Dealing with global illumination

15-463, 15-663, 15-862
Computational Photography
Fall 2021, Lecture 20

http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- Homework assignment 6 has been posted.
  - Due on Sunday, December 5th.
  - You can use all your remaining late days.
- Final project presentation logistics posted on Piazza.
- Optional extra lecture on Friday 11:40 am – 1:00 pm, at GHC 4303.

Final project competition judges

Matthew O'Toole

Jun-Yan Zhu

- Final project does not need to be fully done by presentation date.
- But judges will only see presentations, not final reports.

Overview of today's lecture

- Direct and global illumination.
- Direct-global separation using high-frequency illumination.
- Back to structured light.

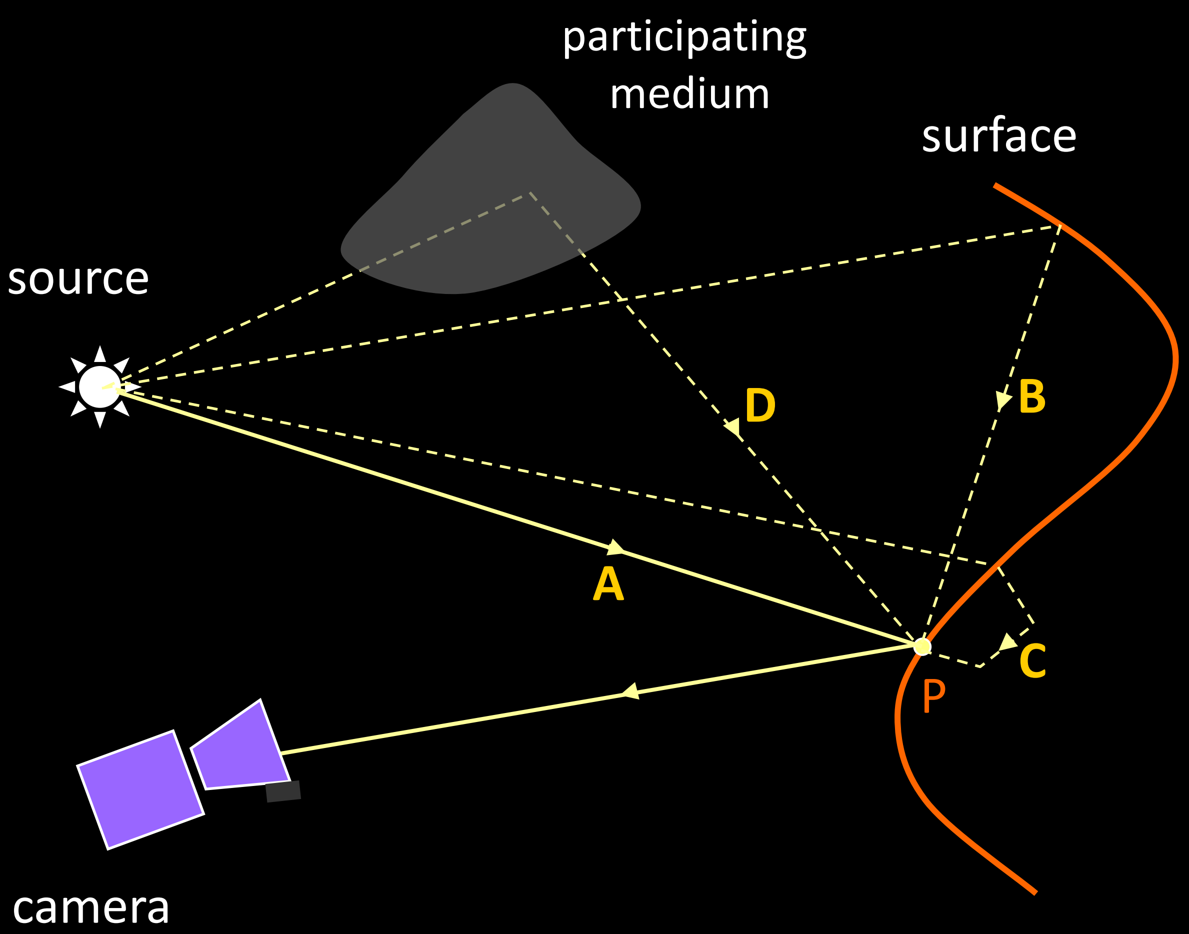
Slide credits

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



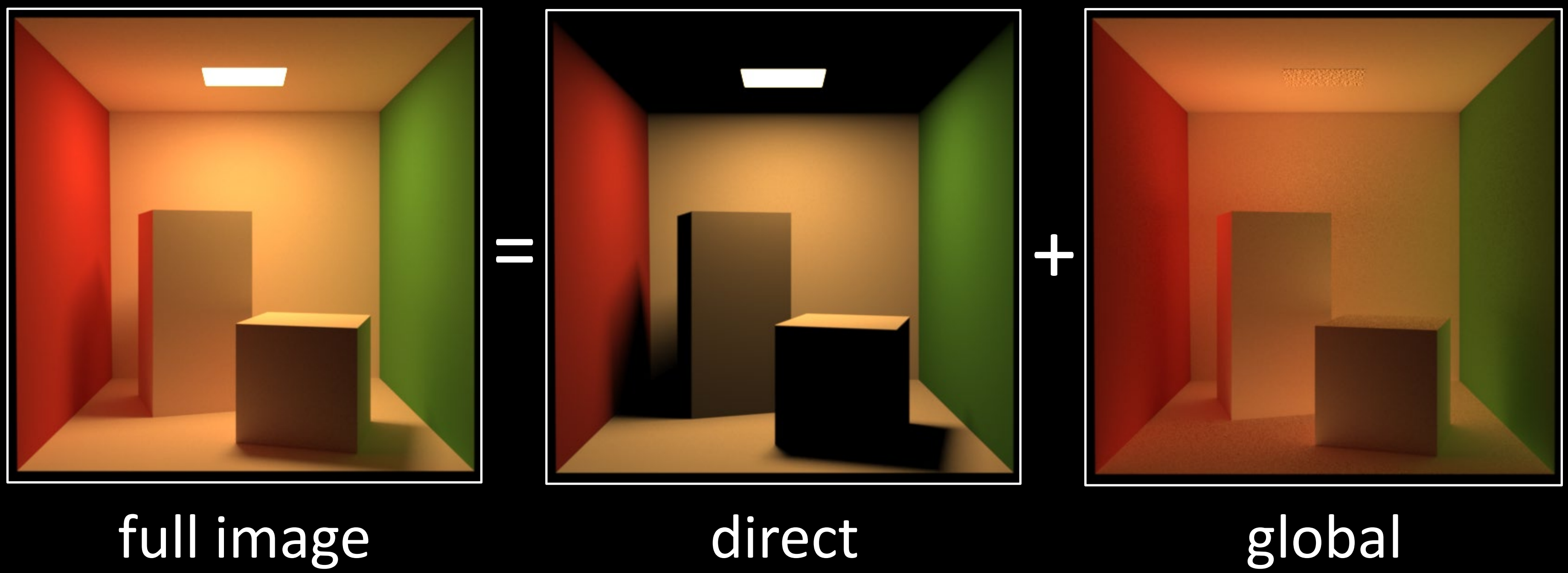
A : Direct

B : Interreflection

C : Subsurface

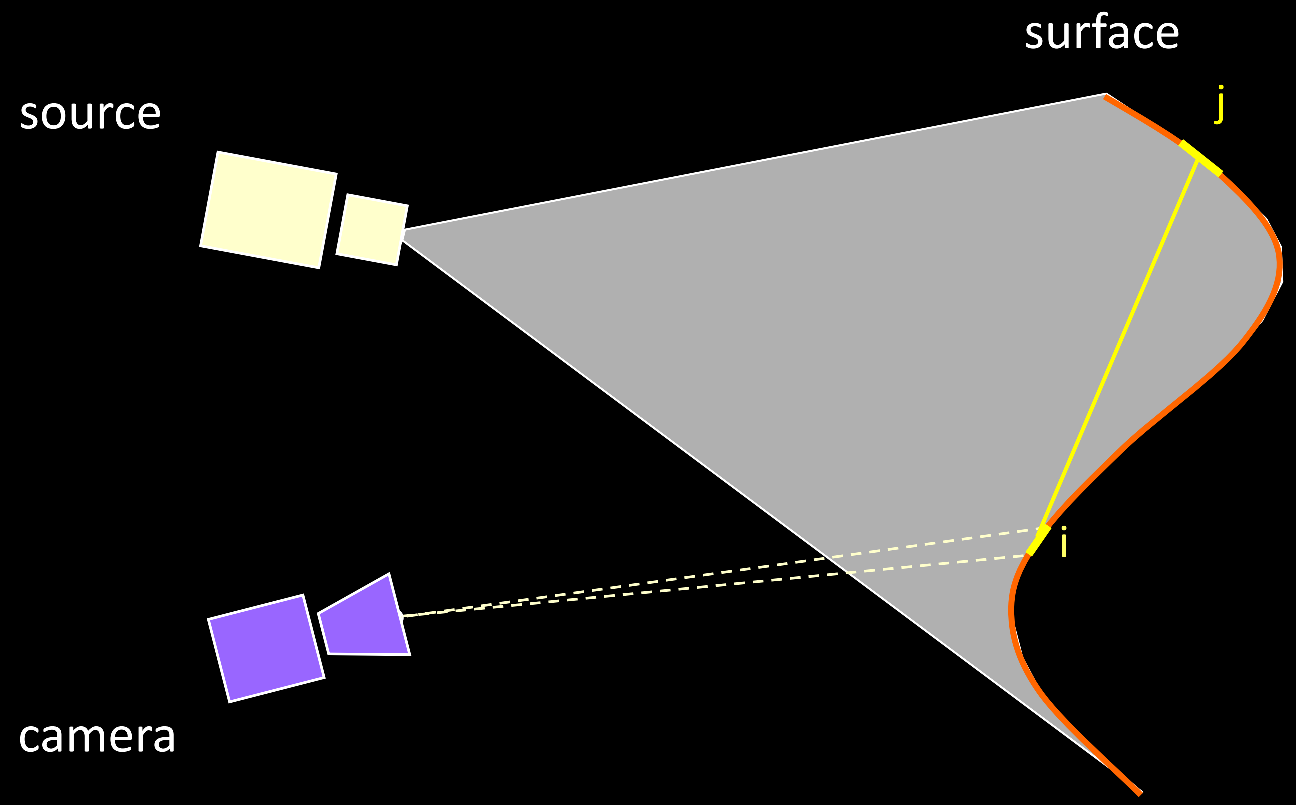
D : Volumetric

Easy to separate in a renderer



Direct-global separation using high-frequency illumination

Direct and Global Components: Interreflections



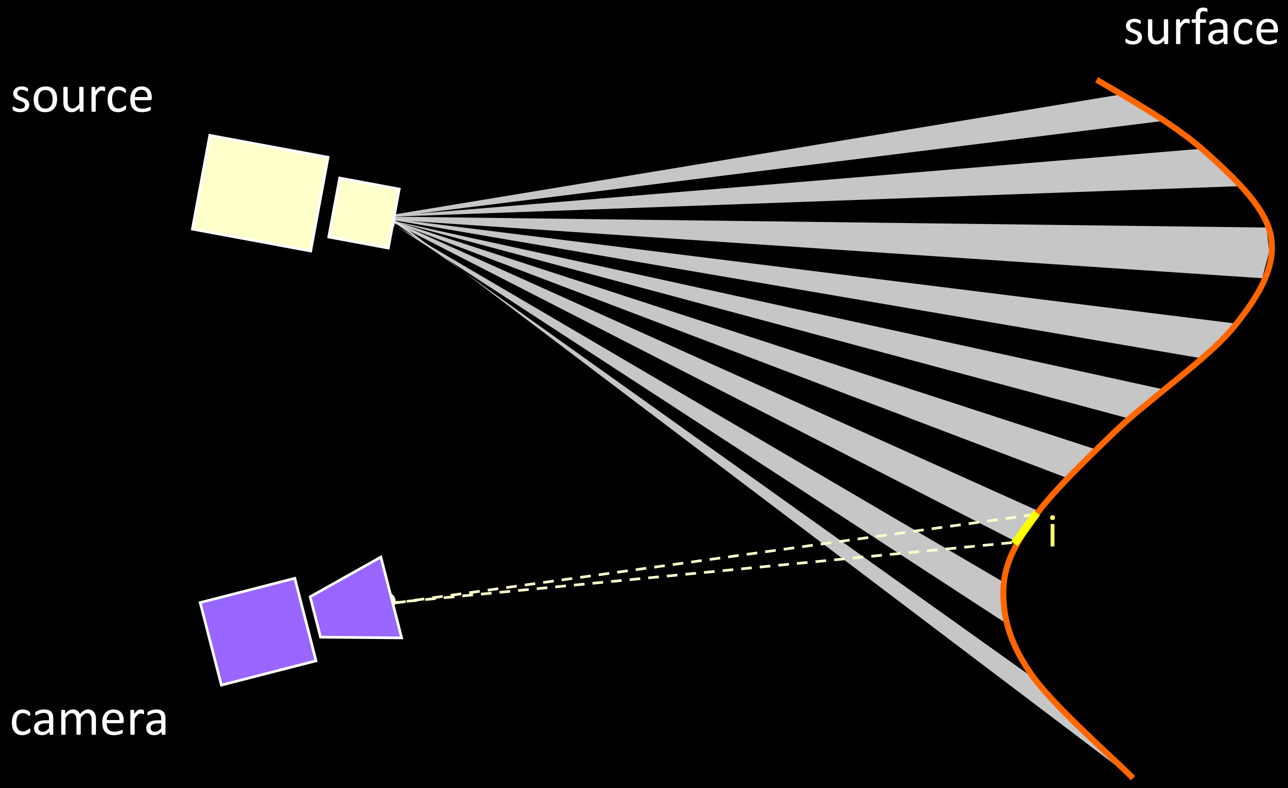
$$L[c,i] = L_d[c,i] + L_g[c,i]$$

radiance direct global

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

BRDF and geometry

