

Dealing with global illumination



15-463, 15-663, 15-862
Computational Photography
Fall 2020, Lecture 24

Course announcements

- Homework 6 has been posted.
 - Due on Friday, December 11th.
 - Make sure to re-download (no changes to writeup, but removed an erroneous source file).
- If you have not yet scheduled a project checkpointing meeting, please do so ASAP.
- Suggest topics for Friday's reading group.

Computational photography talk next week

- Speaker: Noah Snavely
- Time: Tuesday December 8th, 11:00 AM - noon ET.
- Zoom: see Piazza.
- Title: The Plenoptic Camera
- Abstract: Imagine a futuristic version of Google Street View that could dial up any possible place in the world, at any possible time. Effectively, such a service would be a recording of the plenoptic function—the hypothetical function described by Adelson and Bergen that captures all light rays passing through space at all times. While the plenoptic function is completely impractical to capture in its totality, every photo ever taken represents a sample of this function. I will present recent methods we've developed to reconstruct the plenoptic function from sparse space-time samples of photos—including Street View itself, as well as tourist photos of famous landmarks. The results of this work include the ability to take a single photo and synthesize a full dawn-to-dusk timelapse video, as well as compelling 4D view synthesis capabilities where a scene can simultaneously be explored in space and time.
- Bio: Noah Snavely is an associate professor of Computer Science at Cornell University and Cornell Tech, and also a researcher at Google Research. Noah's research interests are in computer vision and graphics, in particular 3D understanding and depiction of scenes from images. Noah is the recipient of a PECASE, a Microsoft New Faculty Fellowship, an Alfred P. Sloan Fellowship, and a SIGGRAPH Significant New Researcher Award.

Overview of today's lecture

- Leftover from time-of-flight imaging.
- Direct and global illumination.
- Direct-global separation using high-frequency illumination.
- Back to structured light.

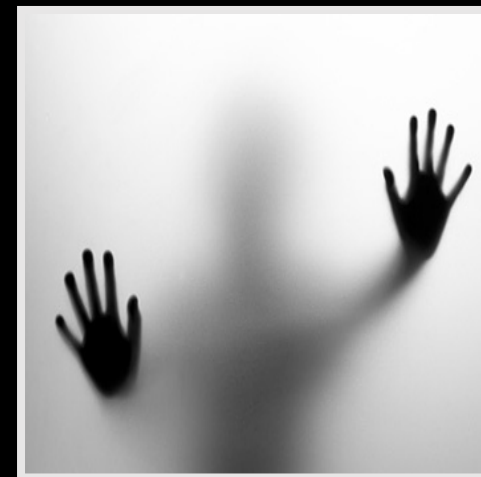
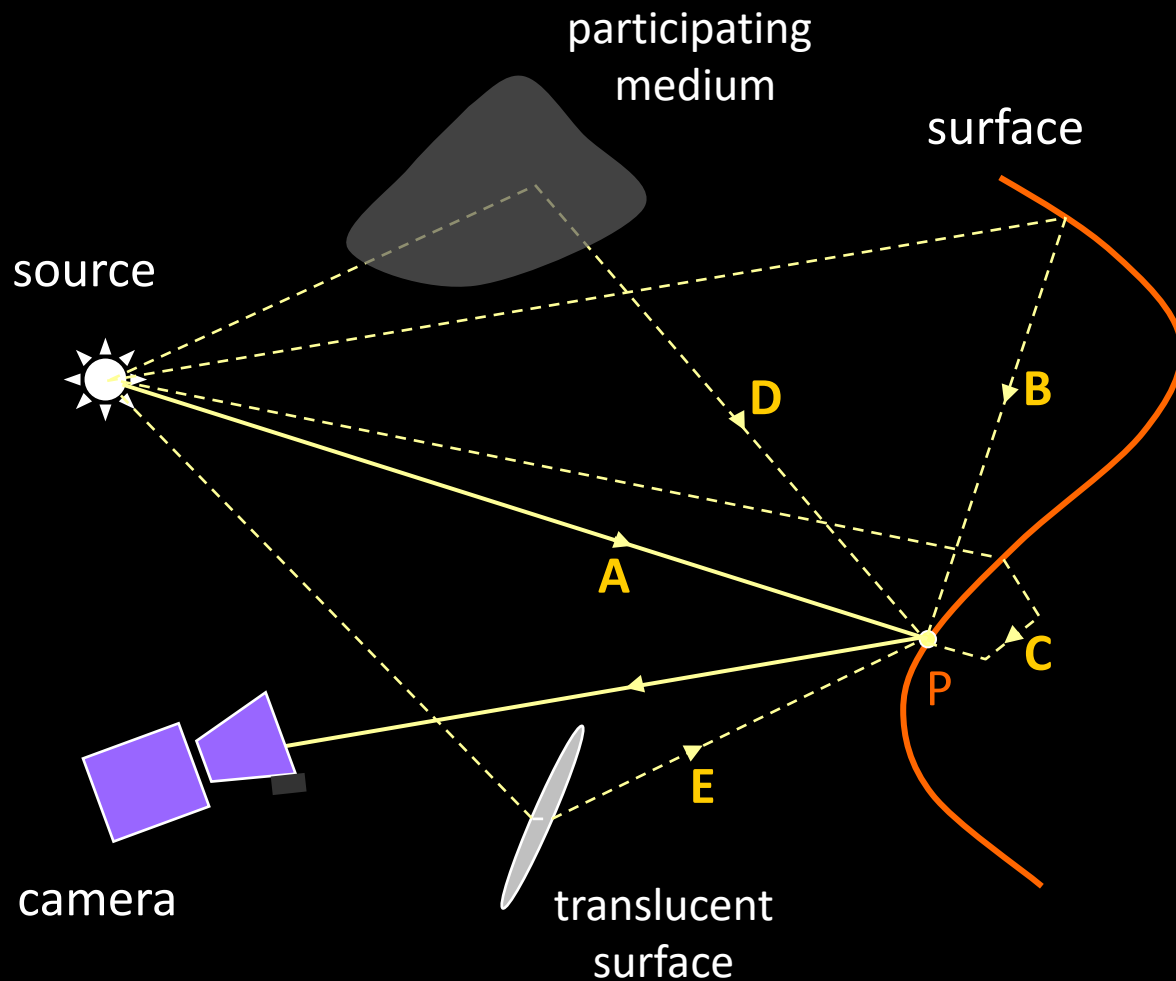
Slide credits

These slides were directly adapted from:

- Shree Nayar (Columbia).
- Matthew O'Toole (CMU).
- Supreeth Achar (Google, formerly CMU).
- Mohit Gupta (Wisconsin).

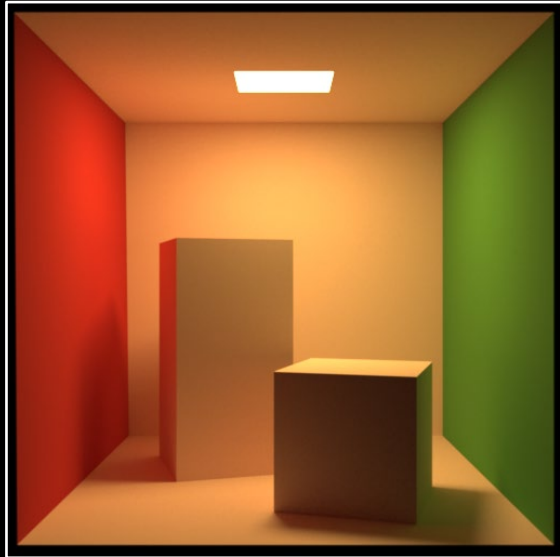
Direct and global illumination

Direct and Global Illumination



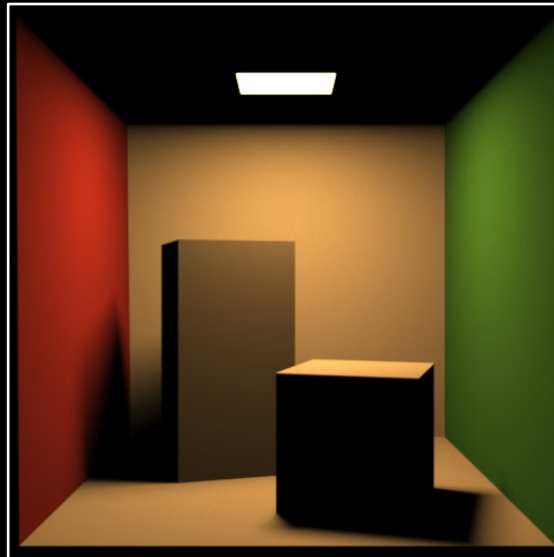
- A : Direct
- B : Interreflection
- C : Subsurface
- D : Volumetric
- E : Diffusion

Easy to separate in a renderer



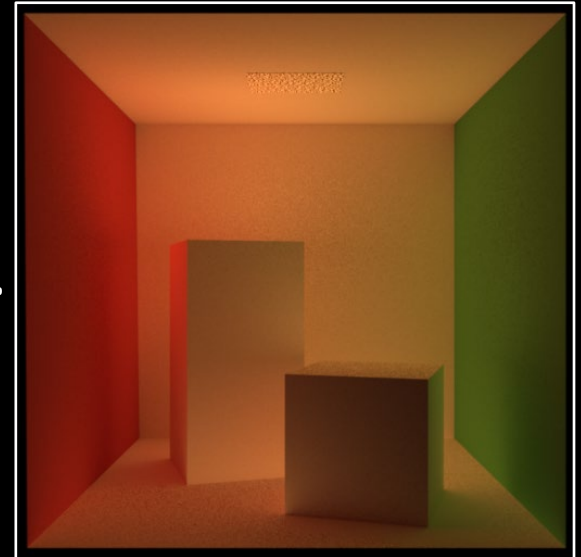
full image

=



direct

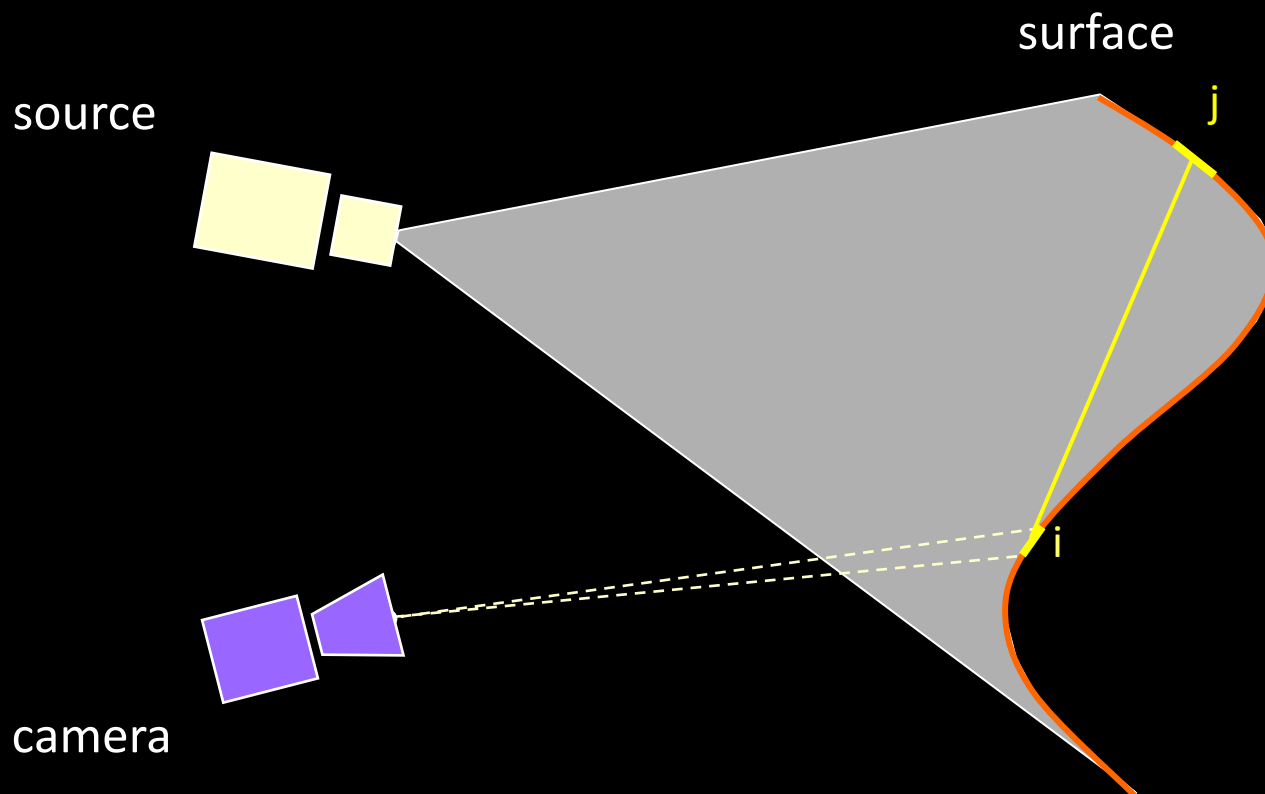
+



global

Direct-global separation using high-frequency illumination

Direct and Global Components: Interreflections



$$L[c, i] = L_d[c, i] + L_g[c, i]$$

radiance

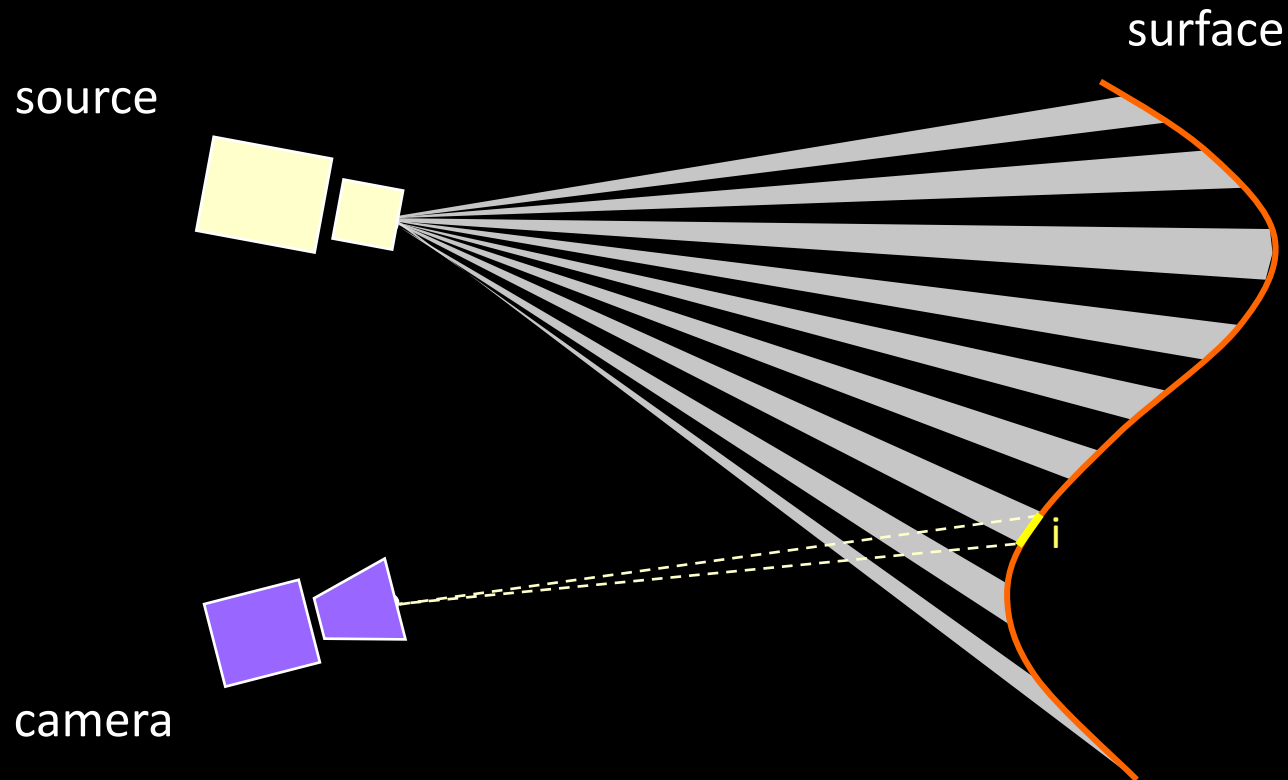
direct

global

$$L_g[c, i] = \sum_P A[i, j] L[i, j]$$

BRDF and geometry

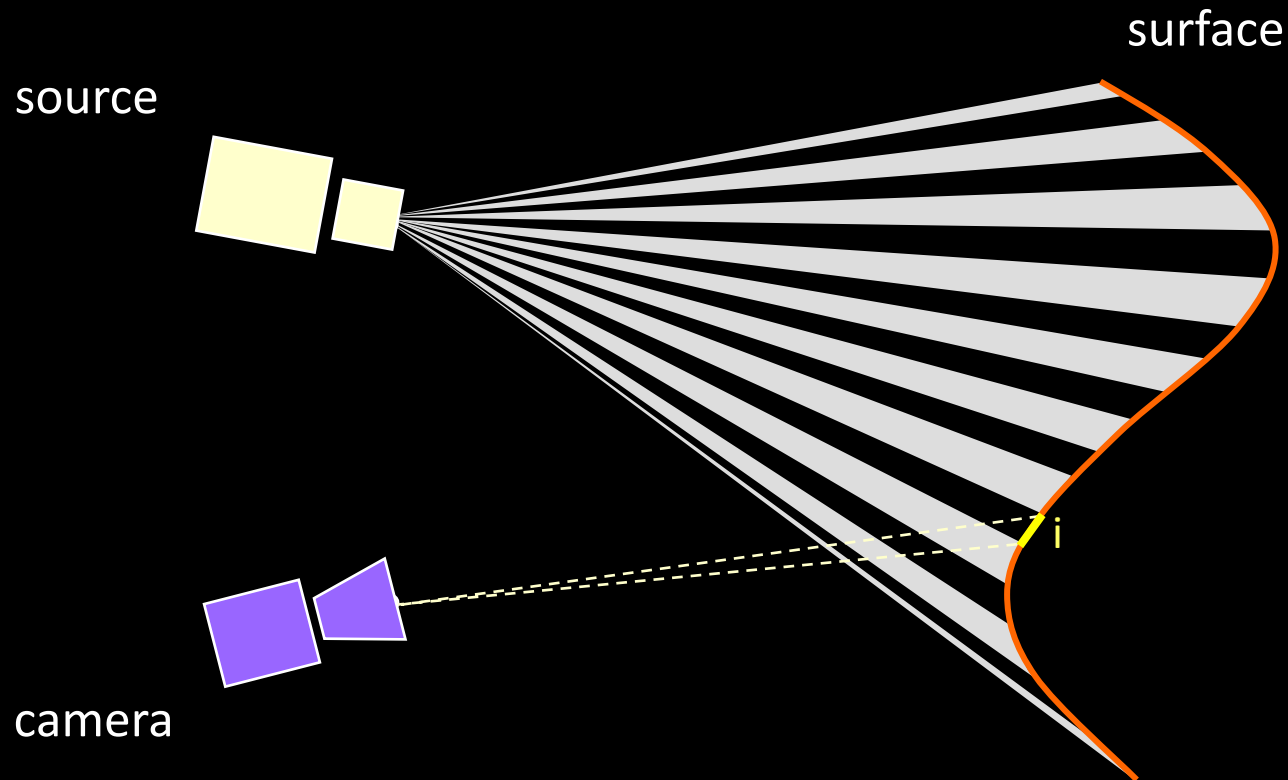
High Frequency Illumination Pattern



$$L^+[c,i] = L_d[c,i] + \alpha L_g[c,i]$$

fraction of activated source elements

High Frequency Illumination Pattern



$$L^+[c, i] = L_d[c, i] + \alpha L_g[c, i]$$

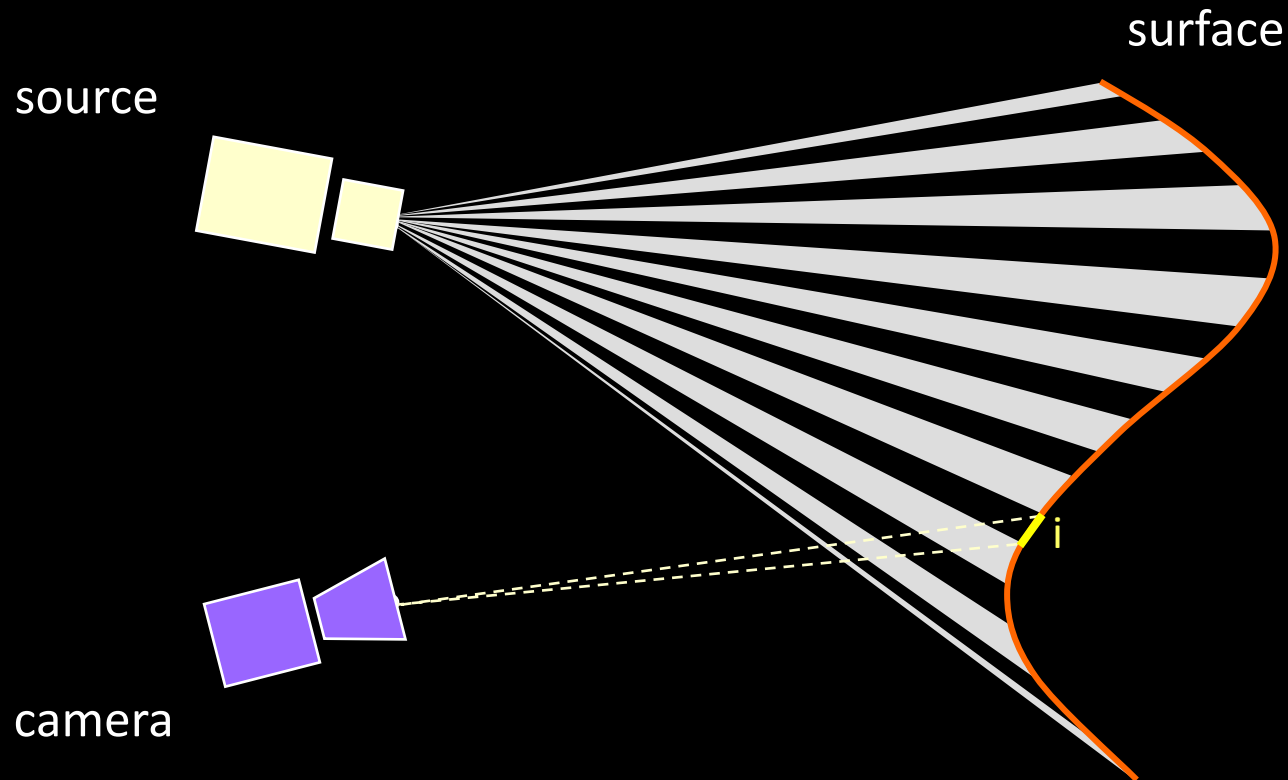
$$L^-[c, i] = (1 - \alpha) L_g[c, i]$$

fraction of activated source elements

Important insight:

- Global illumination is approximately invariant to high-frequency lighting.
- You can think of global illumination effects as a low-pass filter.

High Frequency Illumination Pattern



$$L^+[c, i] = L_d[c, i] + \alpha L_g[c, i]$$

$$\bar{L}^-[c, i] = (1 - \alpha) L_g[c, i]$$

What does approximate invariance mean in this case?

