Towards Next Generation 3D Cameras

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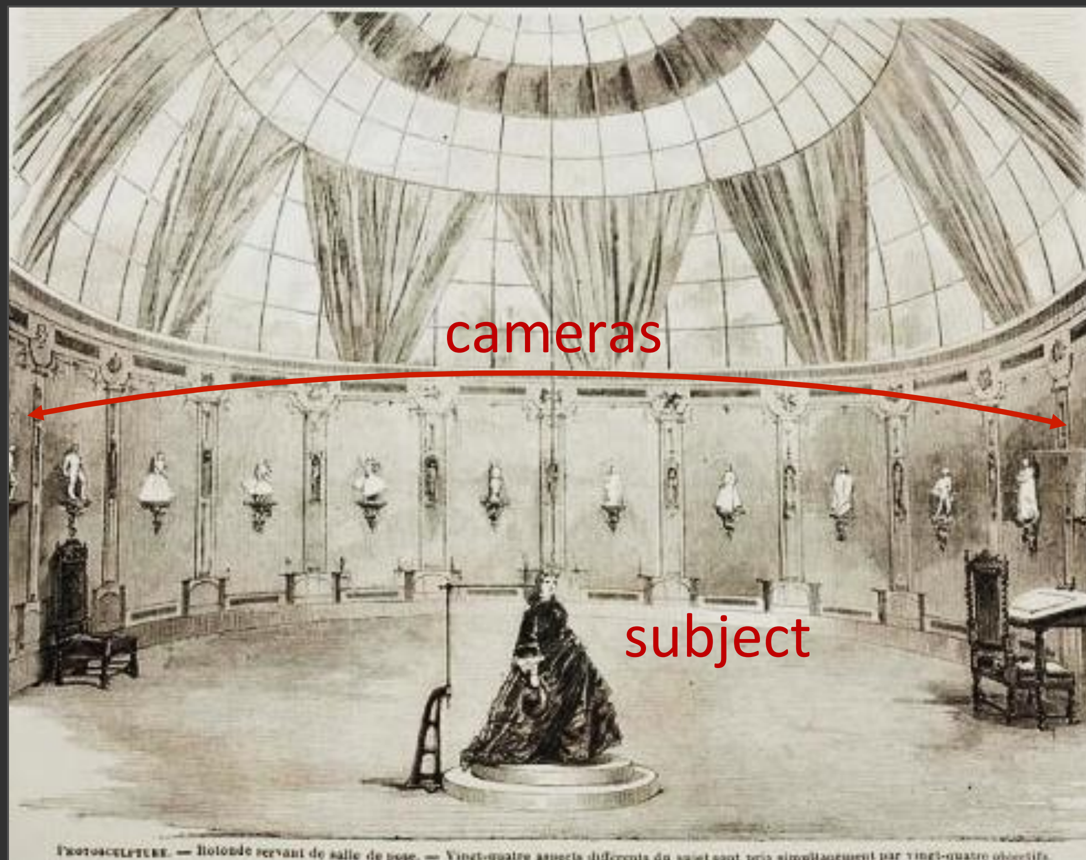
Support: NSF, ONR, DARPA

3D Cameras: History



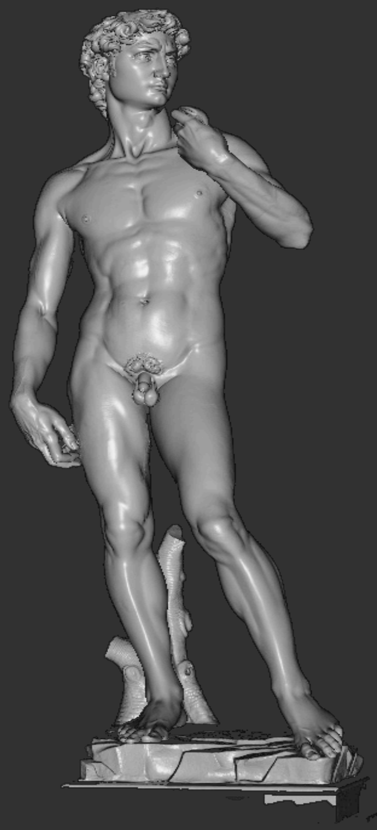
PHOTOSCULPTURE. — Rotonde servant de salle de pose. — Vingt-quatre aspects différents du sujet sont pris simultanément par vingt-quatre objectifs.

photo-sculpture

[Francois Willeme, 1860]

image courtesy: http://p2.la-img.com/427/15943/5255594_5_l.jpg

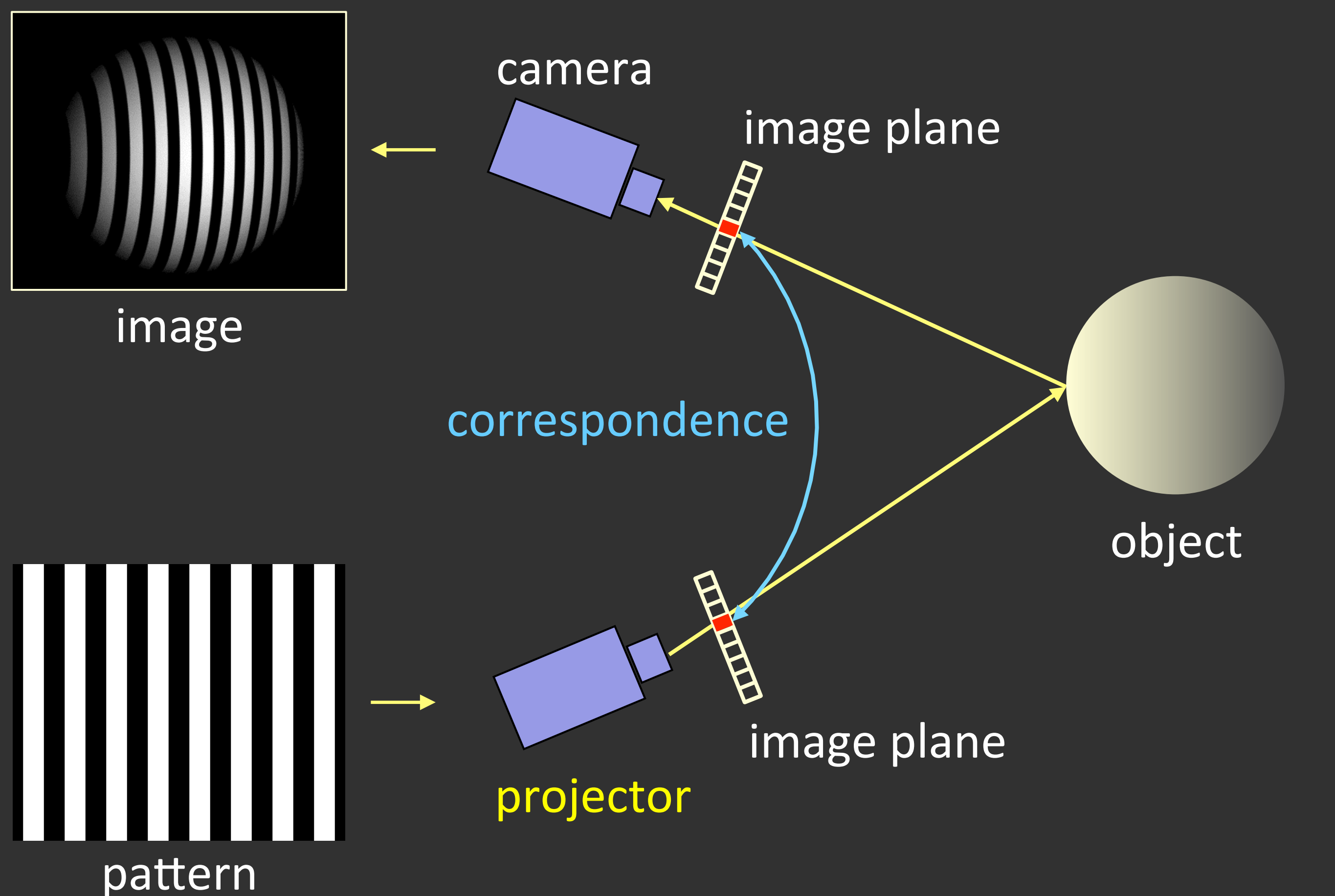
3D Cameras: Present



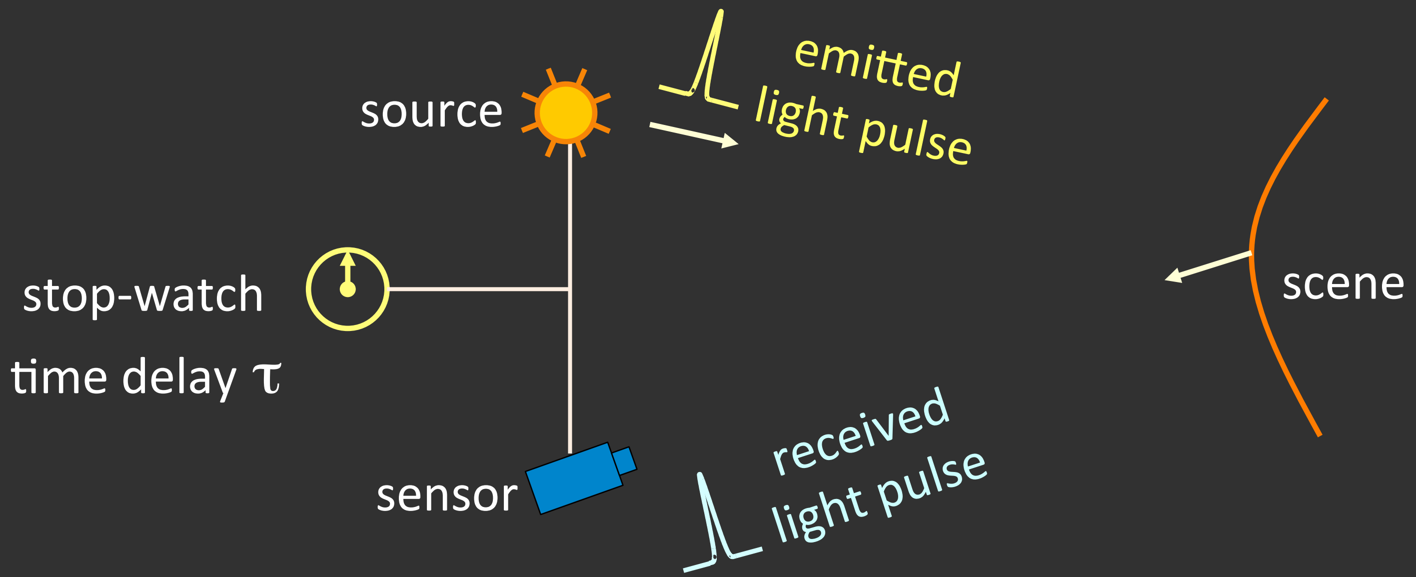
High resolution 3D
[Levoy *et. al.* 2009]

3D capture of dynamic scenes
[Zhang *et. al.* 2003]

3D Imaging: Structured Light Triangulation



3D Imaging: Time-of-Flight



$$depth = c/2\tau$$

← speed of light

[Koechner, 1968]

Modern 3D Cameras

Microsoft Kinect
5 million sold in last 6 months

SoftKinectic
Consumer devices

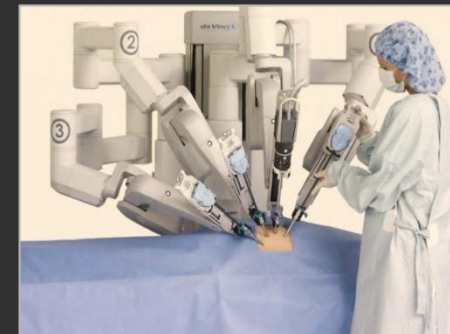
Potential to Revolutionize Diverse Application Domains

http://news.xbox.com/2014/04/xbox-one-march-npd
http://www.engadget.com/2013/06/04/intel-announces-creative-depth-vision-camera-at-computex-2013/

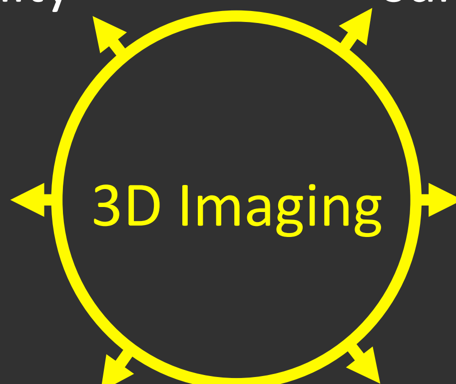
3D Revolution

augmented reality

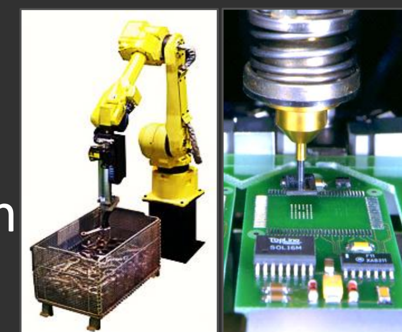
robotic surgery



underwater exploration



industrial automation

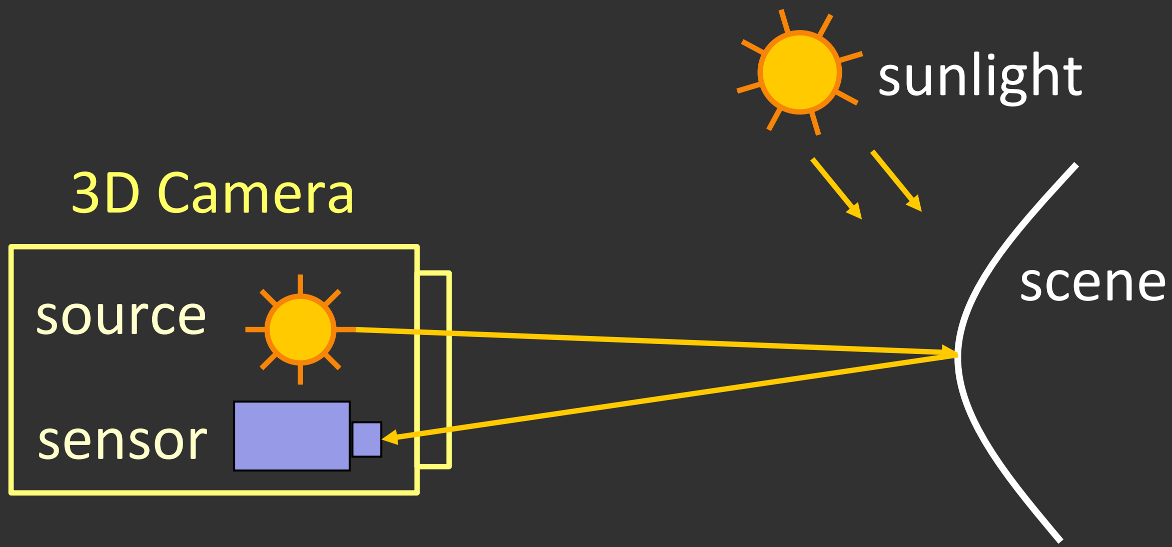


autonomous cars

exploratory robots

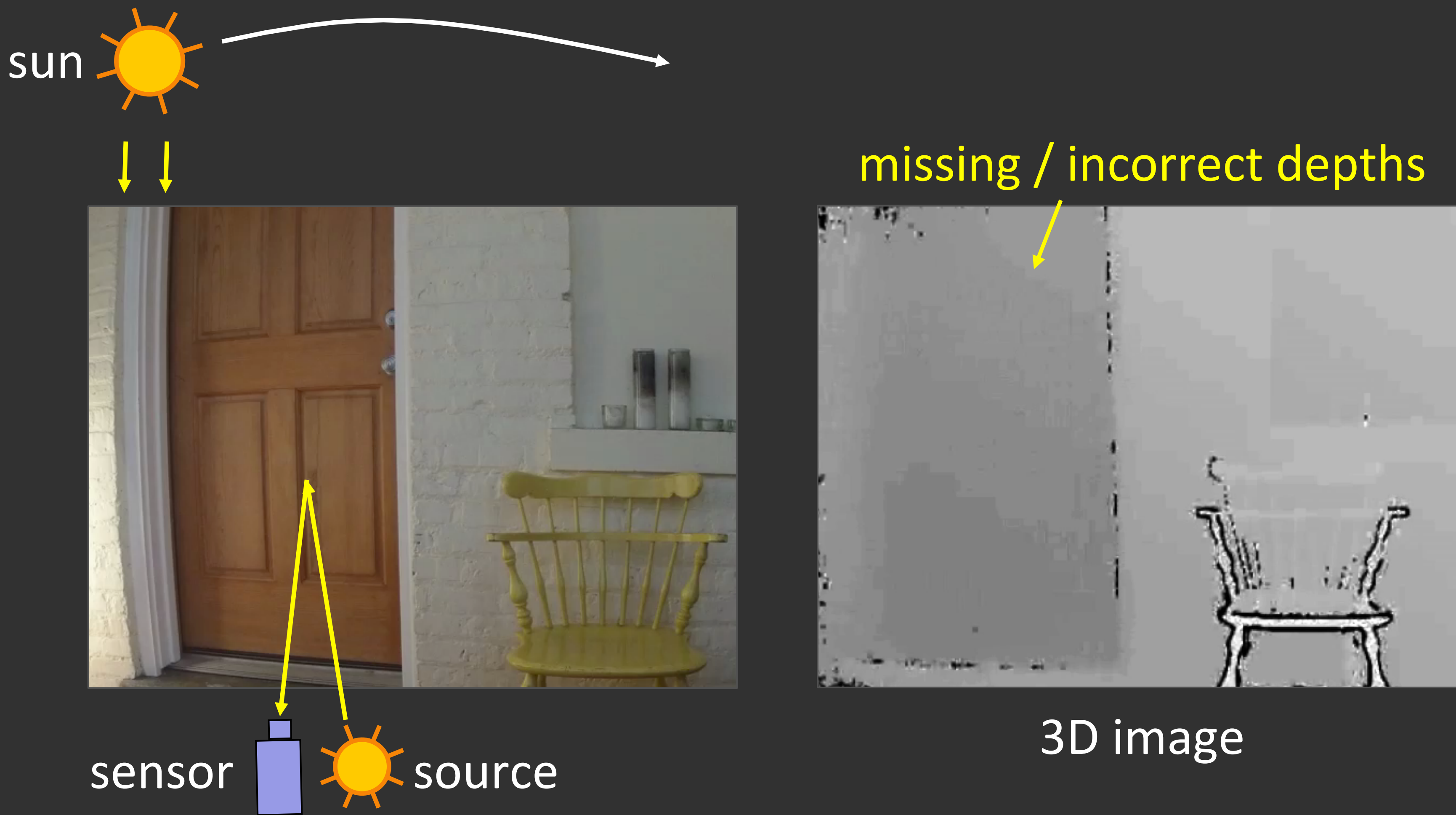
image courtesy: www.magicleap.com/, http://www.upi.com/