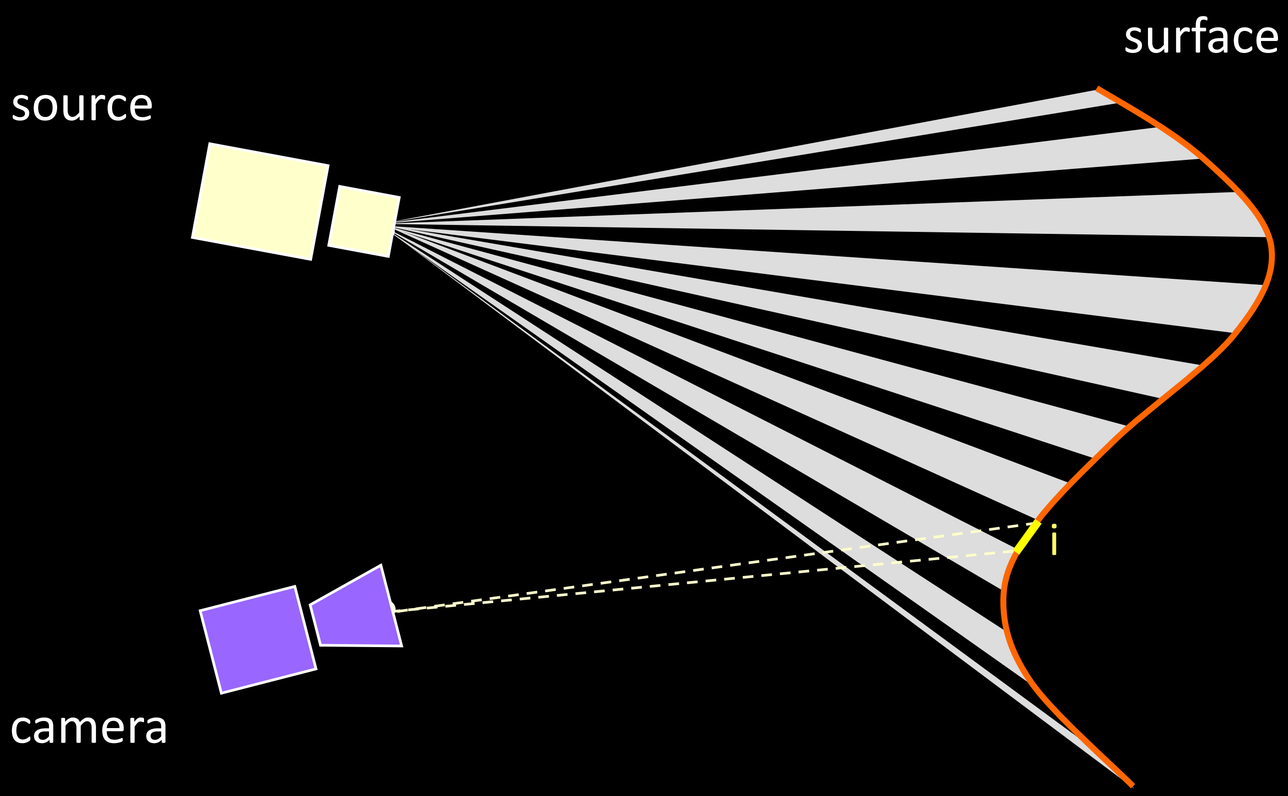
High Frequency Illumination Pattern



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

fraction of activated source elements

High Frequency Illumination Pattern



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

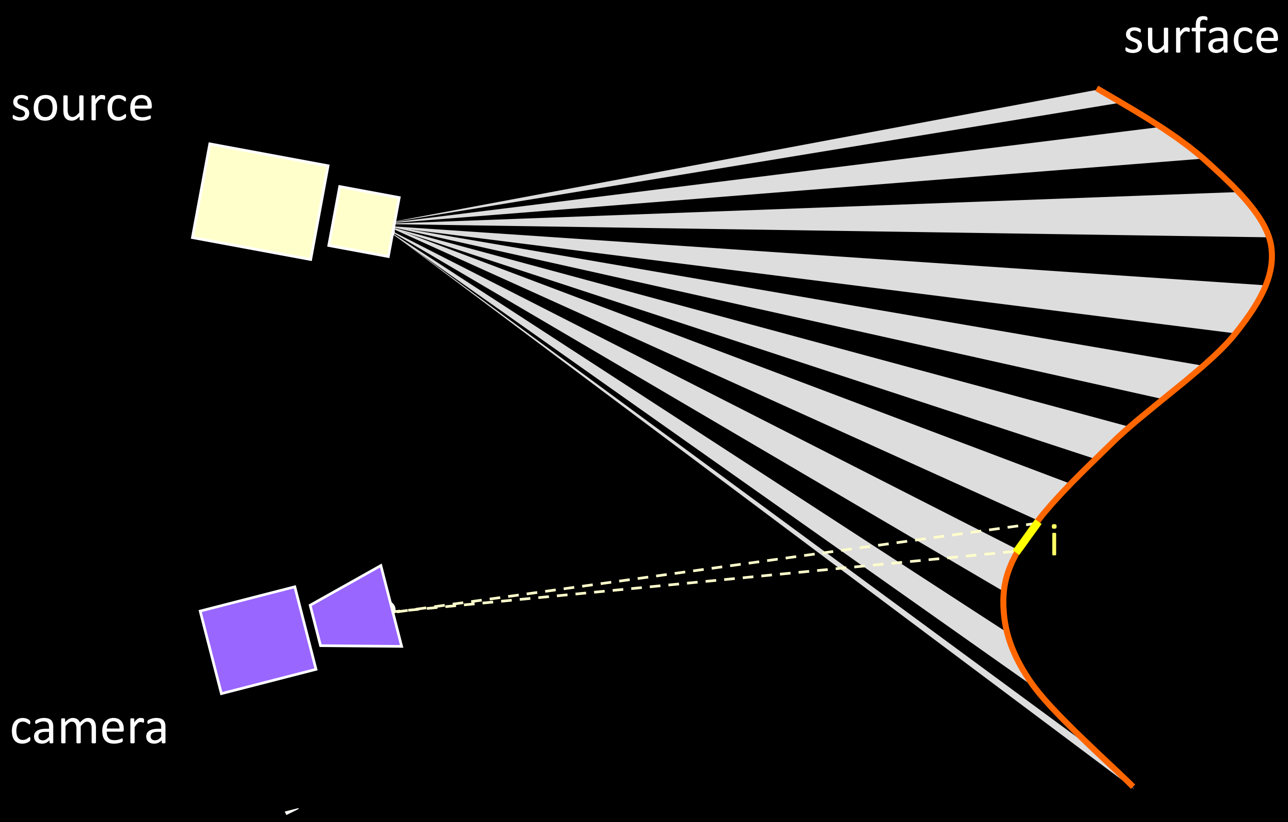
$$L^{-}[c,i] = (1-\alpha) L_g[c,i]$$

fraction of activated source elements

Important insight:

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

High Frequency Illumination Pattern



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

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

What does approximate invariance mean in this case?