Separation from Two Images

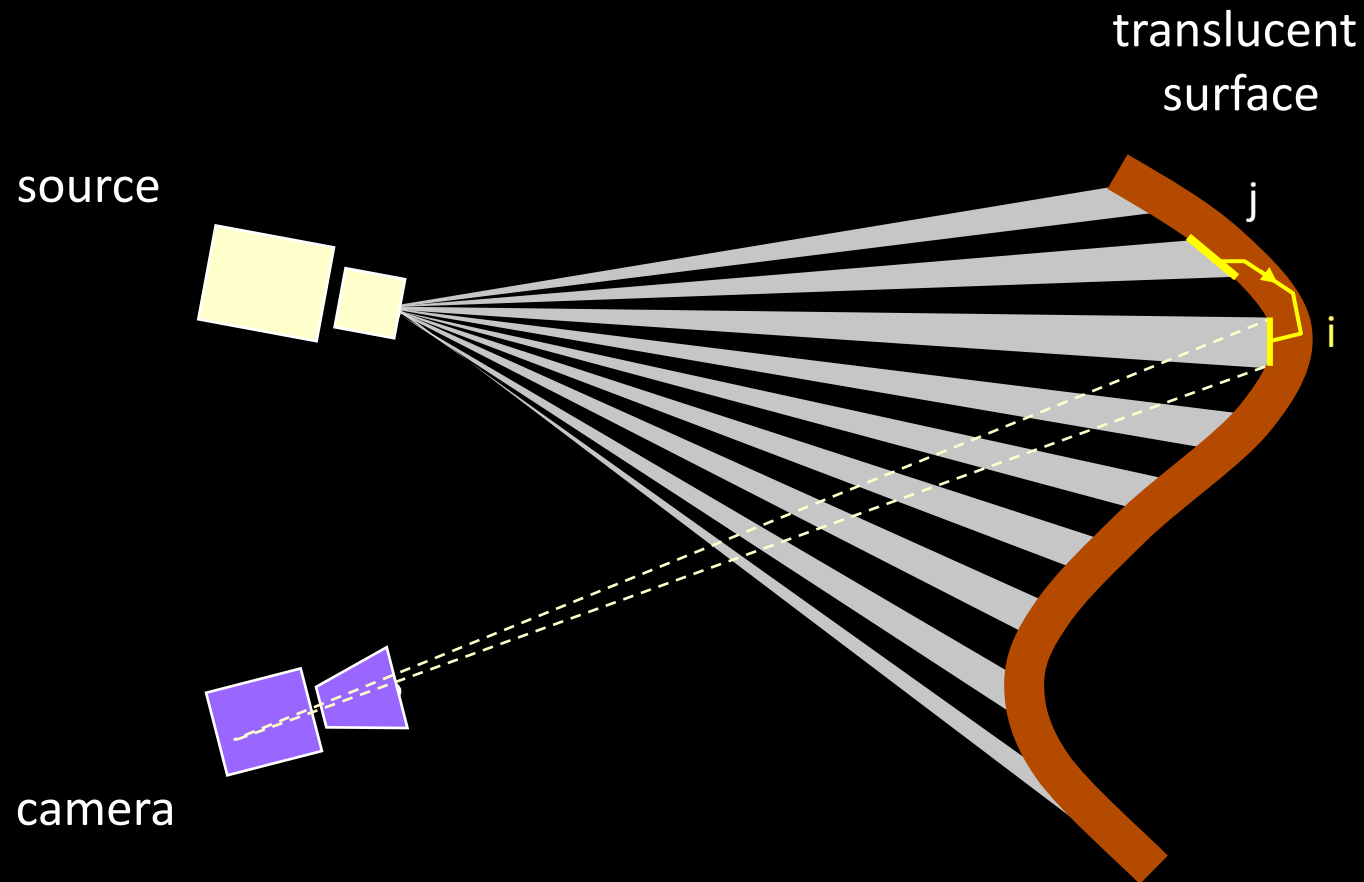
$$\alpha = \frac{1}{2}:$$

$$L_d = L_{\max} - L_{\min}, \quad L_g = 2L_{\min}$$

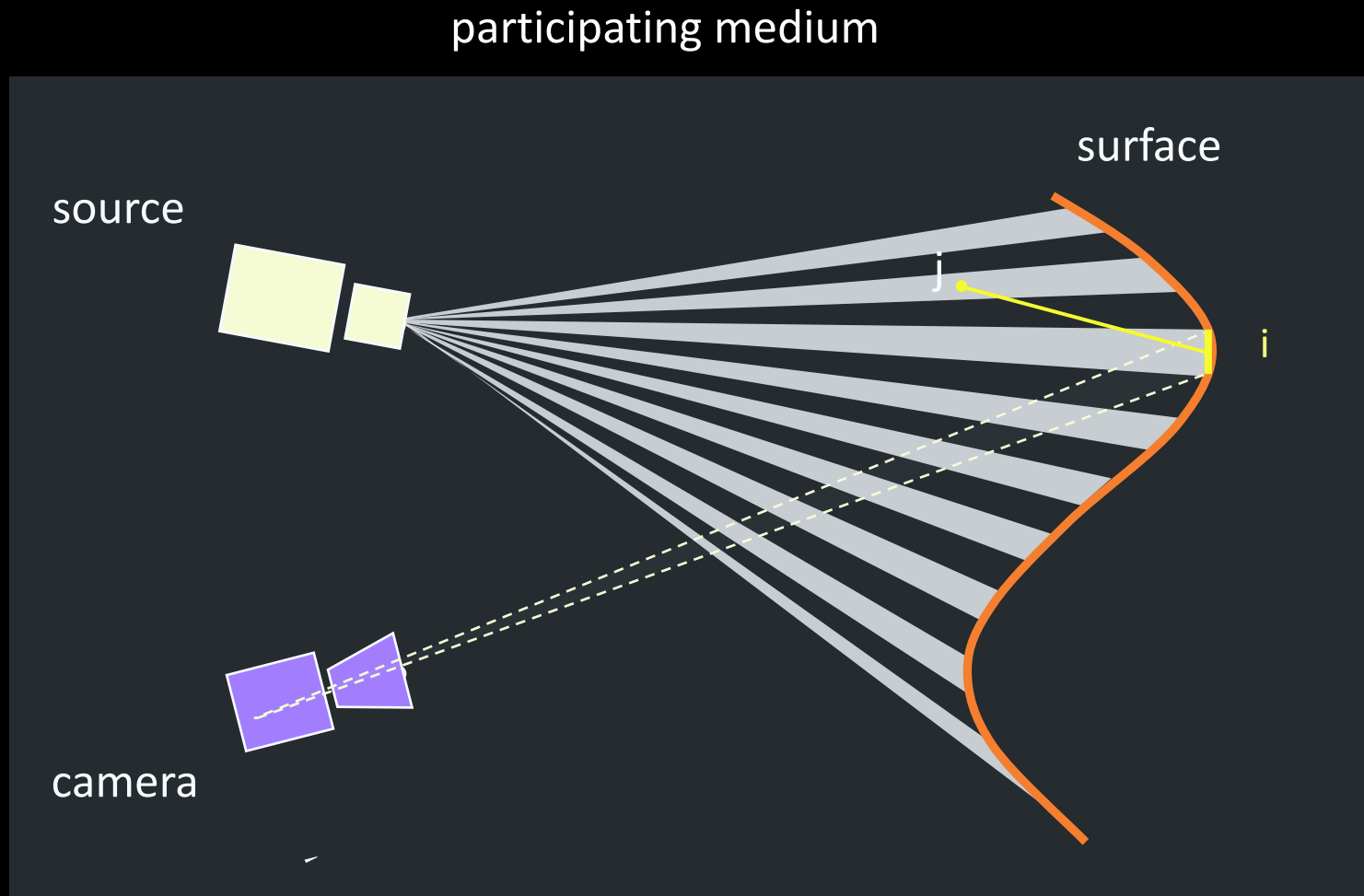
direct

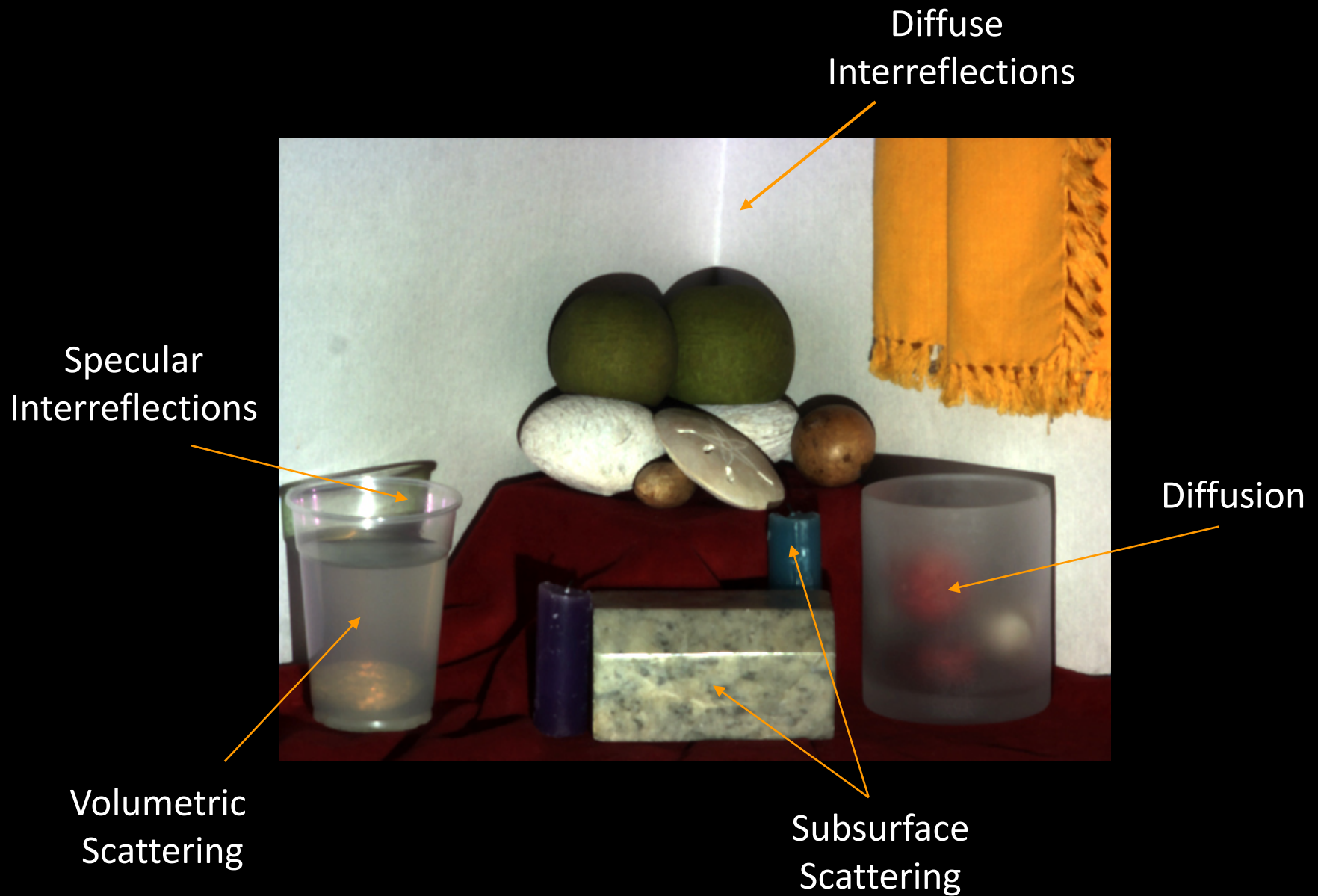
global

Other Global Effects: Subsurface Scattering

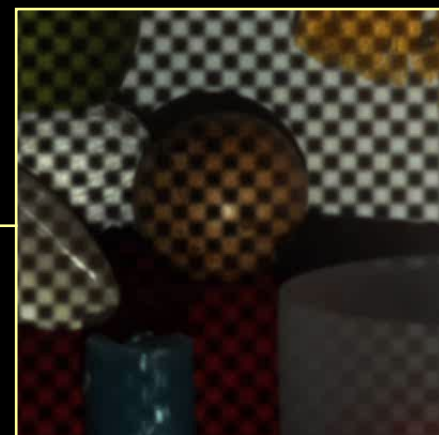


Other Global Effects: Volumetric Scattering





Scene



Direct

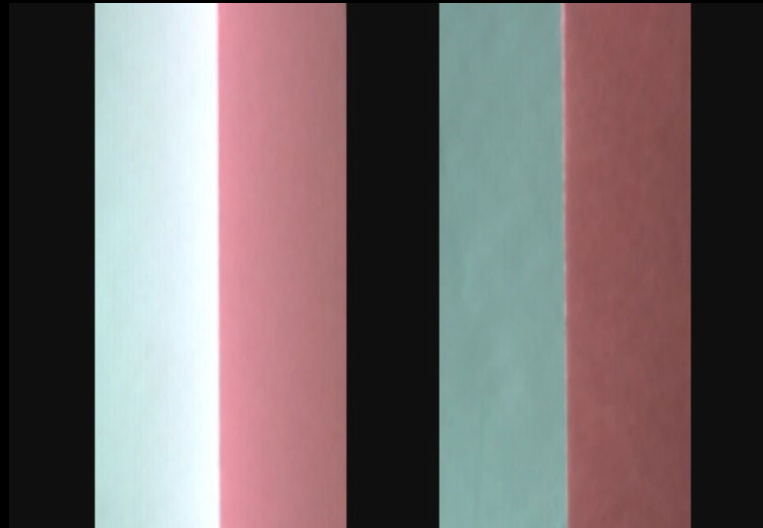


Global

V-Grooves: Diffuse Interreflections

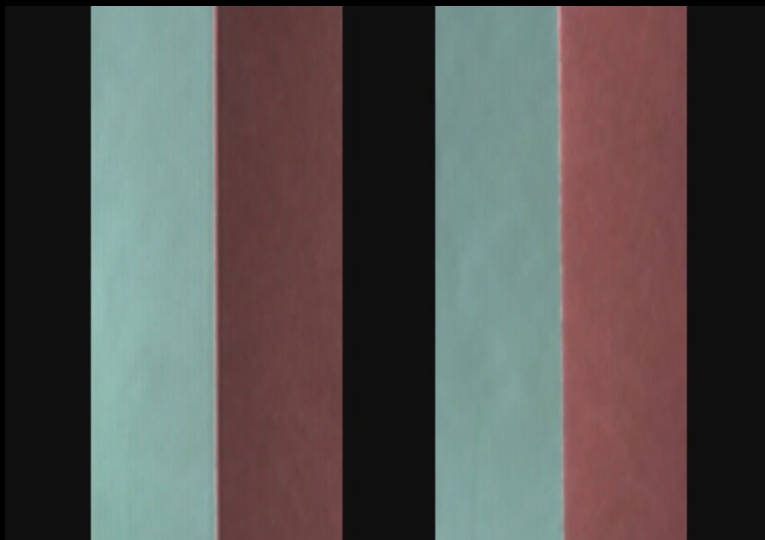
concave

convex

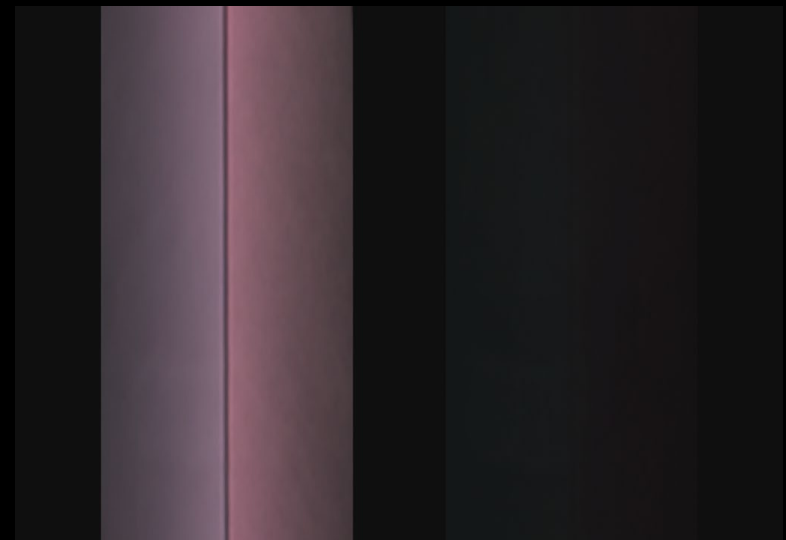


Psychophysics:

Gilchrist 79, Bloj et al. 04



Direct



Global

Real World Examples:

Can You Guess the Images?

Eggs: Diffuse Interreflections

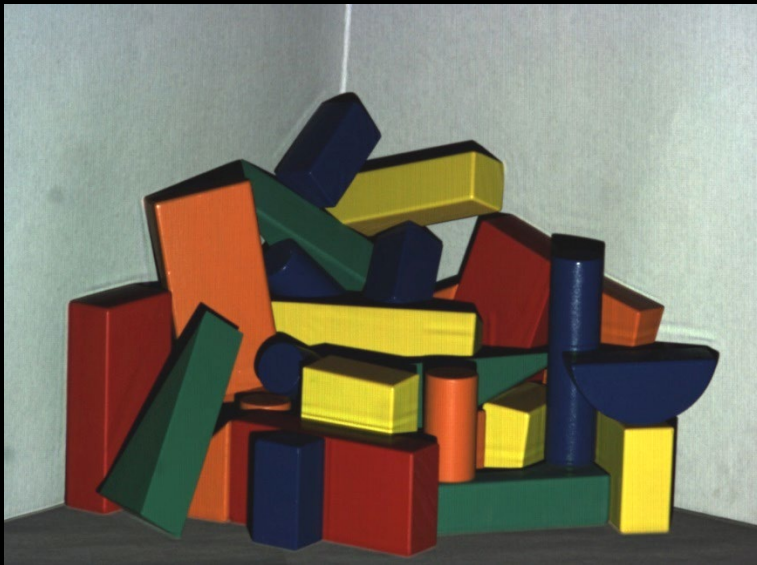
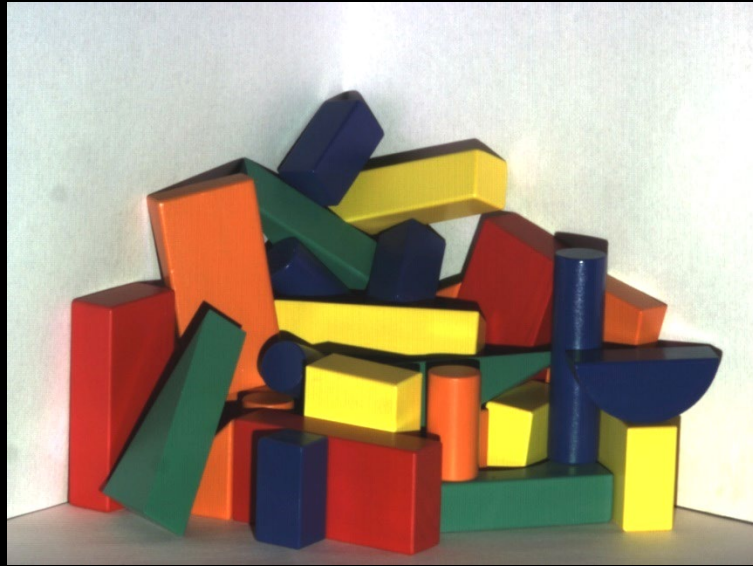


Direct



Global

Wooden Blocks: Specular Interreflections

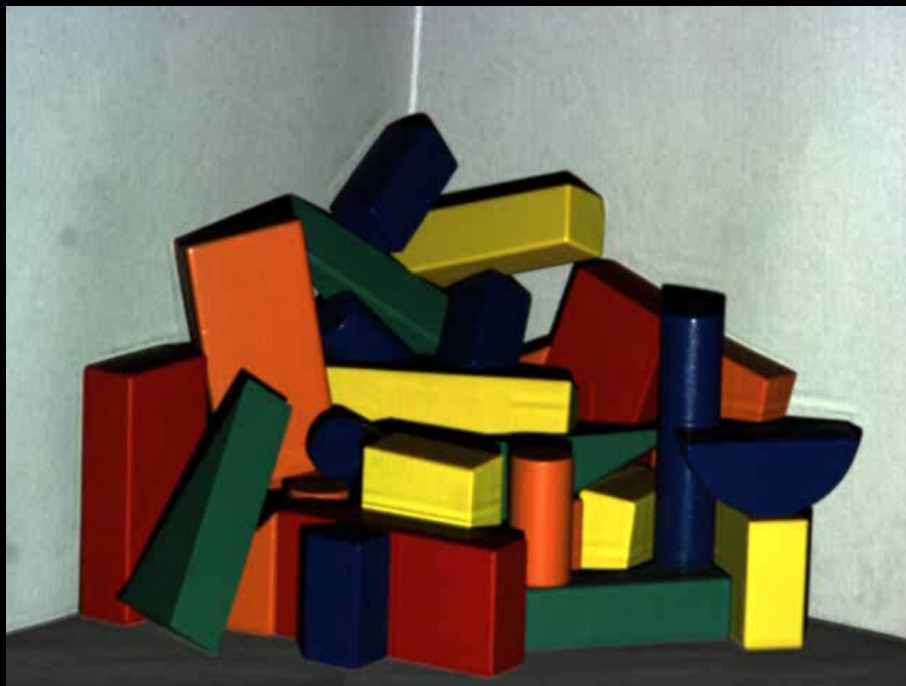


Direct

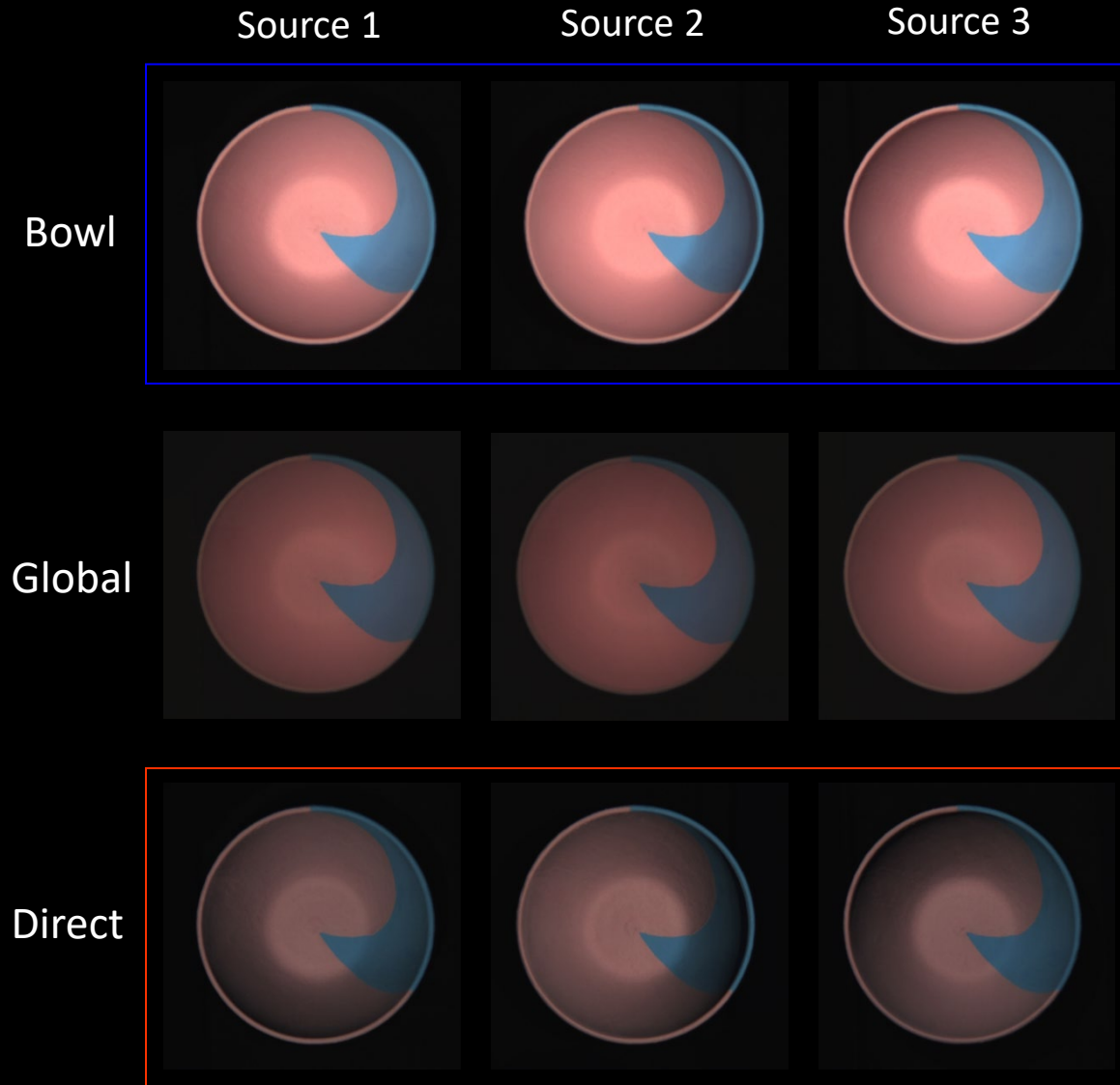


Global

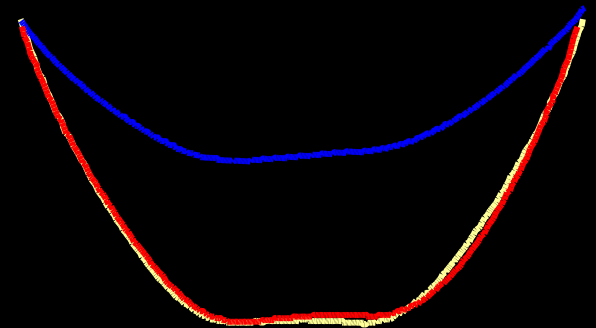
Novel Images



Photometric Stereo using Direct Images

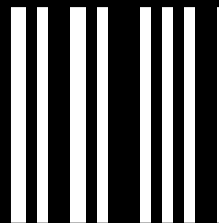


Shape



Variants of Separation Method

- Coded Structured Light



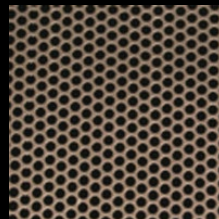
- Shifted Sinusoids



- Shadow of Line Occluder



- Shadow of Mesh Occluders



Building Corner



Stick



Shadow

3D from Shadows:
Bouguet and Perona 99

$$L_d = L_{\max} - L_{\min} , \quad L_g = L_{\min}$$

direct

global

Building Corner

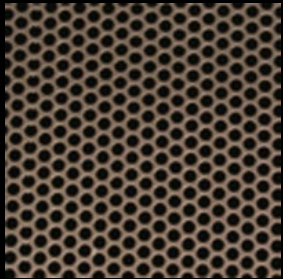


Direct



Global

Shower Curtain: Diffuser



Mesh



Shadow

$$L_d = L_{\max} - \beta L_{\min}, \quad L_g = \beta L_{\min}$$

direct

global

Shower Curtain: Diffuser

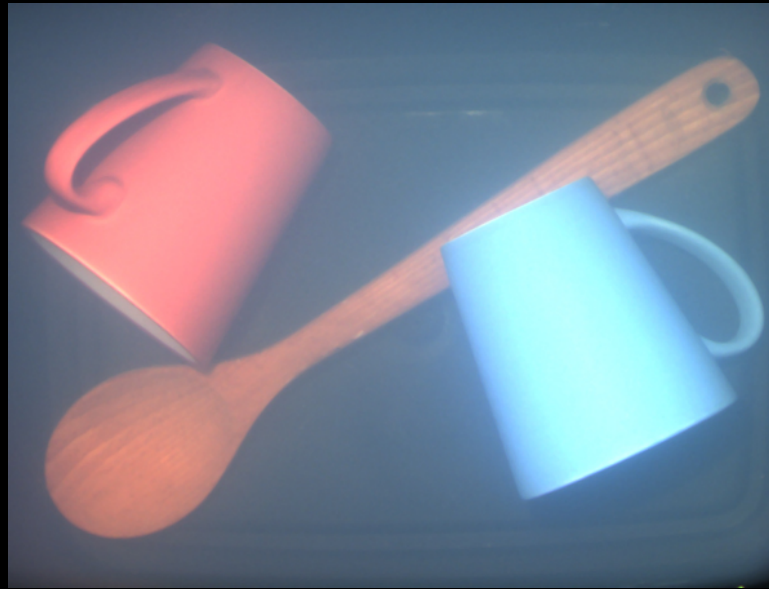


Direct

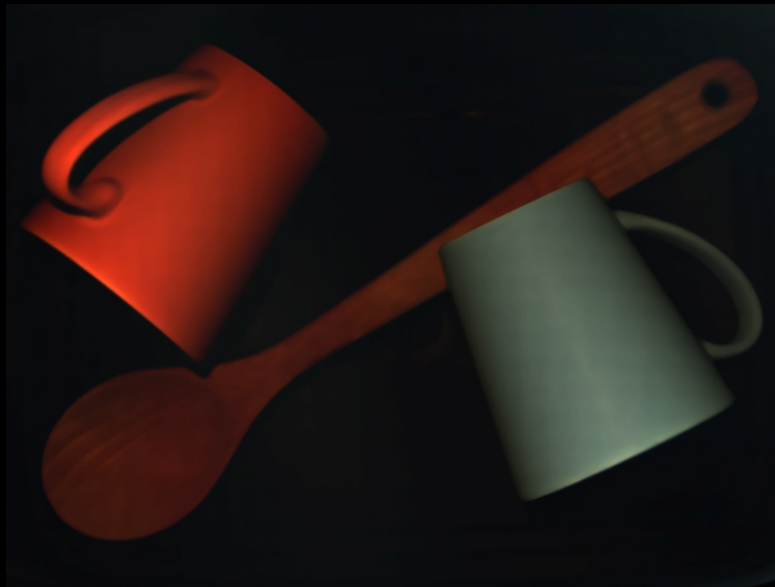


Global

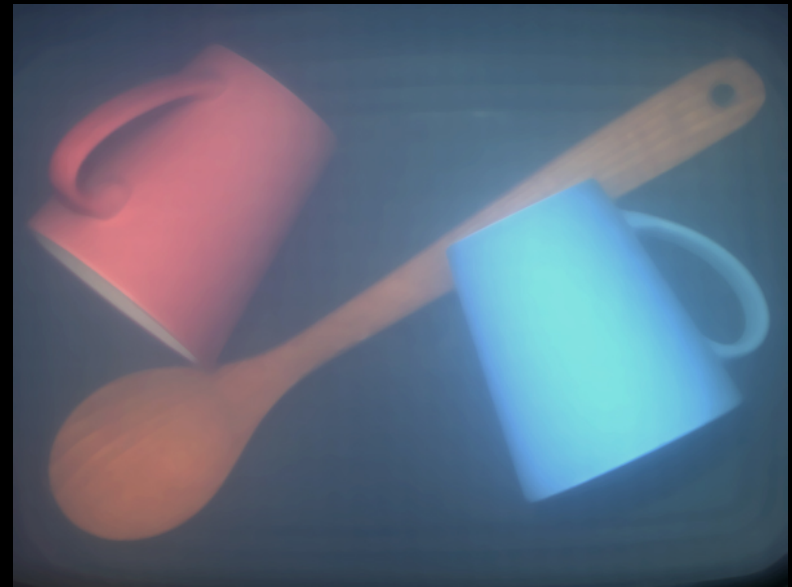
Kitchen Sink: Volumetric Scattering



Volumetric Scattering:
Chandrasekar 50, Ishimaru 78



Direct

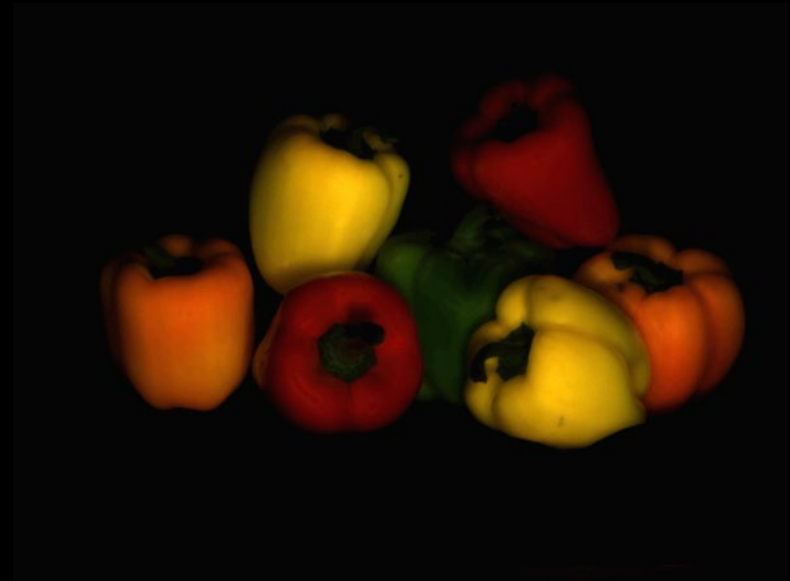


Global

Peppers: Subsurface Scattering

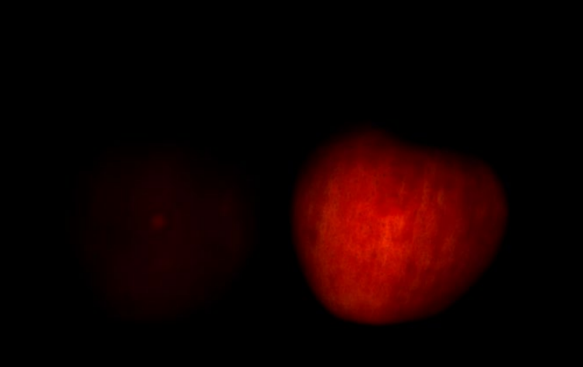
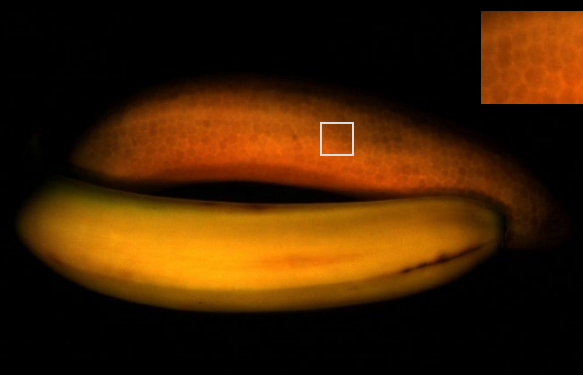
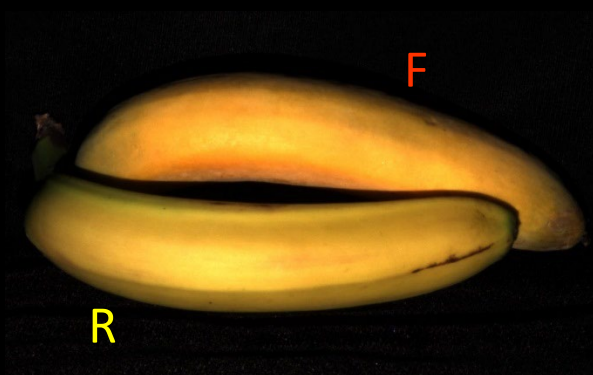


Direct



Global

Real Fake



Direct

Global

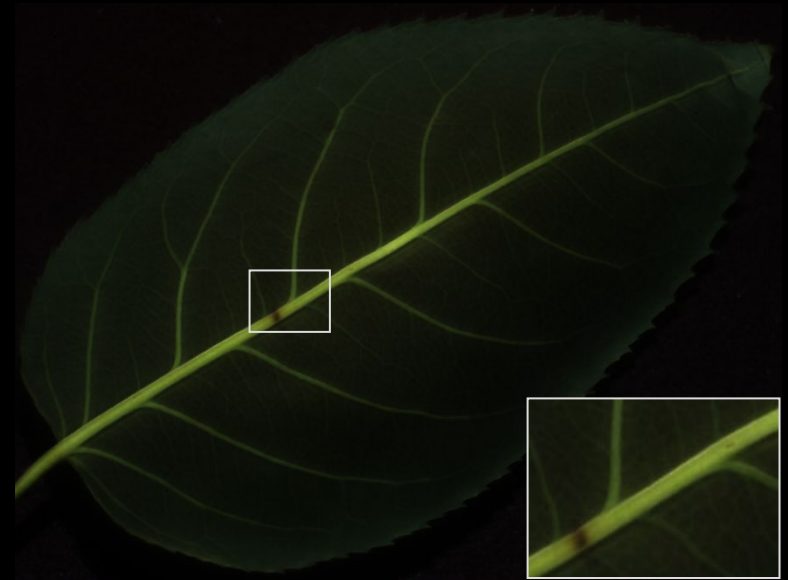
Tea Rose Leaf



Leaf Anatomy: Purves et al. 03



Direct

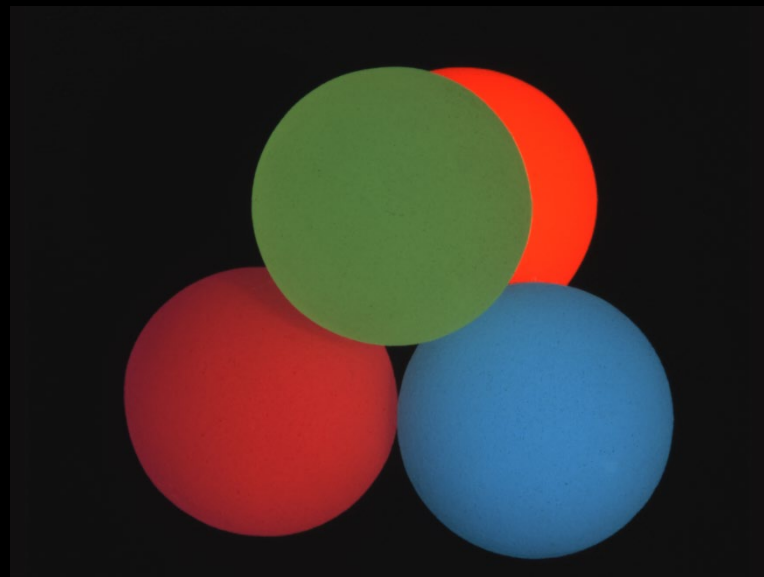


Global

Translucent Rubber Balls

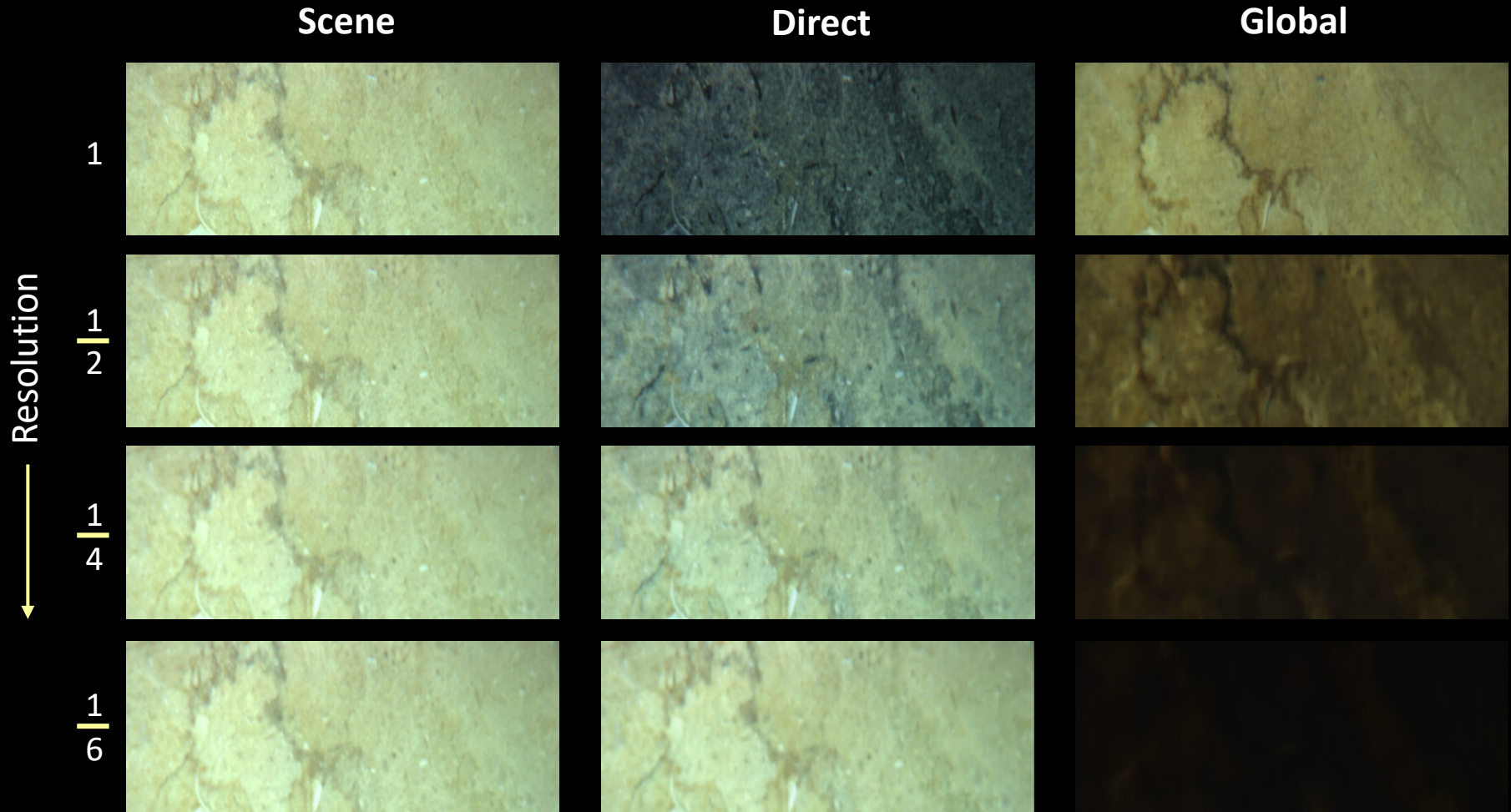


Direct



Global

Marble: When BSSRDF becomes BRDF



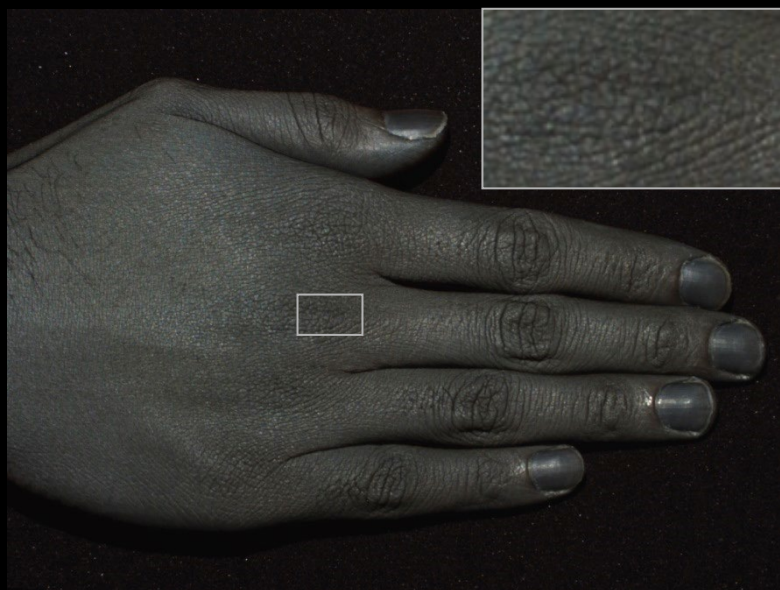
Subsurface Measurements:

Jensen et al. 01, Goesele et al. 04

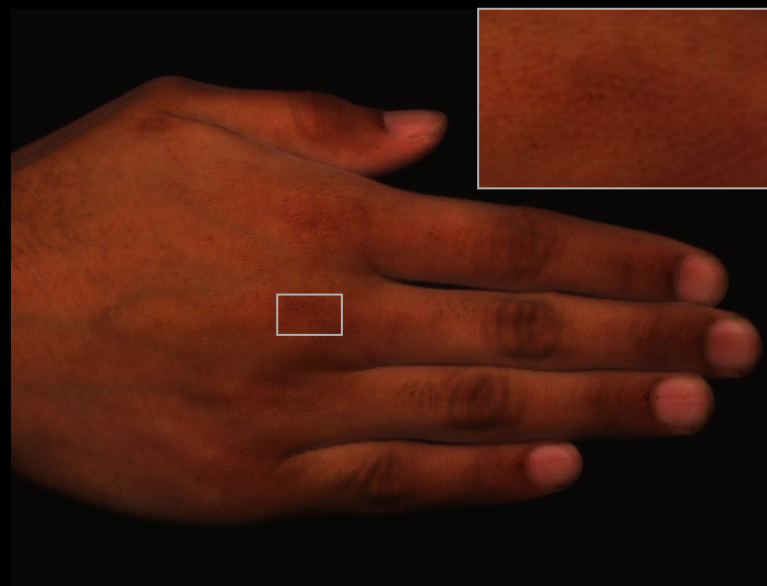
Hand



Skin: Hanrahan and Krueger 93,
Uchida 96, Haro 01, Jensen et al. 01,
Igarashi et al. 05, Weyrich et al. 05



Direct



Global

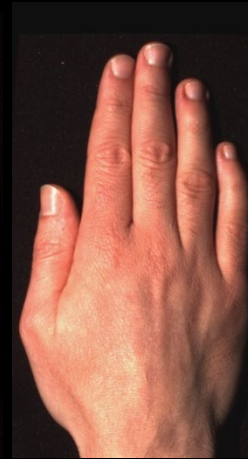
Hands



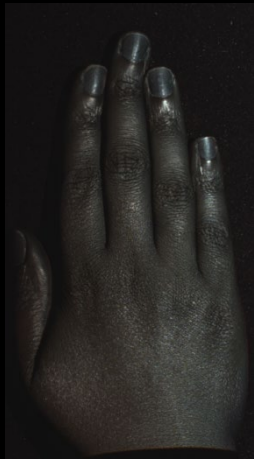
Afric. Amer.
Female



Chinese
Male



Spanish
Male



Afric. Amer.
Female



Chinese
Male



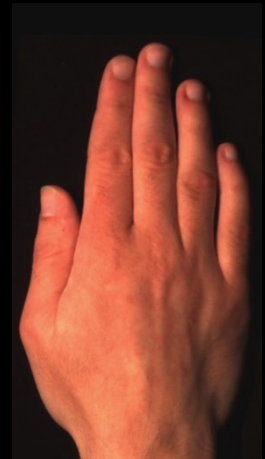
Spanish
Male



Afric. Amer.
Female



Chinese
Male

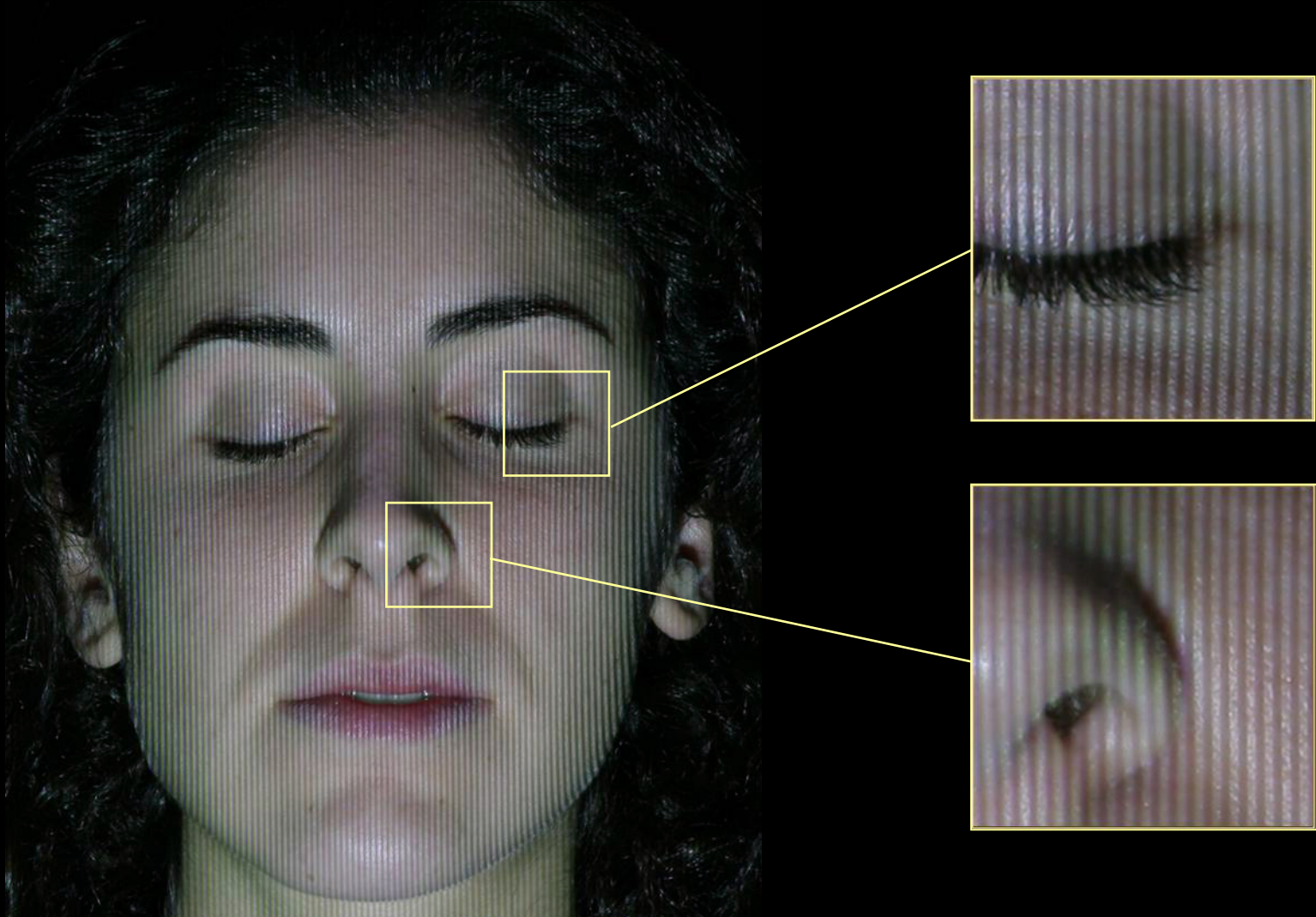


Spanish
Male

Direct

Global

Separation from a Single Image



Face



Direct



Global



Sum

Blonde Hair



Hair Scattering: Stamm et al. 77,
Bustard and Smith 91, Lu et al. 00
Marschner et al. 03



Direct

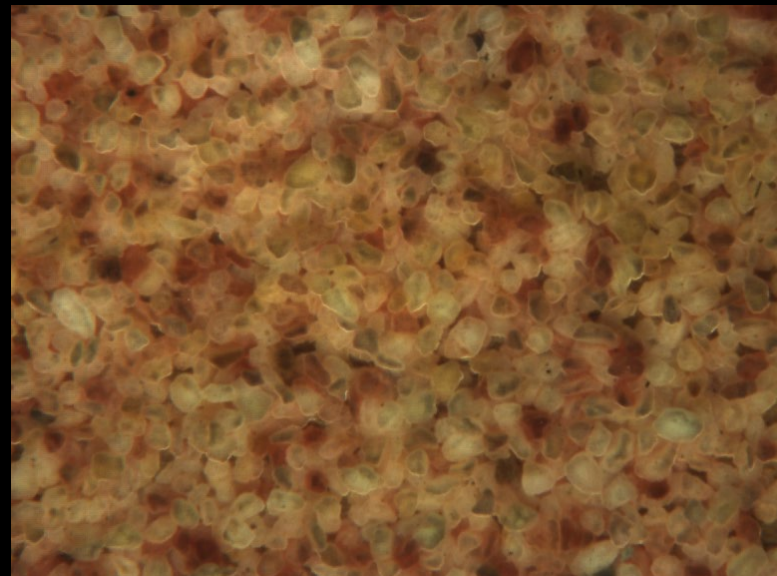


Global

Pebbles: 3D Texture



Direct



Global

Pink Carnation



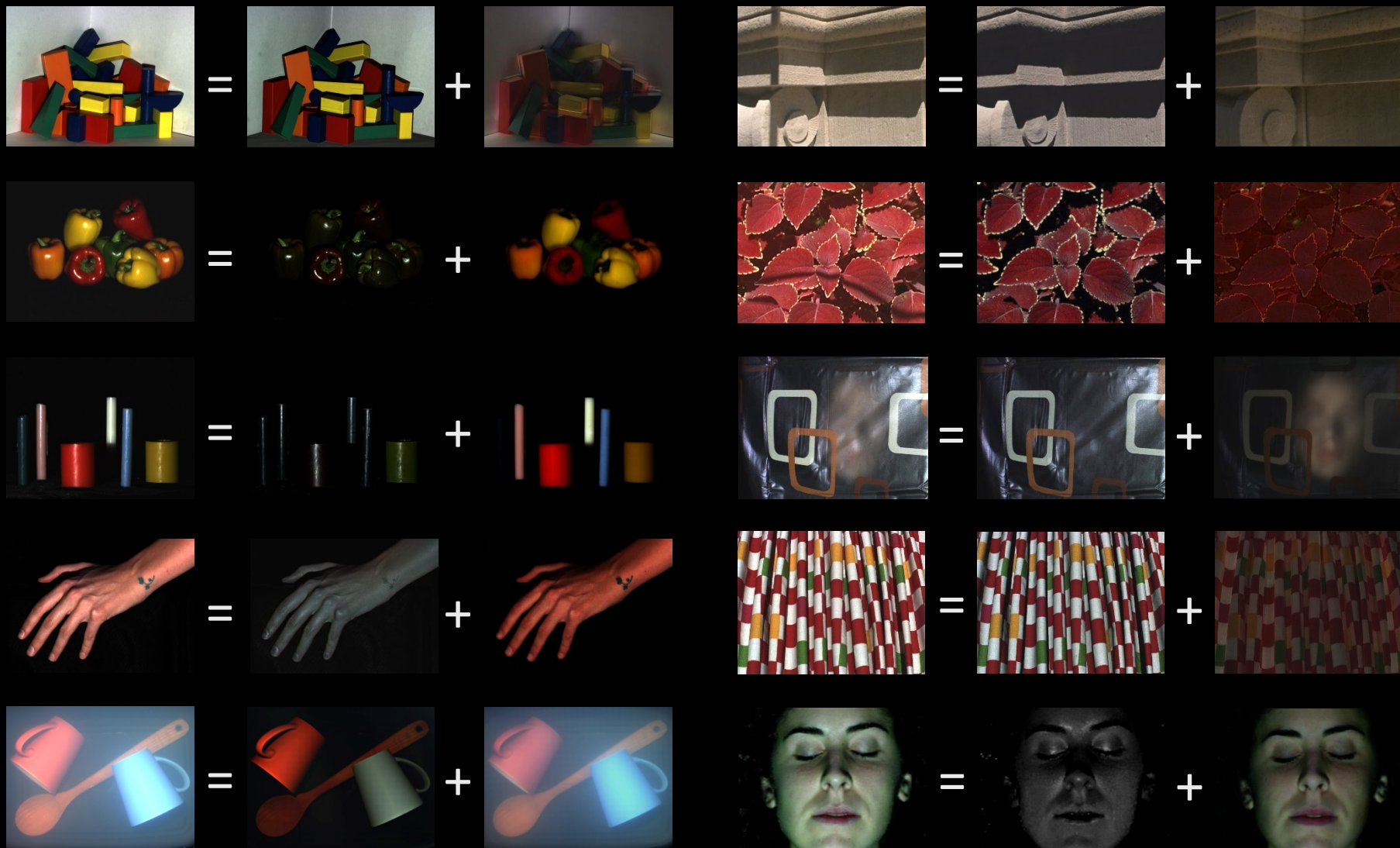
Spectral Bleeding: Funt et al. 91



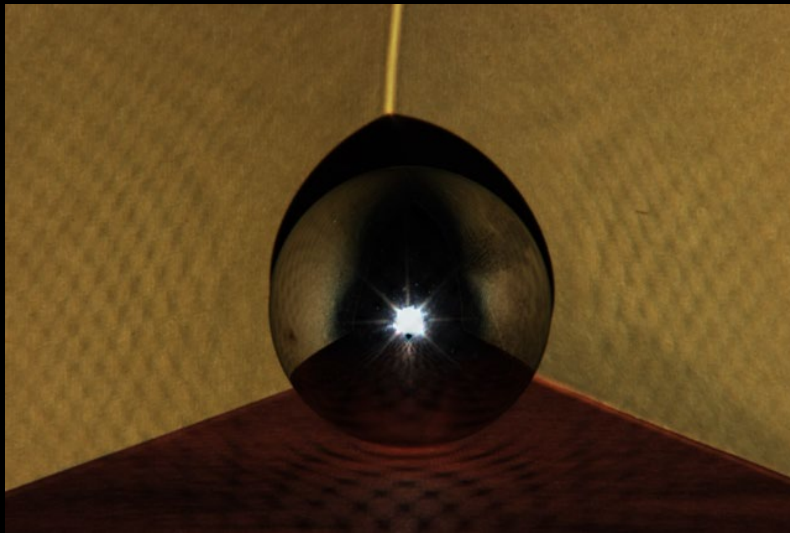
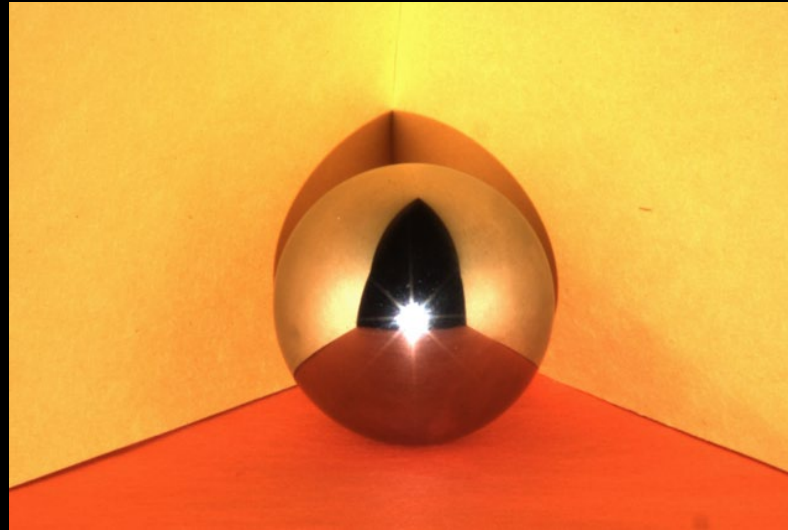
Direct



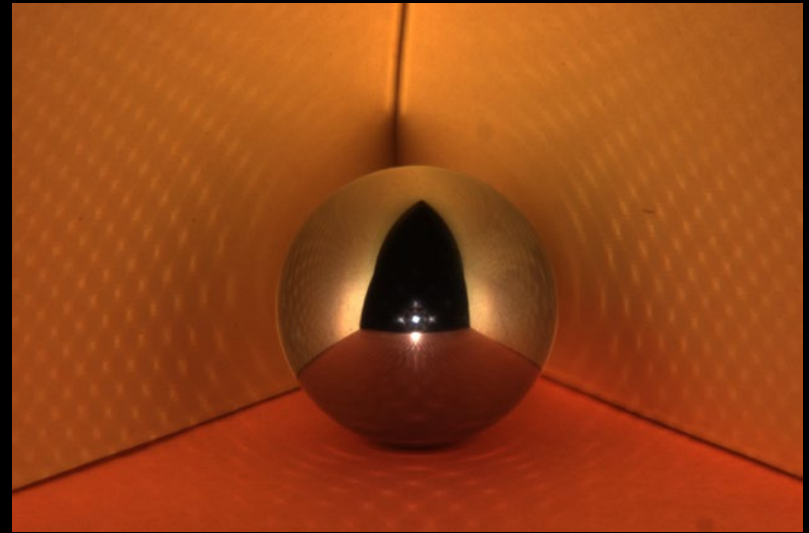
Global



Mirror Ball: Failure Case



Direct

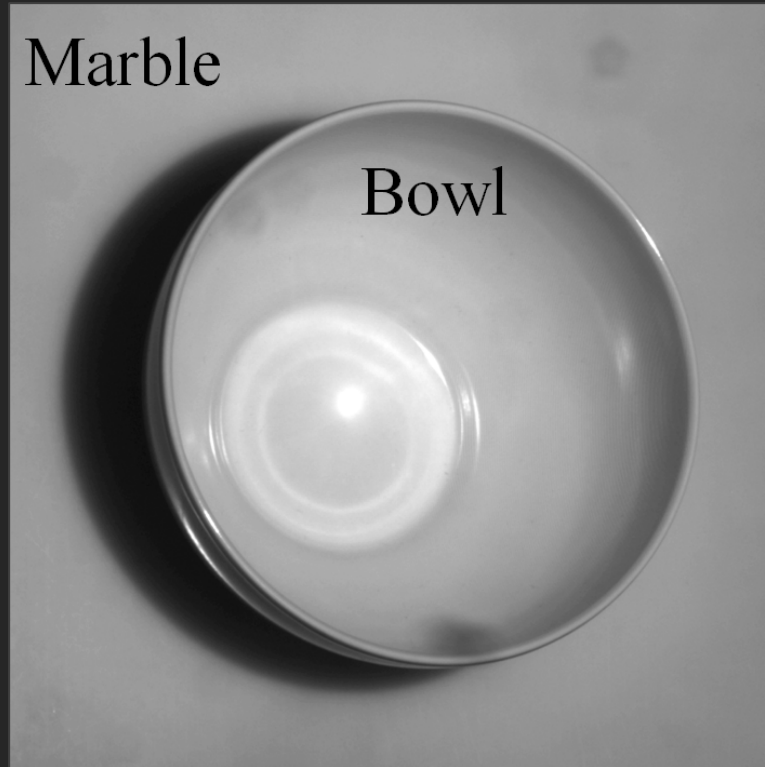


Global

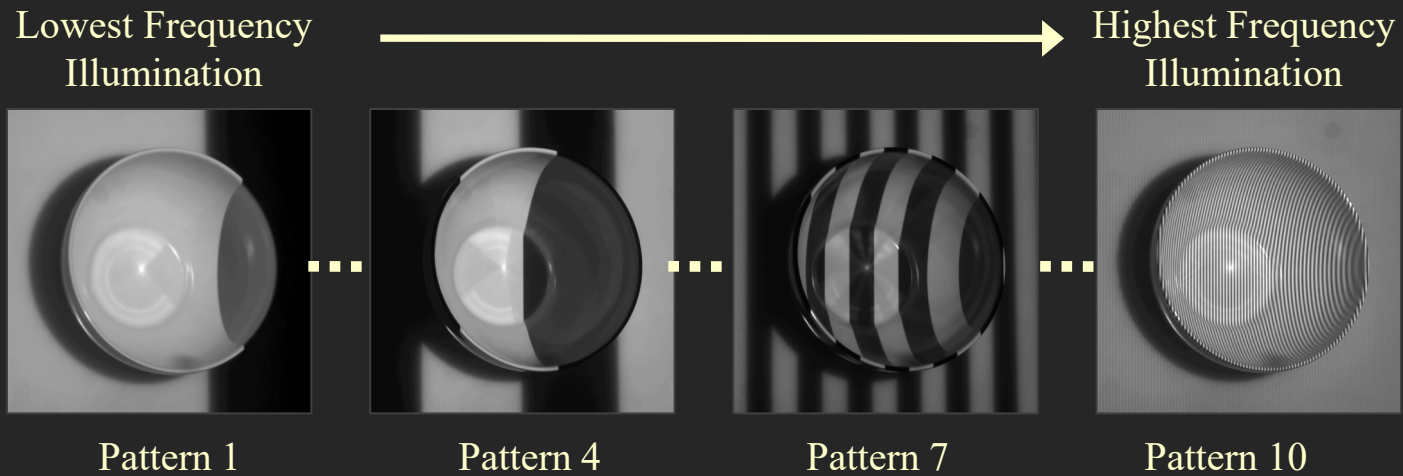
Application to structured light

Why is global illumination a problem?

Bowl on a Marble Slab

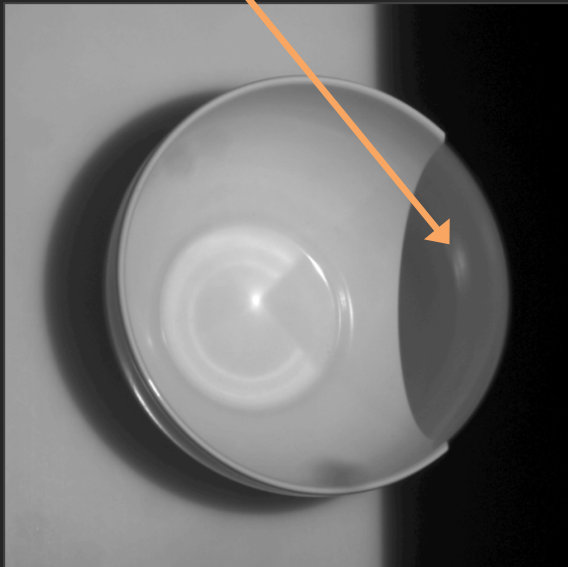


Captured images under conventional Gray codes



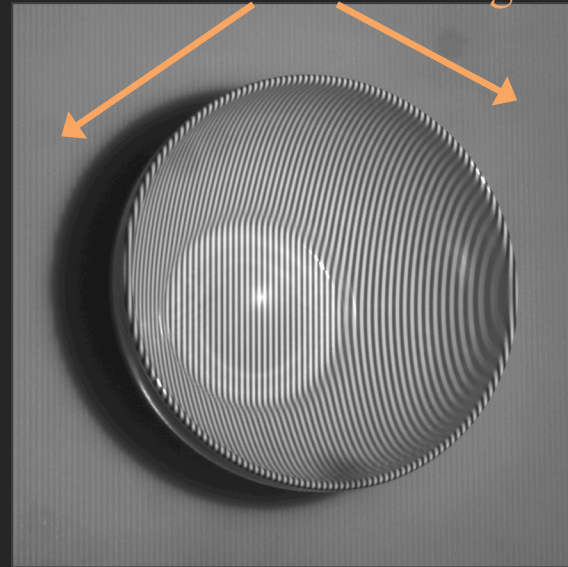
Issues due to global illumination effects

Strong Inter-reflections



Low-frequency pattern

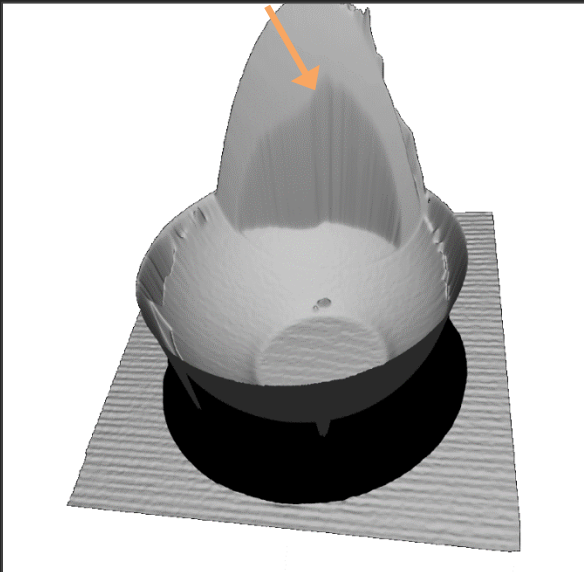
Blurring due to
Sub-surface Scattering



High-frequency pattern

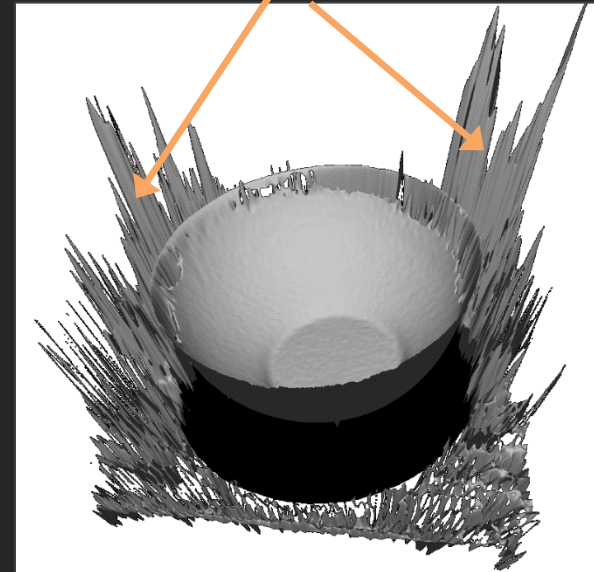
3D Visualizations: State of the Art

Errors due to
interreflections



Conventional Gray
(11 images)

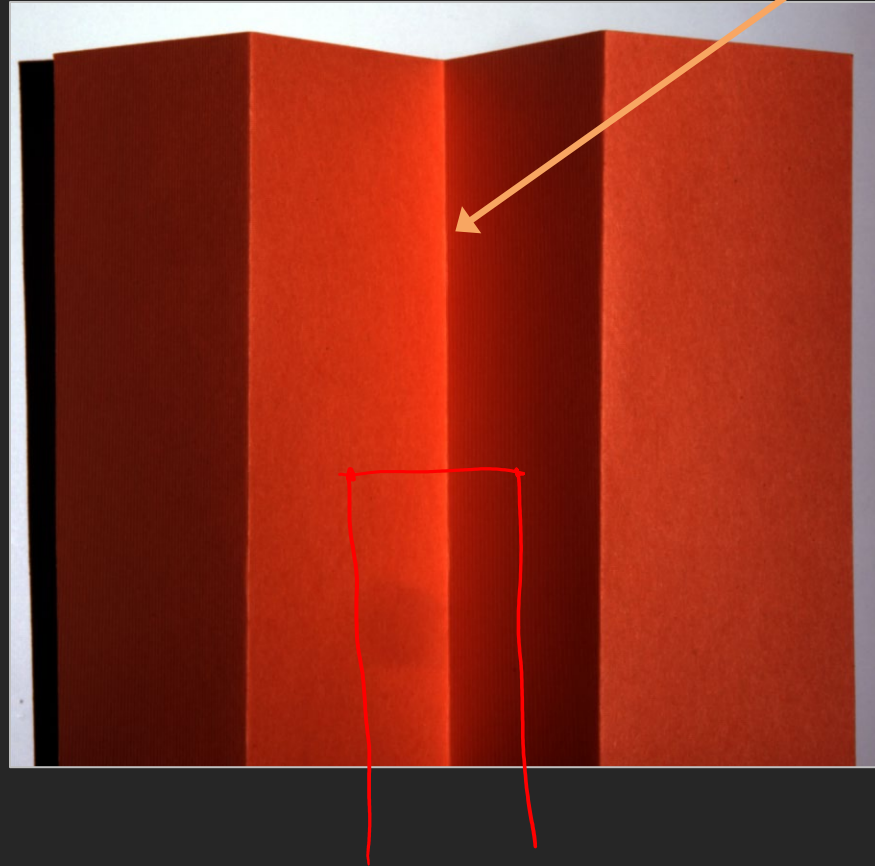
Errors due to
sub-surface scattering



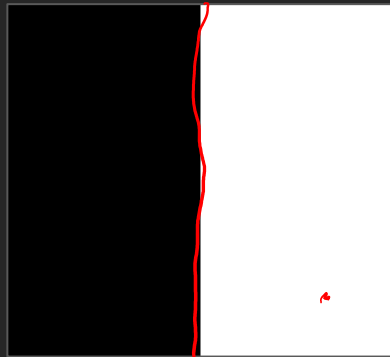
Modulated Phase-Shifting
(162 images)

V-Groove Scene

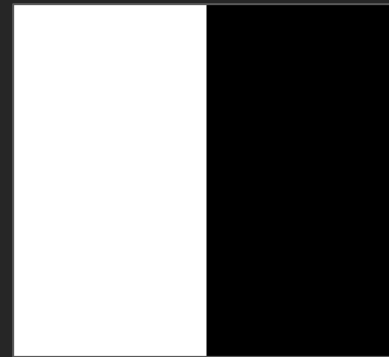
Inter-reflections



Conventional Gray codes

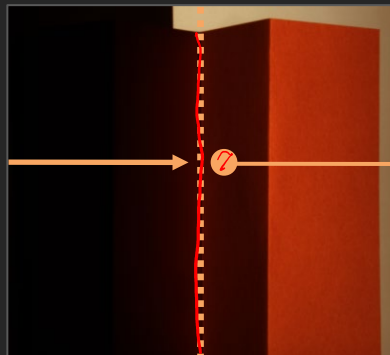


Low frequency pattern



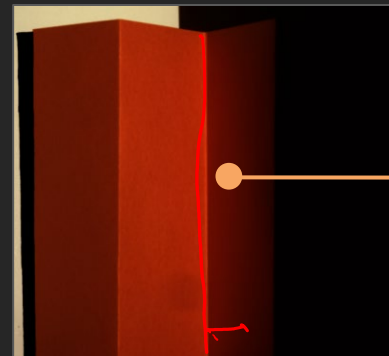
Inverse Pattern

Pattern
Edge



Captured Image

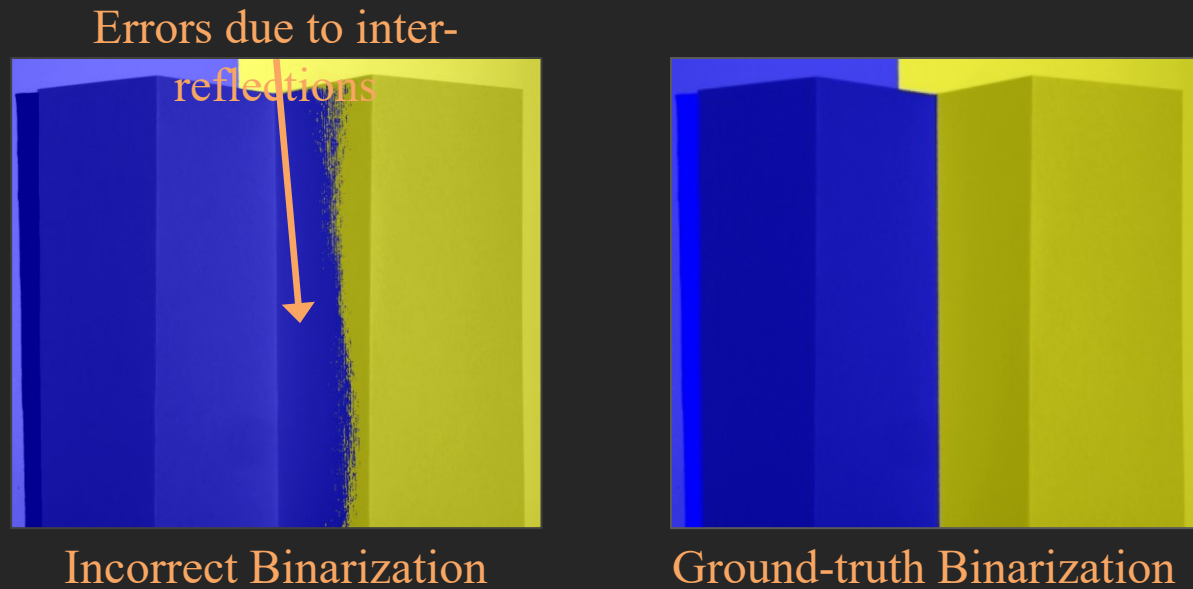
$$I = 0.16$$



Captured Image

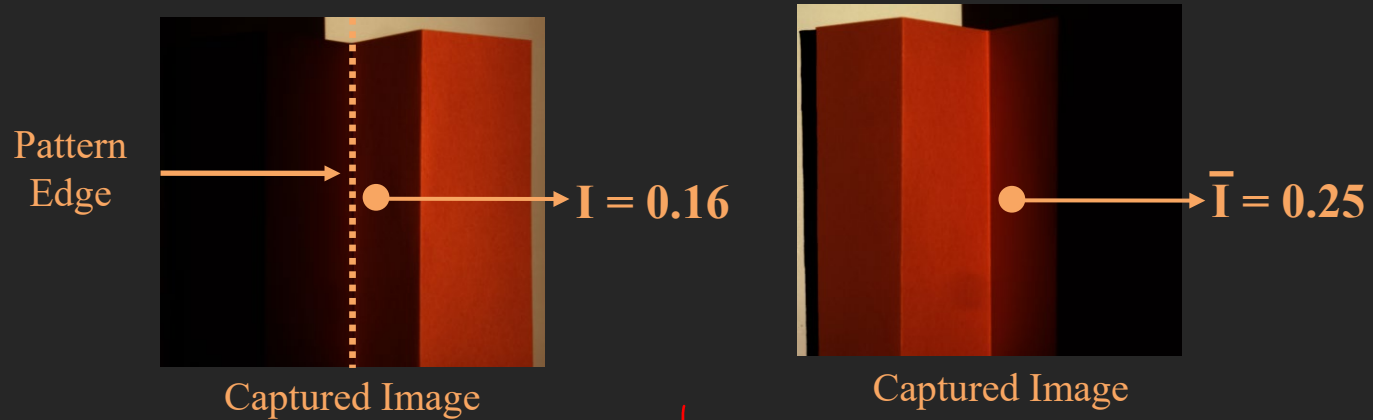
$$\bar{I} = 0.25$$

Binarization error



■ One (illuminated) ■ Zero (not-illuminated)