3D Imaging: Challenges

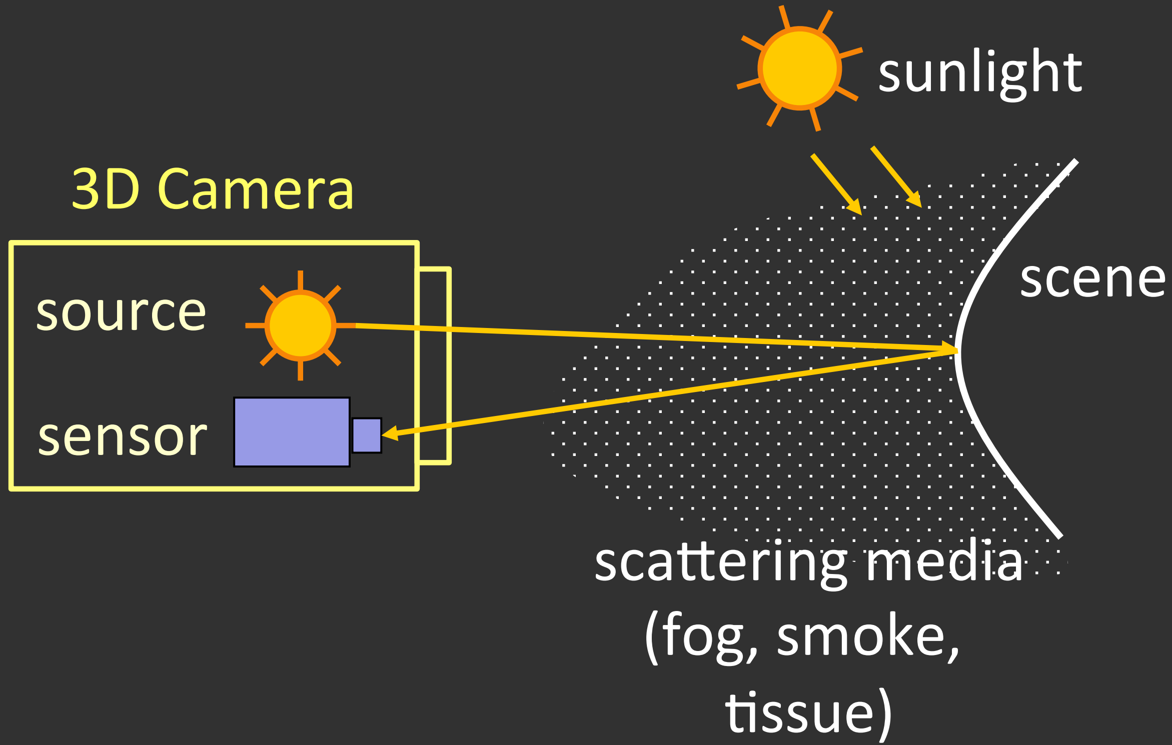


ambient illumination

3D Imaging In Sunlight



3D Imaging: Challenges



ambient illumination

scattering

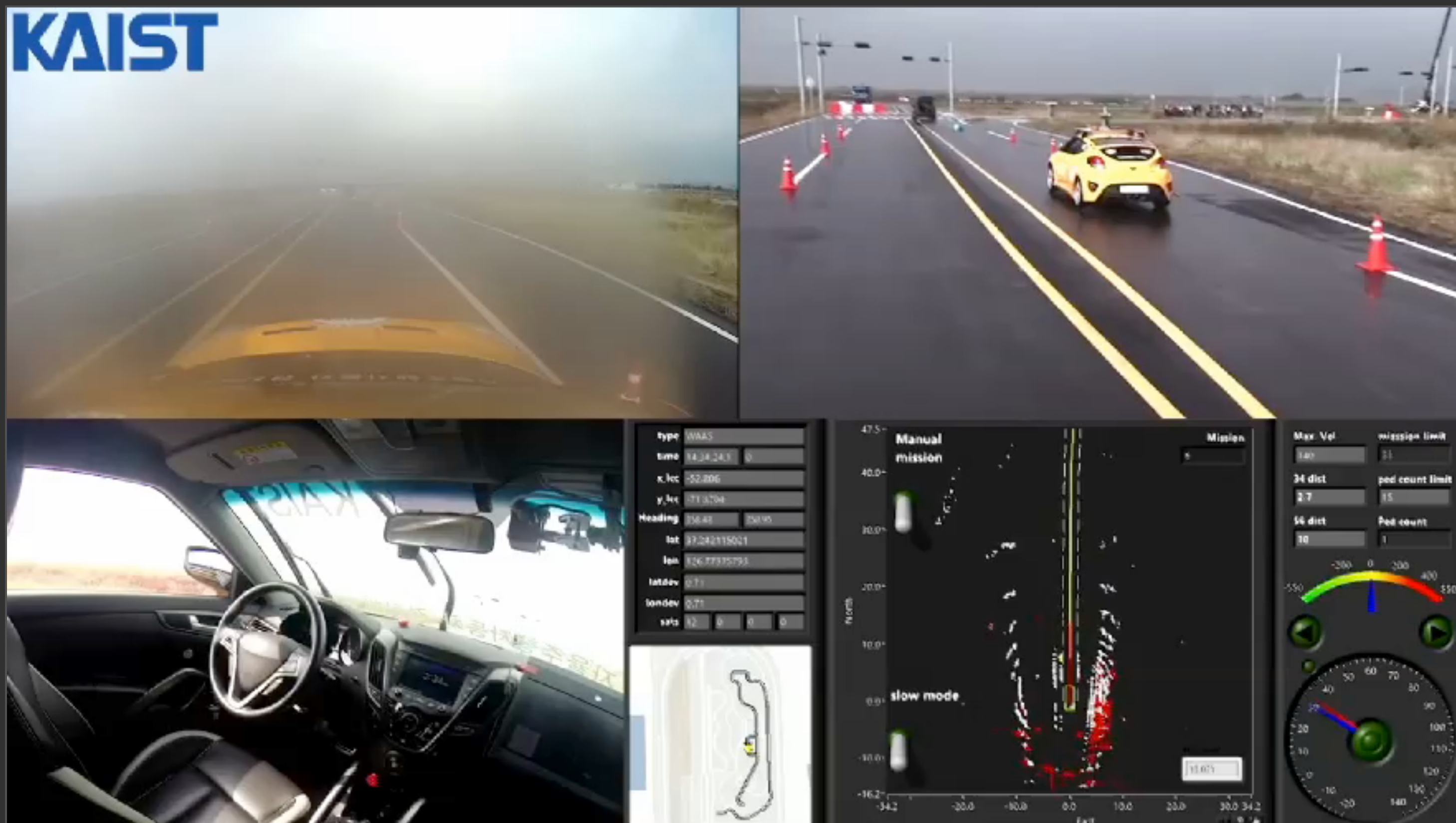
Effect of Scattering in Autonomous Driving

KAIST EureCar: Self Driving Car

[Hyundai Autonomous Vehicles Competition]

videos from: https://www.youtube.com/watch?v=D7WtSB55q4s, https://www.youtube.com/watch?v=xs9Gr9V2mOE

Effect of Scattering in Autonomous Driving

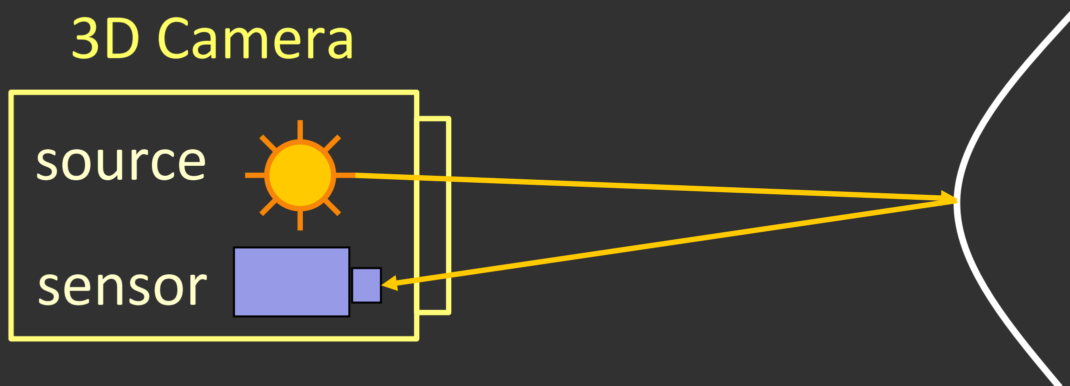


KAIST EureCar: Self Driving Car

[Hyundai Autonomous Vehicles Competition]

videos from: https://www.youtube.com/watch?v=D7WtSB55q4s, https://www.youtube.com/watch?v=xs9Gr9V2mOE