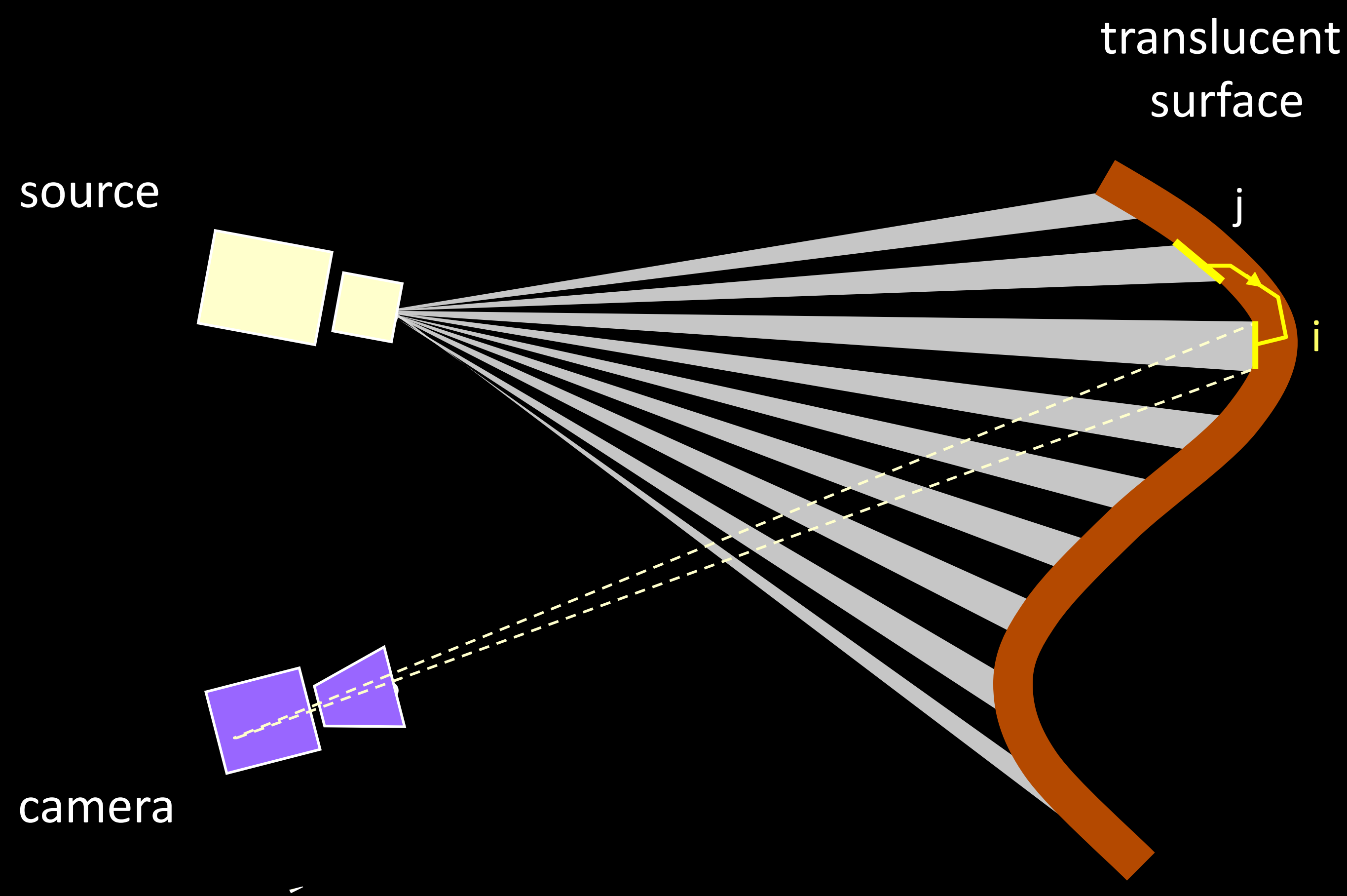
Separation from Two Images

$$\alpha = \frac{1}{2}: \quad L_d = L_{\max} - L_{\min}\ , \quad L_g = 2L_{\min}$$