Low-frequency patterns

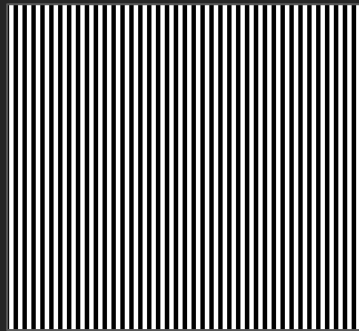


$$I = \underbrace{\text{Direct}} + \underbrace{\alpha \cdot \text{Global}} \quad \bar{I} = \underbrace{(1 - \alpha) \cdot \text{Global}}$$

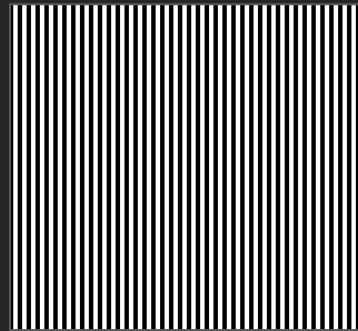
$\alpha = \frac{1}{2}$

$$\alpha \approx 0, \text{ Direct} < \text{Global} \Rightarrow I < \bar{I}$$

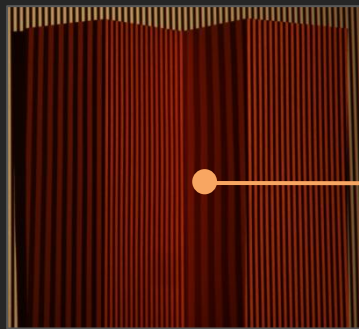
High-frequency patterns



Pattern

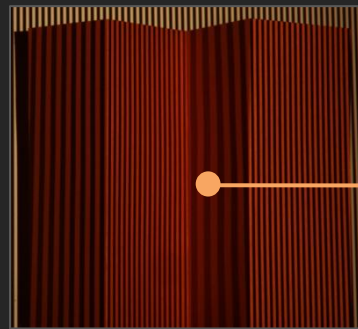


Inverse Pattern



Captured Image

$I = 0.25$

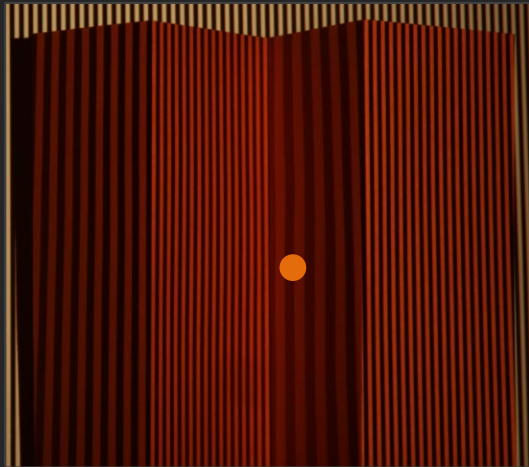


Captured Image

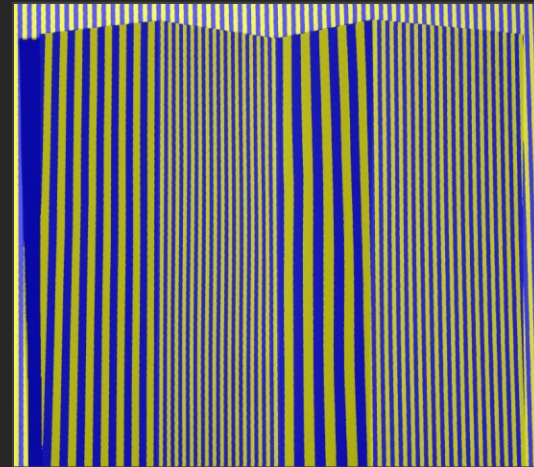
$\bar{I} = 0.16$

$$I = \text{Direct} + 0.5 \text{ Global} > \bar{I} = 0.5 \text{ Global}$$

High-frequency Patterns are Decoded Correctly



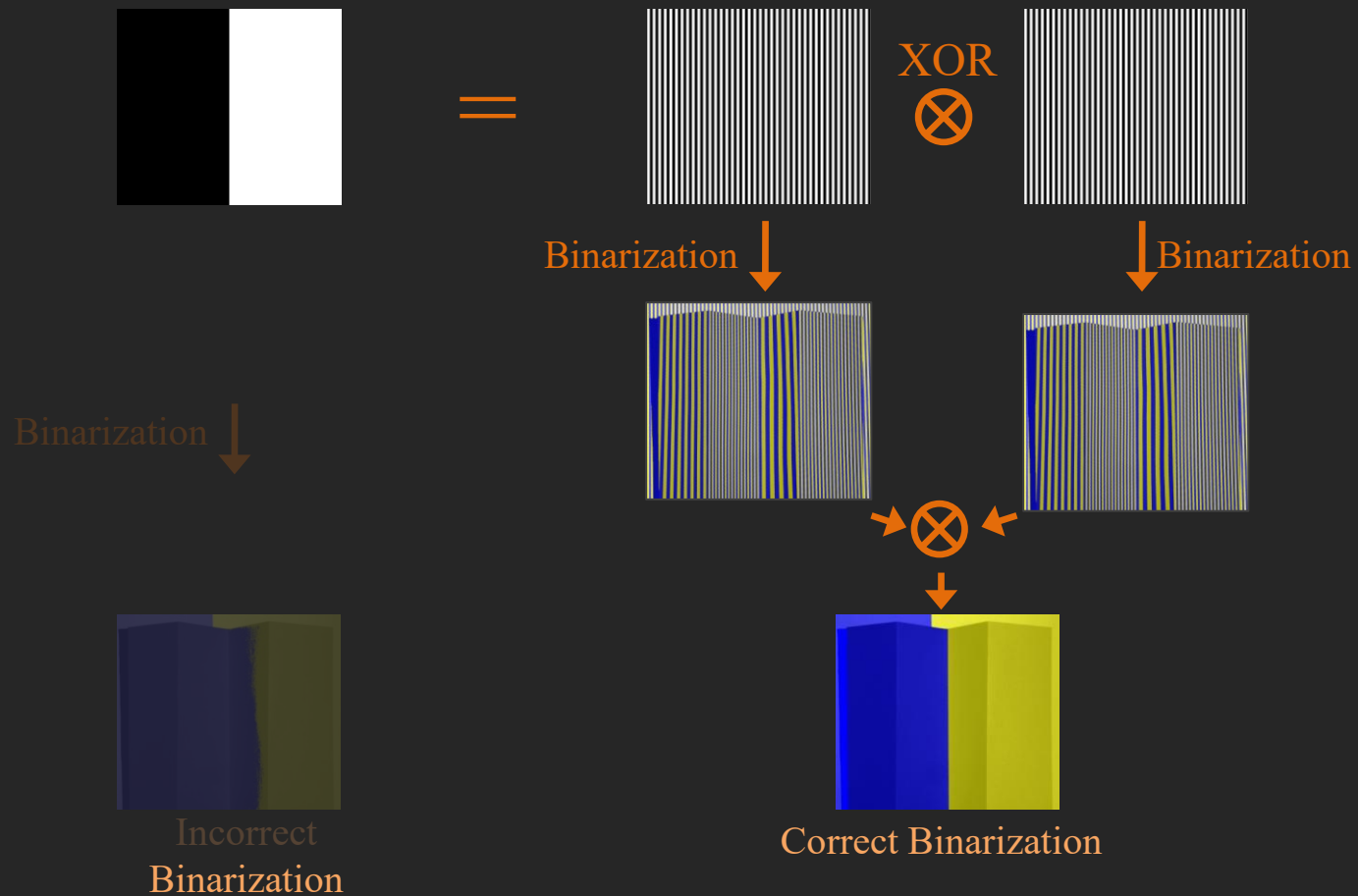
Captured Image



Binary Decoding

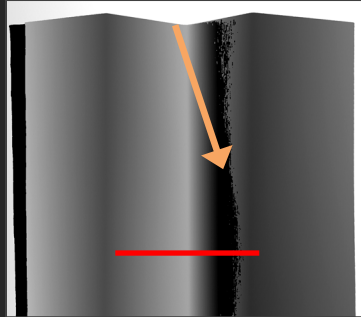
Logical Coding and Decoding

Logical Coding and Decoding

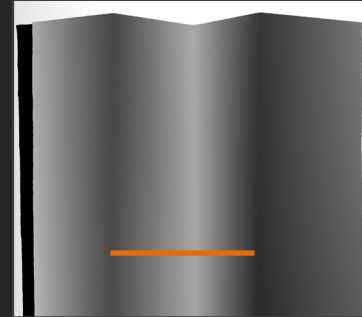


Depth Map Comparison

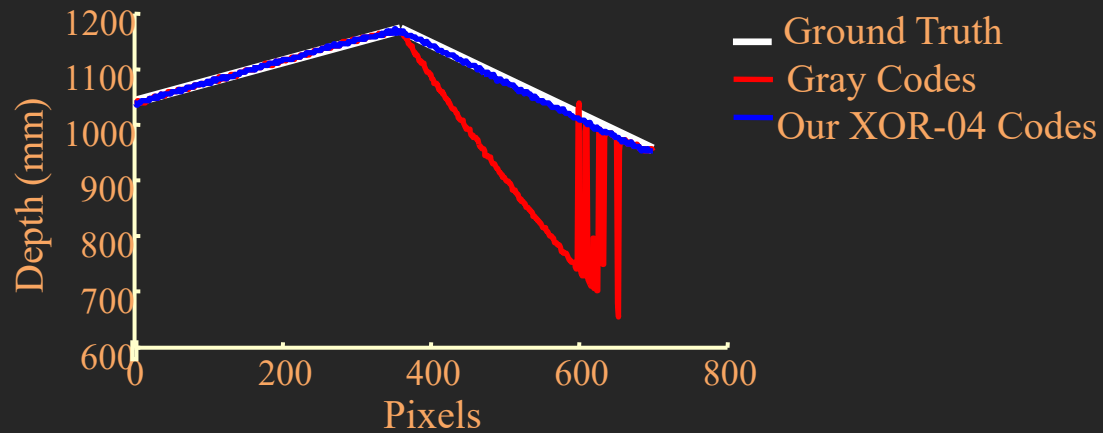
Errors due to Inter-reflections



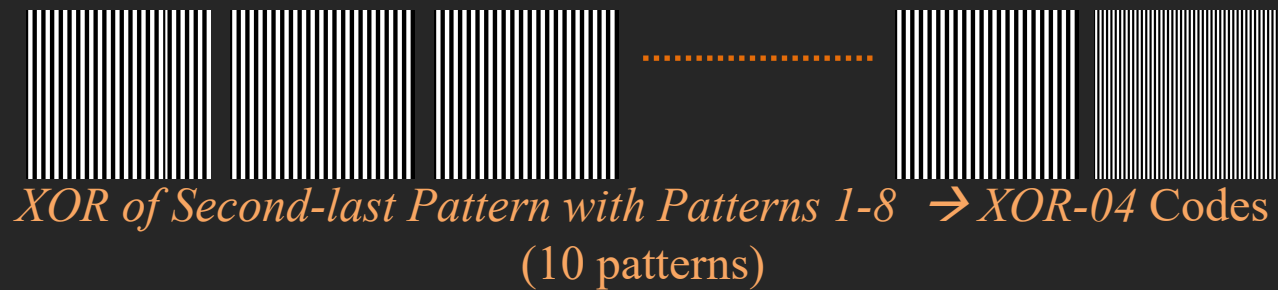
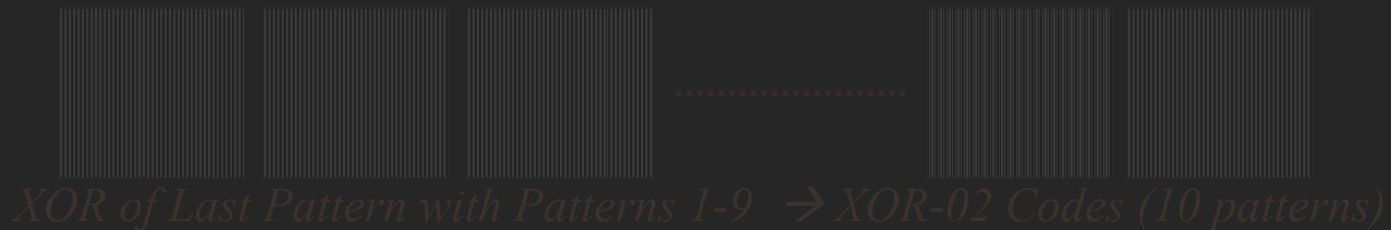
Conventional Gray Codes (11 images)



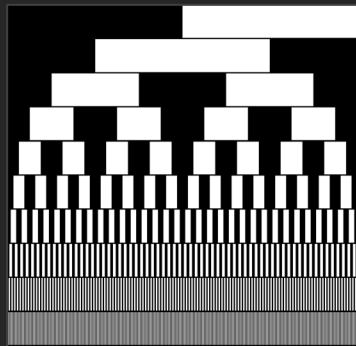
Our XOR-04 Codes (11 images)



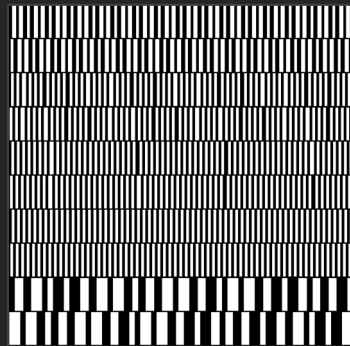
Making the Logical XOR Codes



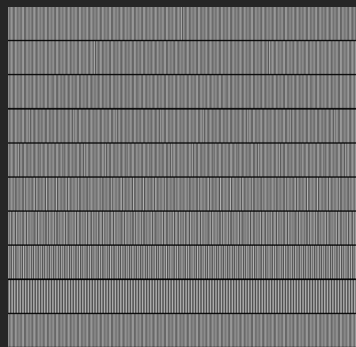
Ensemble of Codes for General Scenes



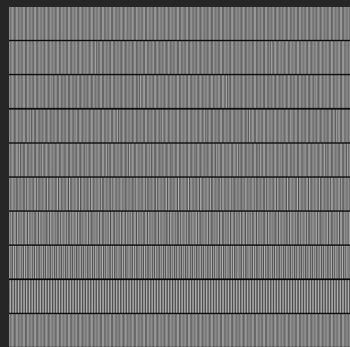
Conventional Gray (10 images)



Max min-SW Gray (10 images)

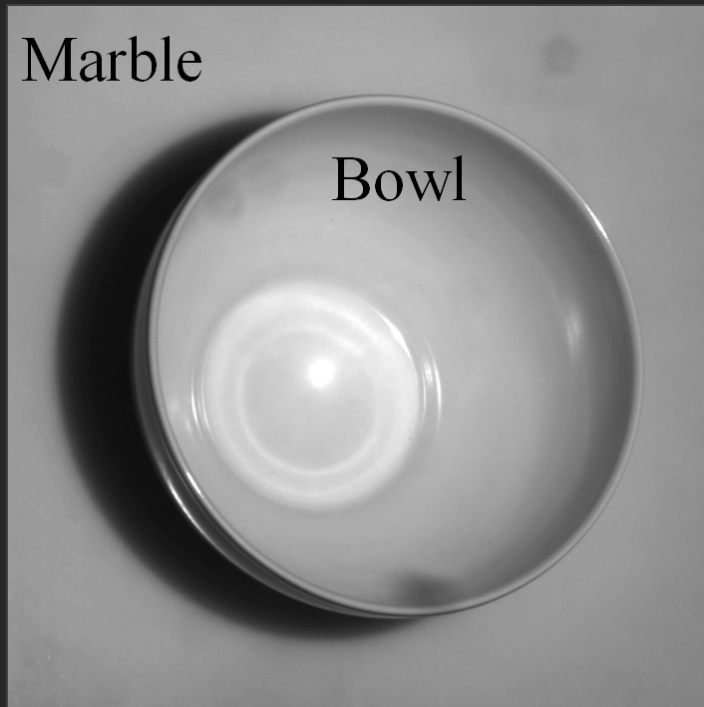


XOR-04 (10 images)

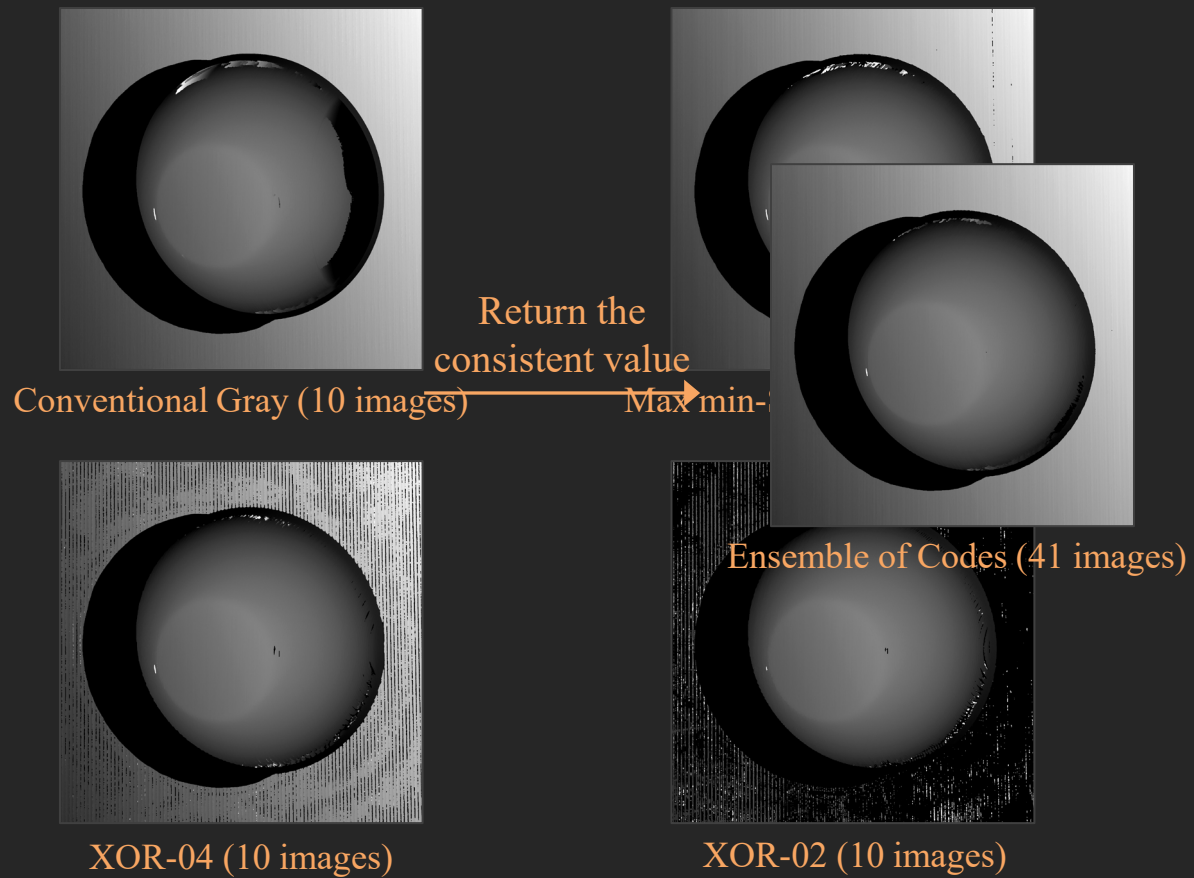


XOR-02 (10 images)

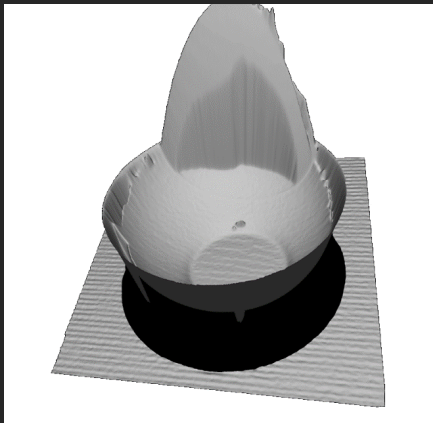
Reconstructing General Scenes



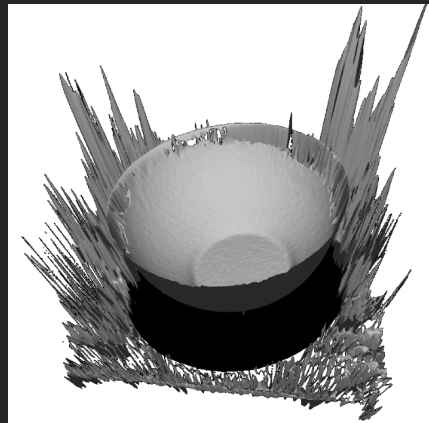
Ensemble of Codes for General Scenes



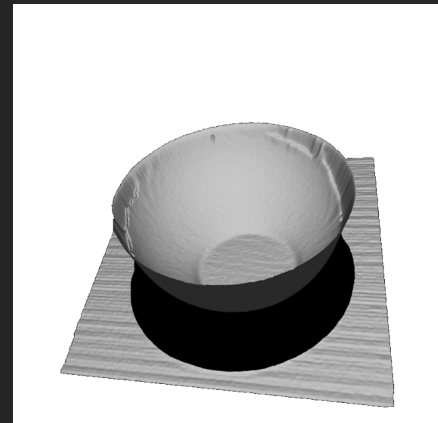
Shape Comparison



Conventional Gray
(11 images)

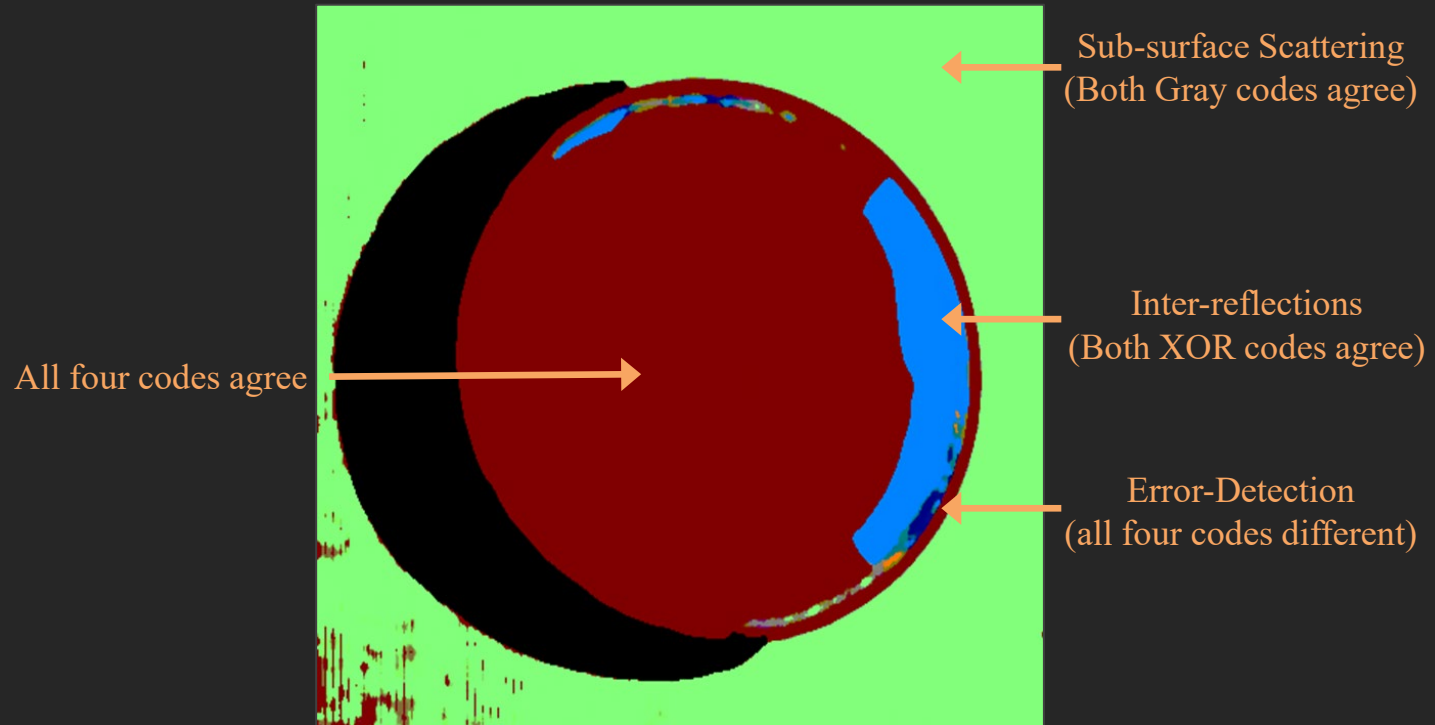


Modulated Phase-Shifting
(162 images)



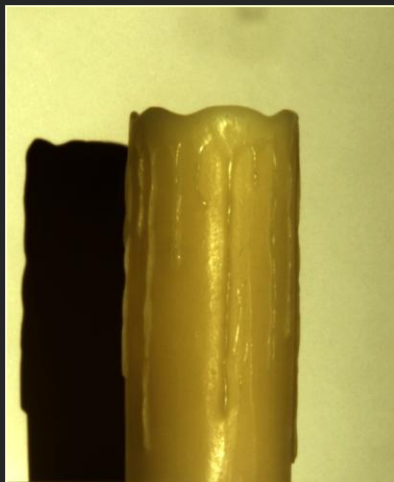
Our Technique
(41 images)

Qualitative Light Transport Analysis

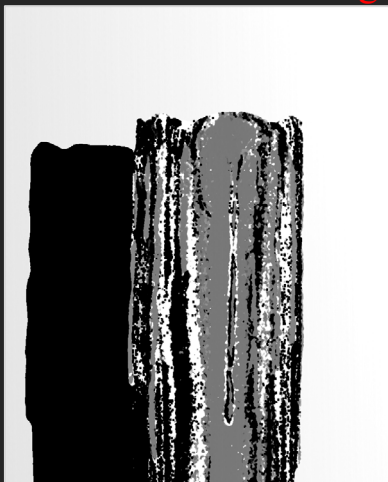


Translucent Wax Candle

Errors due to strong
sub-surface scattering



Scene



Modulated Phase-
Shifting (162 images)



Our Ensemble Codes
(41 images)

Translucent Wax Object

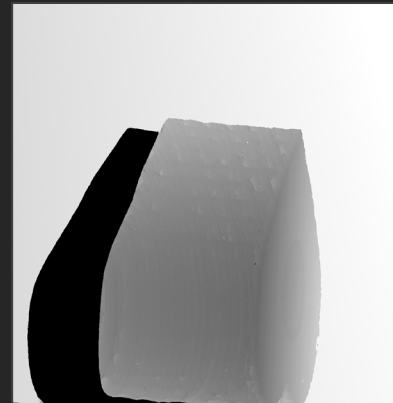
Errors due to strong
sub-surface scattering



Scene



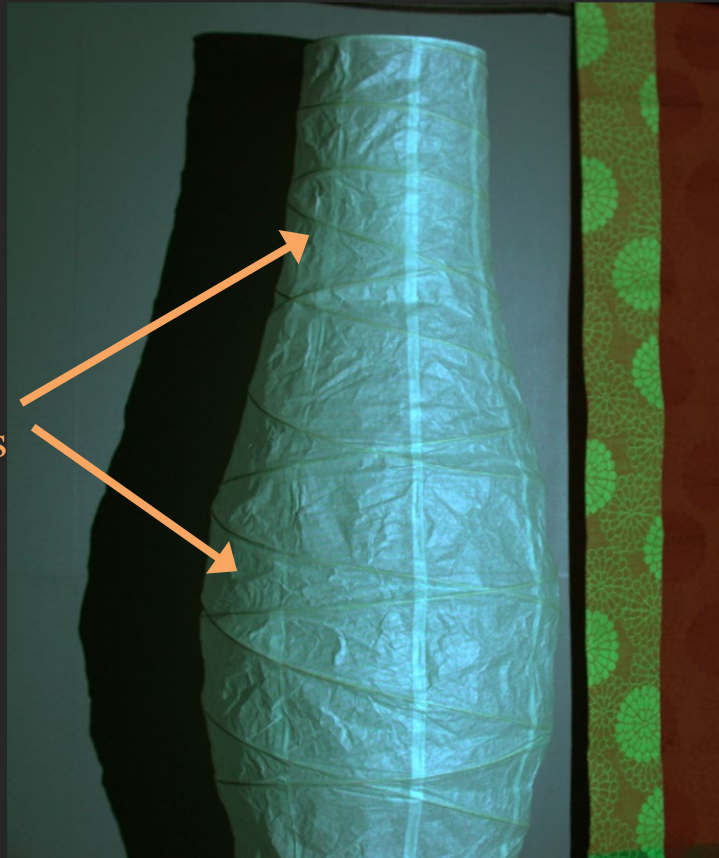
Modulated Phase-
Shifting (162 images)



Our Ensemble Codes
(41 images)

Ikea Lamp

Diffusion +
Inter-reflections



Depth-Map Comparison

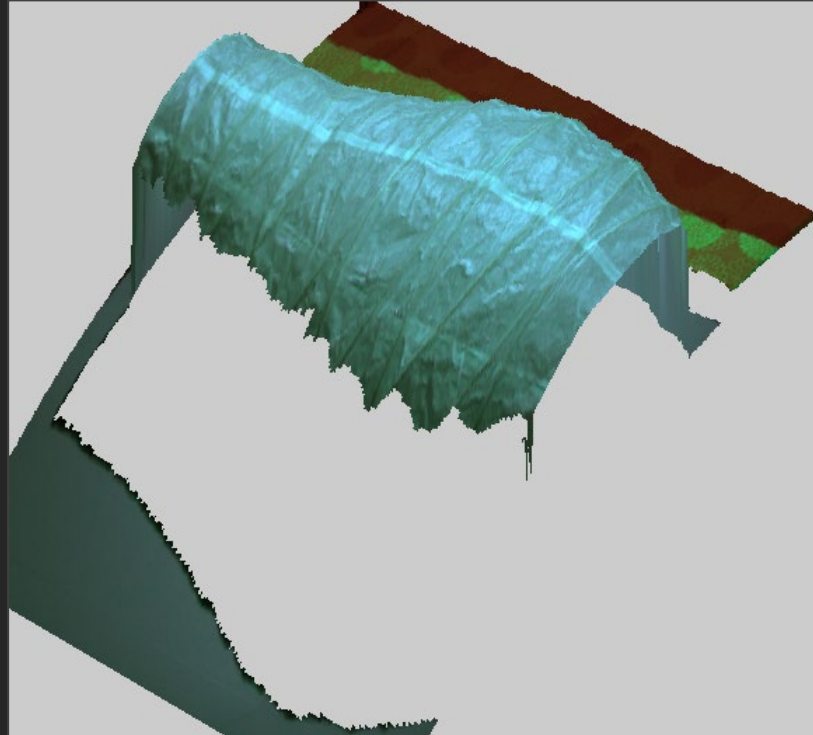


Regular Gray Codes (11 images)

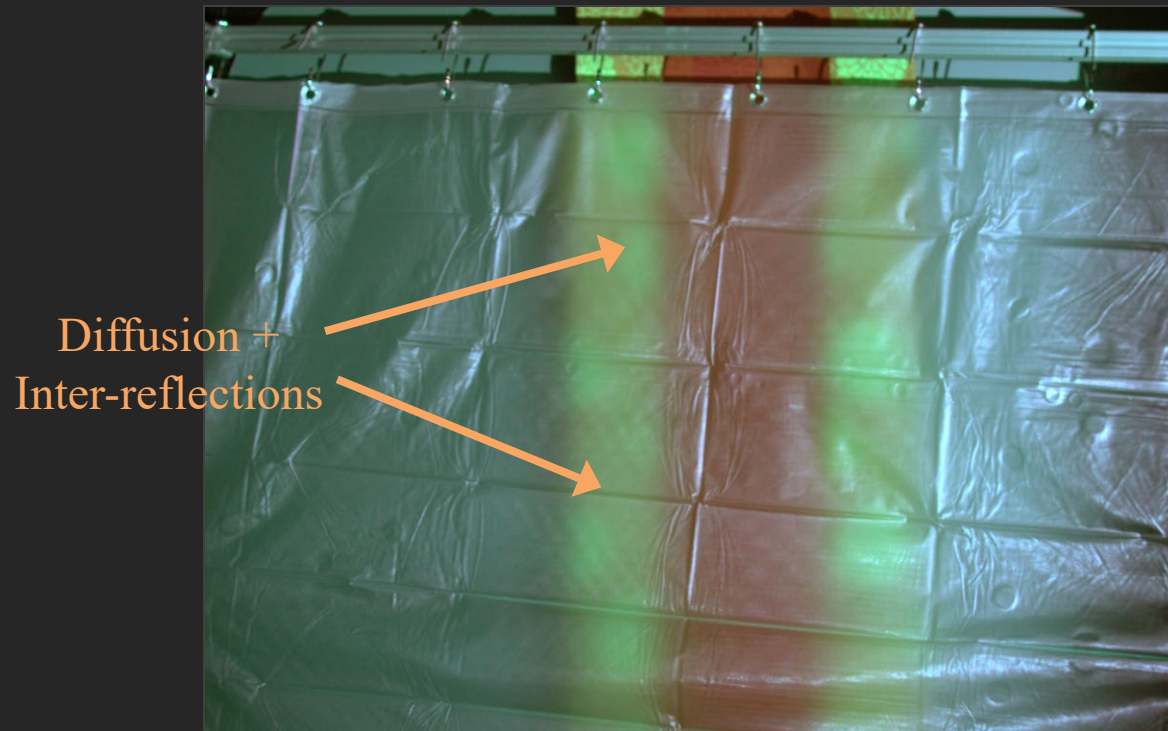


Our Ensemble Codes (41 images)

3D Visualization using our ensemble codes

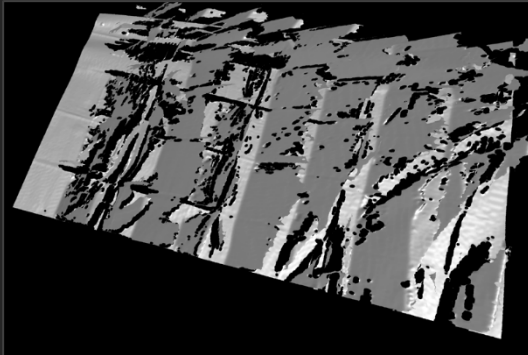


Shower Curtain

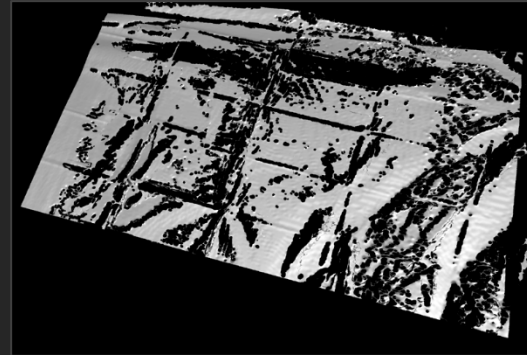


Goal is to reconstruct the shape of the shower-curtain. Shape of the curtain is planar because it was taped to the rod to avoid movement while capture.