3D Imaging: Challenges

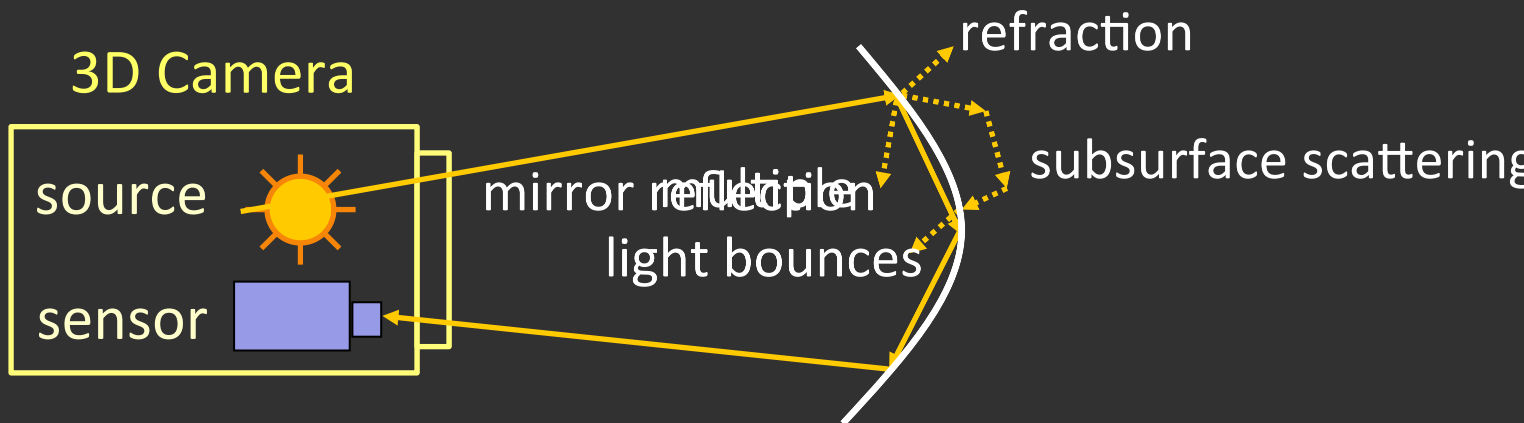


environmental factors

ambient illumination

scattering

3D Imaging: Challenges

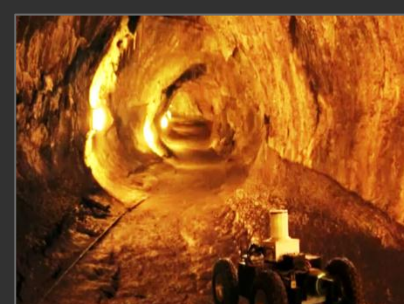


environmental factors

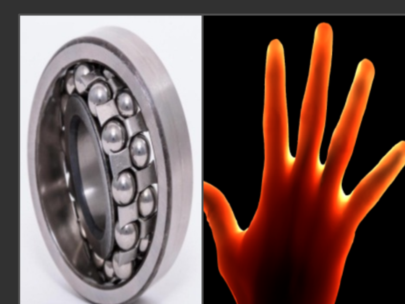
ambient illumination

scattering

scene-dependent factors

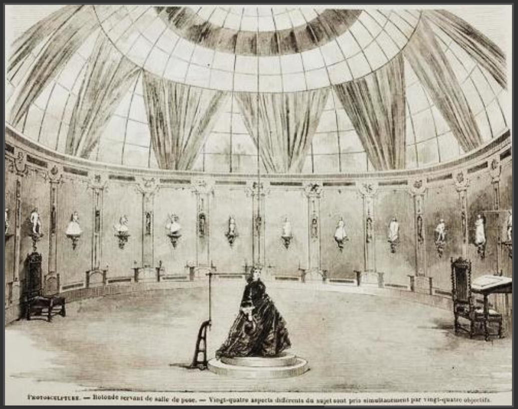


geometry



material properties

Evolution of 3D Cameras



1860

now

next generation
3D cameras

future

speed
resolution
portability

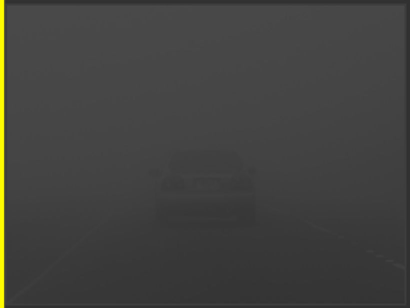
High
performance
in-the-wild

3D Cameras Of The Future

3D Cameras That Work Reliably In-The-Wild

In Every Environment

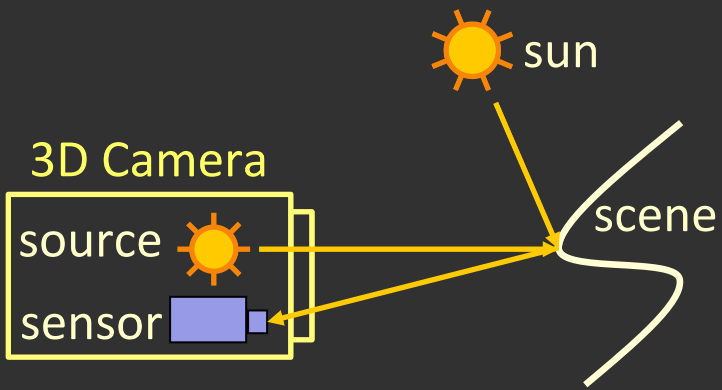

ambient illumination

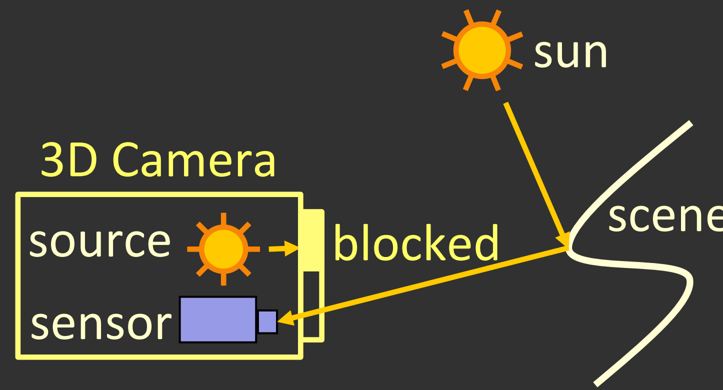

scattering


geometry


material properties

3D Imaging In Sunlight



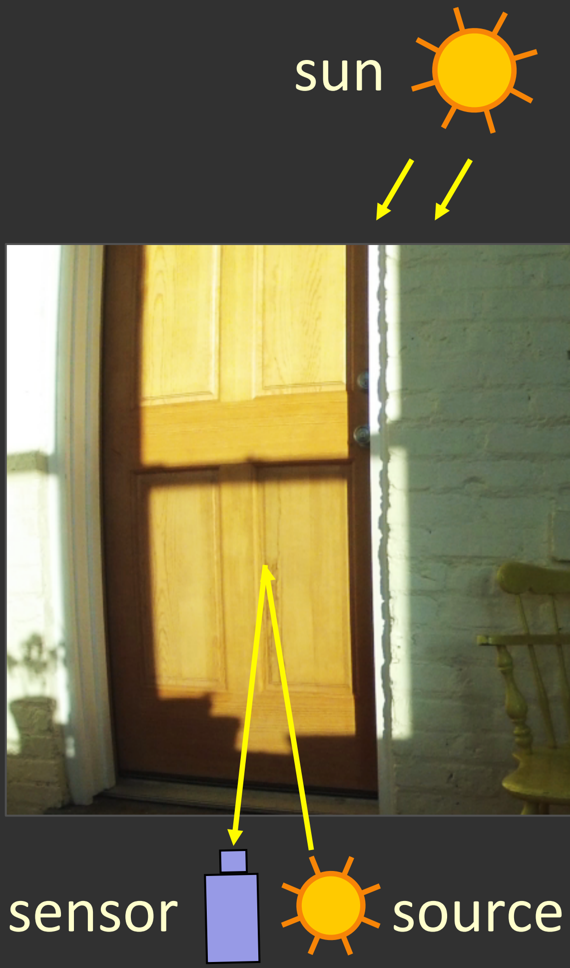


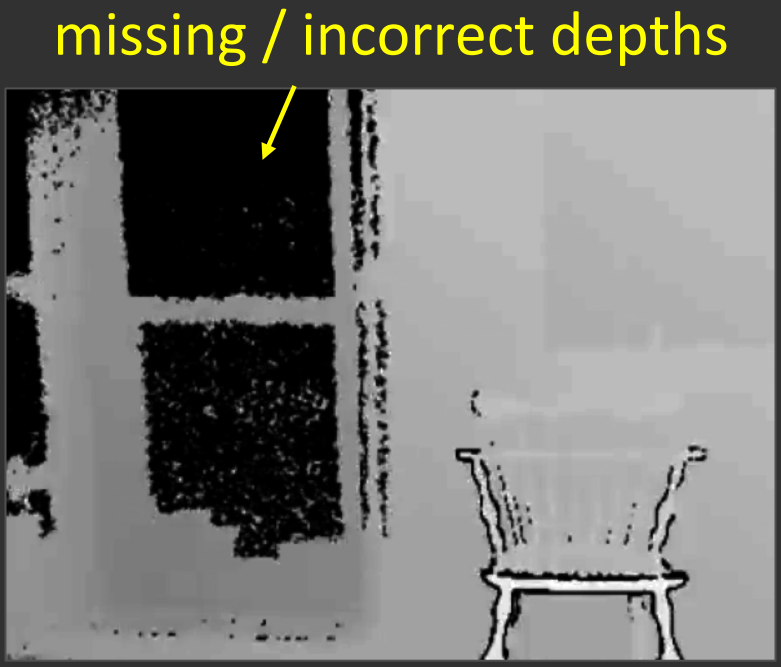
$$I_1 = I_{source} + I_{sun}$$

$$I_2 = I_{sun}$$

$$I_{diff} = I_1 - I_2 = I_{source}$$

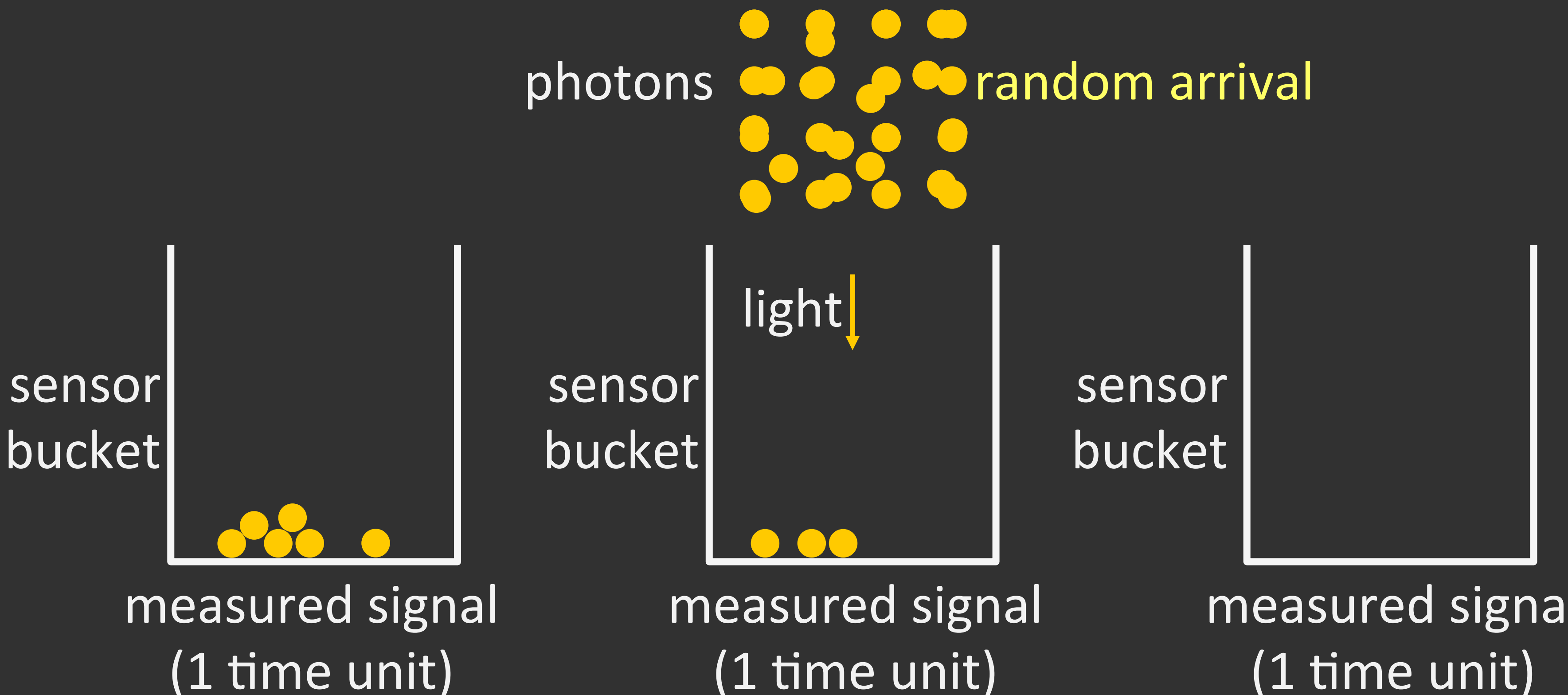
3D Imaging In Sunlight





3D image

Problem: Random Arrival Of Photons



arrival of light is a discrete random Process

mean photon flux (per unit time) = 3 Photons

Problem: Photon Noise

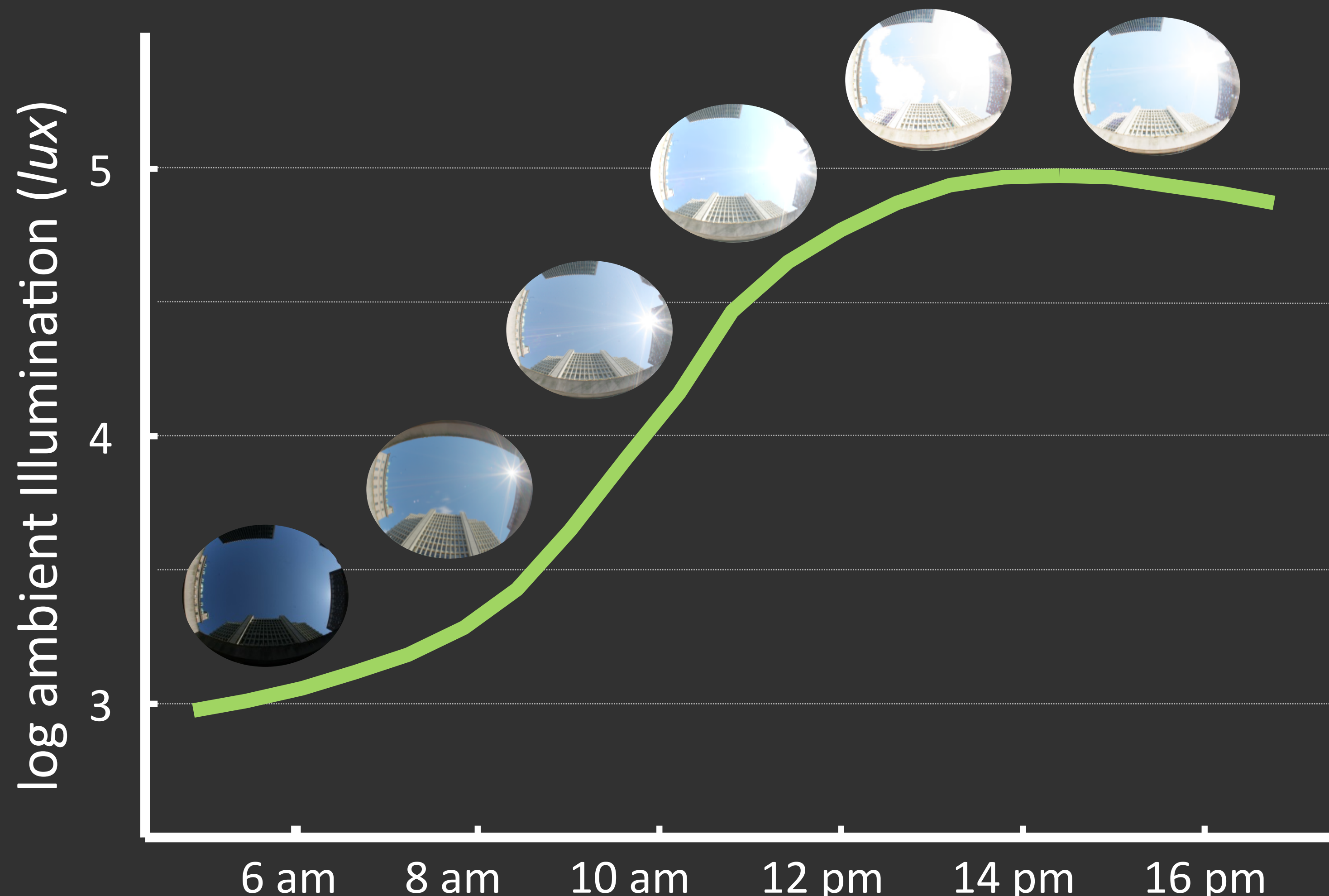
measured value | true (mean) value | photon noise

$$I_{meas} = I_{true} + \sigma_{photon}$$

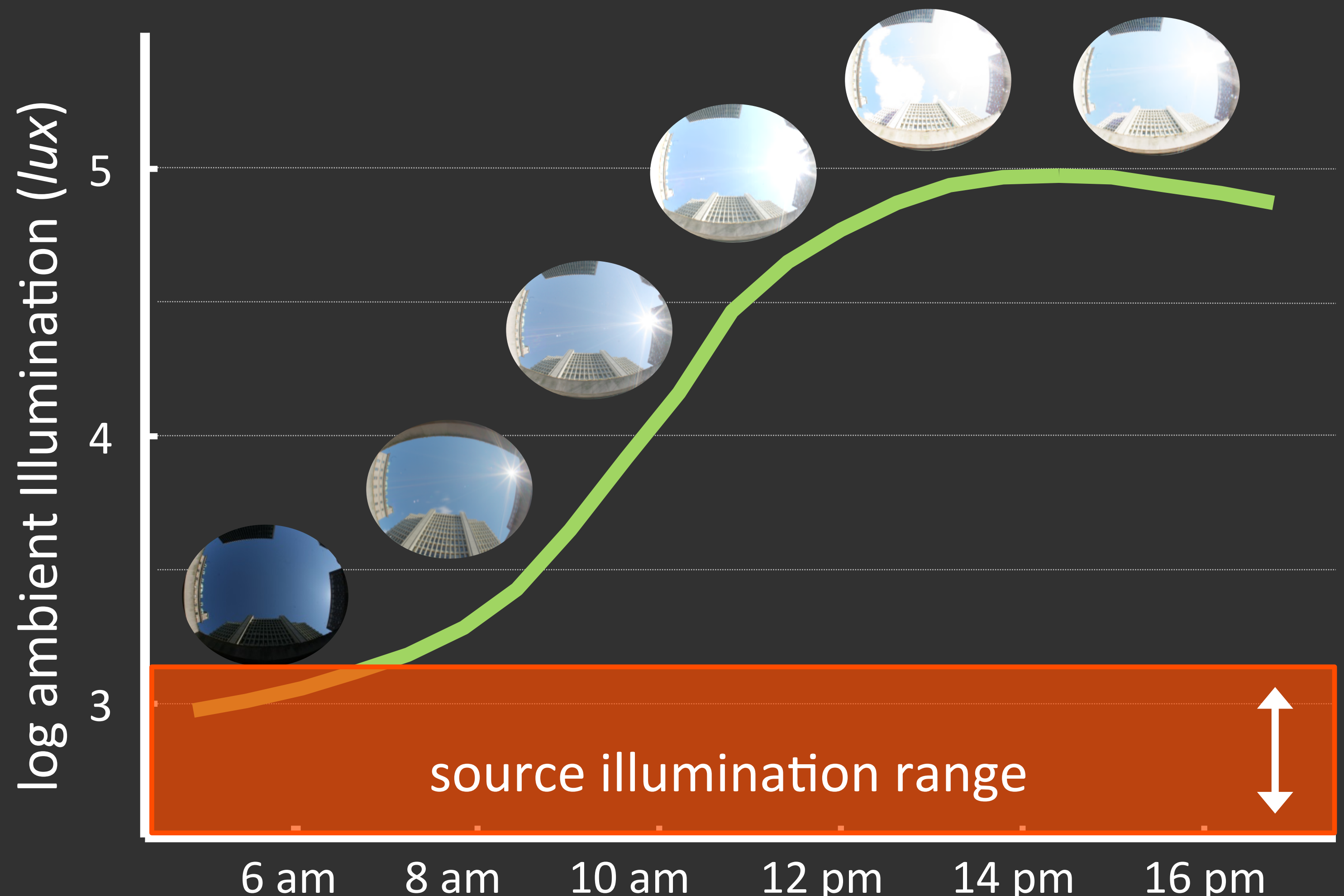
$$\boxed{std(\sigma_{photon}) = \sqrt{I_{true}}}$$

photon noise follows Poisson distribution

Source Light Versus Sunlight

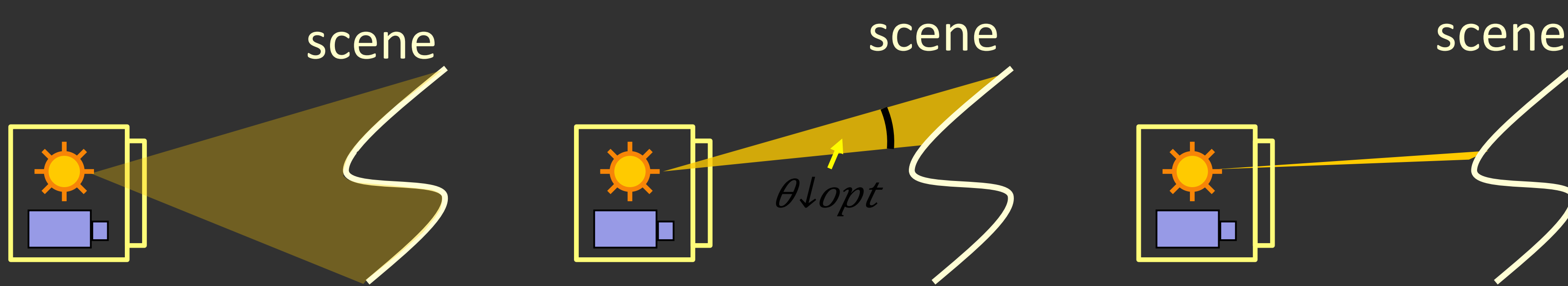


Source Light Versus Sunlight



2-5 orders of magnitude weaker as compared to sunlight

Camera Design for Outdoor 3D Imaging



flood-lighting
inaccurate

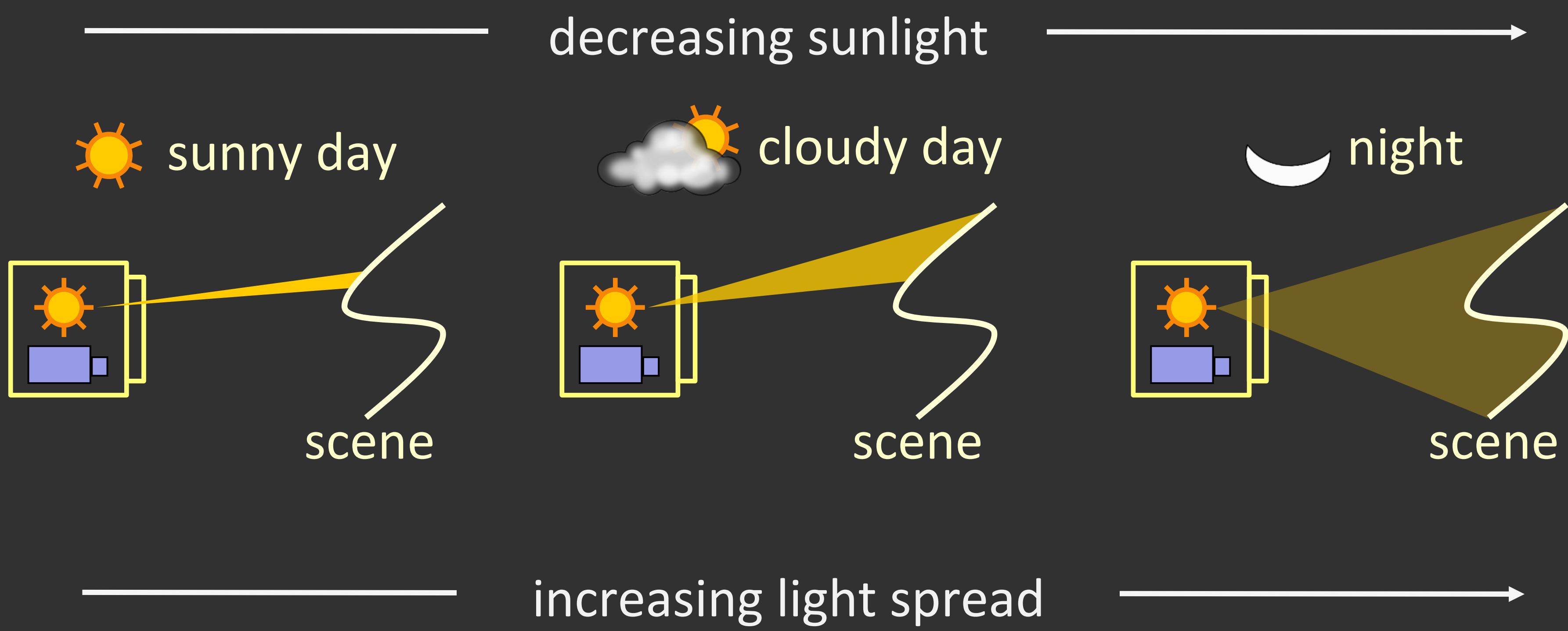
optimal spread

point scanning
slow

system constant

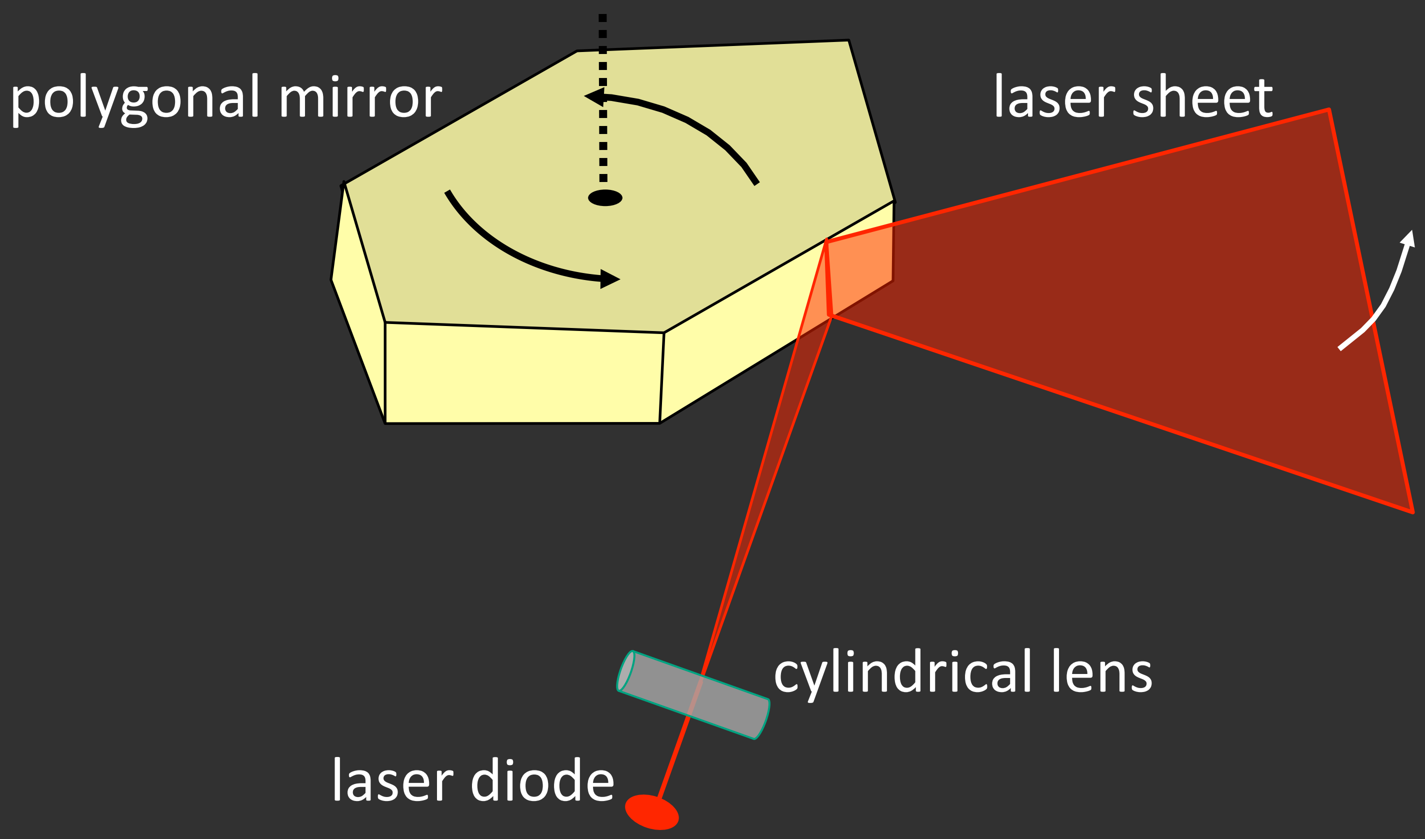
$$\theta_{opt} = \rho\, I_{source} / \sqrt{I_{sun}}$$