direct

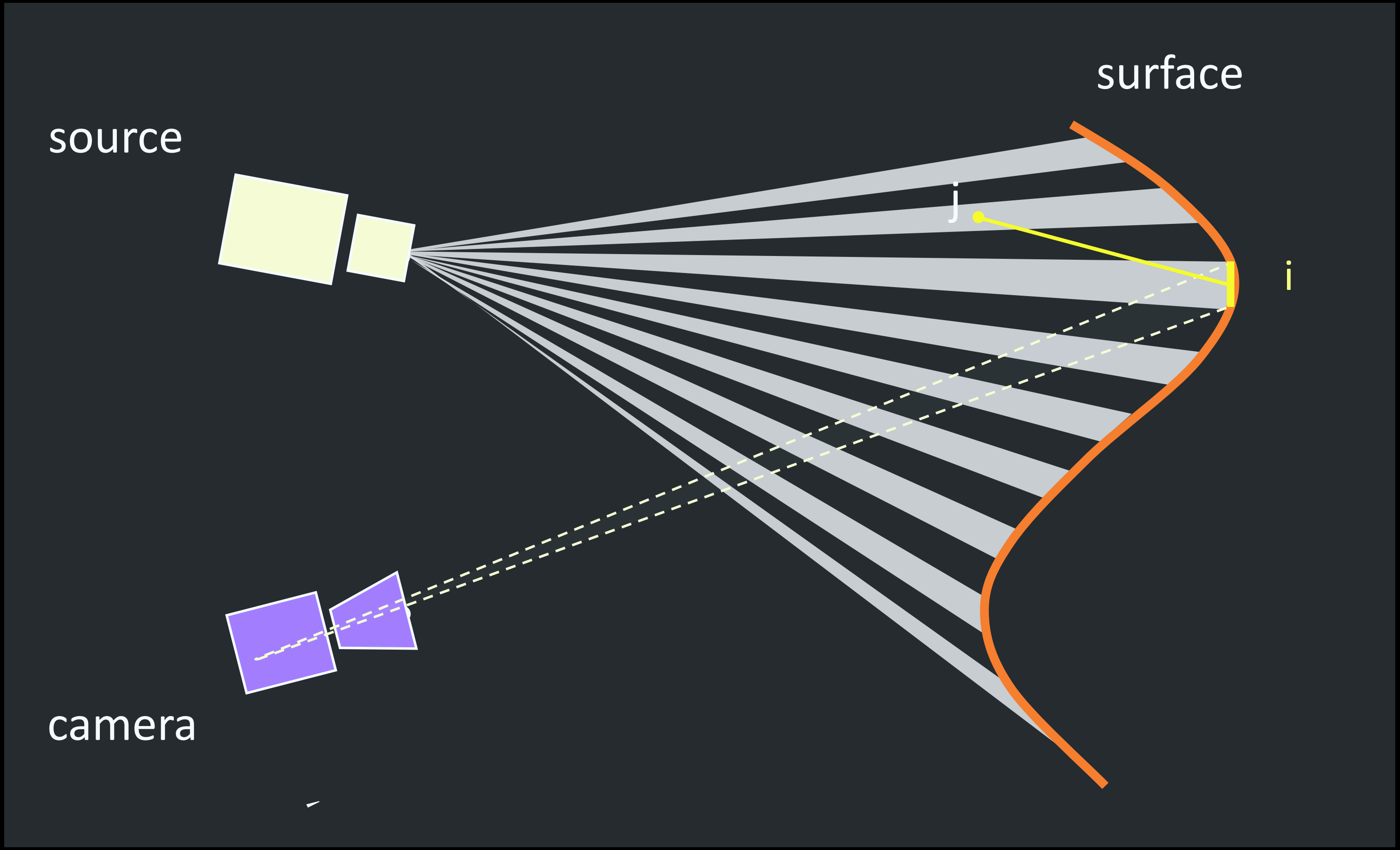
global

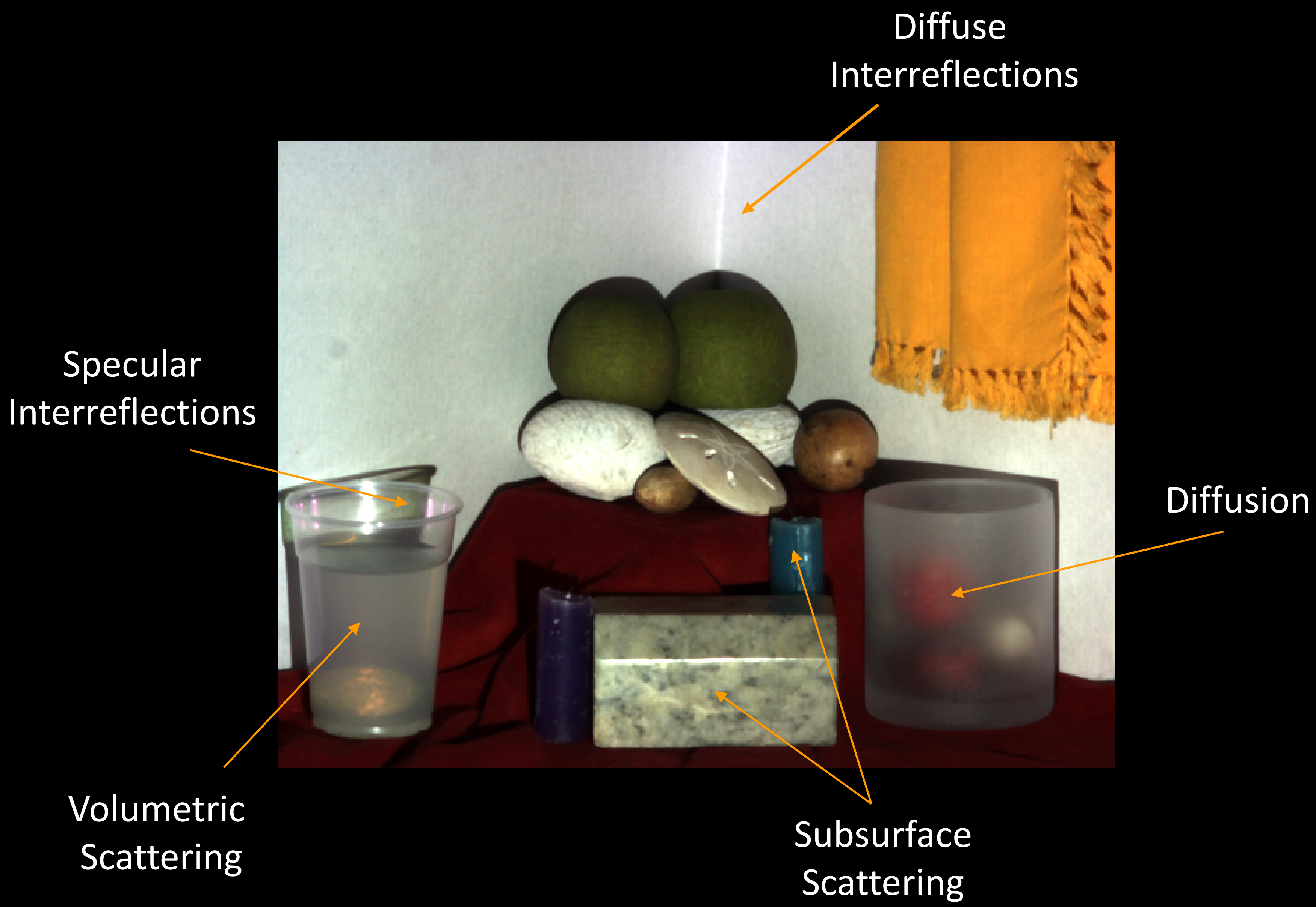
Other Global Effects: Subsurface Scattering



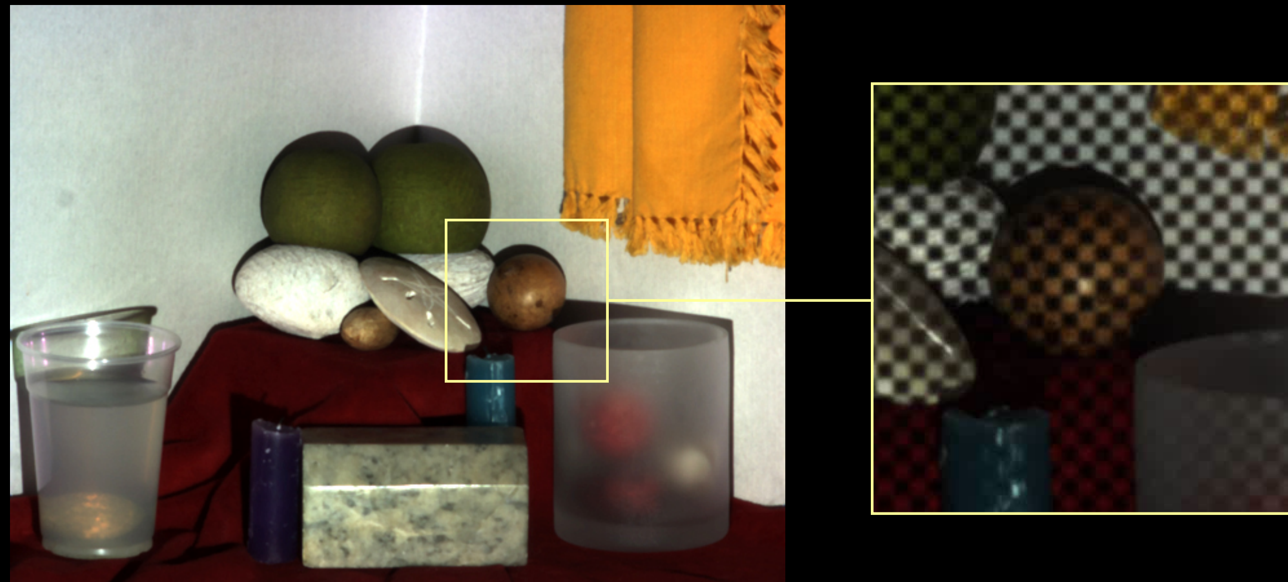
Other Global Effects: Volumetric Scattering

participating medium




Diffuse Interreflections
Specular Interreflections
Diffusion
Volumetric Scattering
Subsurface Scattering