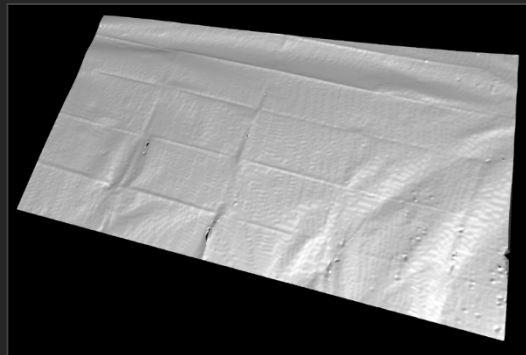
Shape Comparisons



Regular Gray Codes (11 images)

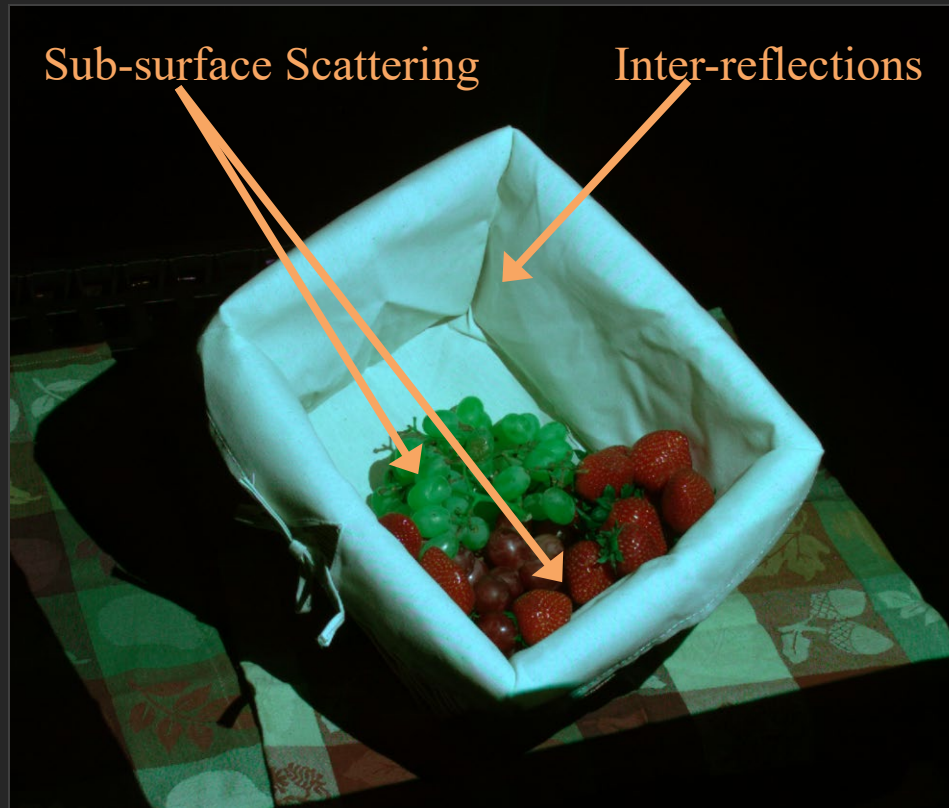


Phase-Shifting (18 images)

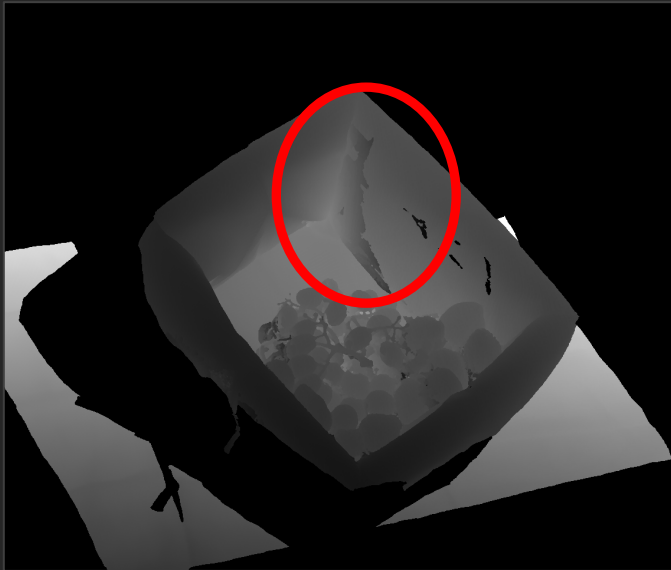


Our XOR Codes (11 images)

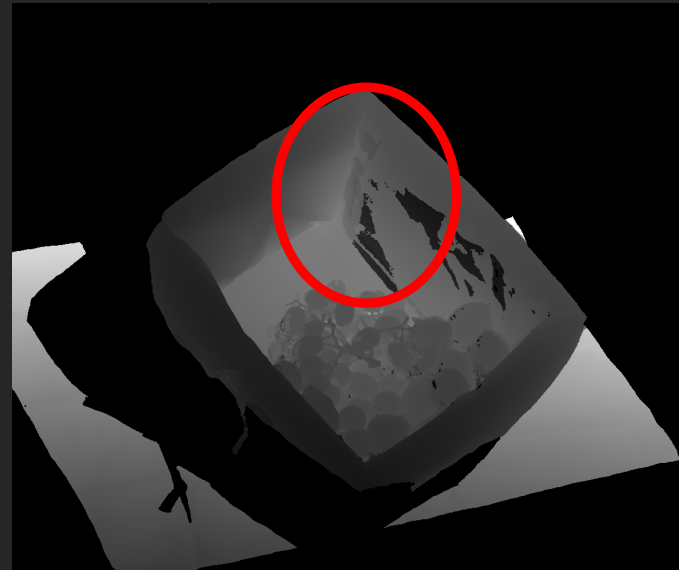
Fruit Basket: Multiple Effects



Depth-maps with previous state of the art

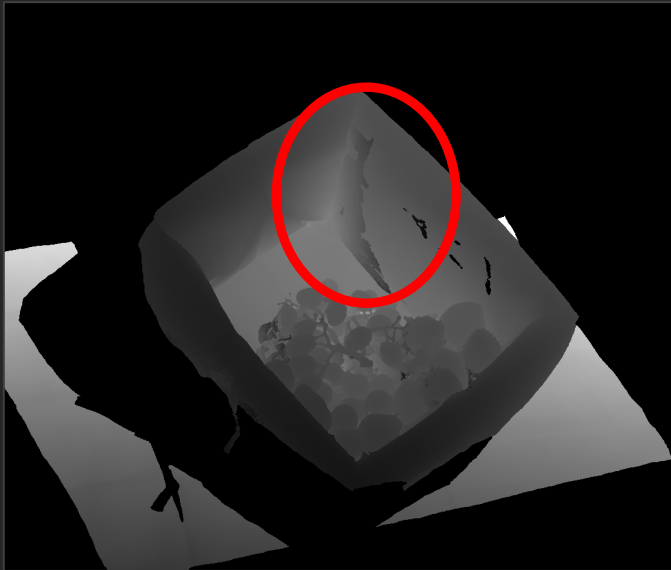


Regular Gray (11 images)

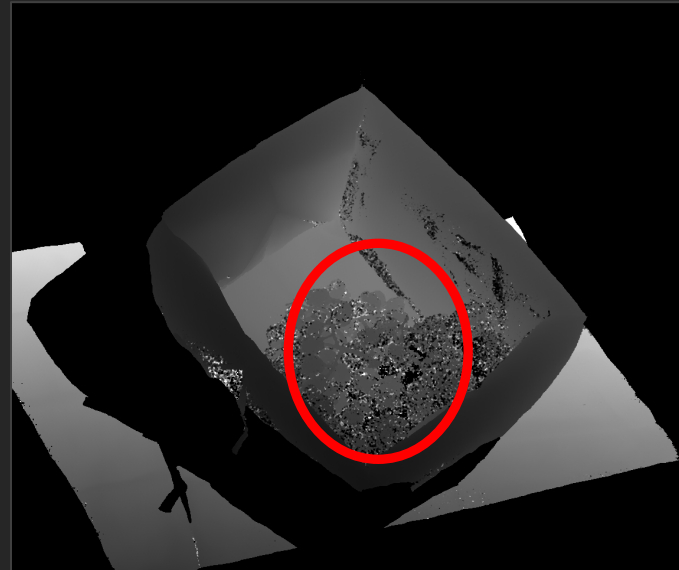


Phase-Shifting (18 images)

Depth-maps with previous state of the art

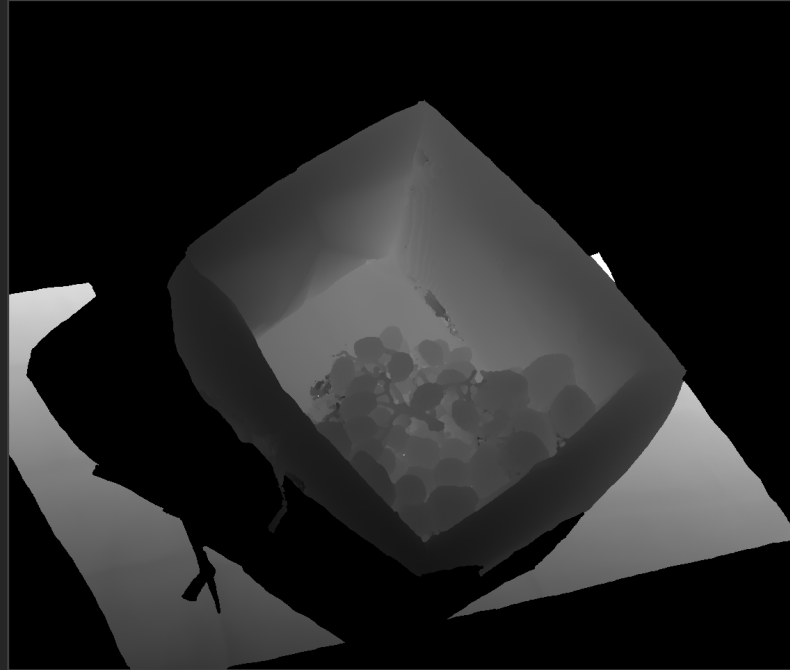


Regular Gray (11 images)



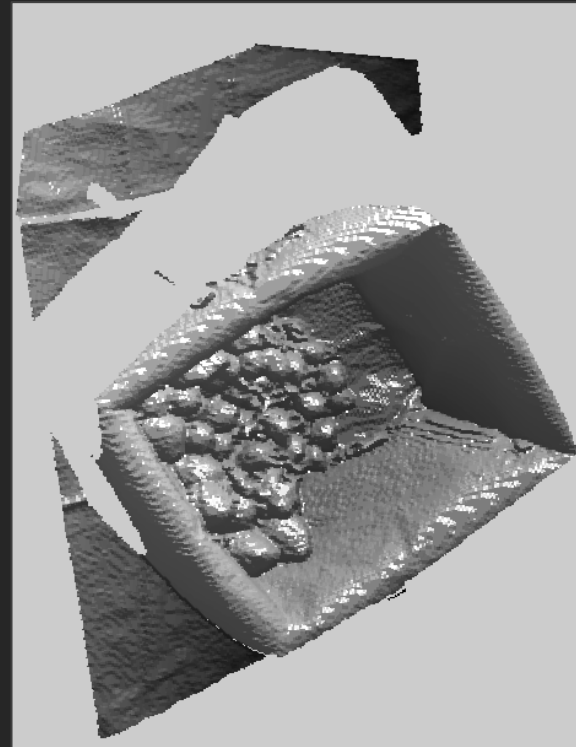
Modulated Phase-Shifting (162 images)

Depth-maps with our Ensemble Codes



Our Ensemble Codes (41 images)

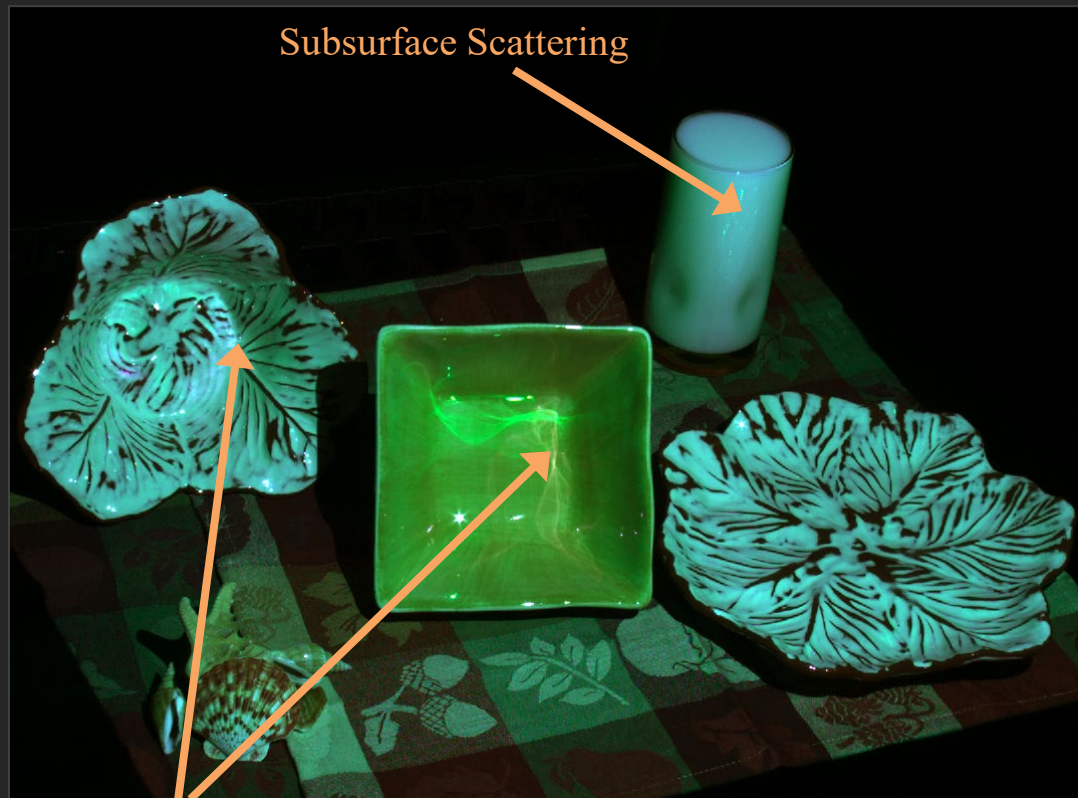
3D Visualizations with our ensemble codes



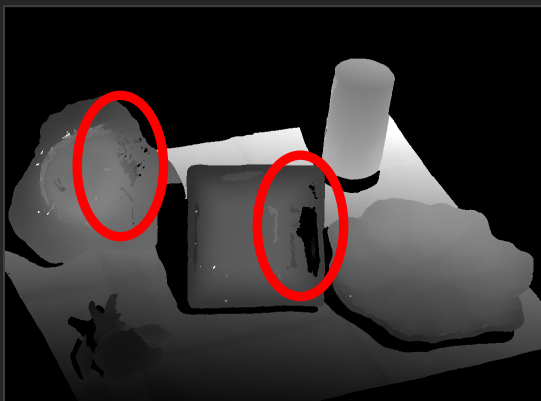
3D Visualization with our ensemble codes



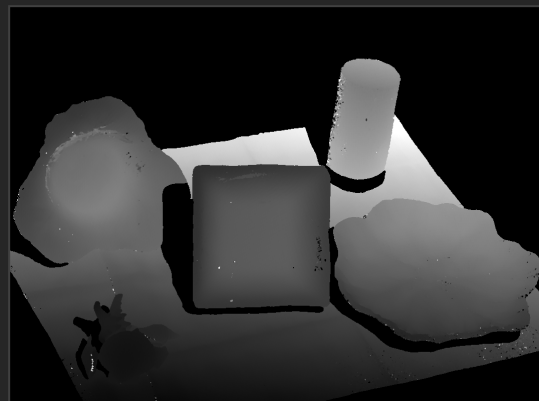
Bowls and Milk: Multiple Effects



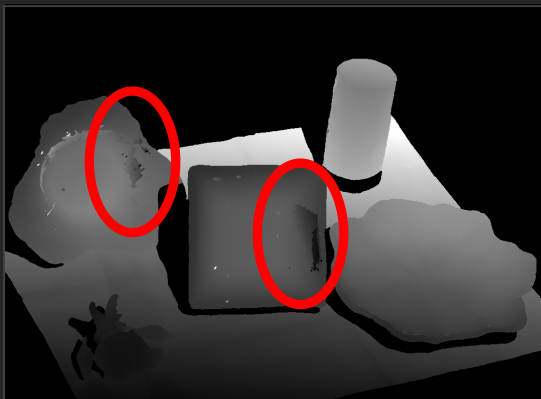
Interreflections



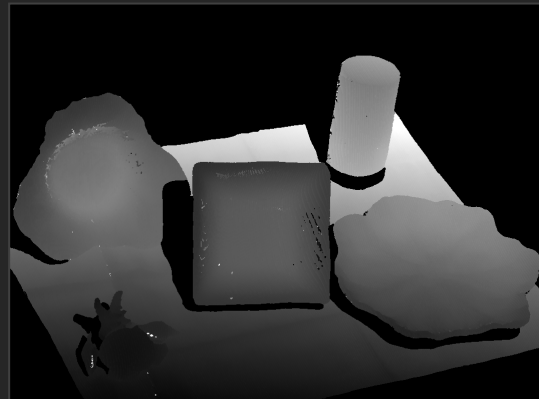
Phase-Shifting (18 images)



Modulated Phase-Shifting (162 images)

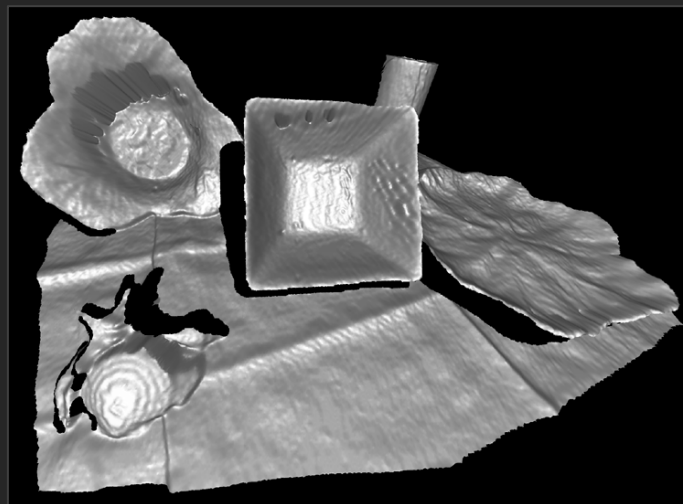
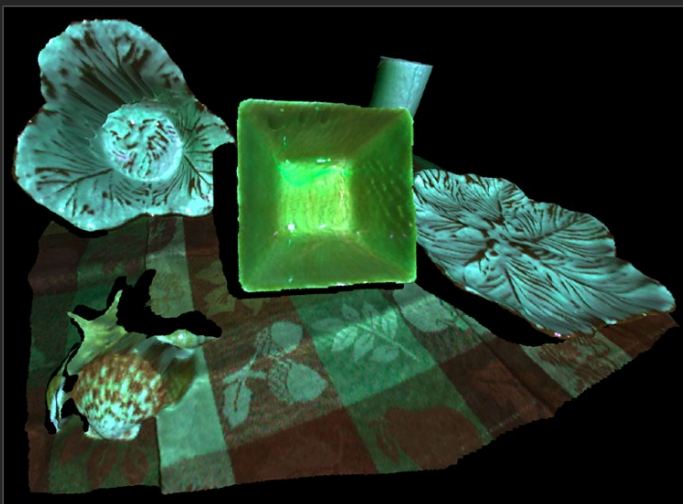


Regular Gray Codes (11 images)

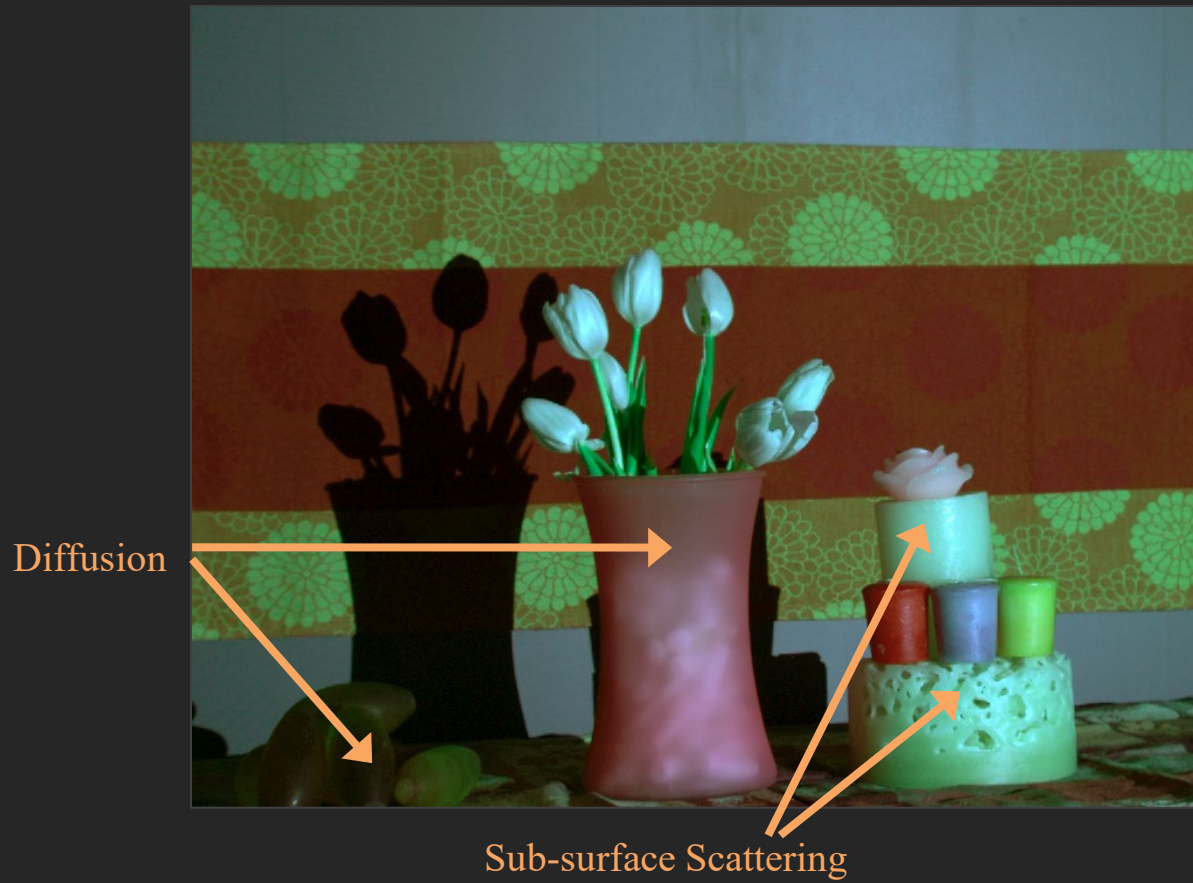


Our XOR Codes (11 images)

3D Visualizations with our ensemble codes



Flower-Vase



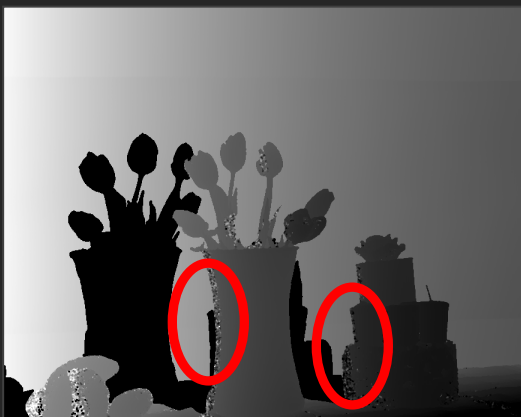
Comparison



Phase-Shifting (18 images)



Regular Gray Code (11 images)

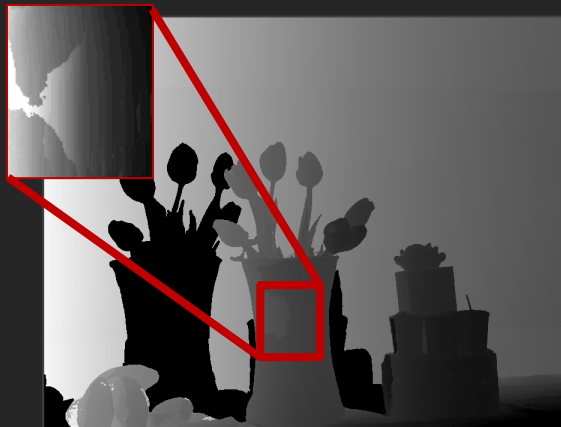


Modulated Phase-Shifting (162 images)



Our Ensemble Codes (41 images)

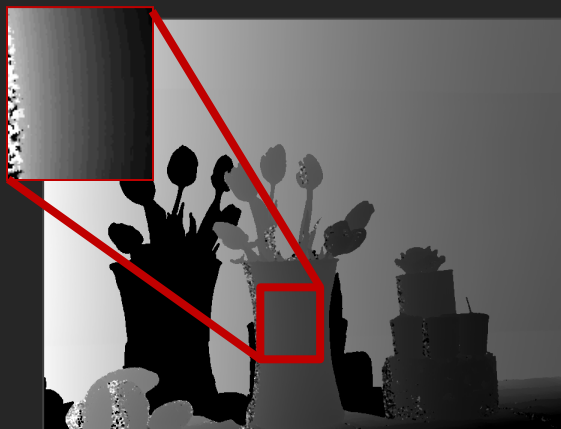
Comparison



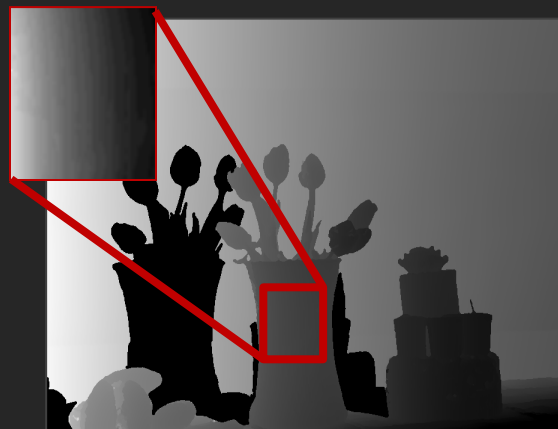
Phase-Shifting (18 images)



Regular Gray Code (11 images)



Modulated Phase-Shifting (162 images)

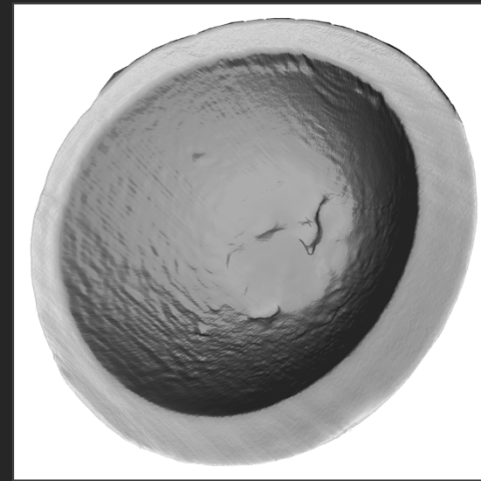


Our Ensemble Codes (41 images)