Camera Adapts to the Environment



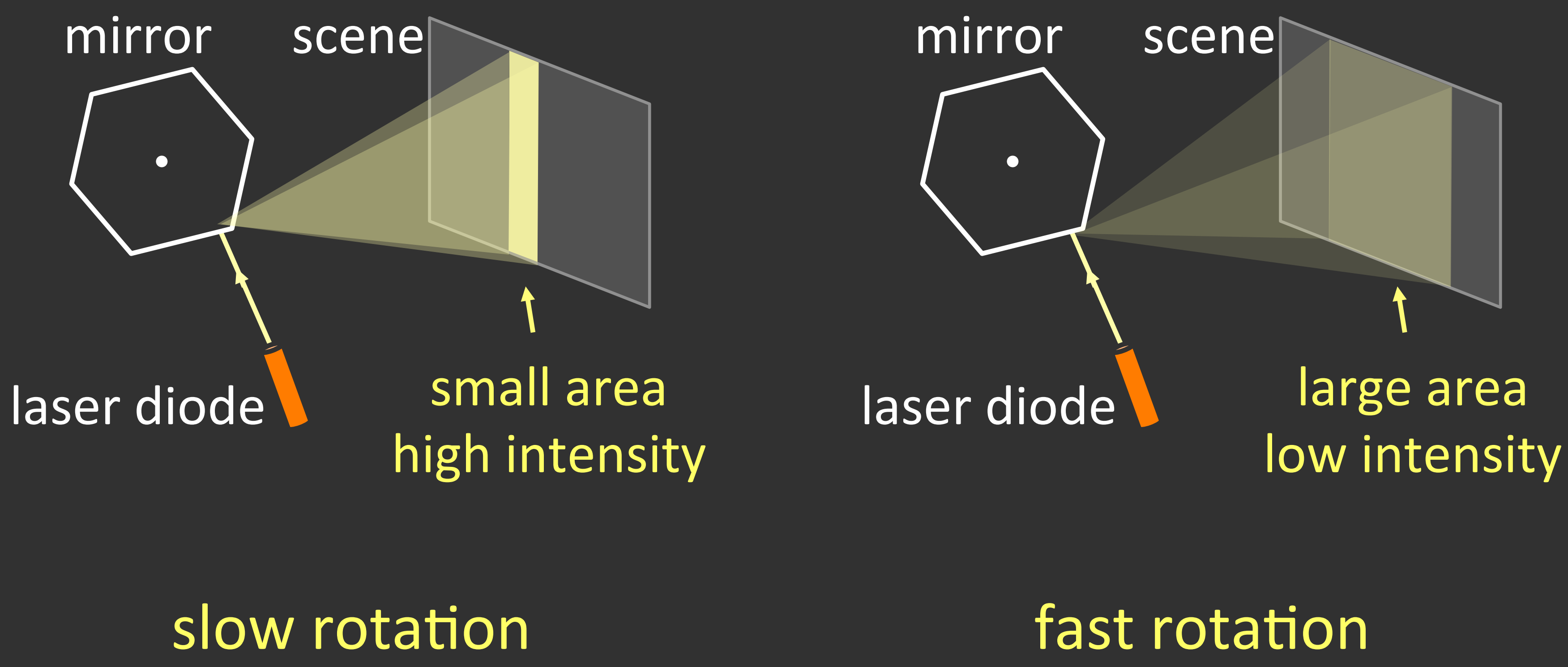
environment adaptive light distribution

Achieving Different Light Spreads



vary the rotation speed of the mirror

Achieving Different Light Spreads

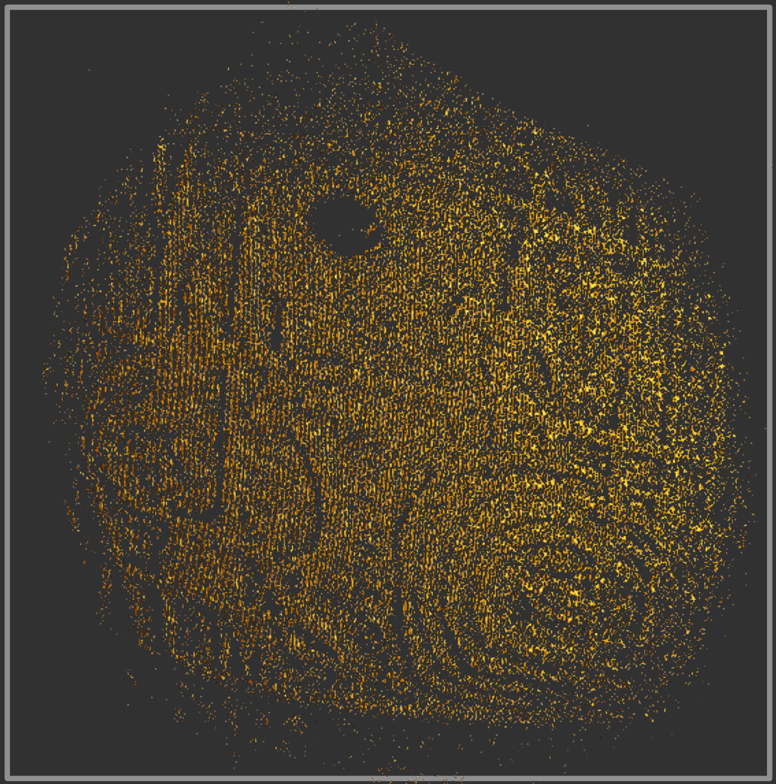


Experimental Results

Clay Pot Placed Outdoors

11:00 AM. Ambient light = 75,000 lux.

Shape Comparison



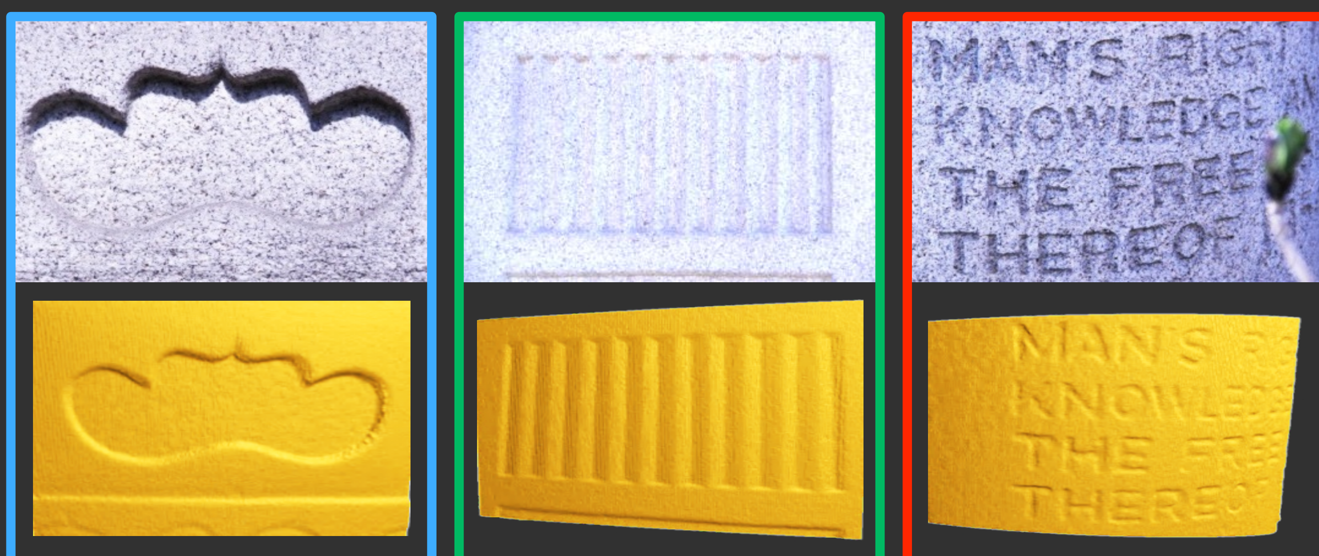
frame averaging

adaptive approach [Gupta *et. al.*, ICCV'13]

(same acquisition time for both methods)

Scanning Columbia Campus

12:00 PM. Ambient light = 90,000 lux.



Scanning Columbia Campus

13:00 PM. Ambient light = 94,000 lux.

3D Cameras Of The Future

3D Cameras That Work Reliably In-The-Wild

In Every Environment

For Every Scene

ambient illumination

scattering

geometry

material properties

3D Imaging Of Indoor Scenes

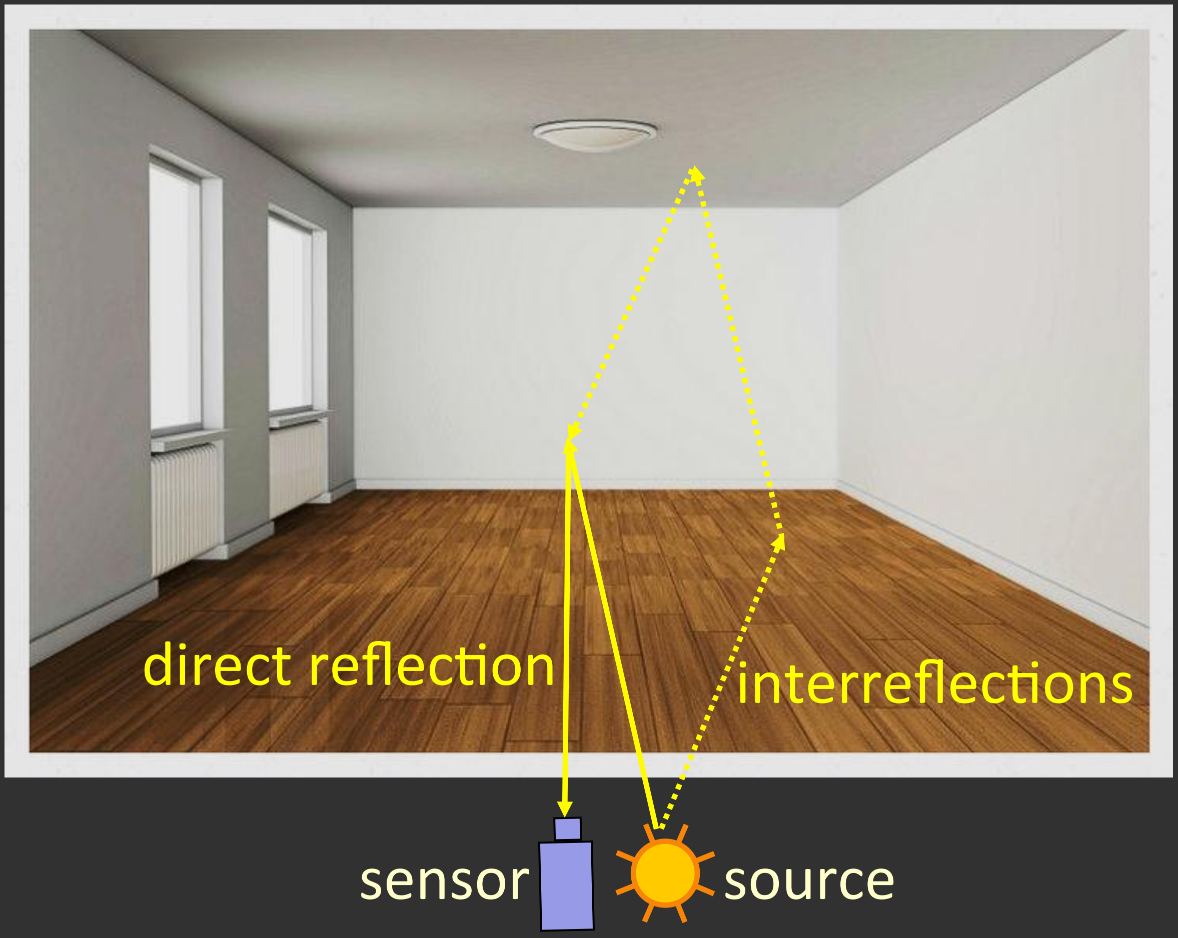
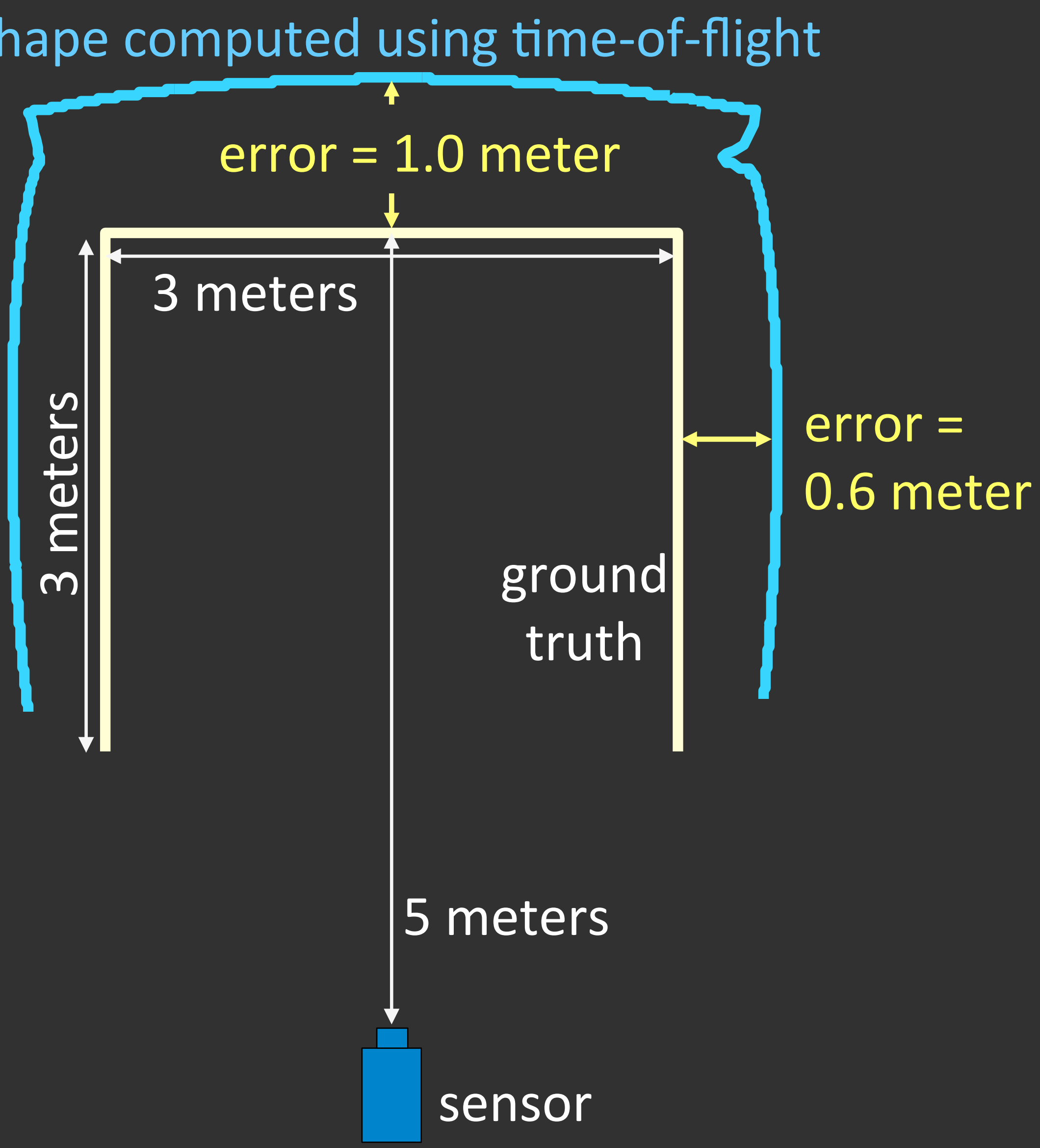