Scene

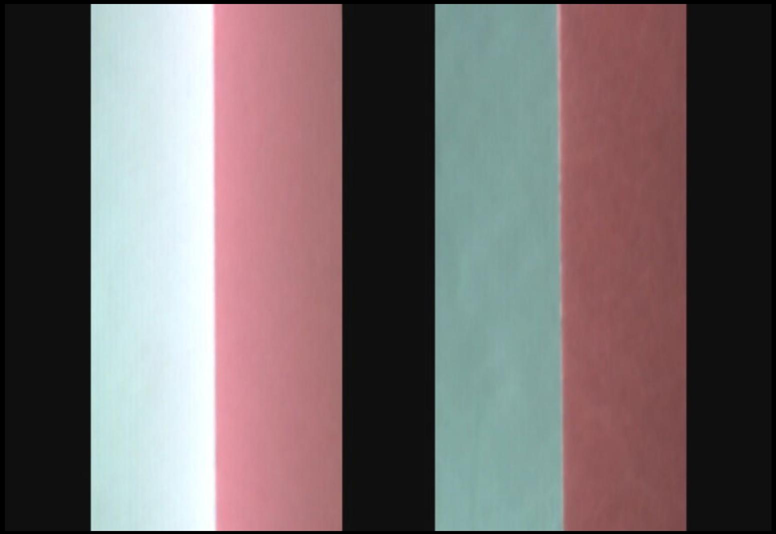


Direct

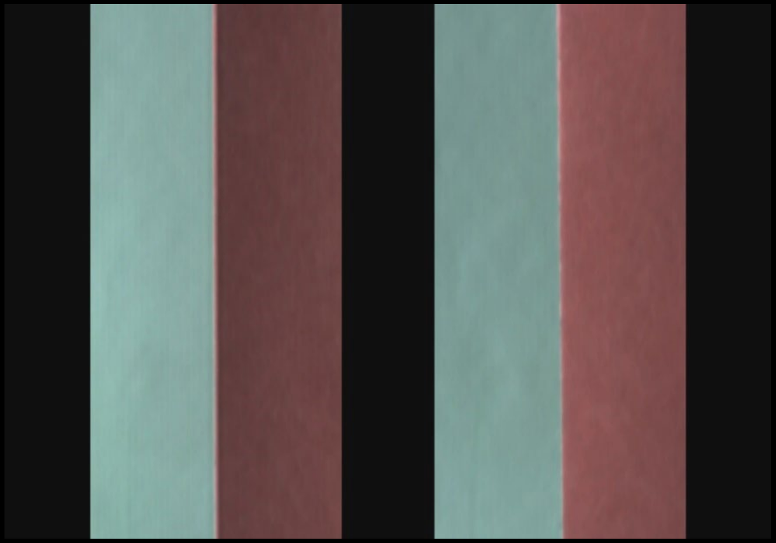
Global

V-Grooves: Diffuse Interreflections

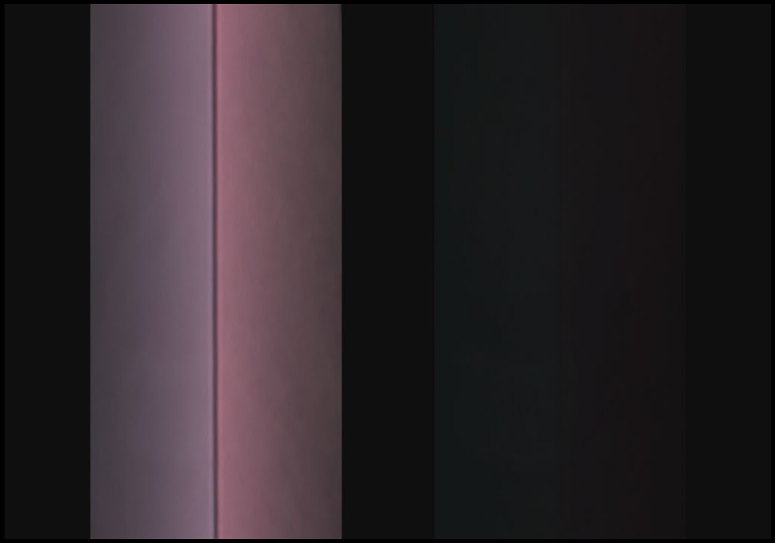
concave convex



Psychophysics:
Gilchrist 79, Bloj et al. 04



Direct



Global

Real World Examples:

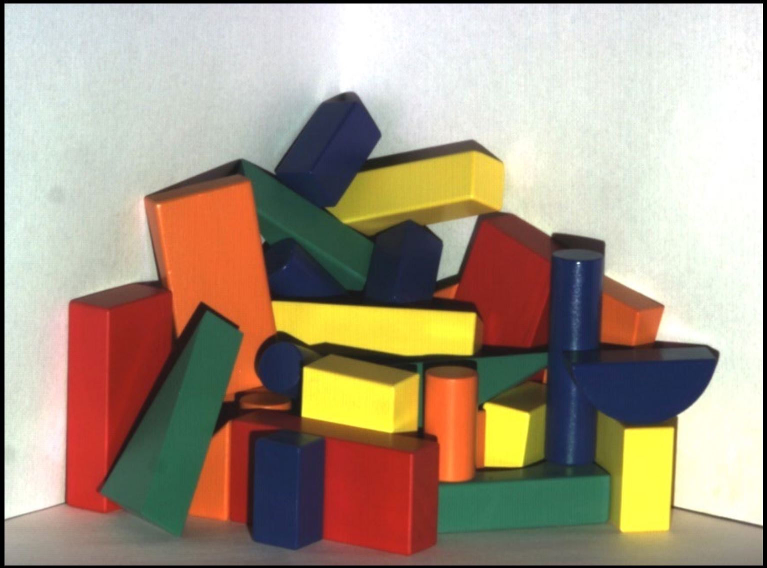
Can You Guess the Images?

