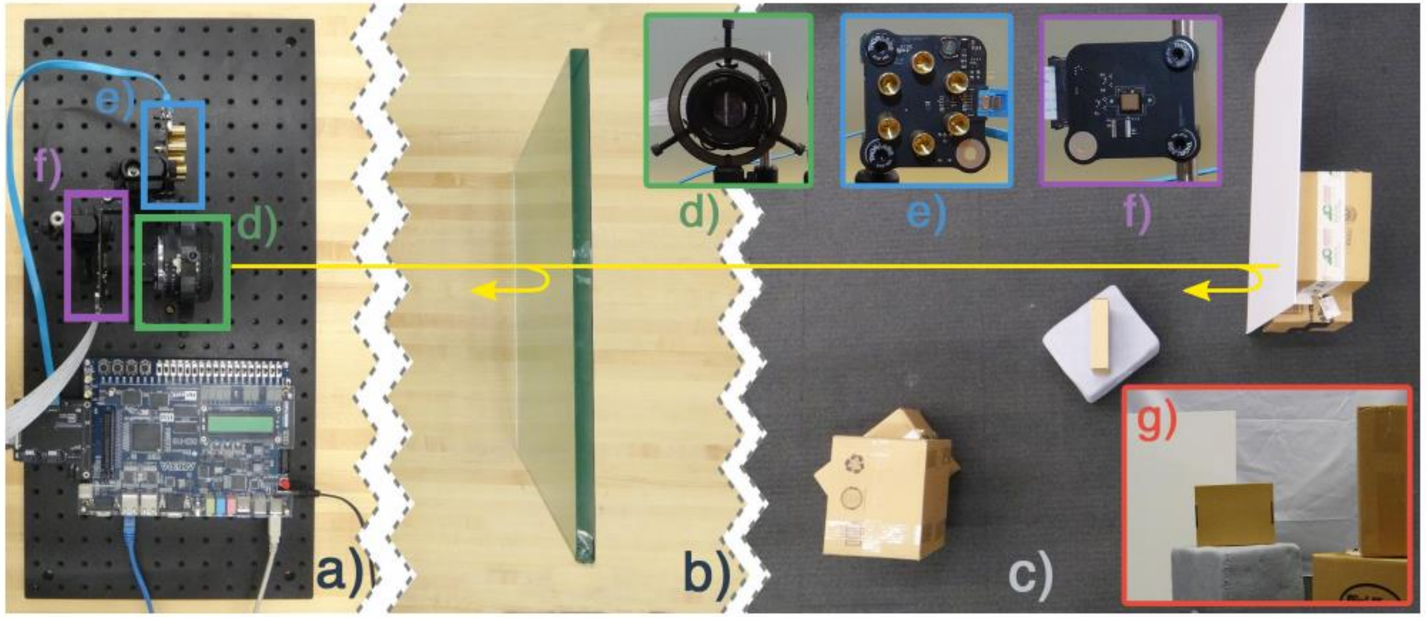




Conclusion

Formalize link between ToF cameras and optical interferometry

Changed primal-domain for multi-depth, low SNR, long-range 3D



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