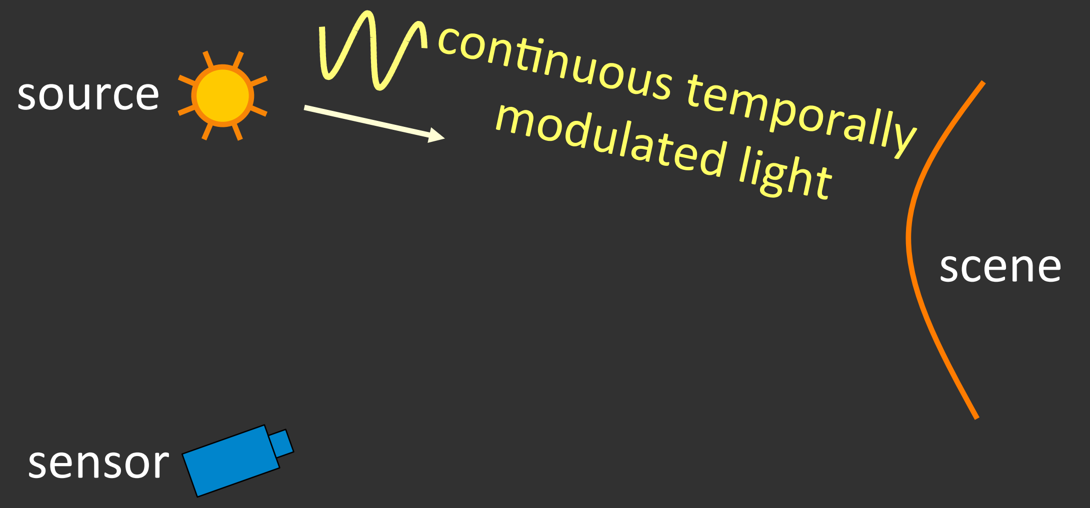
Image courtesy: http://www.annsliee.com/

Errors in Shape Recovery

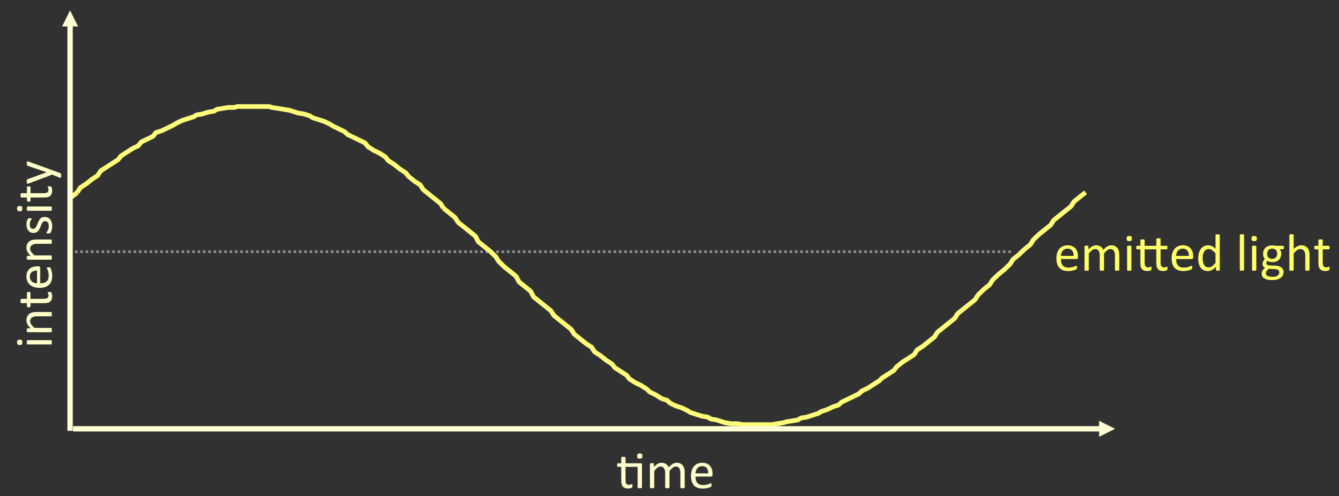
camera view



Continuous Wave ToF Imaging

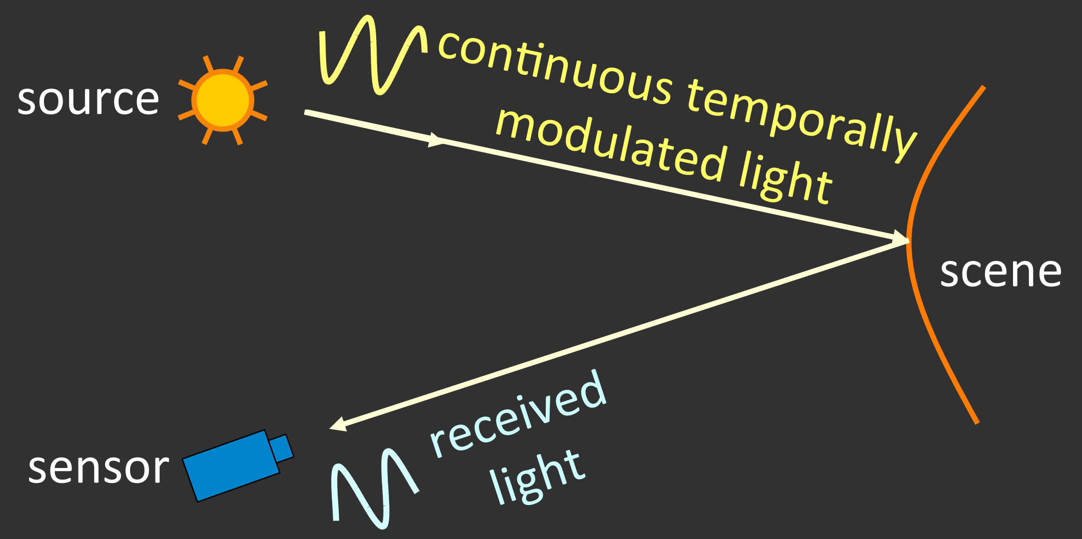


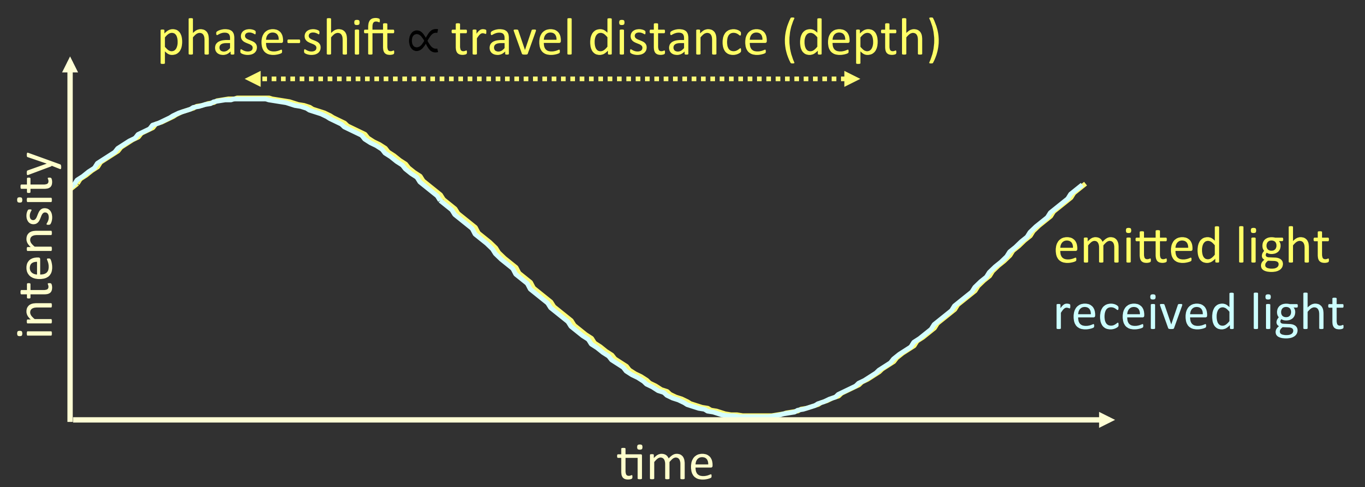
sinusoid



[Smith, 1980; Schwarte 1995; Lange, 2000]

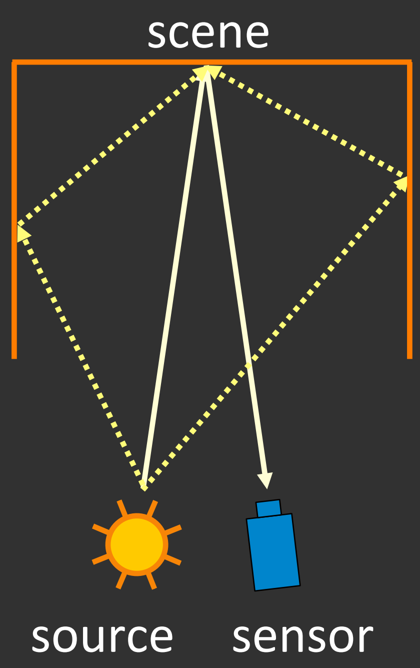
Continuous Wave ToF Imaging

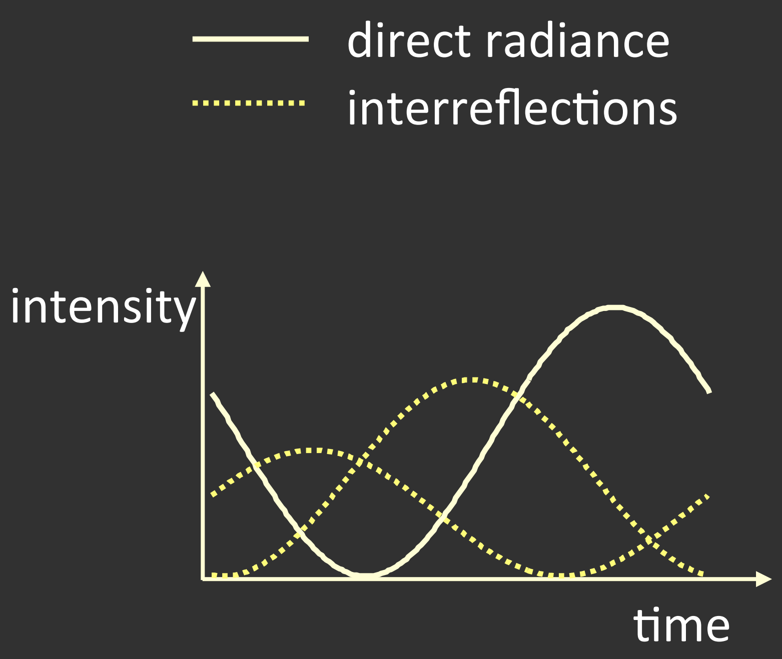




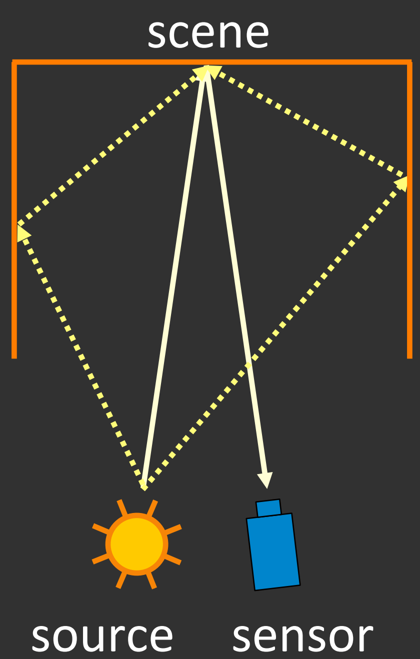
[Smith, 1980; Schwarte 1995; Lange, 2000]

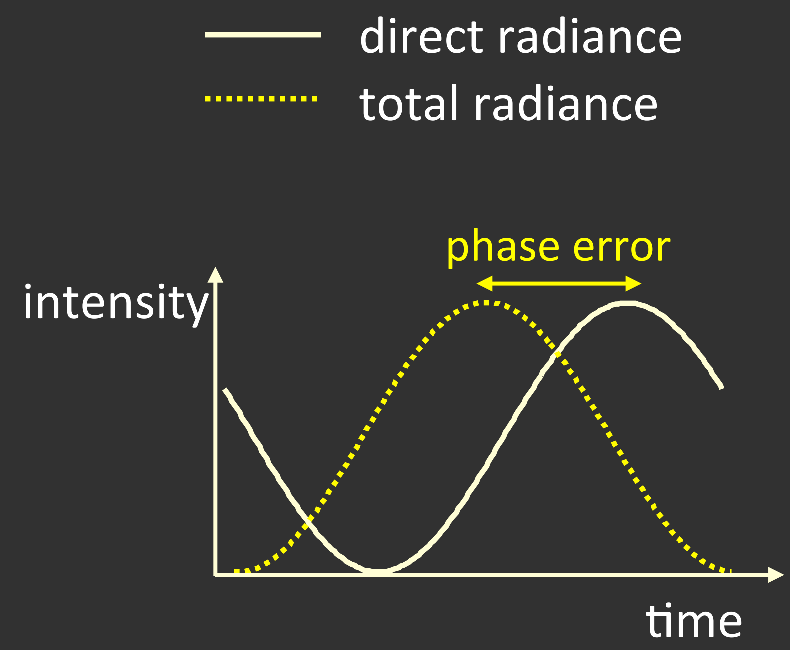
Interreflections and ToF Imaging





Interreflections and ToF Imaging

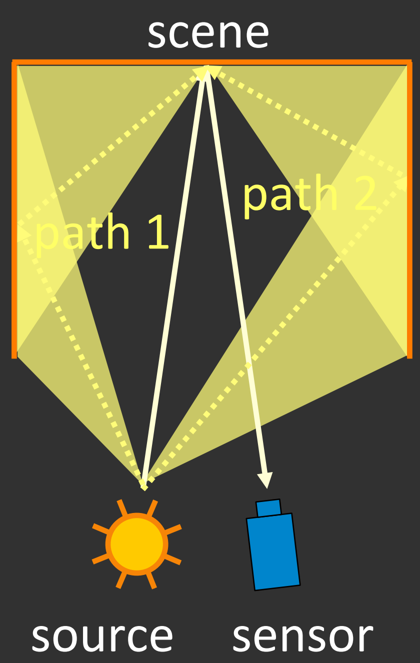


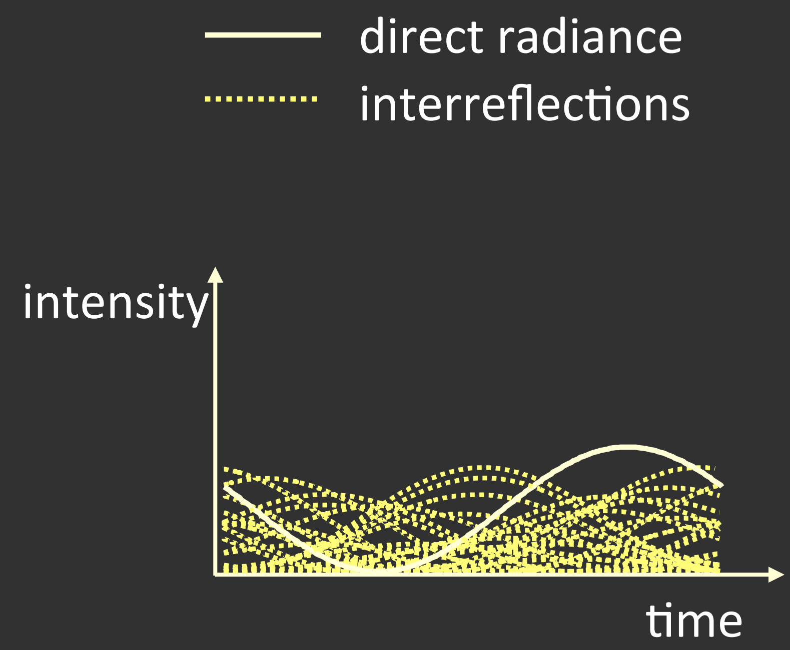


Interreflections Result In Incorrect Phase

And Hence, Incorrect Depths

Interreflections: Existing Work





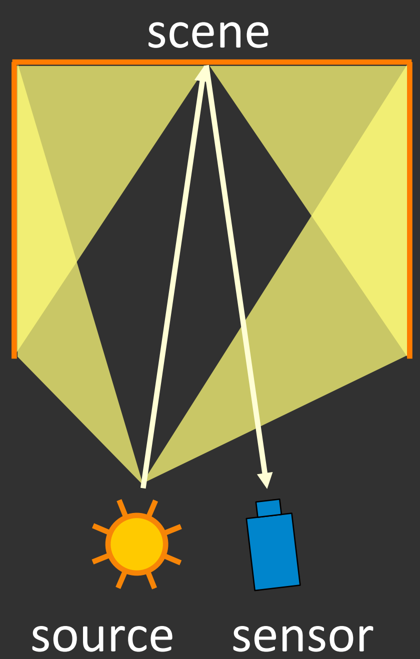
2-3 Indirect Paths

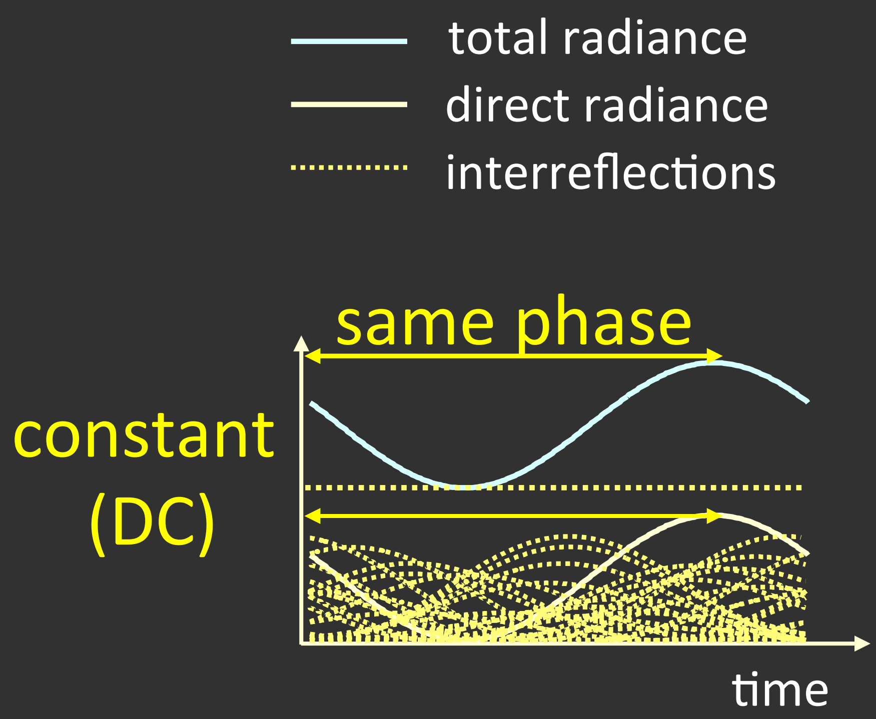
[Godbaz *et al.* 2008, Jimenez *et al.* 2012, Dorrington *et al.* 2011]

Infinite Indirect Paths

[Godbaz *et al.* 2012, Kadambi *et al.* 2013, Kirmani *et al.* 2013, Freedman *et al.* 2014]