Multiple Global Illumination Effects



Wax Bowl

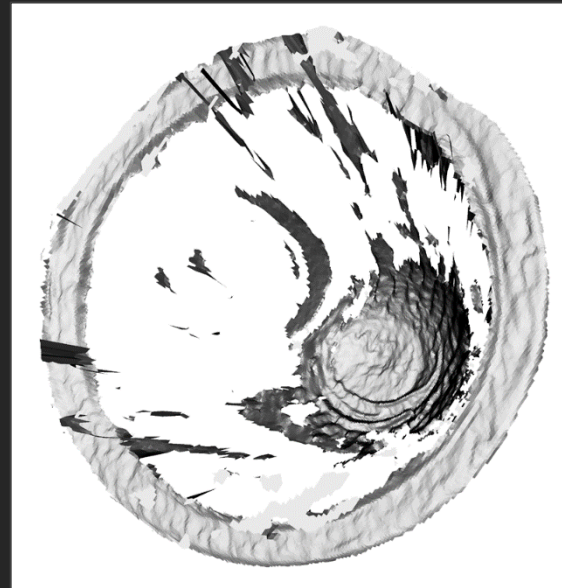


Shape Using Ensemble Codes

Multiple Global Illumination Effects



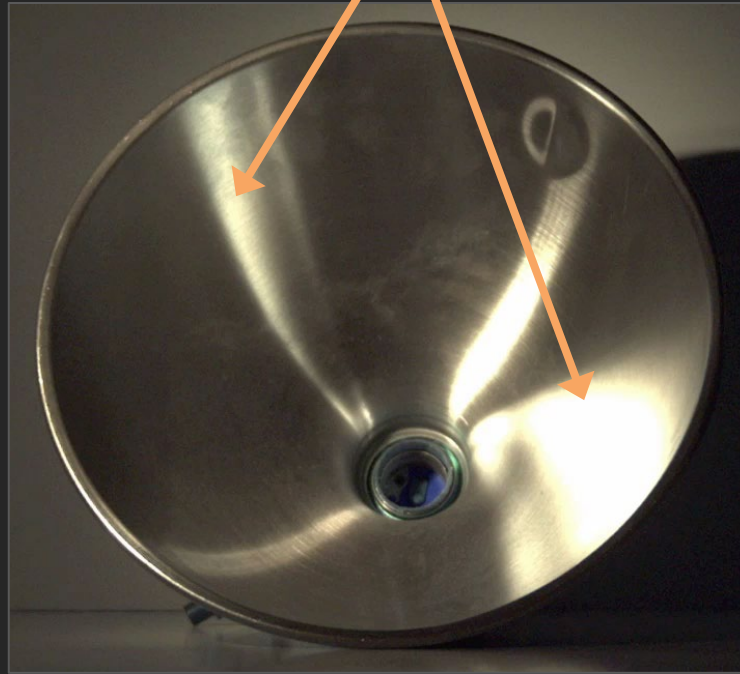
Deep Wax Container



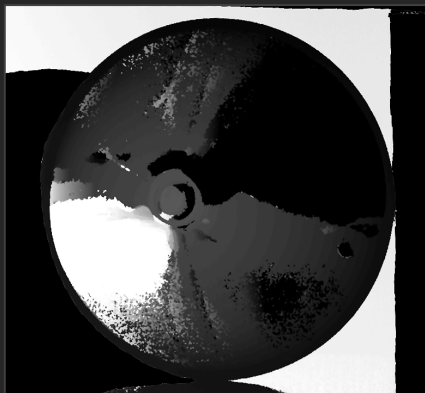
Shape Using Ensemble Codes

Lamp made of shiny brushed metal

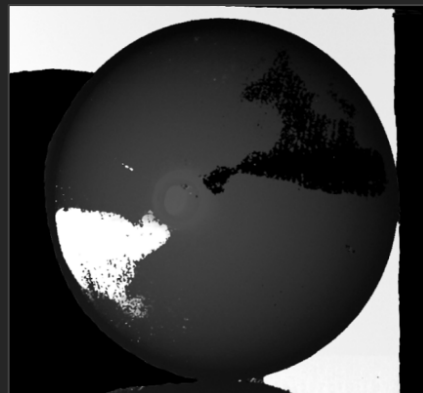
Strong and high-frequency inter-reflections



Depth Map Comparison



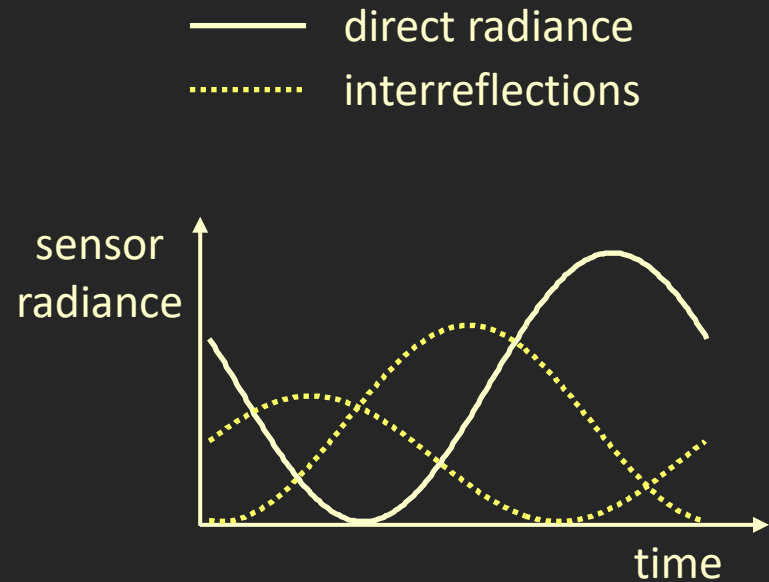
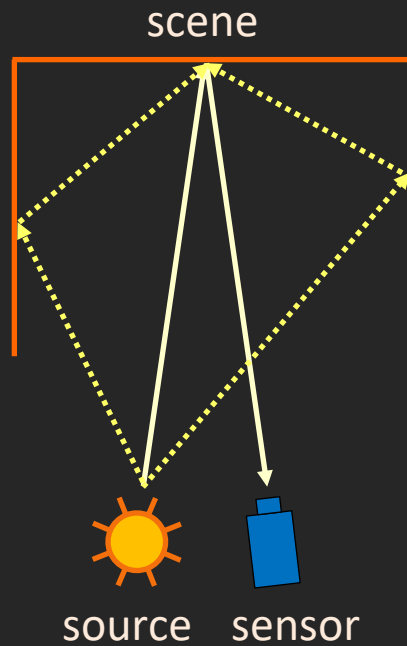
Regular Gray (11 images)



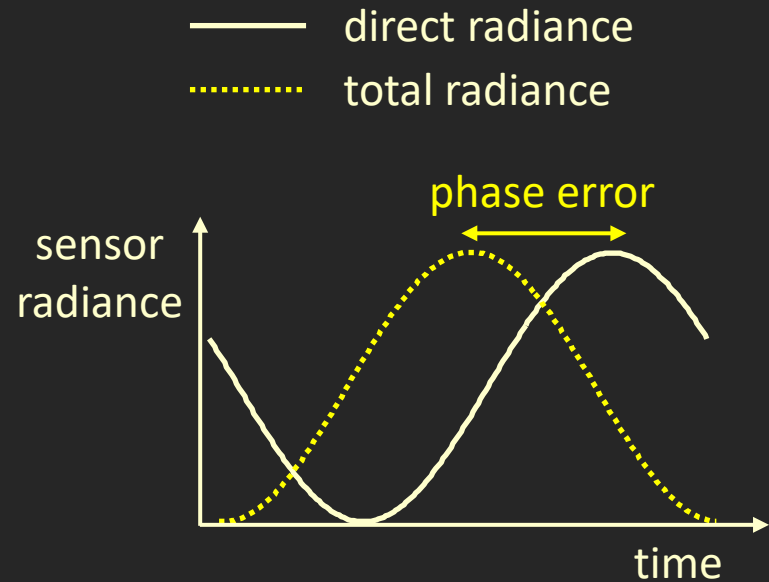
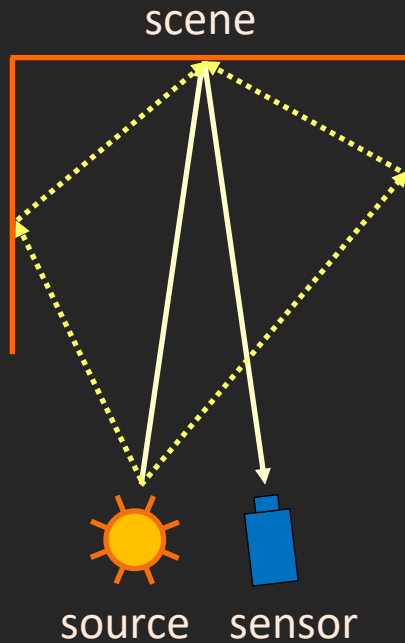
Our Ensemble Codes (41 images)

Application to time-of-flight imaging

Interreflections and ToF Imaging

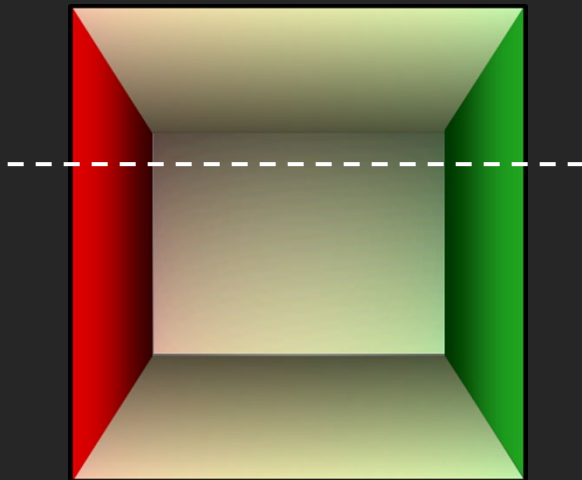


Interreflections and ToF Imaging

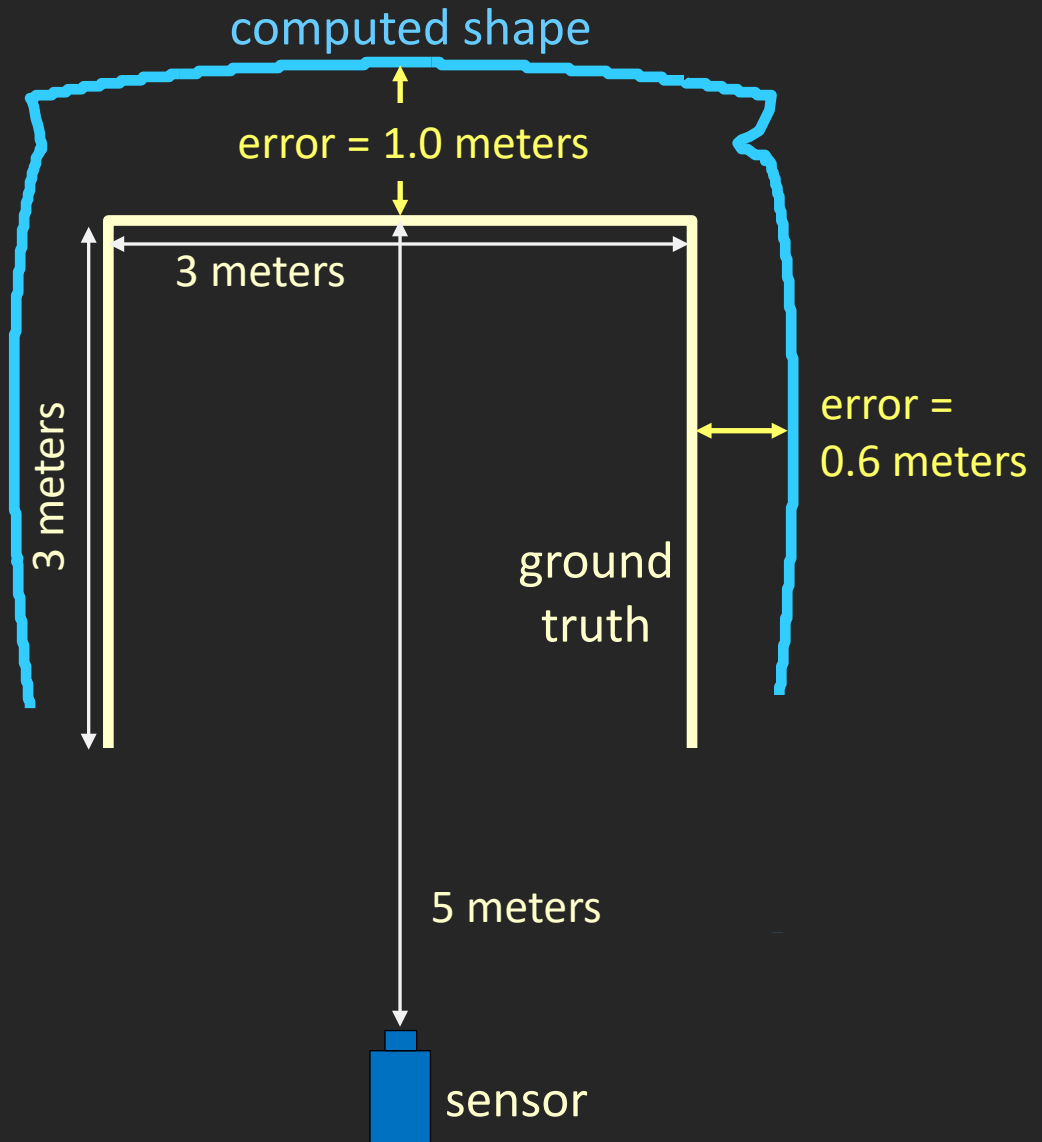


Interreflections Produce Incorrect Phase

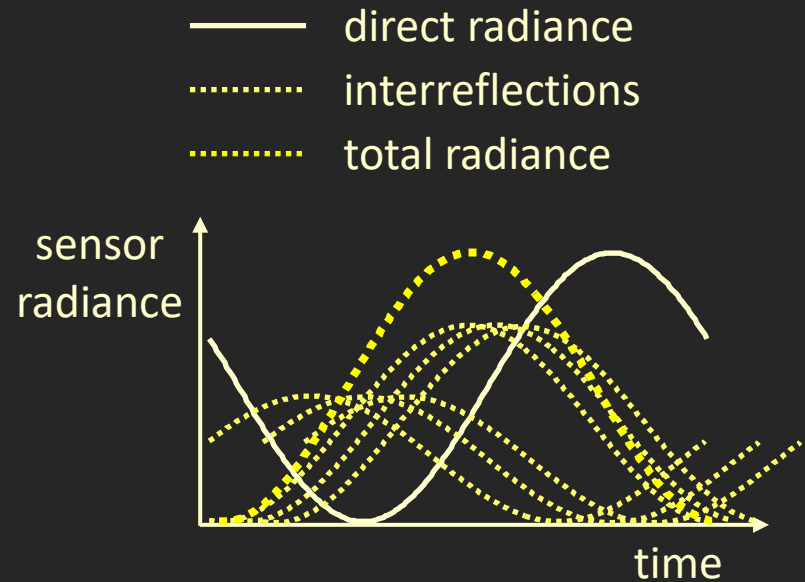
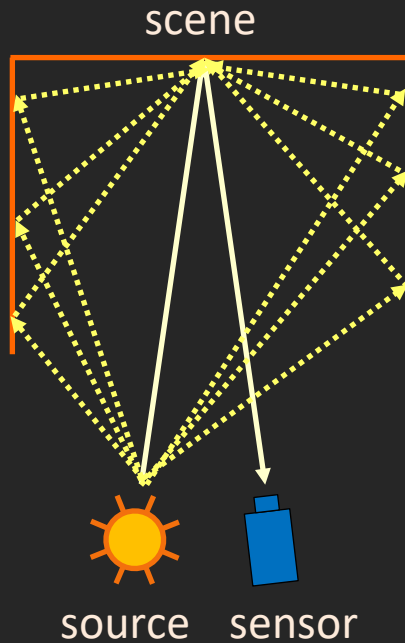
Errors in Shape Recovery



camera view

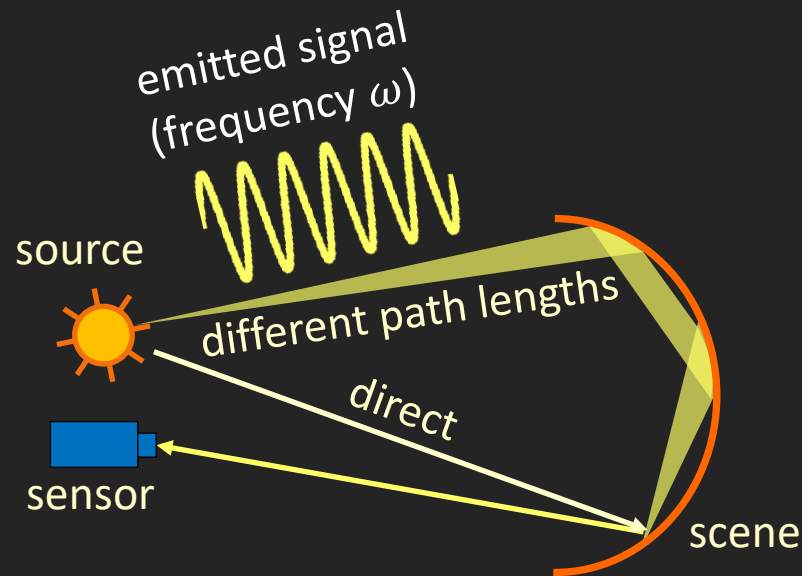


Multipath Interference: Existing Work

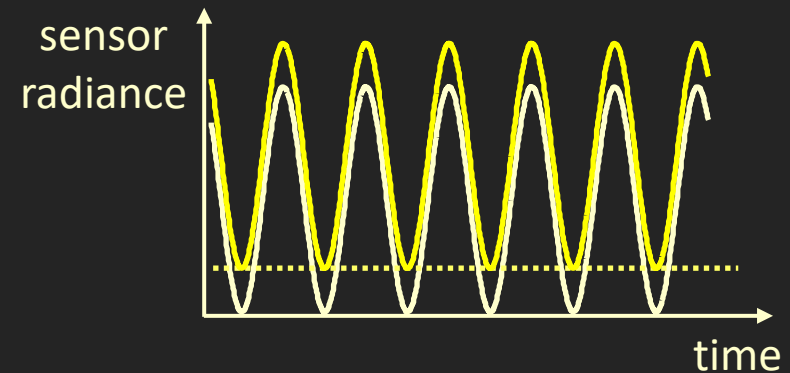


How To Separate Different Components?

Interreflections vs. Modulation Frequency

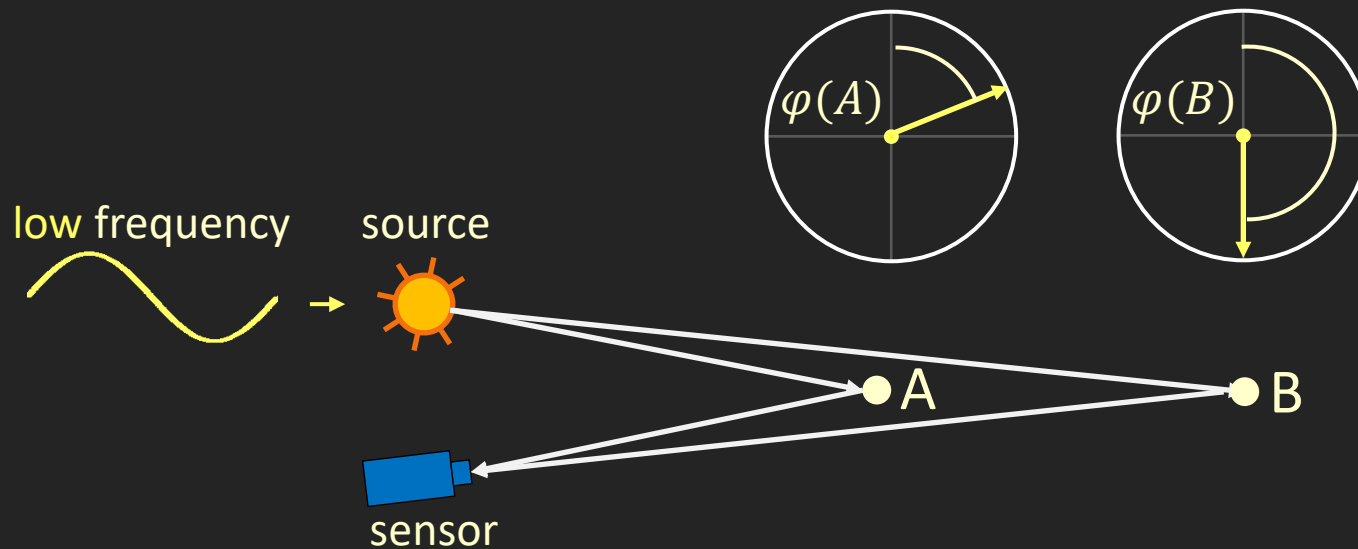


— total radiance
 — direct radiance
 interreflection



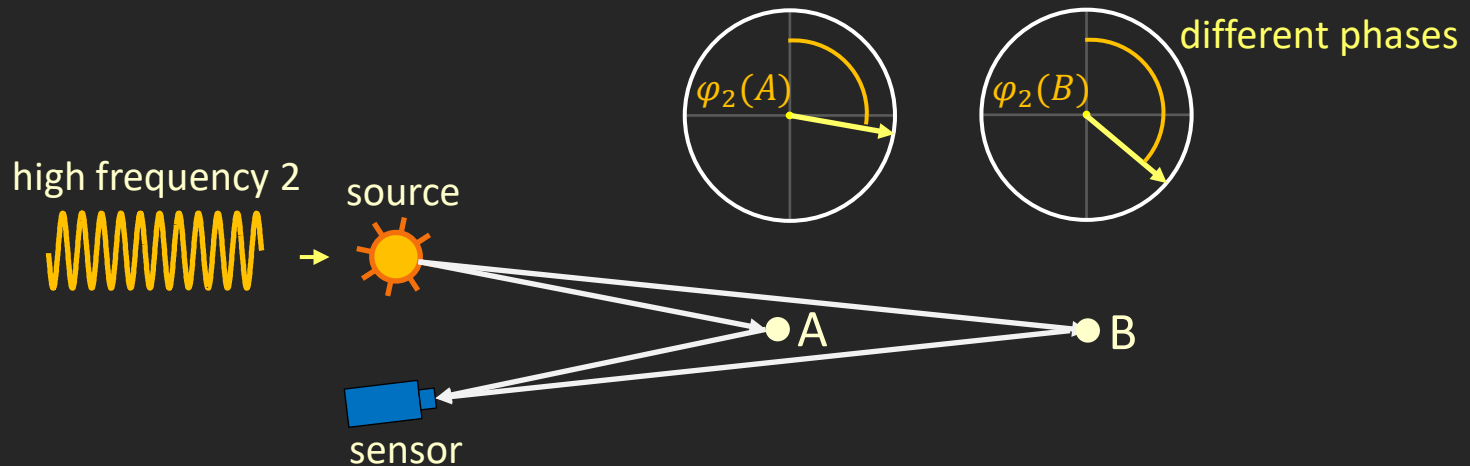
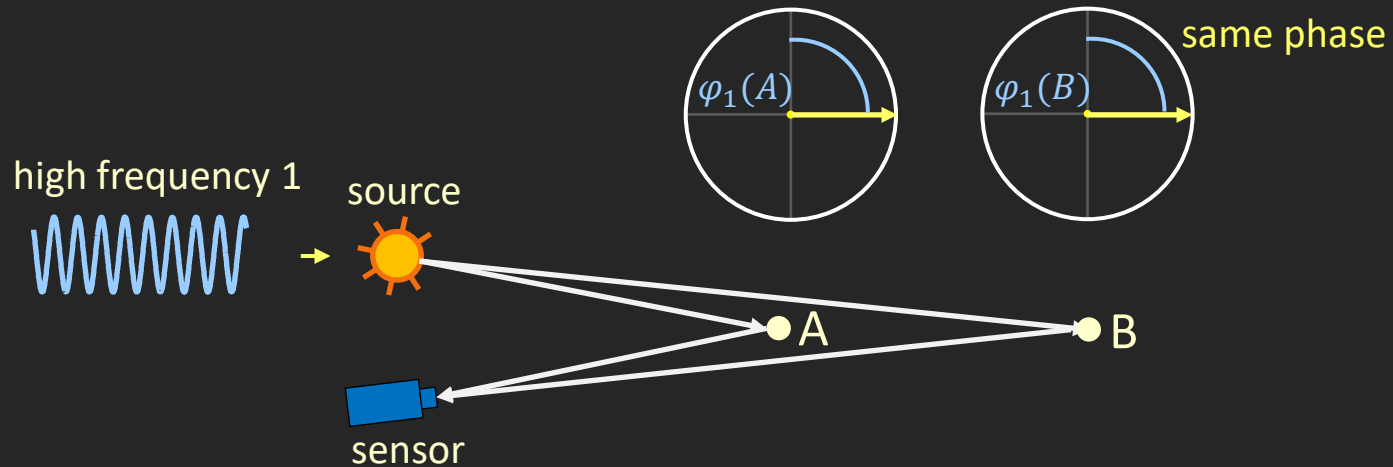
For High Temporal Frequency
 Interreflections Do Not Affect Phase

Phase Ambiguity



Unambiguous Depth Range: $R_{unambiguous} = \frac{1}{2\omega}$

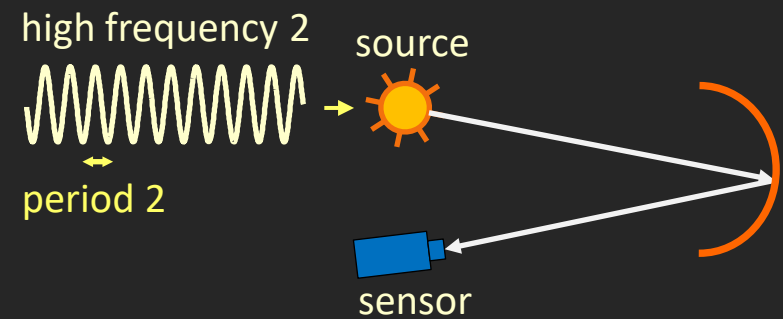
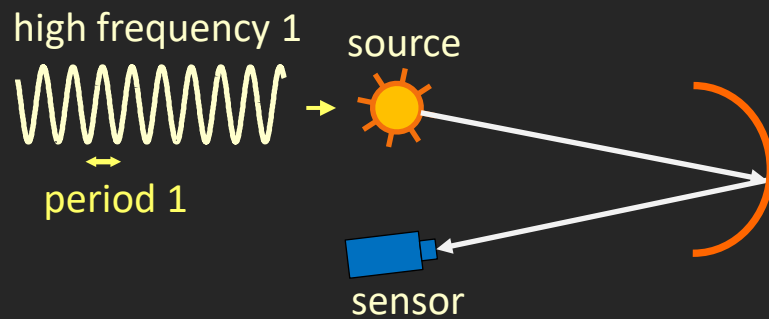
Disambiguating Phase



Compute Phases at Two High Frequencies

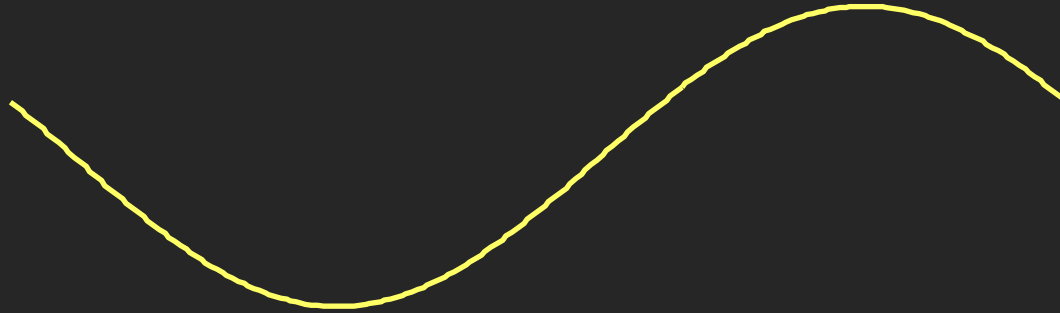
[Jongenelen *et al.* 2010, 2011]