Intuition for Solution

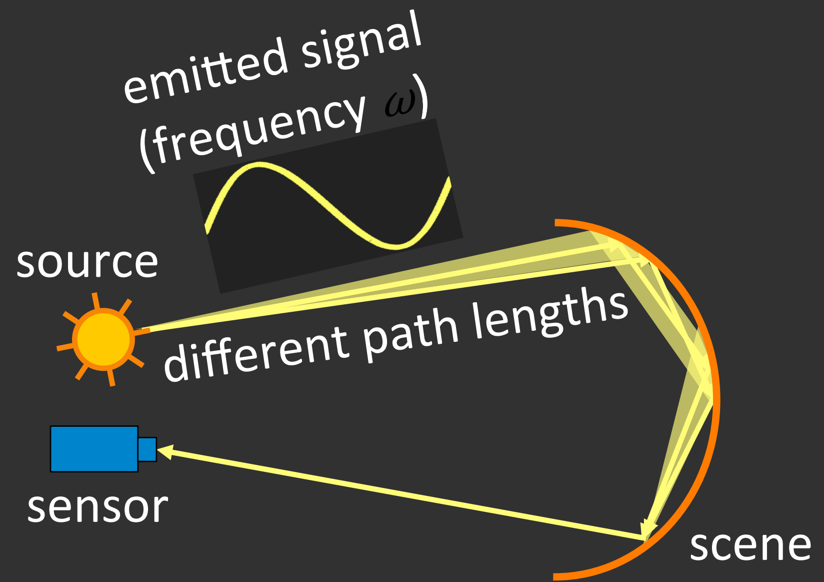


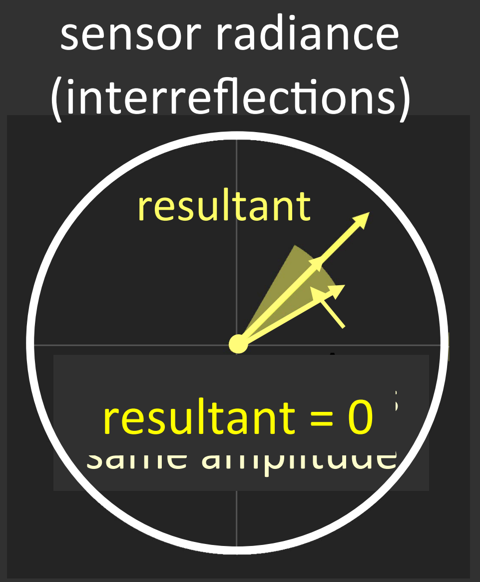


If Interreflection Component Is Constant

Phase is Not Affected

Interreflections vs. Modulation Frequency





Increasing Modulation Frequency

Decreasing Resultant Amplitude

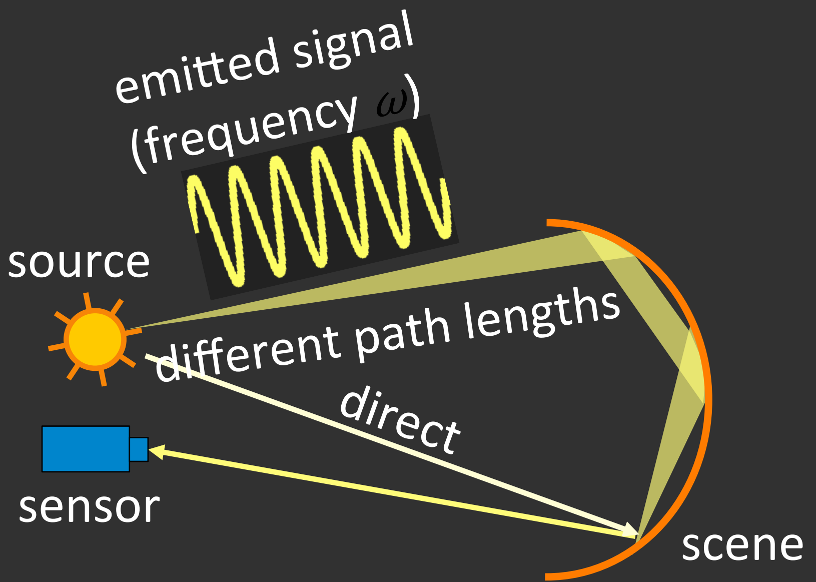
angular spread of phases

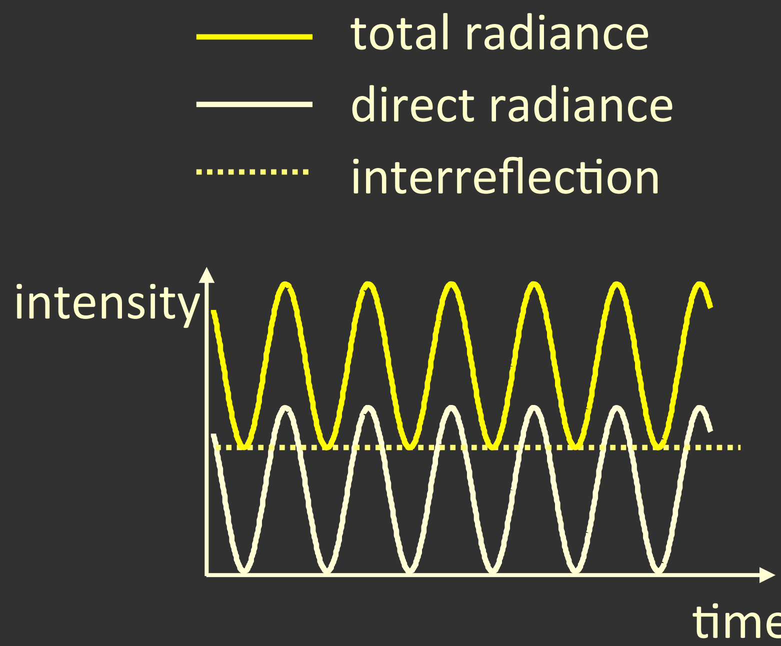
$\Delta\varphi \propto \omega$

Local Smoothness of Light Transport

[Nayar *et al.* 2006]

Interreflections vs. Modulation Frequency



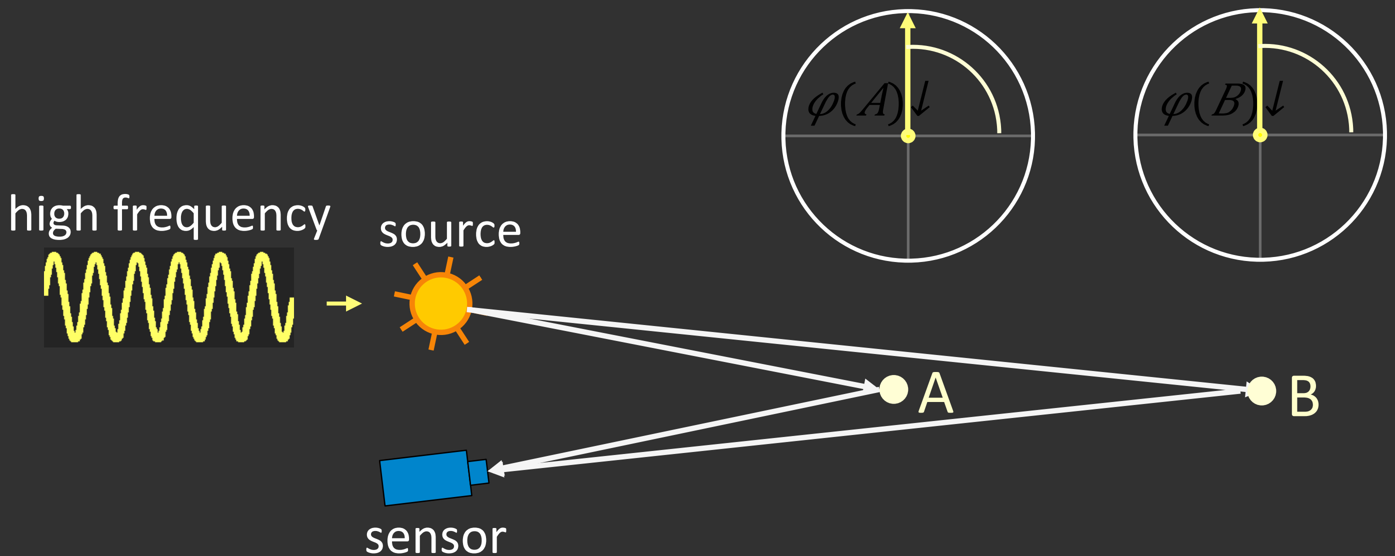


For High Temporal Frequency

Interreflection Component is Constant

Interreflections Do Not Affect Phase

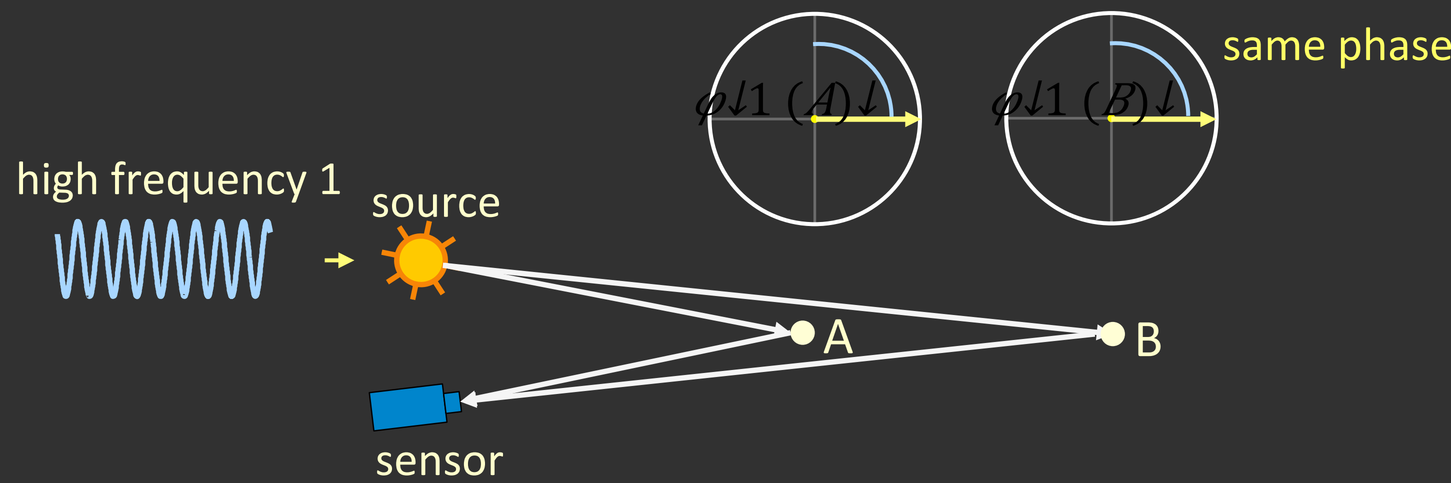
Phase Ambiguity

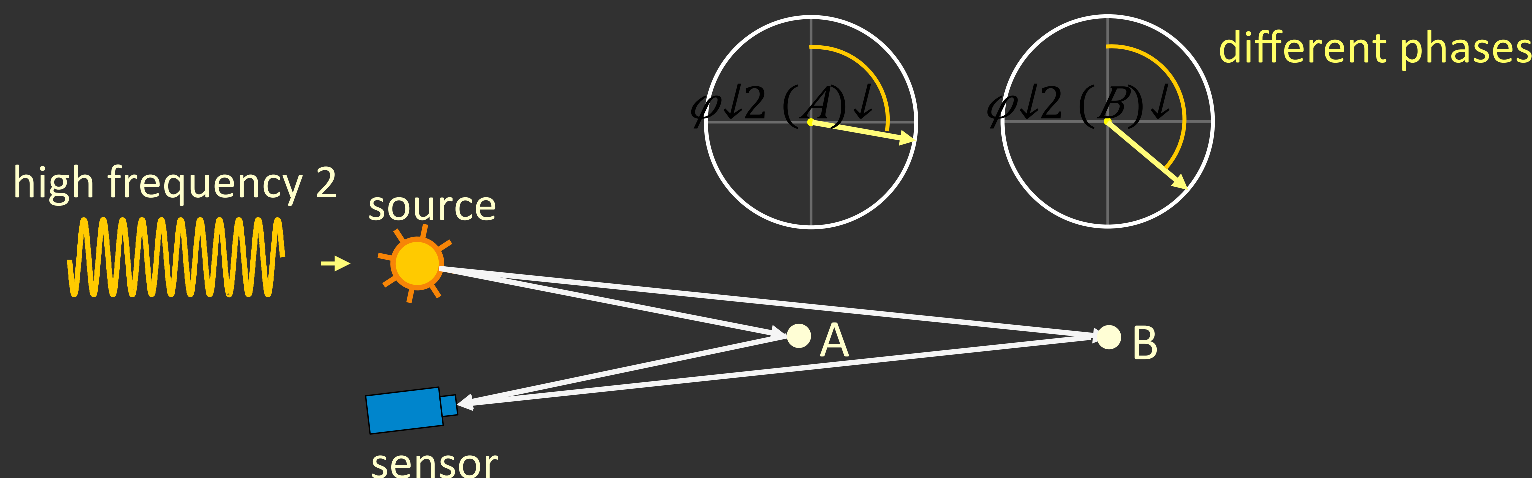


$$\varphi(A)=\varphi(B)$$

Different Scene Depths Have Same Phase

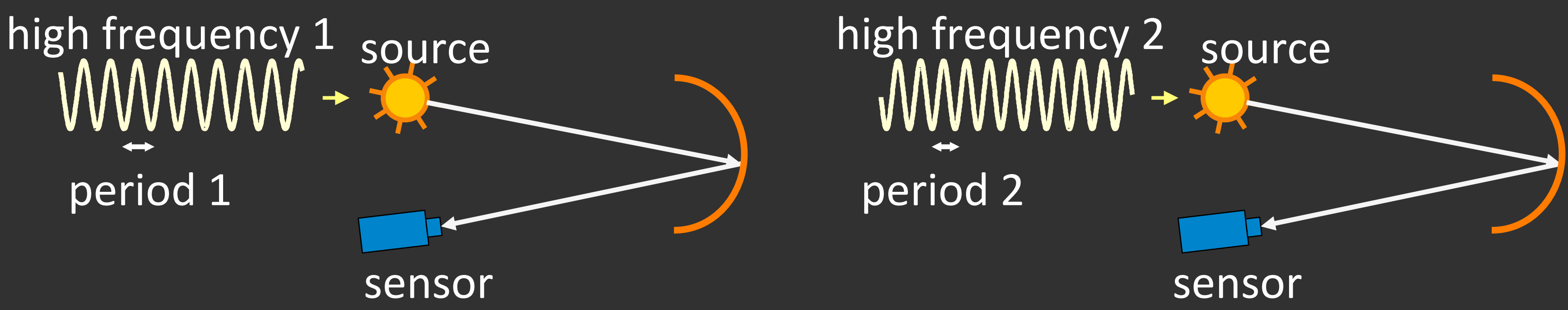
Disambiguating Phase





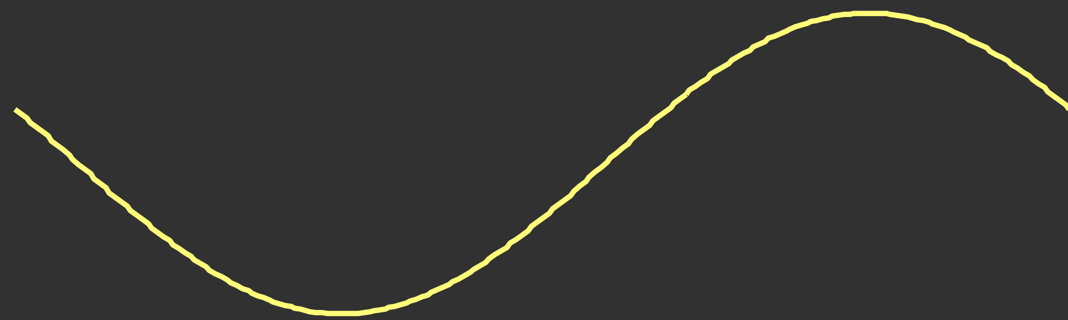
Compute Phases at Multiple High Frequencies

Micro Time-of-Flight Imaging



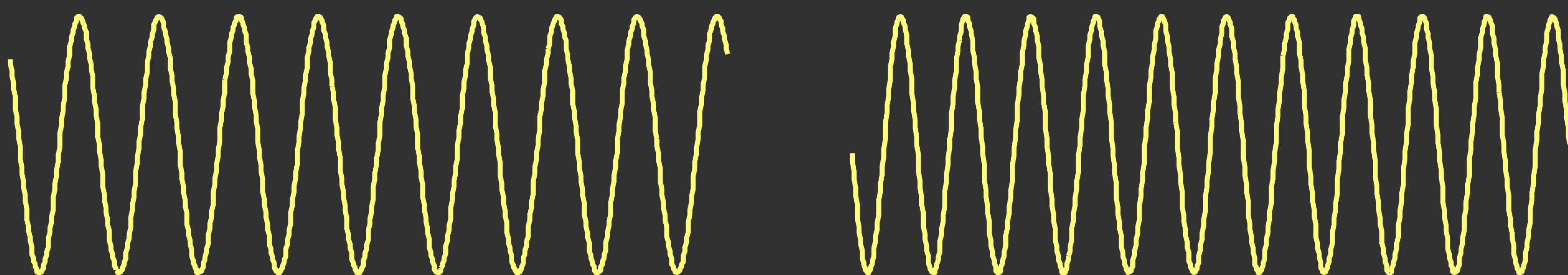
Modulation Signals With Micro (Small) Periods