Micro Time-of-Flight Imaging

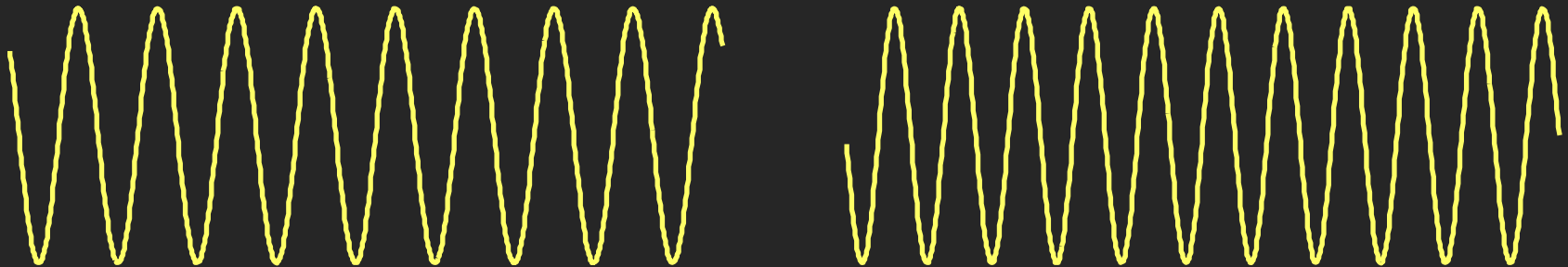


Modulation Signals With Micro (Small) Periods

Conventional vs. Micro ToF Imaging

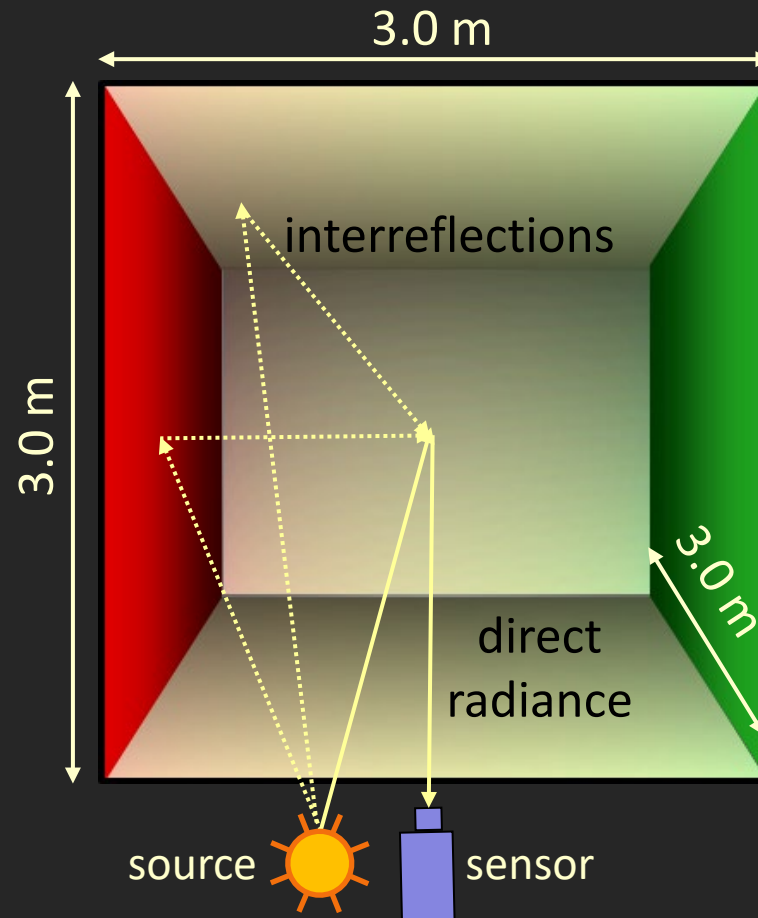


Conventional ToF Shifting: One Low Frequency
Three Measurements

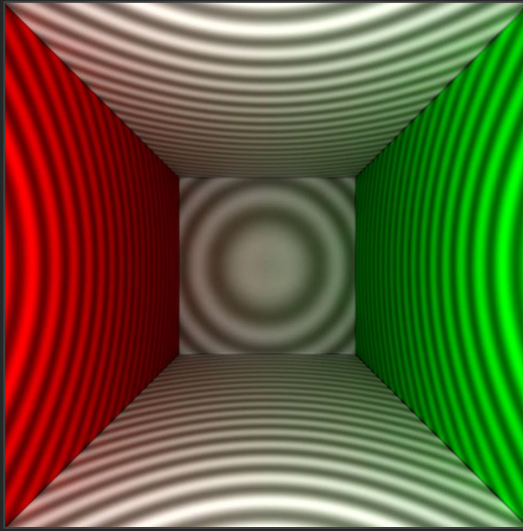


Micro ToF Shifting: Two High Frequencies
Four Measurements

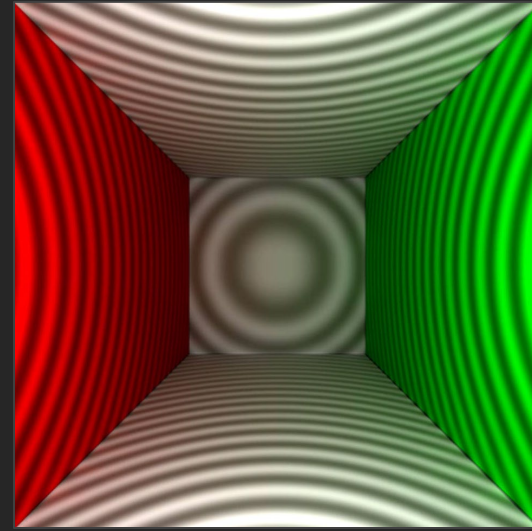
Simulations: Cornell Box



Cornell Box: Input Images

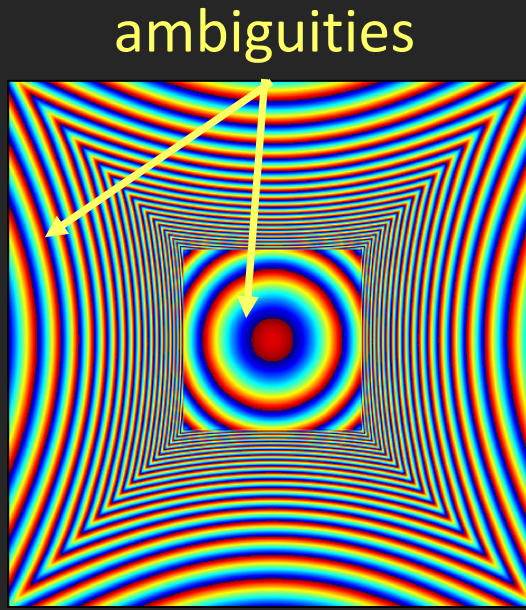


957 MHz.

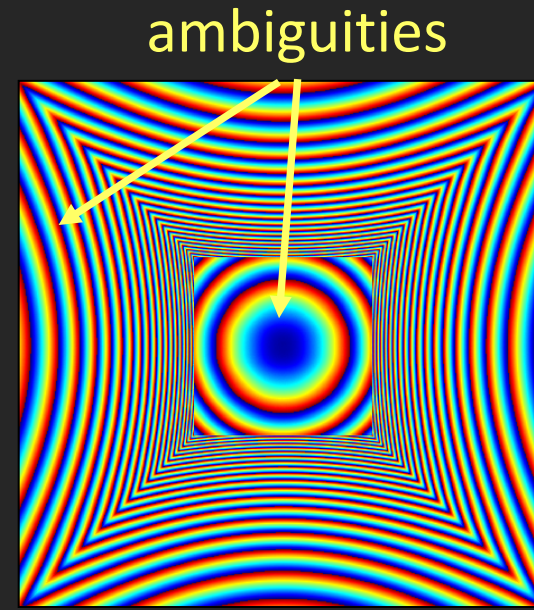


930 MHz.

Cornell Box: Phase Maps



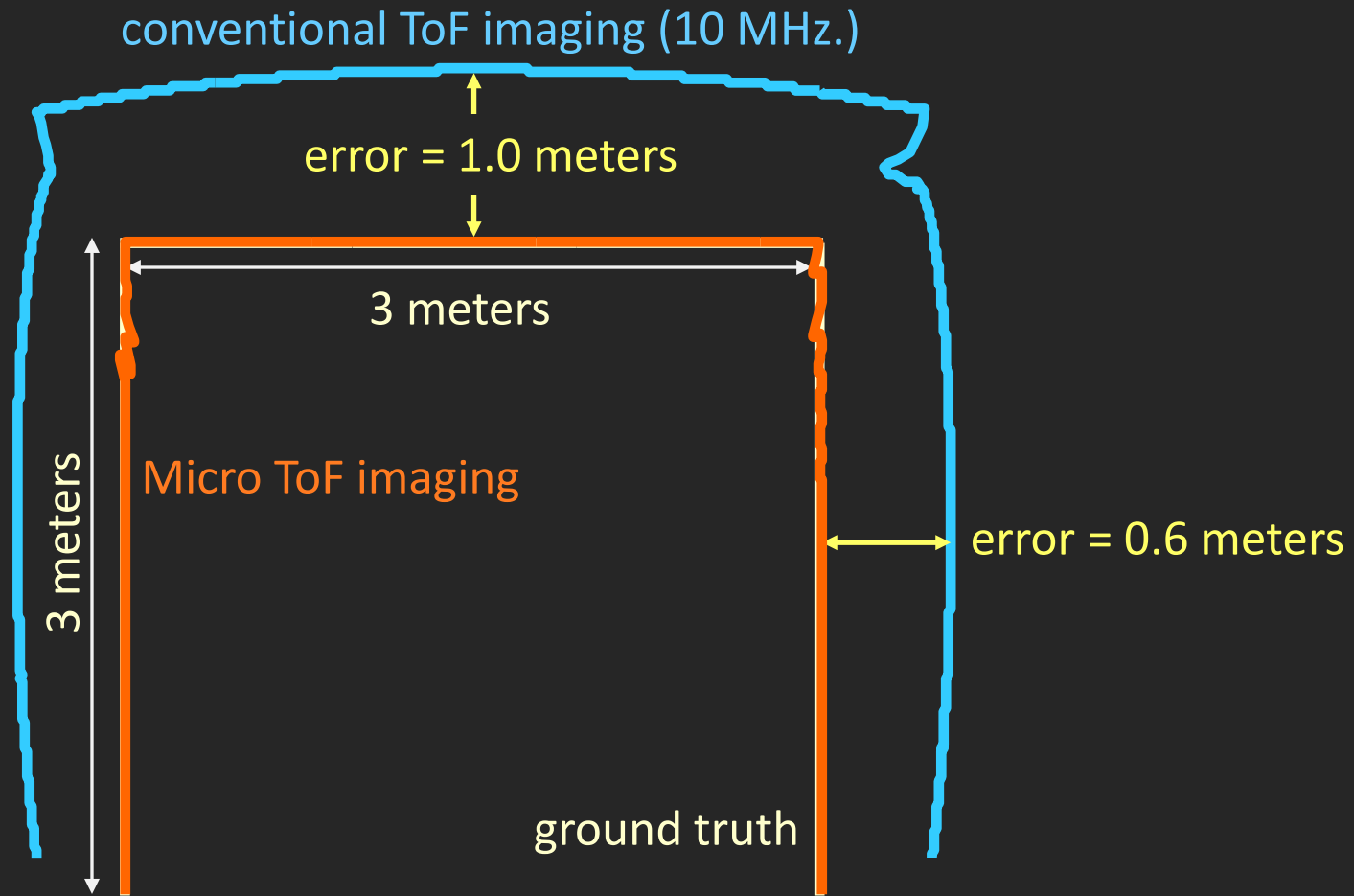
957 MHz.



930 MHz.



Cornell Box: Shape Comparison



Scattering in Real World

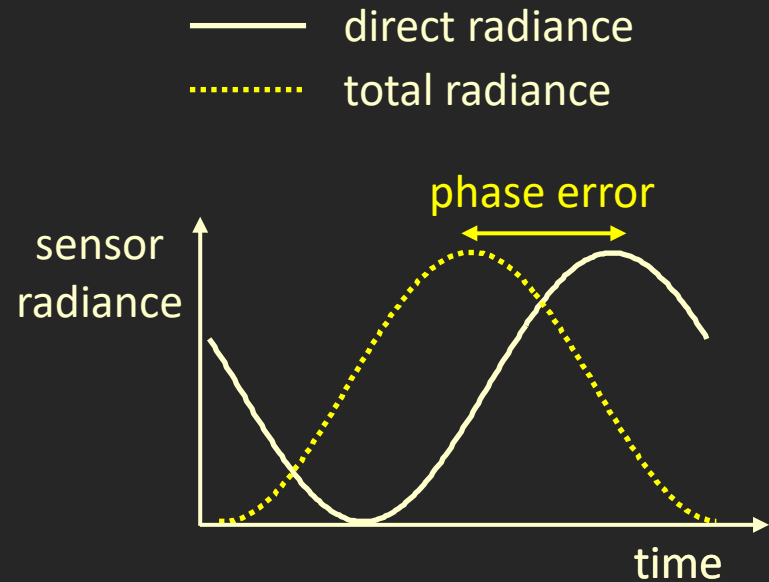
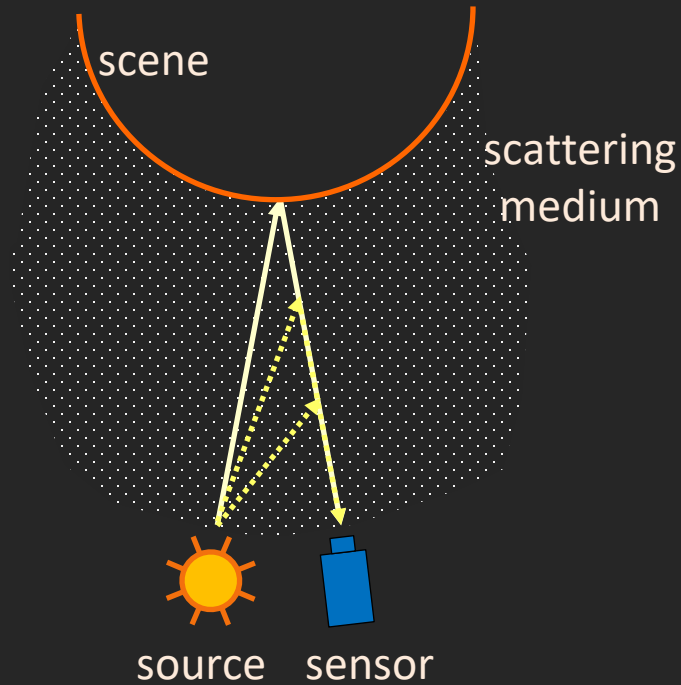


Driving through fog/mist



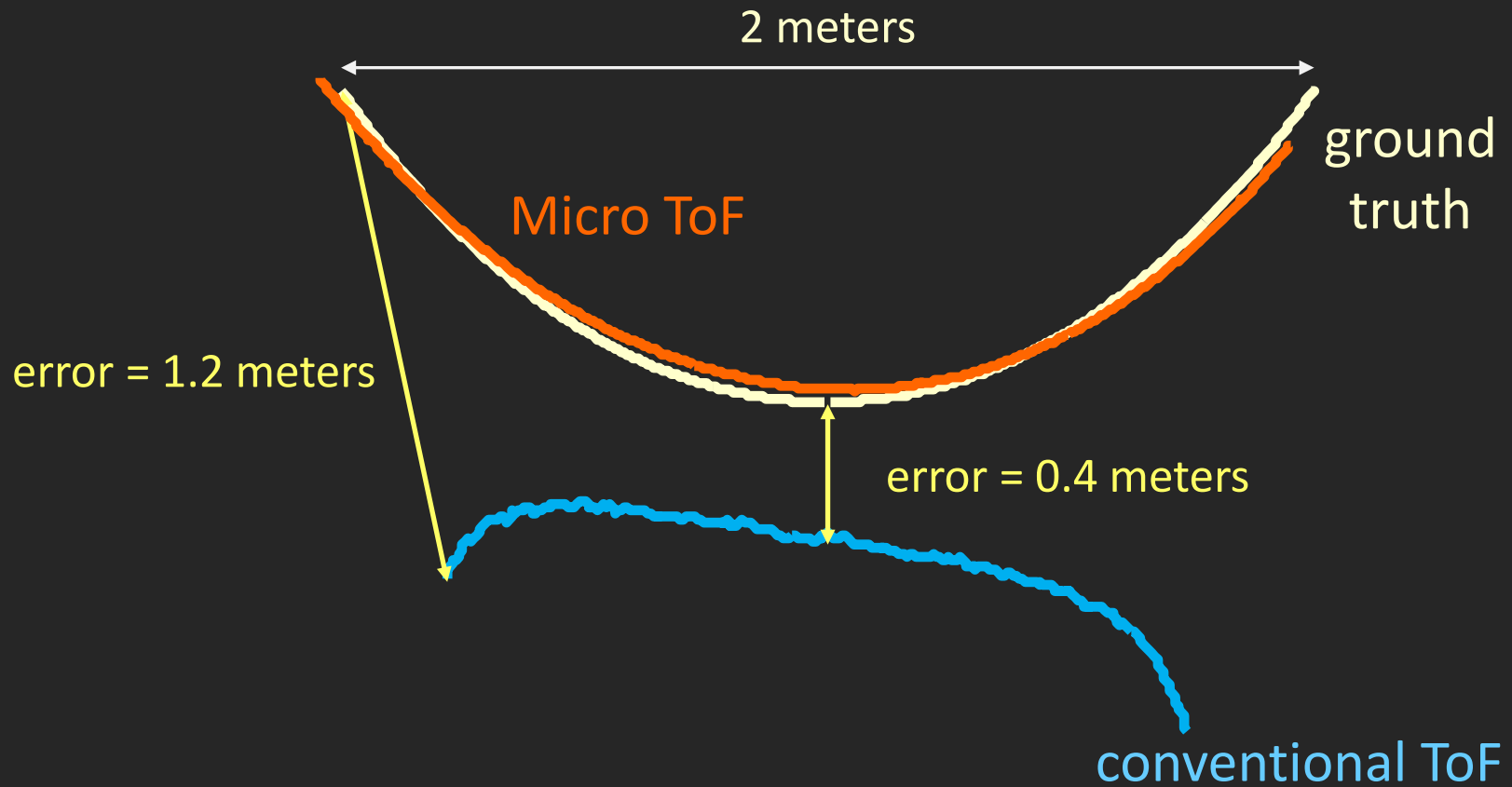
Driving through a dust storm

Scattering and ToF Imaging



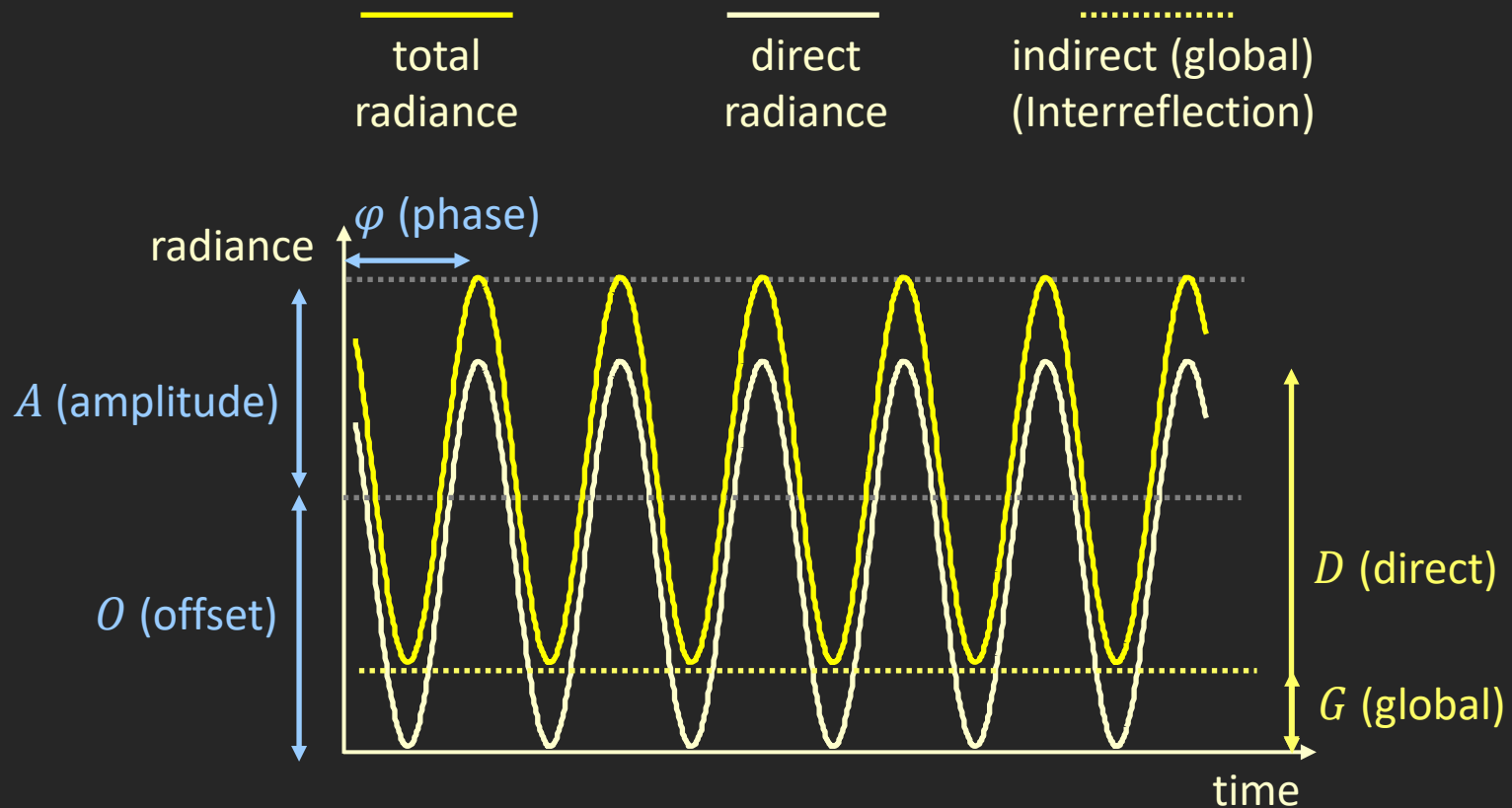
Scattering Produces Incorrect Phase

Sphere: Shape Comparison



Micro ToF Depth is Undersampled Accuracy Shape

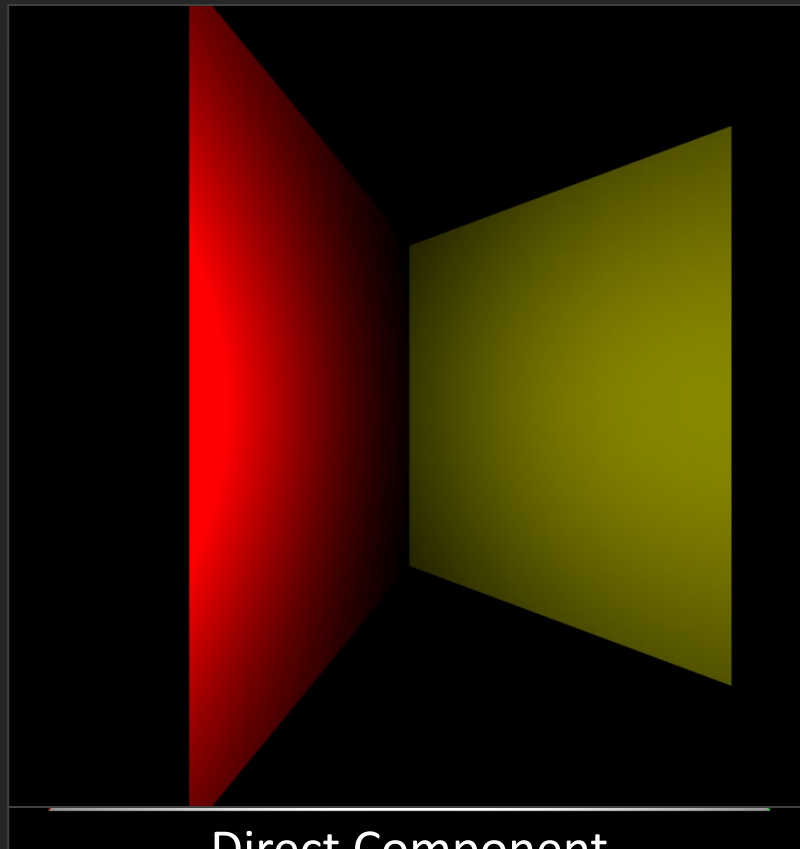
Direct-Indirect Separation



$$D = 2A \quad G = O - A$$

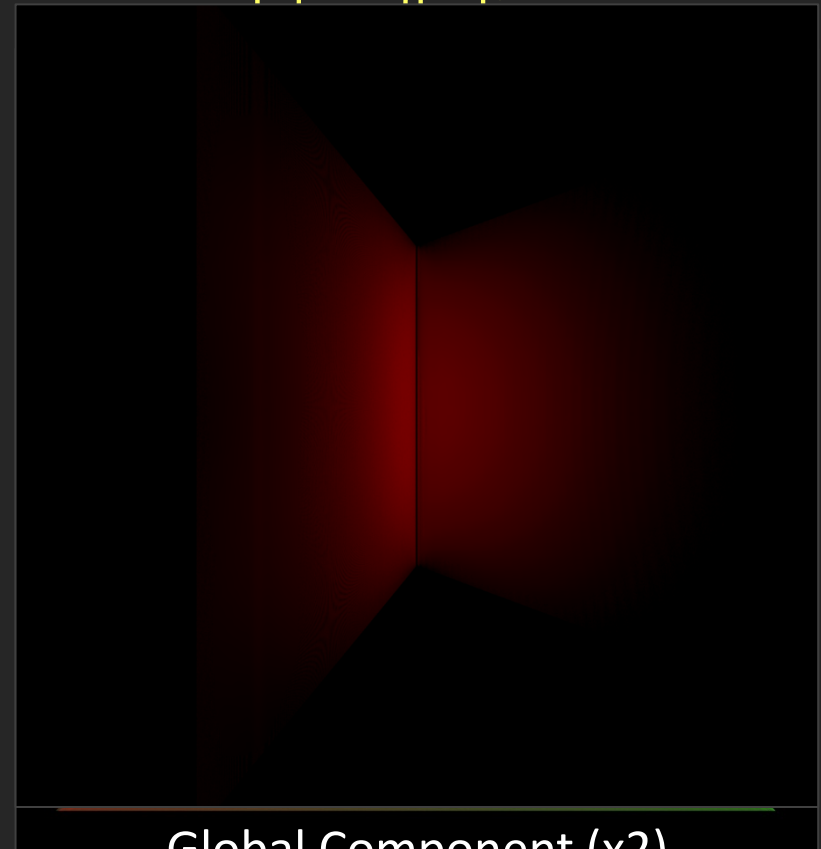
Direct-Global Separation Using Three Measurements

Direct-Global Separation



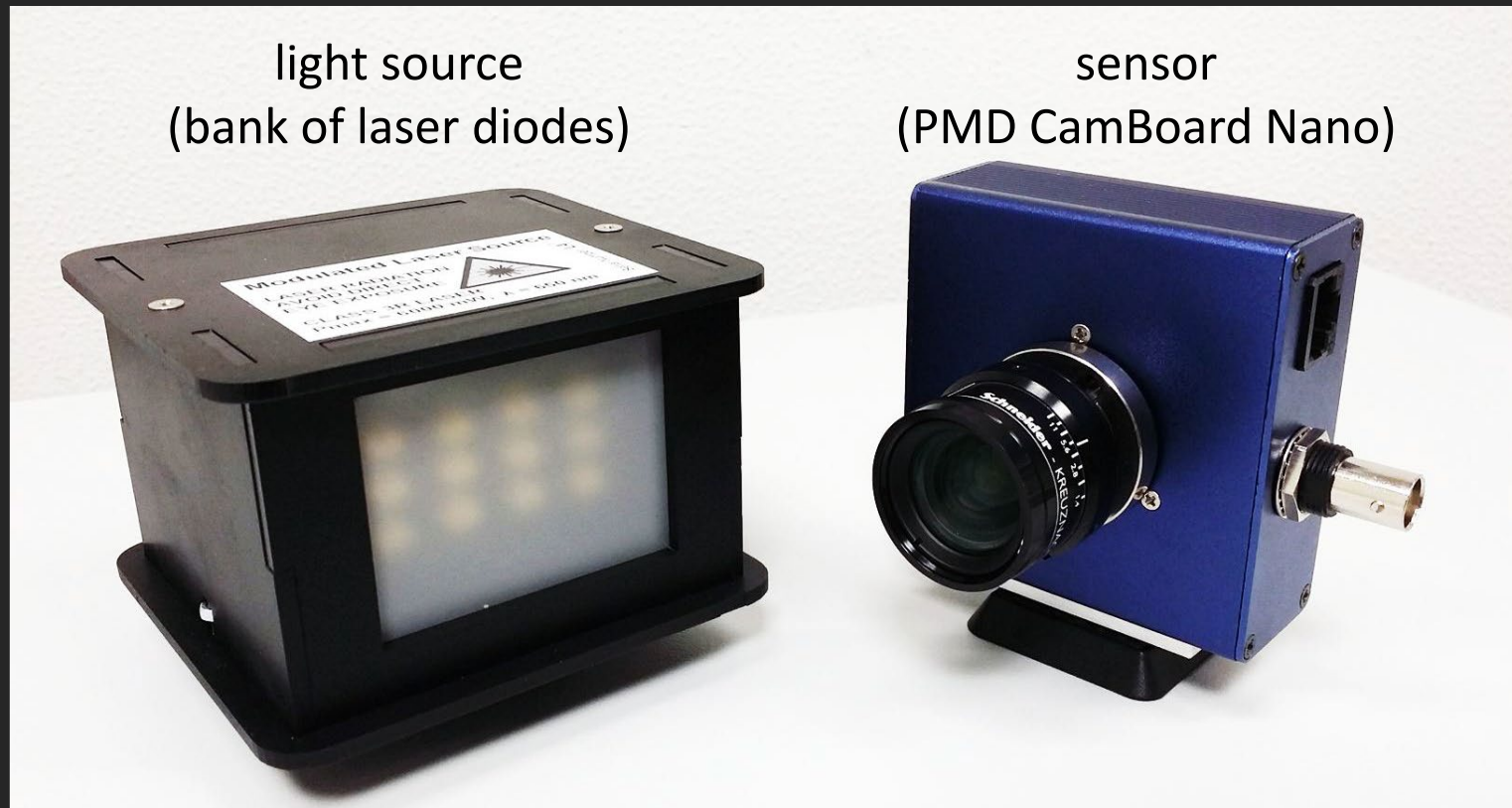
Direct Component
Direct Component

Color Bleeding due to
Global Illumination



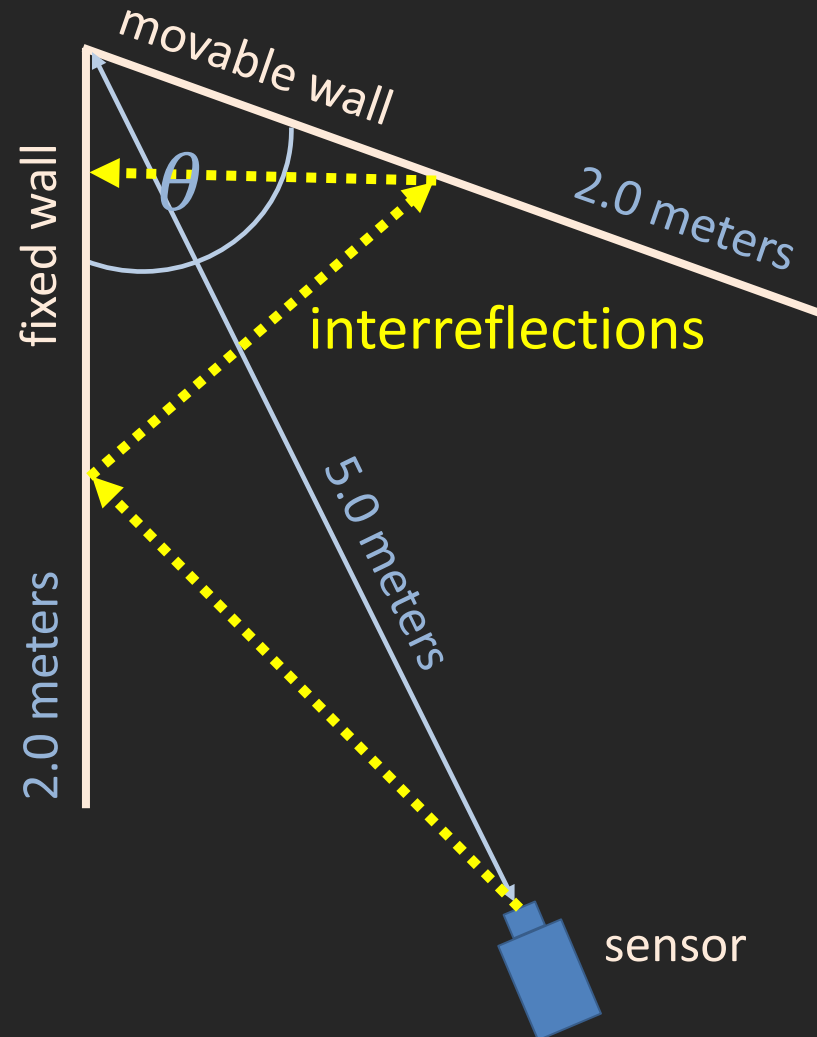
Global Component (x2)
Global Component (x2)

Experimental Setup

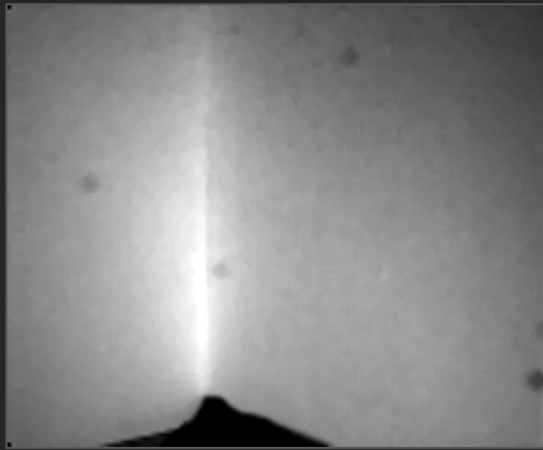


Maximum System Modulation Frequency = 125 MHz.