Conventional vs. Micro ToF Imaging



Conventional ToF Shifting: One Low Frequency

Three Measurements



Micro ToF Shifting: Two High Frequencies

Four Measurements

Simulations: 3D Imaging Of Indoor Scenes

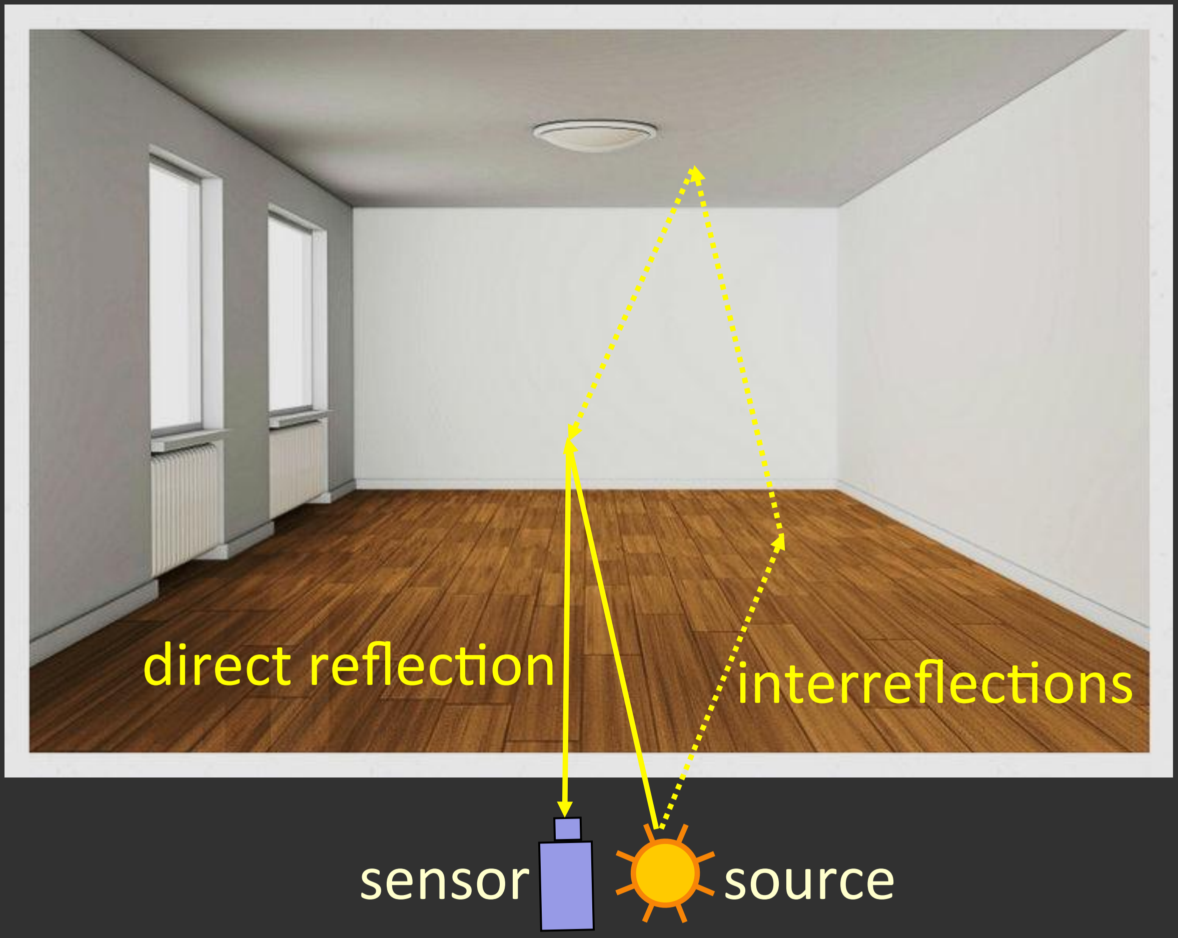
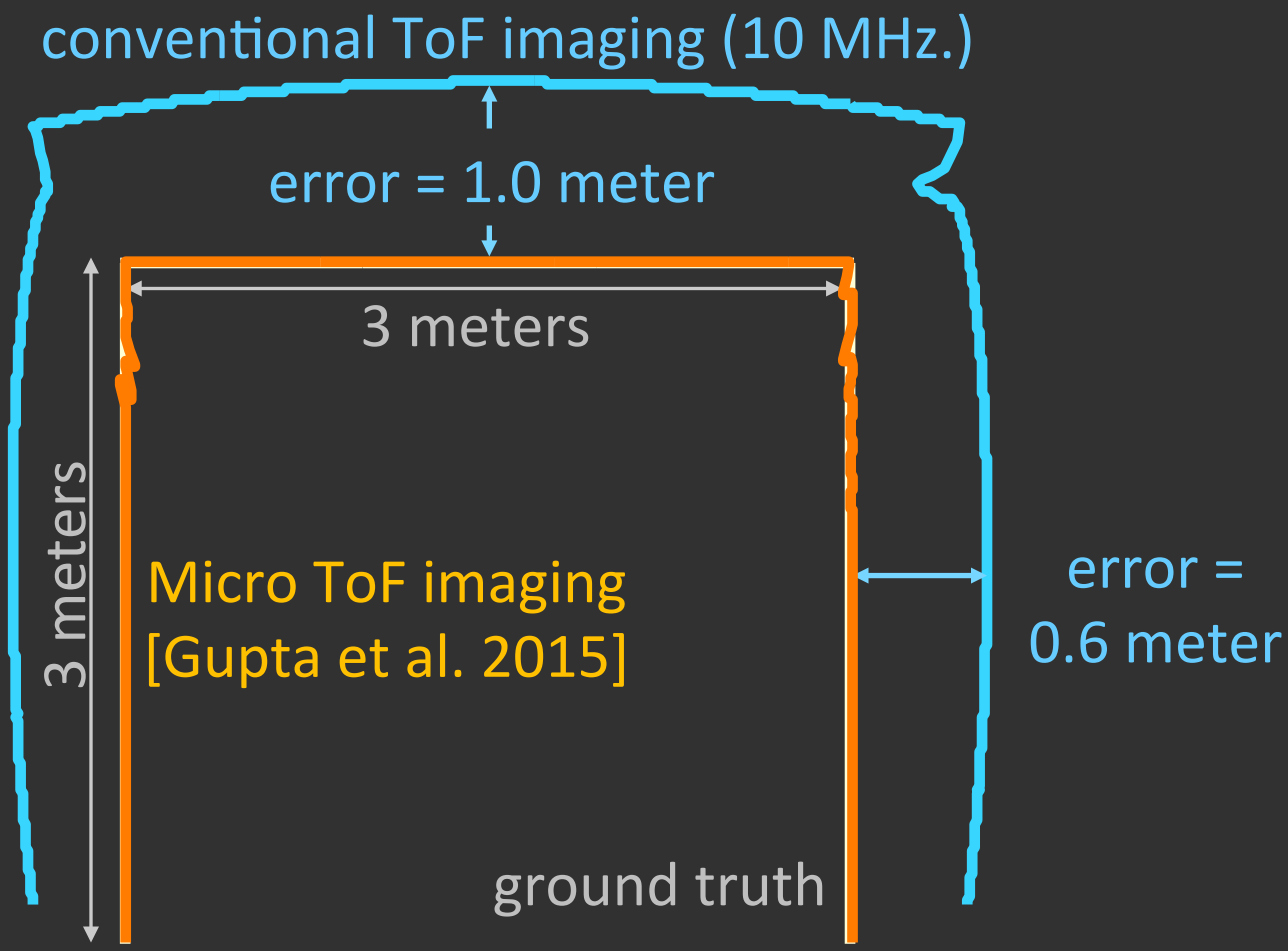
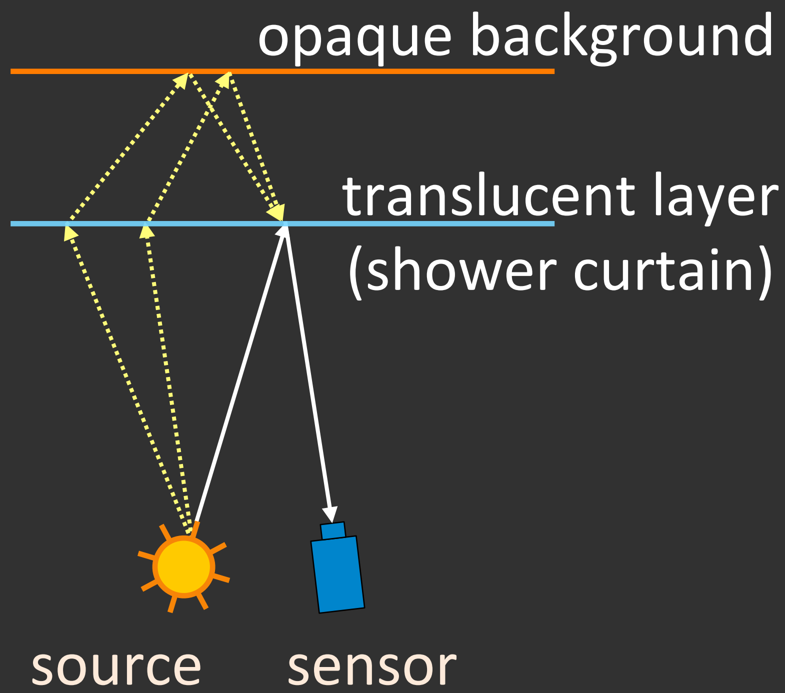


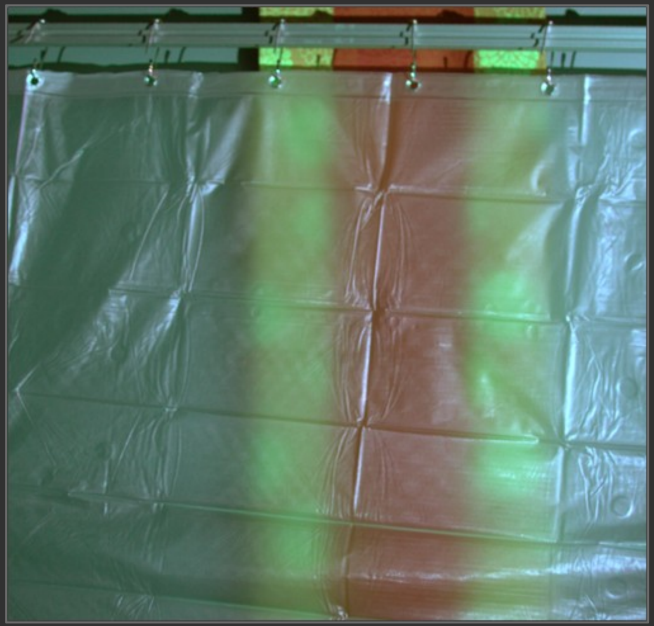
Image courtesy: http://www.annsliee.com/

Room: Shape Comparison



Shower Curtain

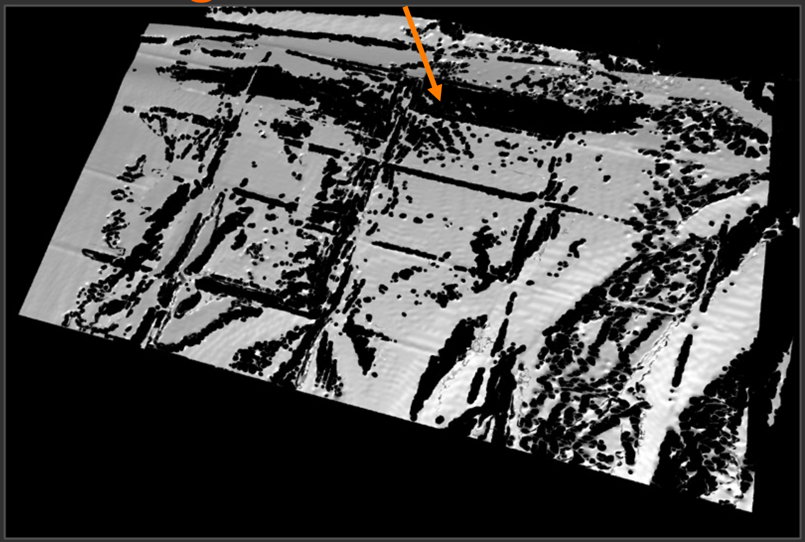




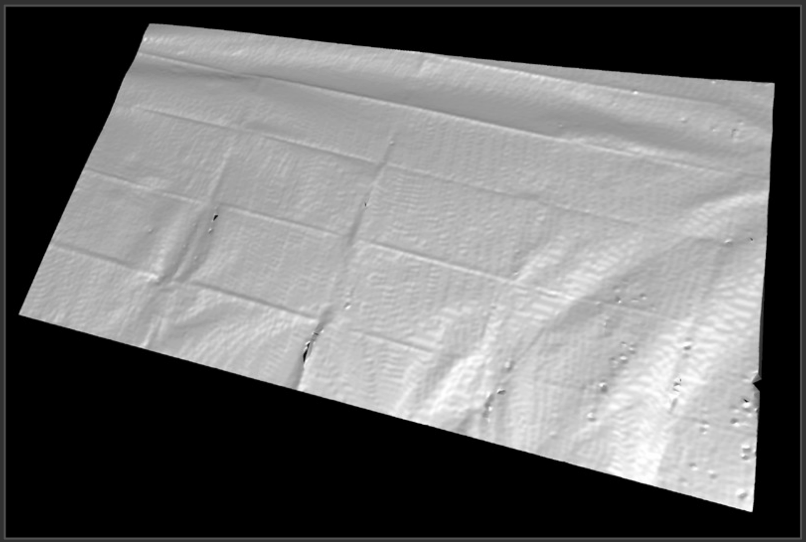
image

Shape Comparison

large errors and holes

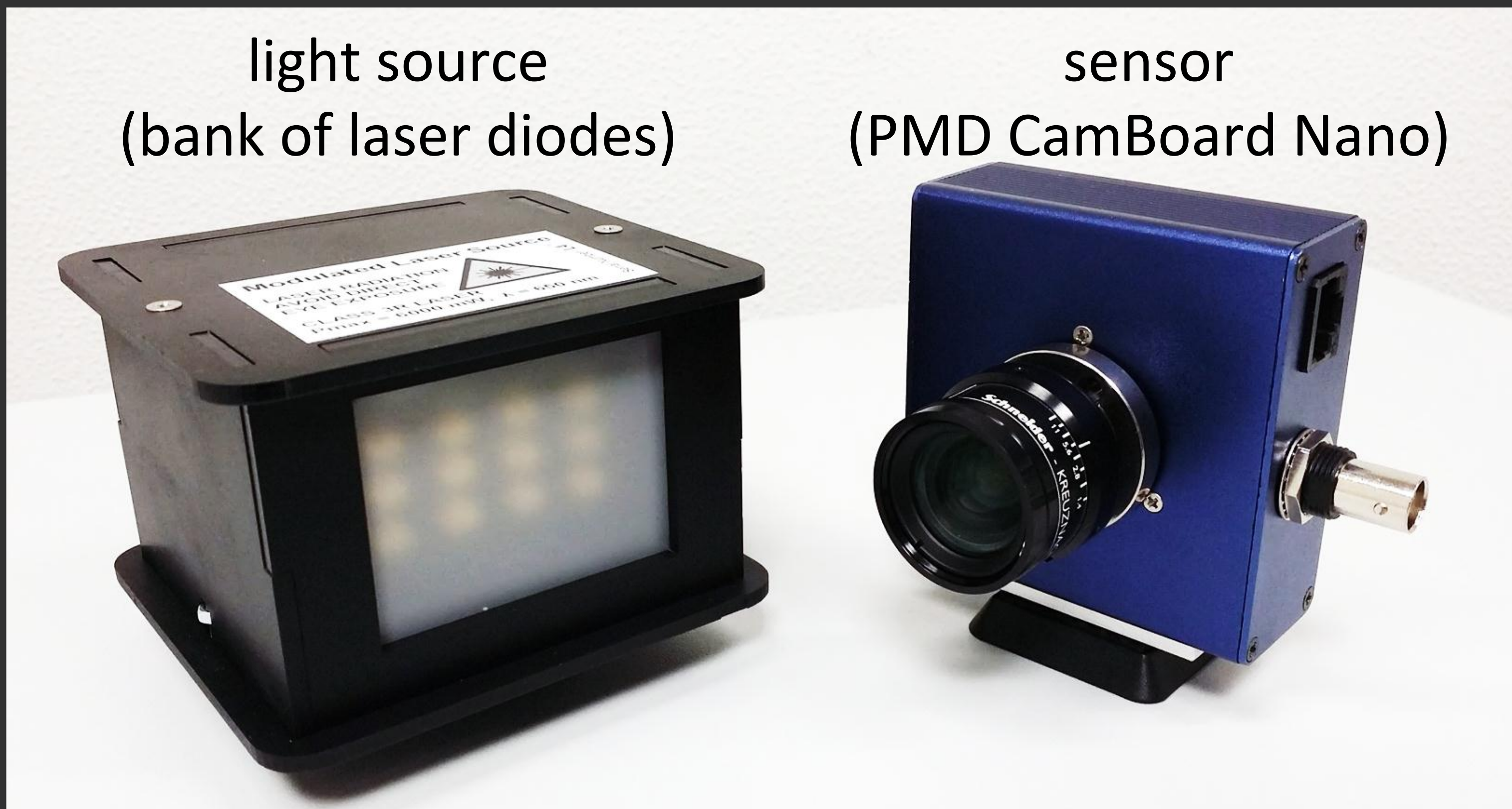


Conventional Phase Shifting



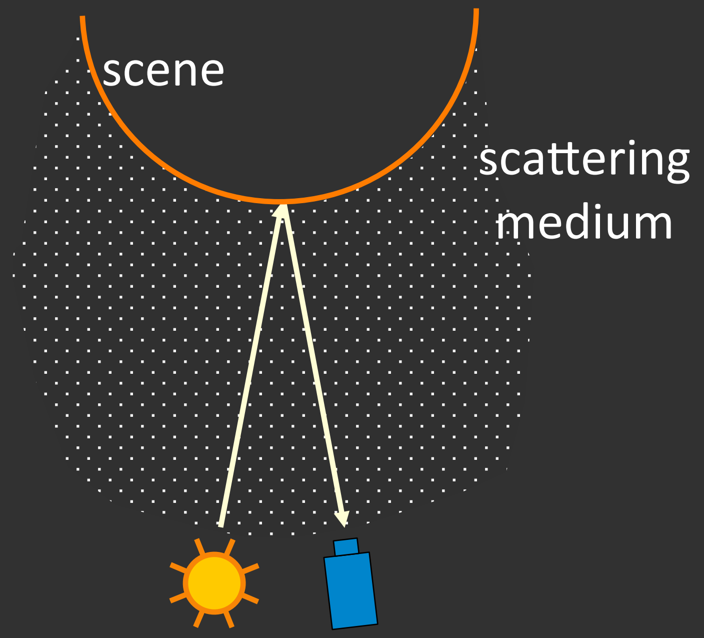
Micro Phase Shifting

Experimental Setup



Maximum System Modulation Frequency = 125 MHz.