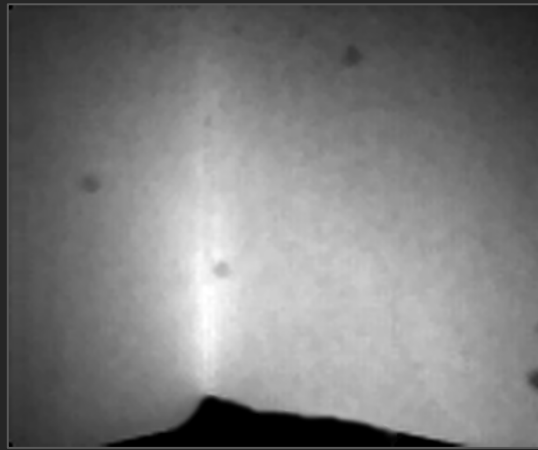
Experiments: V-Groove



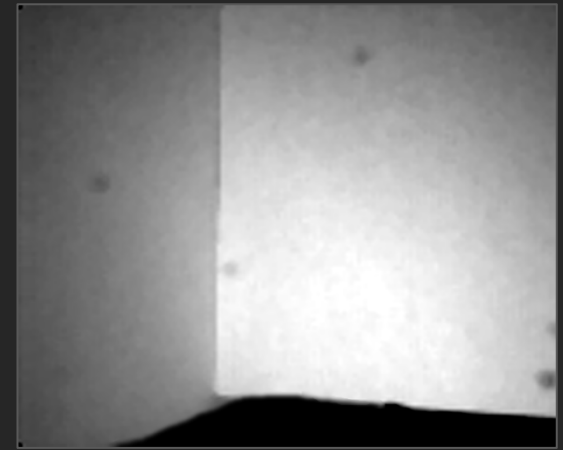
Scene Images Captured By PMD Sensor



apex angle = 45°



apex angle = 60°

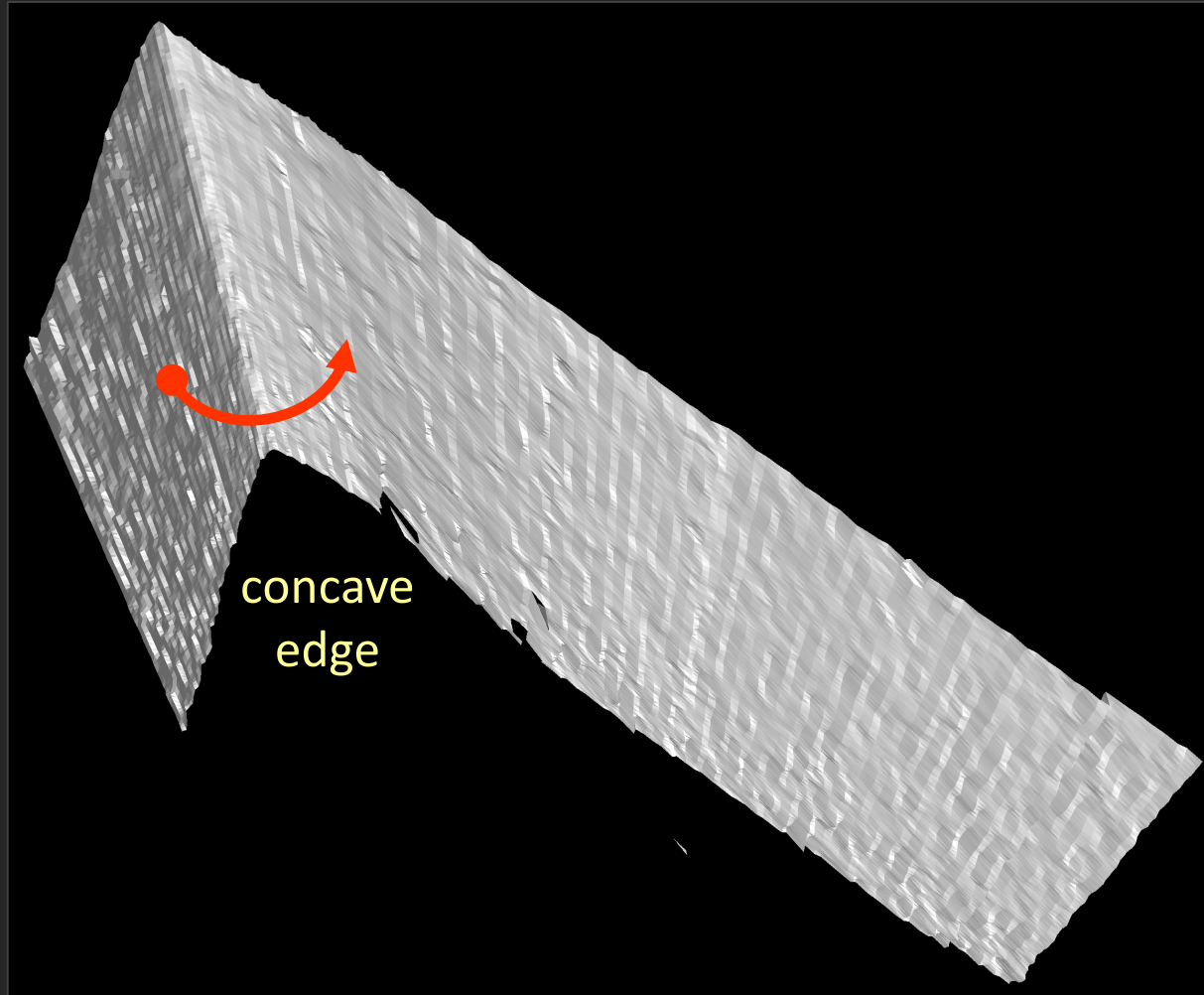


apex angle = 90°

image resolution = 120 x 165

Reconstructed Shape using Micro ToF

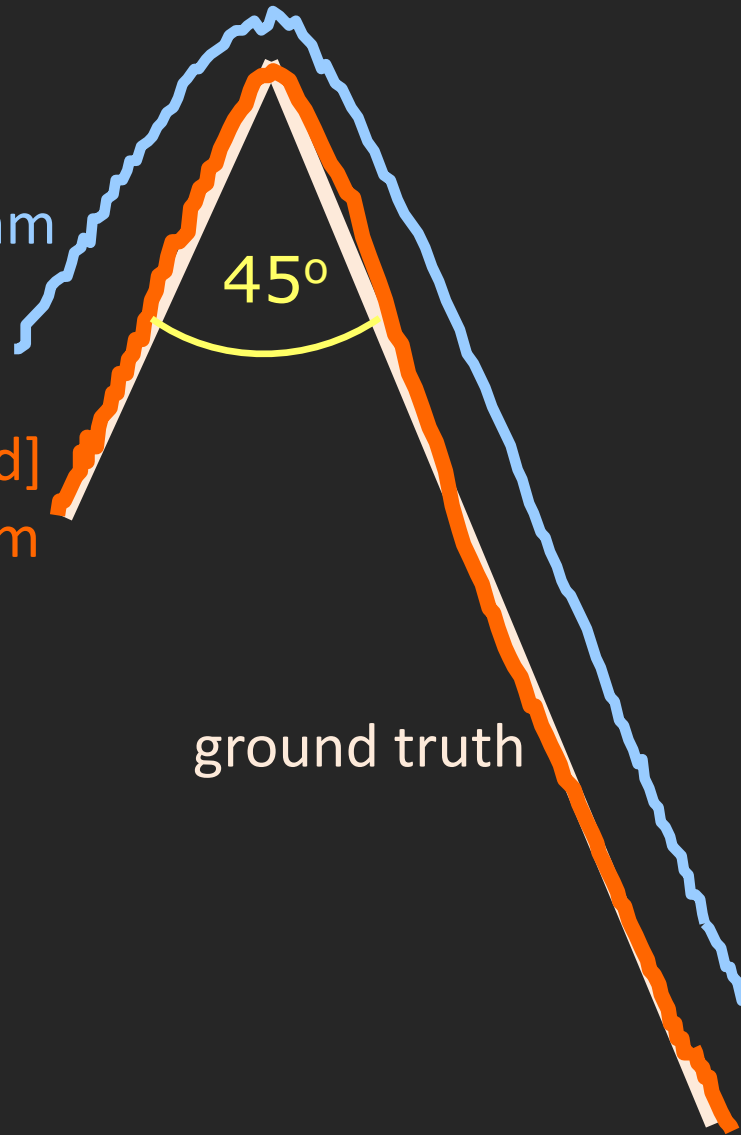
113



Shape Comparisons

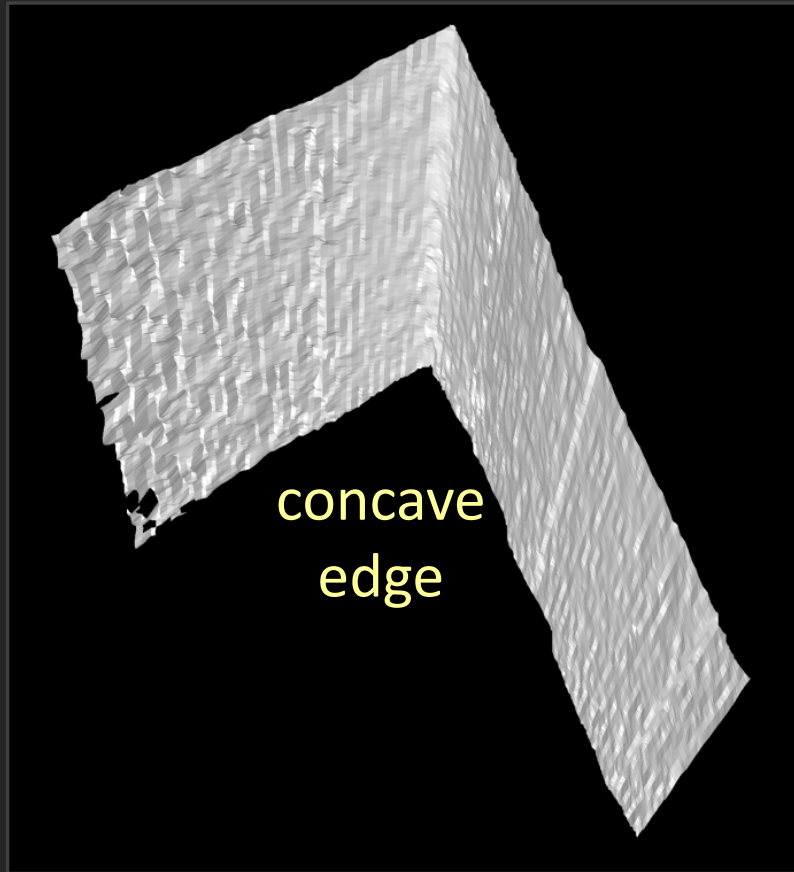
conventional ToF
mean error = 86.6 mm

Micro ToF [proposed]
mean error = 2.8 mm

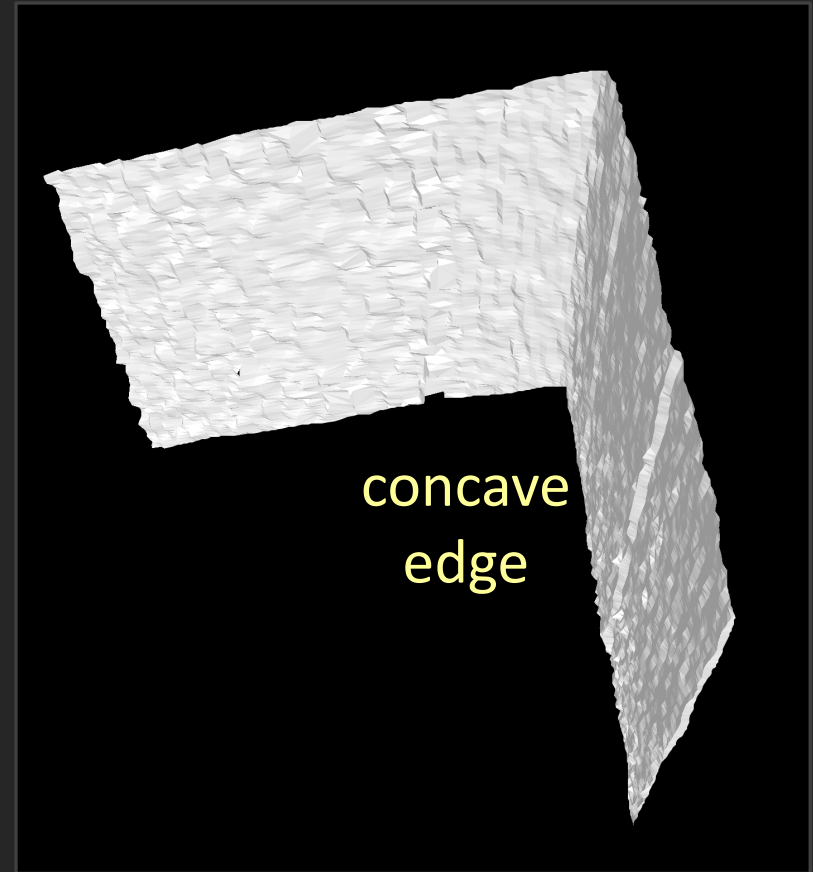


Reconstructed Shapes: Different Angles

115



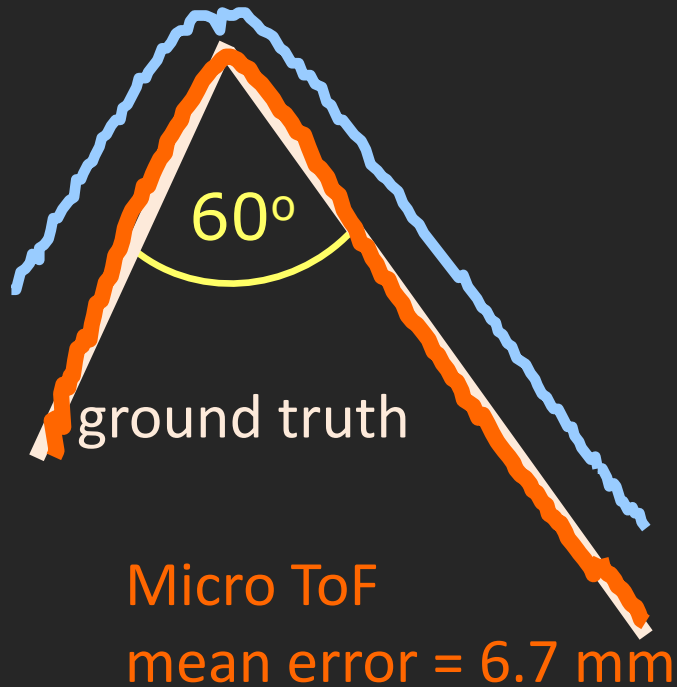
$\theta = 60^\circ$



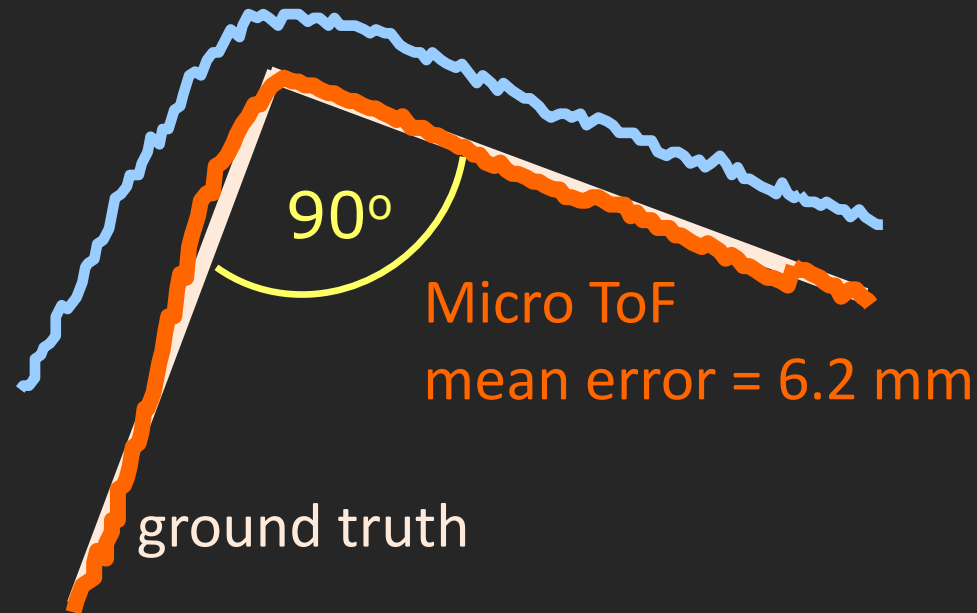
$\theta = 90^\circ$

Shape Comparisons

conventional ToF
mean error = 69.8 mm

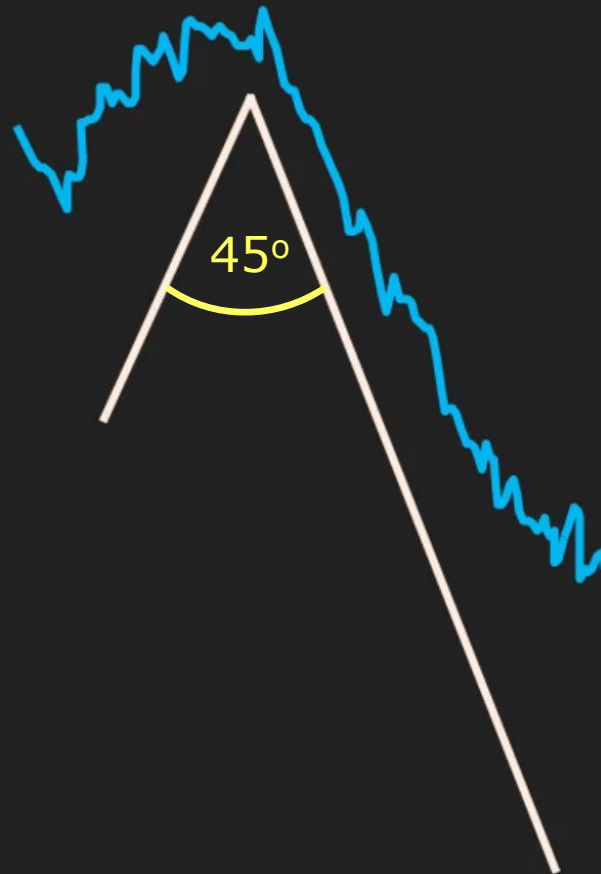


conventional ToF
mean error = 56.9 mm



Recovered Shape vs. Frequency

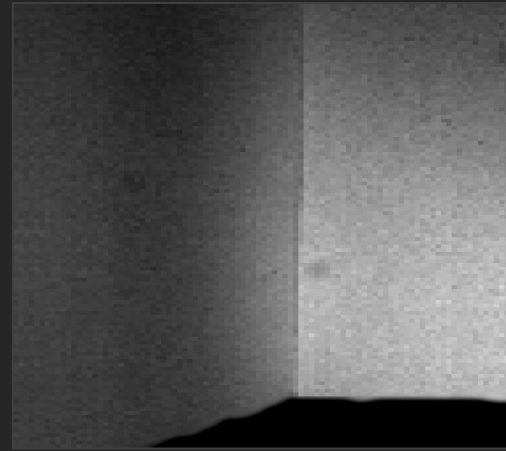
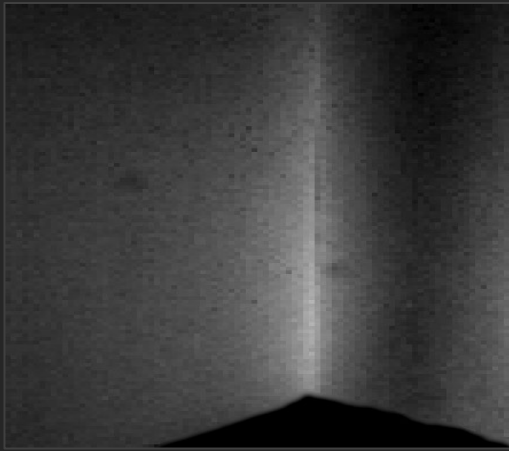
— reconstruction — ground truth



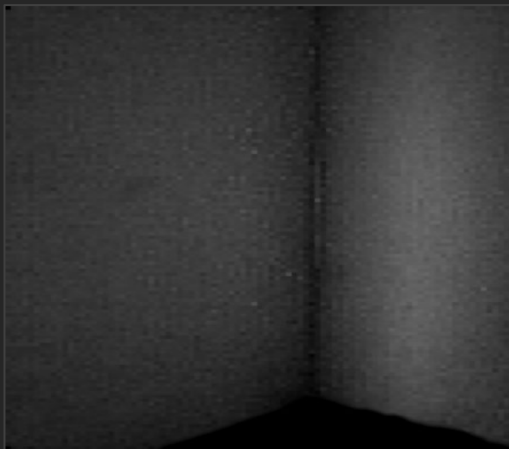
$\omega = 1$ MHz.

Direct-Global Separation Vs. Apex Angle

Direct



Global

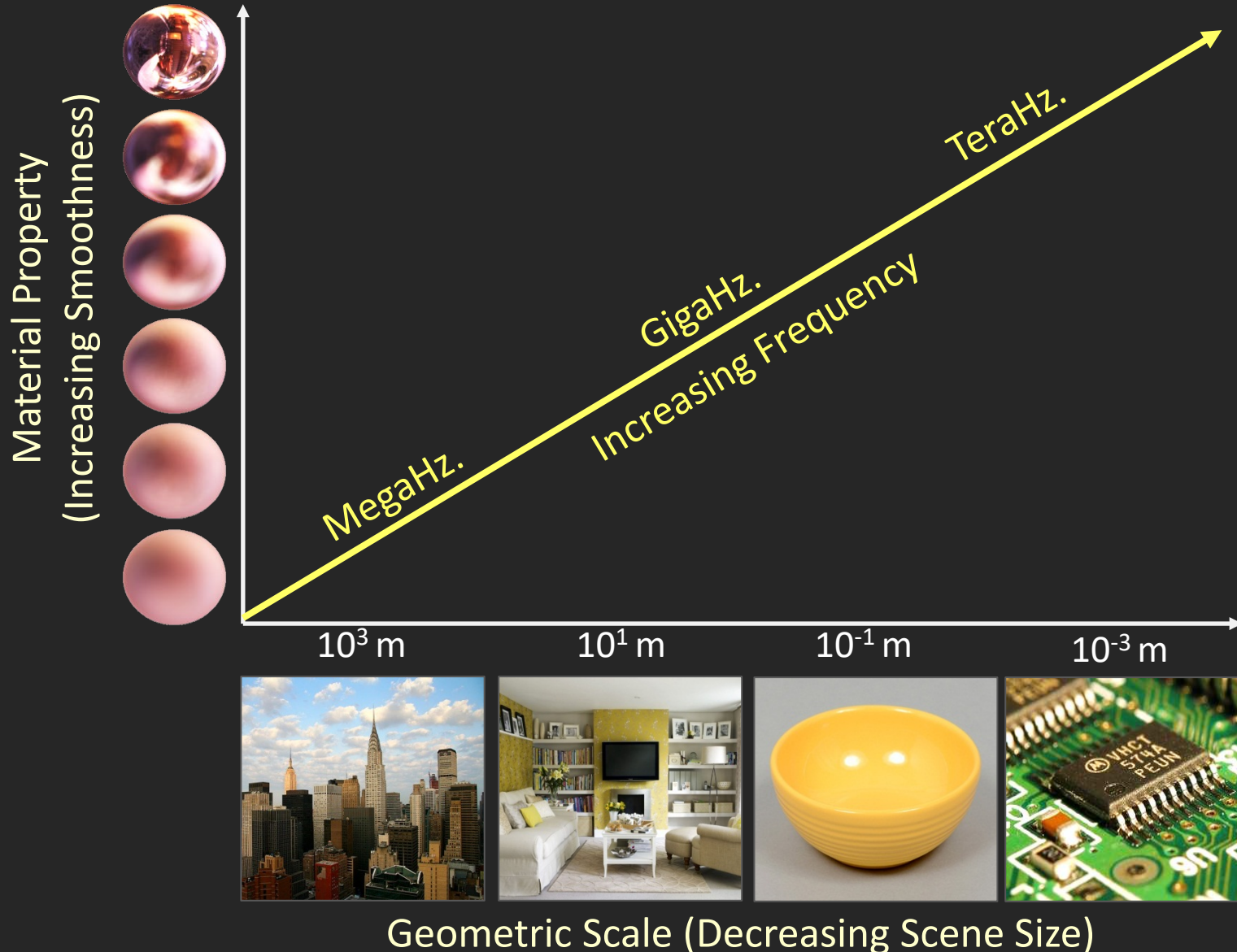


apex angle = 45°

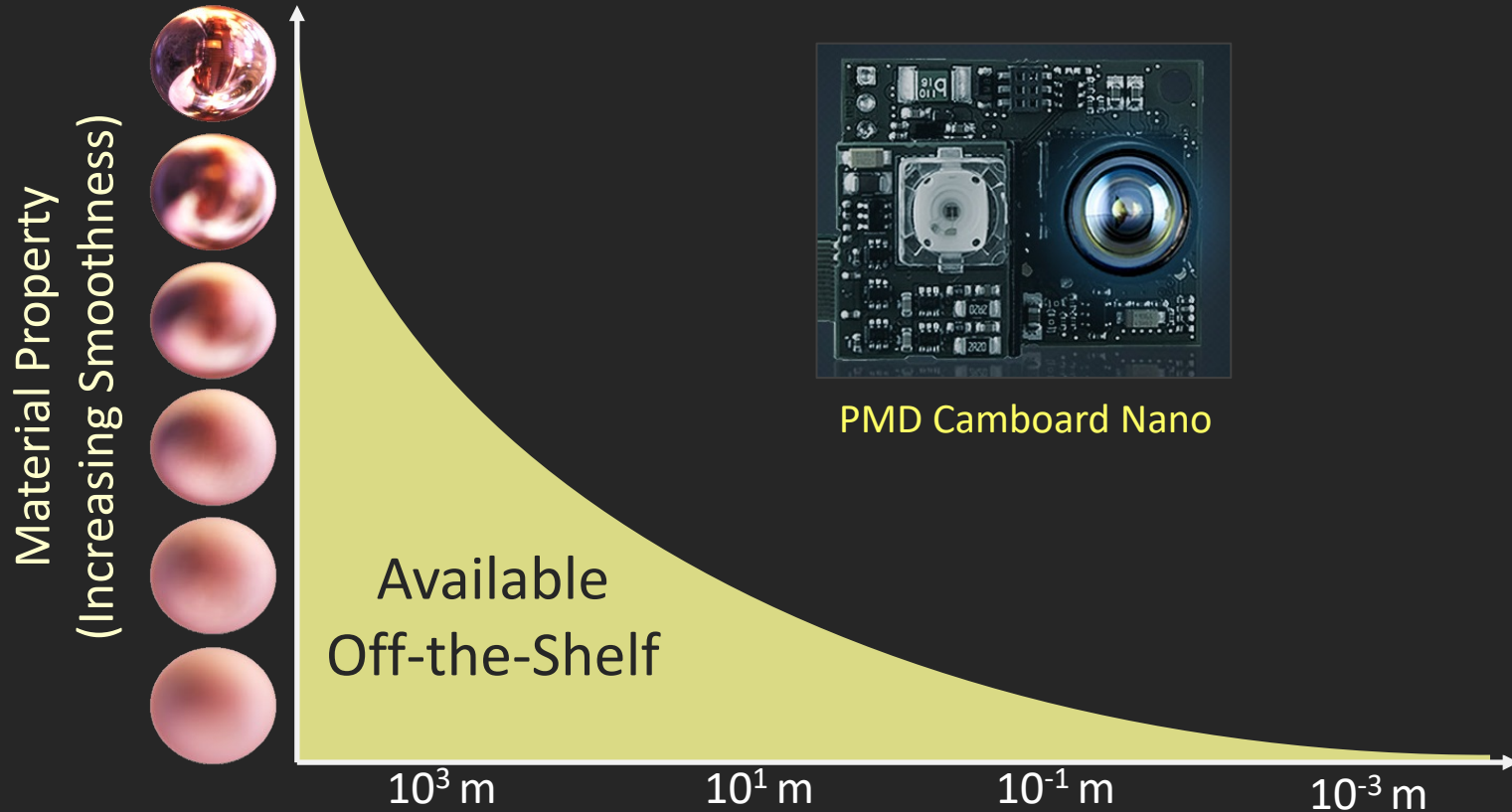
apex angle = 90°

————— decreasing global component —————>

How High Should The Frequency Be?

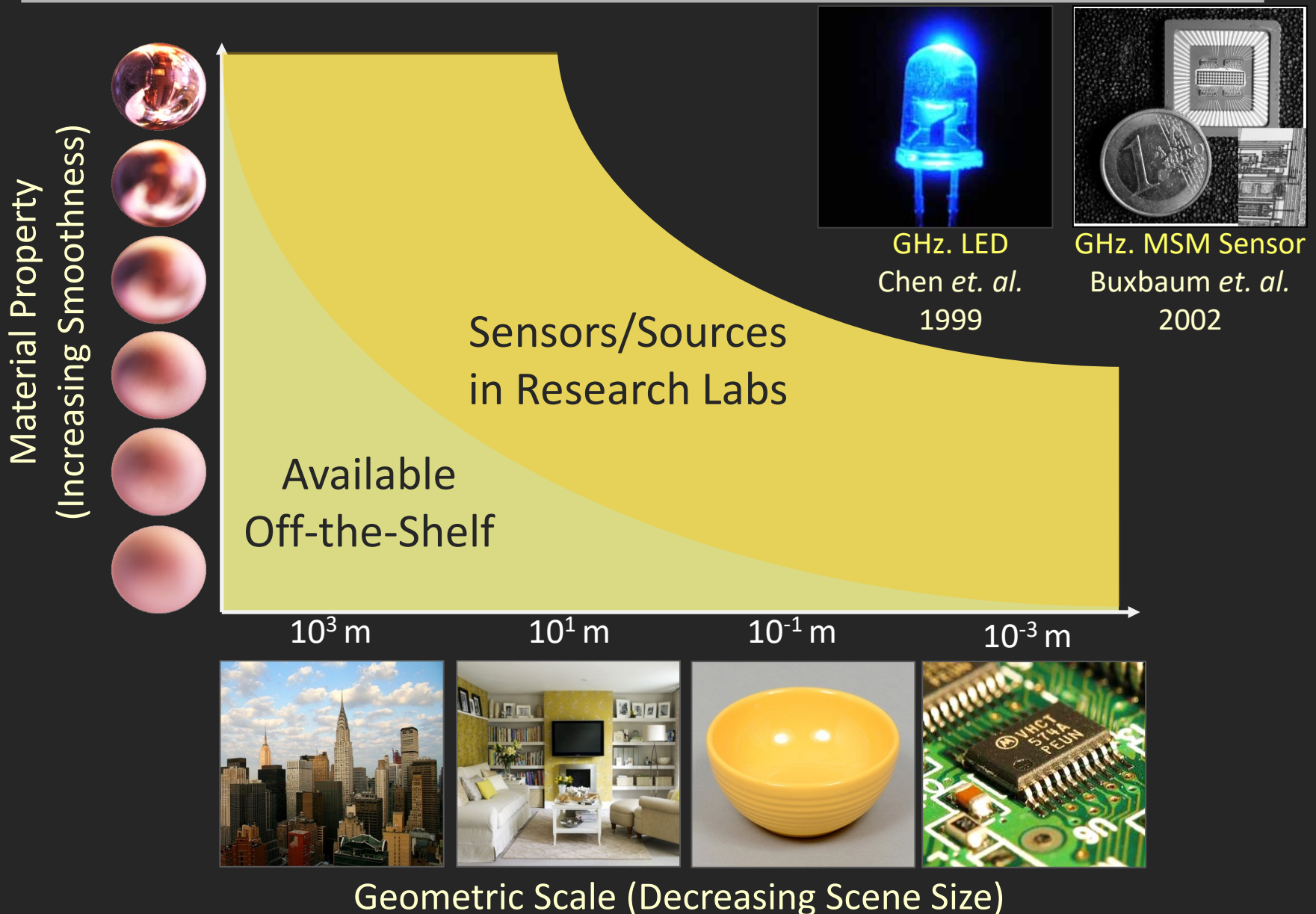


Technology (Devices) Required

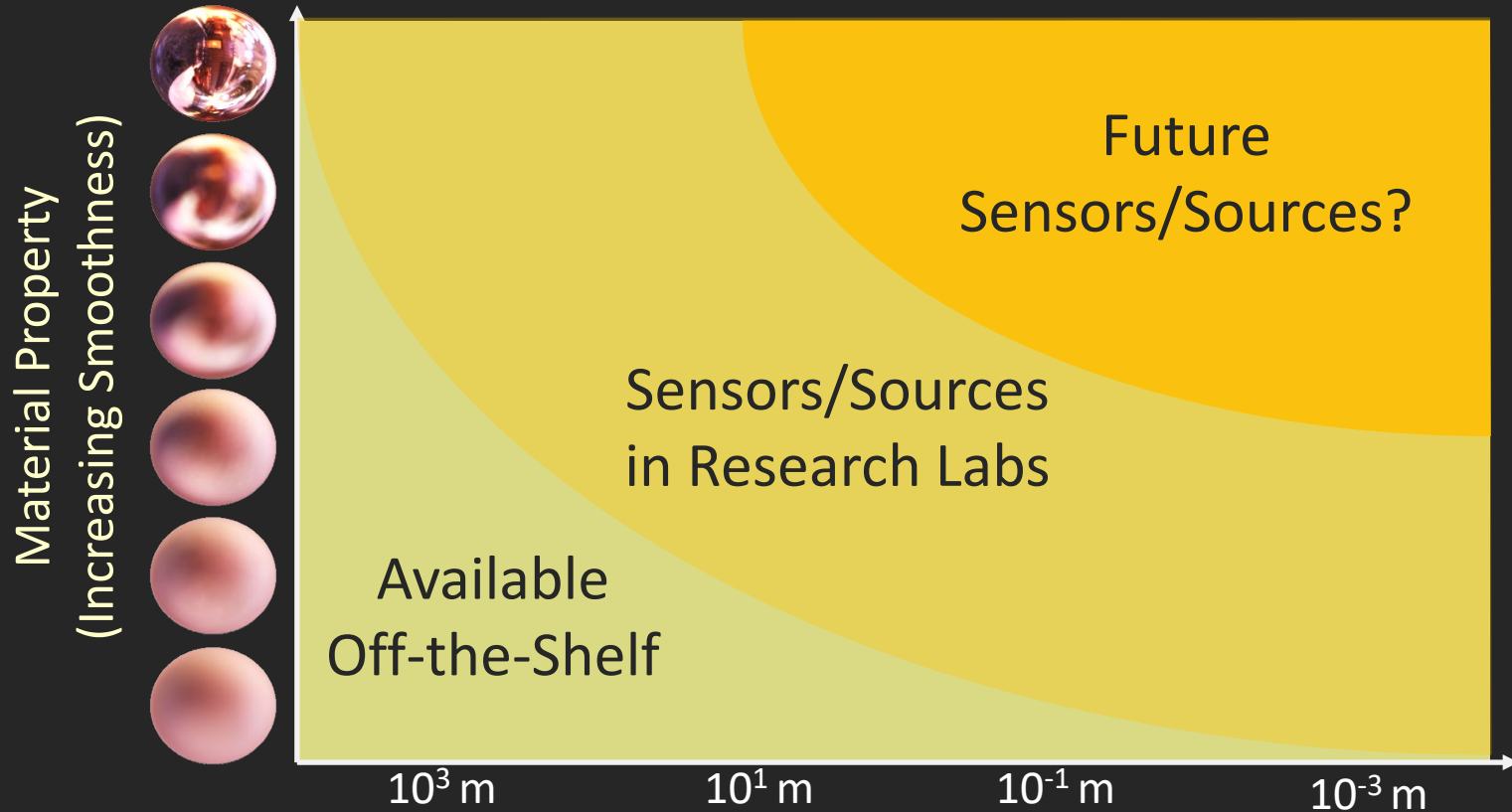


Geometric Scale (Decreasing Scene Size)

Technology (Devices) Required



Technology (Devices) Required



Geometric Scale (Decreasing Scene Size)

References

Basic reading:

- Nayar et al., “Fast separation of direct and global components of a scene using high frequency illumination,” SIGGRAPH 2004.
The paper on separation of direct and global illumination using high-frequency illumination.
- Gupta et al., “A Practical Approach to 3D Scanning in the Presence of Interreflections, Subsurface Scattering and Defocus,” IJCV 2013.
The paper on using XOR codes to deal with global illumination in structured light 3D.
- Gupta et al., “Phasor imaging: A generalization of correlation-based time-of-flight imaging,” TOG 2015.
The paper on using high-frequency modulation to deal with interreflections and MPI in CW-ToF imaging.

Additional reading:

- Seitz et al., “A theory of inverse light transport,” ICCV 2005.
This early paper shows a way to *exactly* decompose light transport by number of bounces, under certain assumptions for the imaged scene.
- Chandraker et al., “On the duality of forward and inverse light transport,” PAMI 2011.
- Reddy et al., “Frequency-space decomposition and acquisition of light transport under spatially varying illumination,” ECCV 2012.
These two papers have additional analysis about the relationship between direct and global illumination and illumination frequency.