Scattering and ToF Imaging

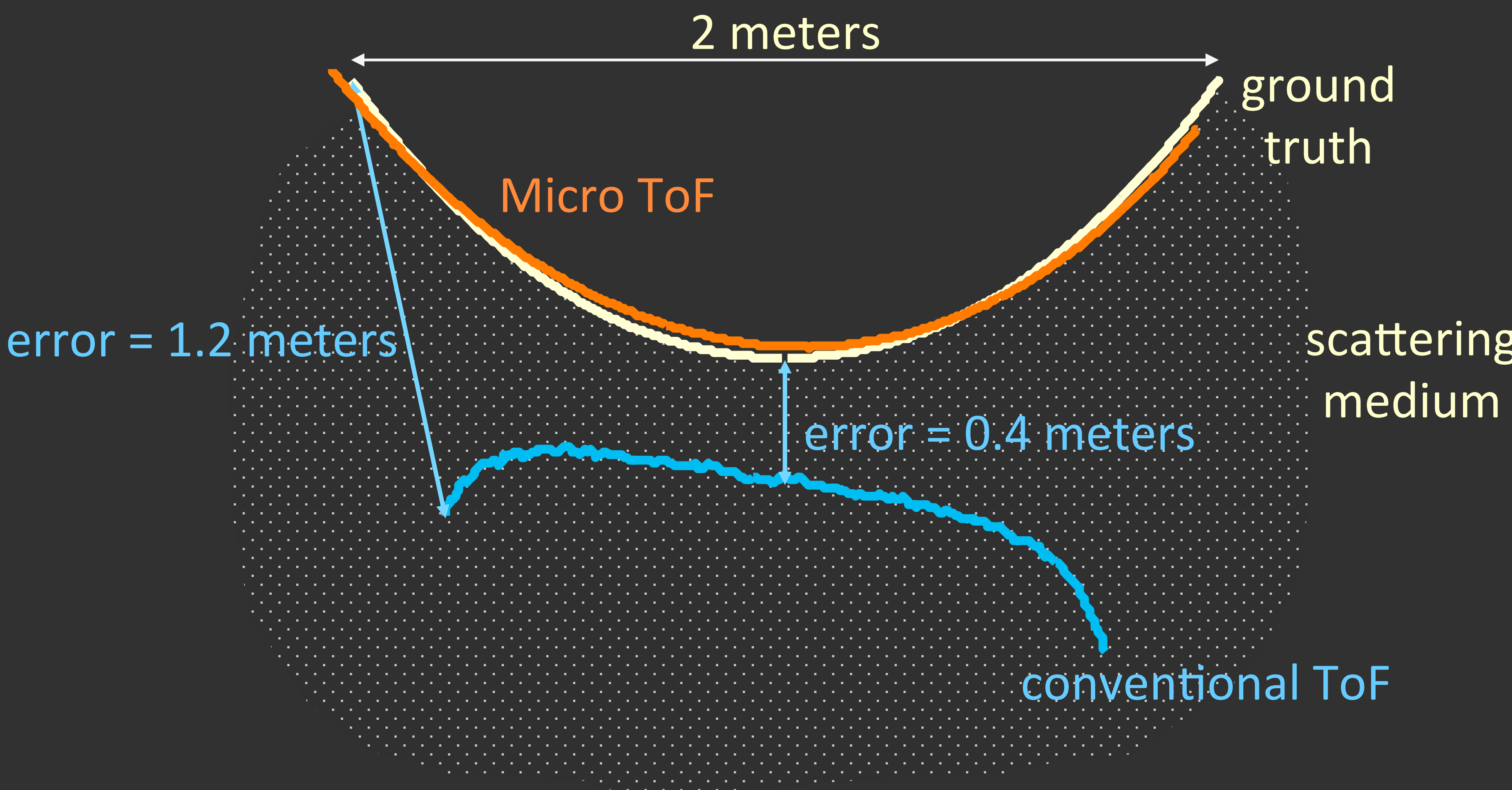


Driving through fog

Driving in a dust storm

Images from: drivinglessonsedinburgh.blogspot.com, ngm.nationalgeographic.com

Sphere: Shape Comparison



Micro ToF Achieves High Accuracy Shape

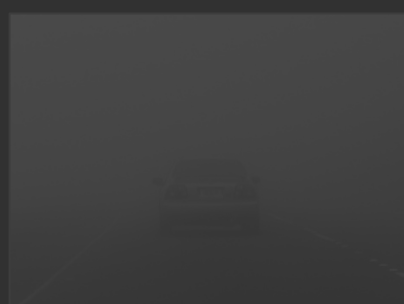
Depths Underestimated

3D Cameras Of The Future

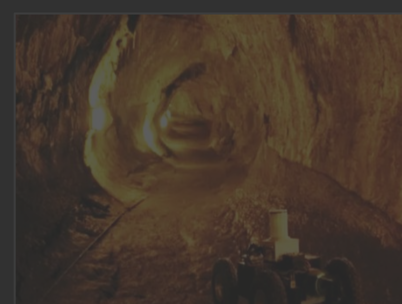
3D Cameras That Work Reliably In-The-Wild

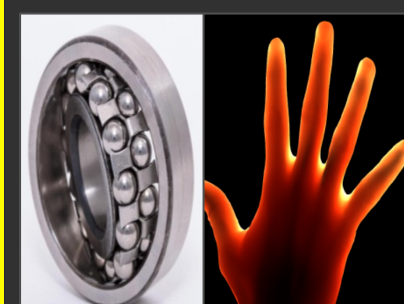
In Every Environment


ambient illumination

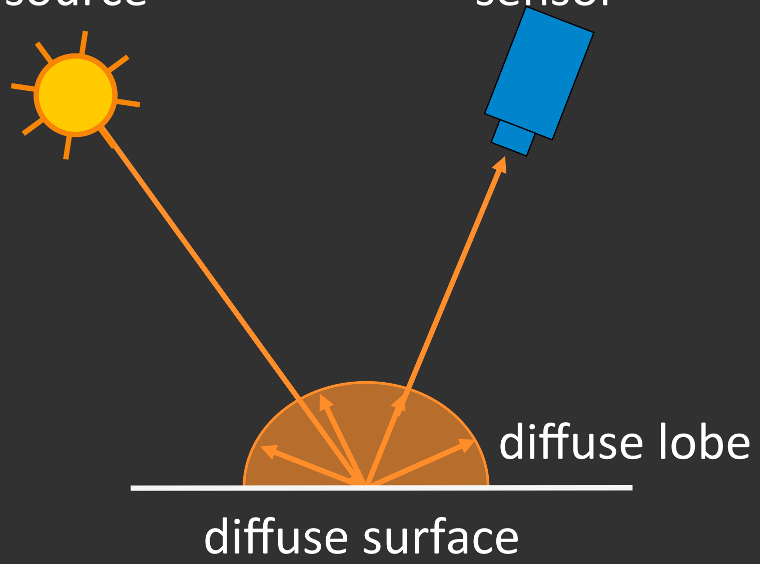

scattering

For Every Scene


geometry

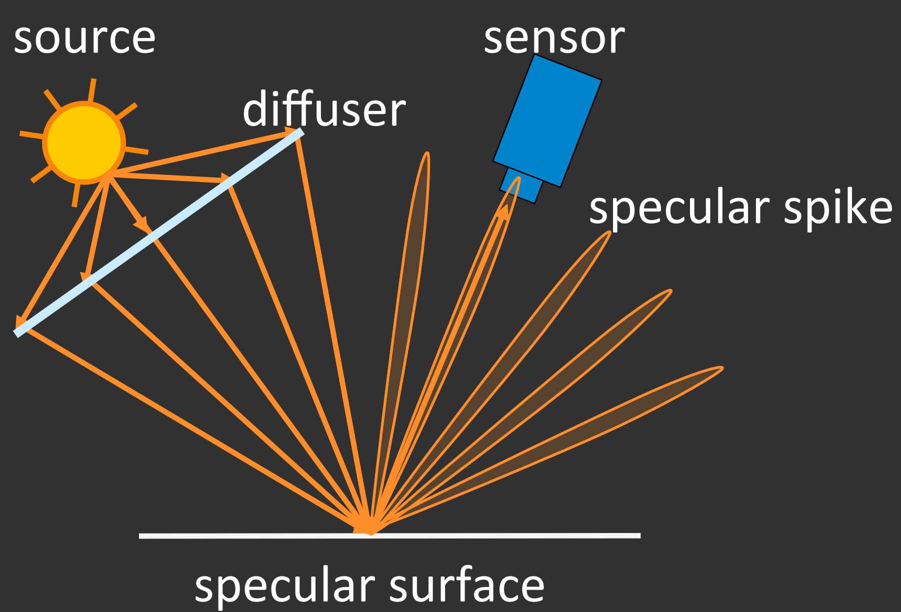

material properties

Challenge of Specular Materials



wood

Challenge of Specular Materials



metal (silver)

$$L_{diff} = E_o \int D(\alpha)\ (n \cdot s_\alpha)\ f(n, v, s_\alpha)\, d\alpha$$

intensity with diffuser

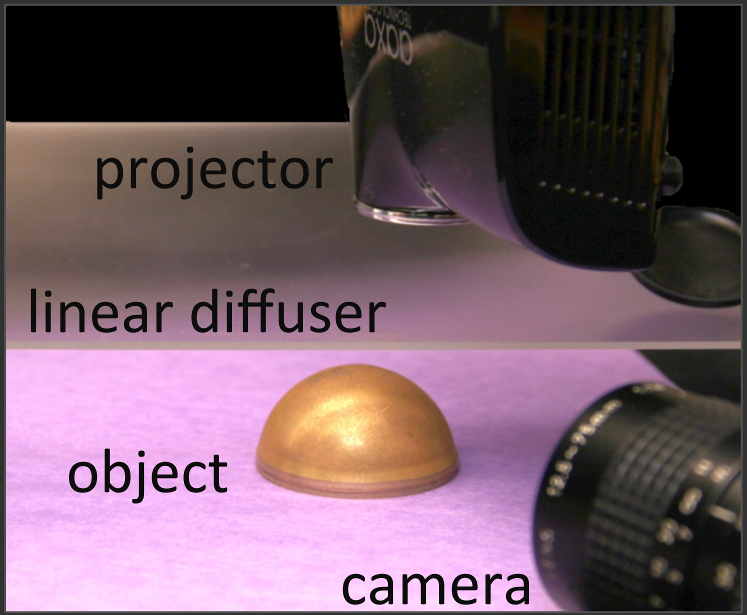
source radiance

integral over directions

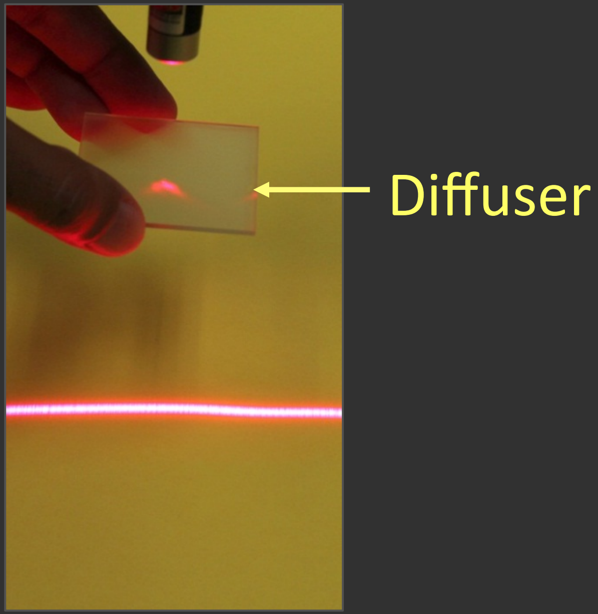
foreshortening

BRDF

3D Imaging Of Optically Challenging Objects



prototype



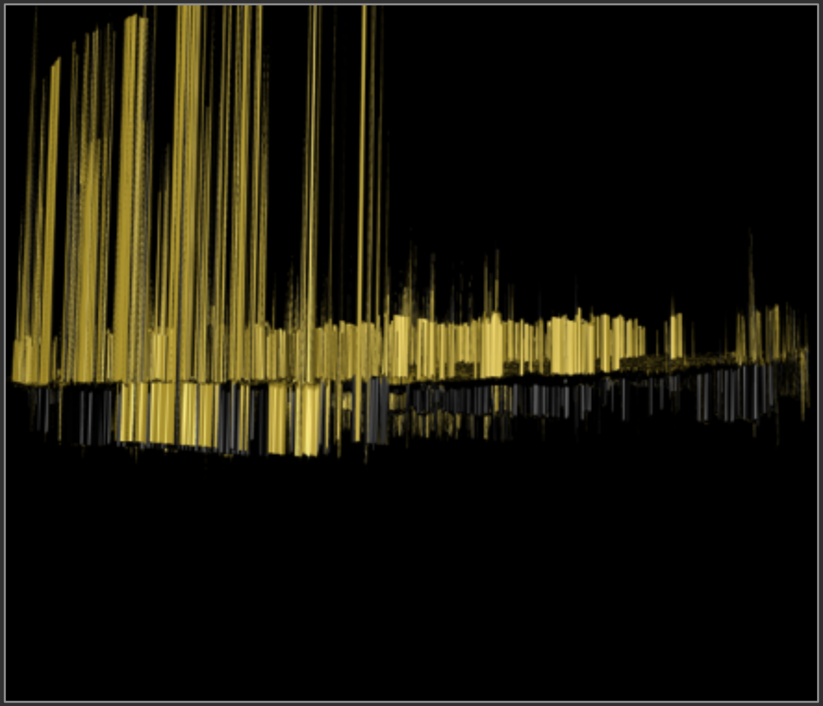
Linear diffuser

Diffuse Structured Light

Coin

Image

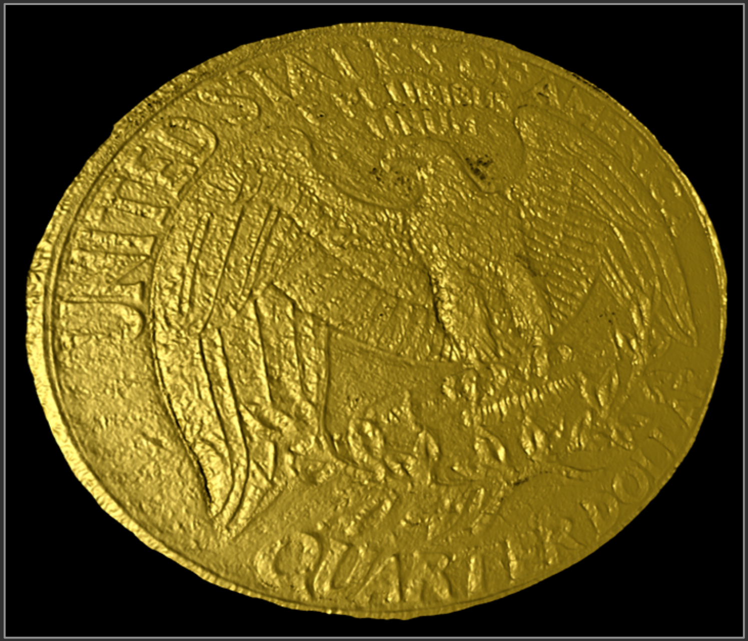
Comparison

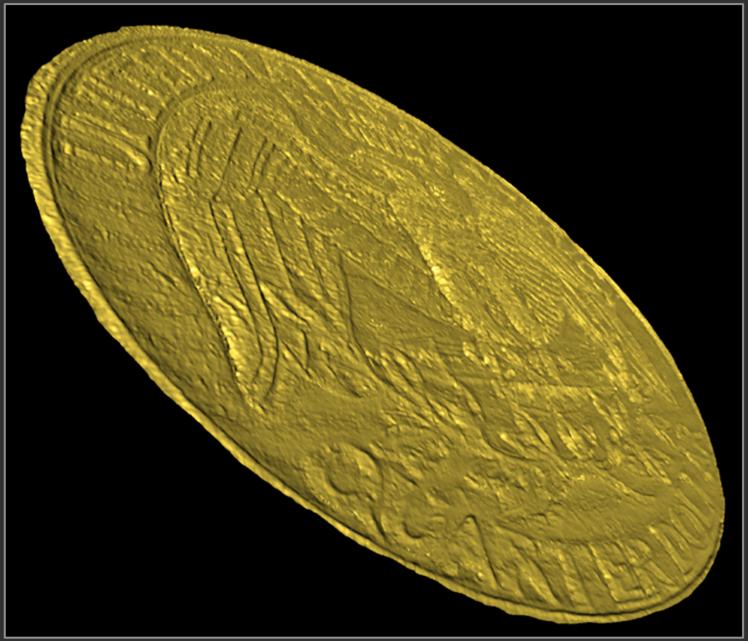


Conventional Structured Light

Diffuse Structured Light
[Nayar and Gupta, ICCP'12]

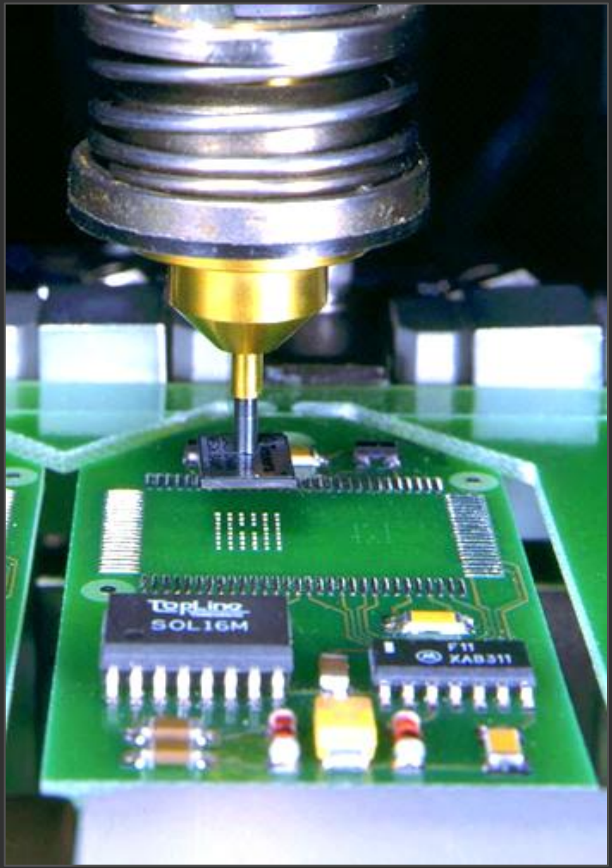
Reconstructions with Our Method





Practical Impact

robotic assembly of machine parts



inspection of printed circuit boards

images courtesy: https://roboticsonline.files.wordpress.com, http://www.btw-inc.com/images/pcb_assy_big.jpg