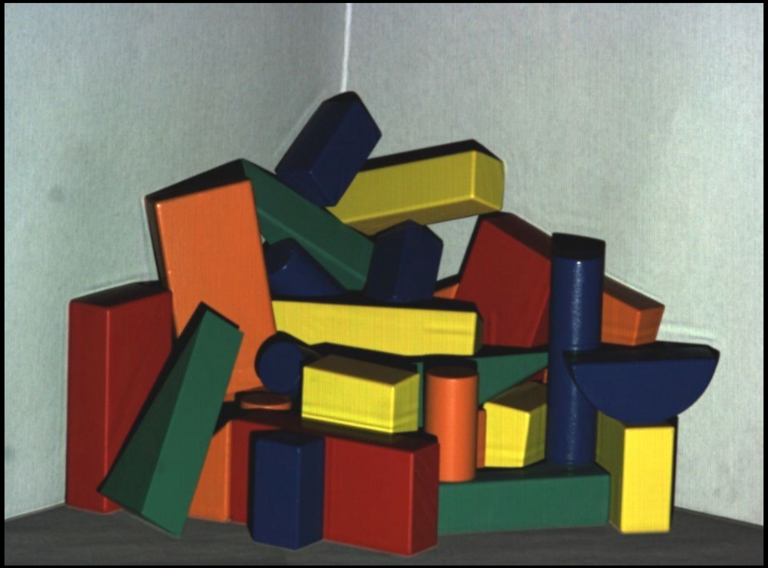
Eggs: Diffuse Interreflections

Direct

Global

Wooden Blocks: Specular Interreflections

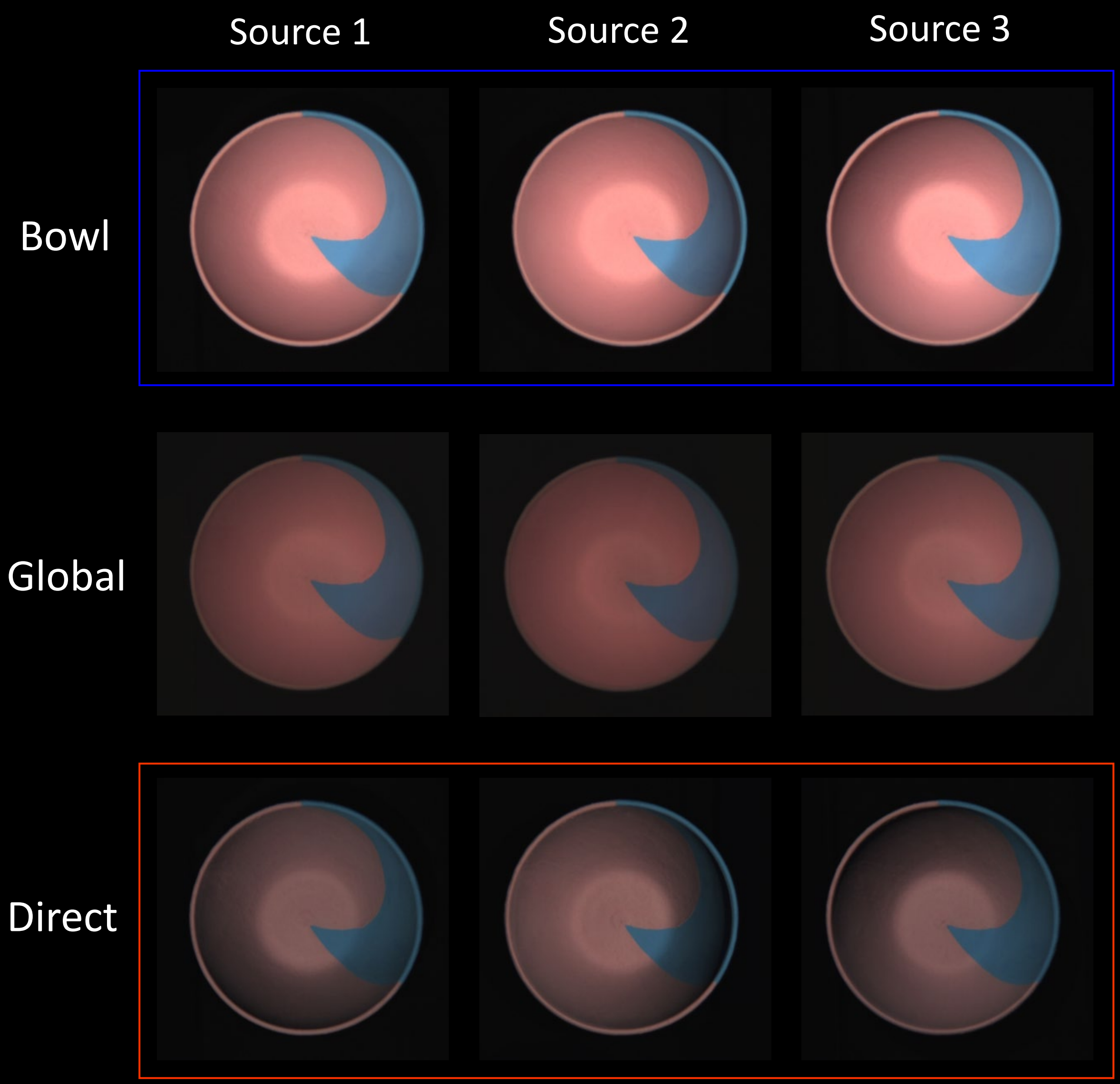


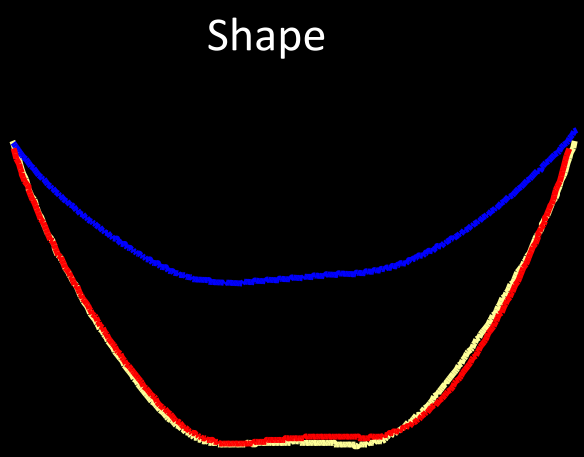


Direct

Global

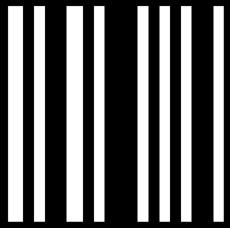
Photometric Stereo using Direct Images



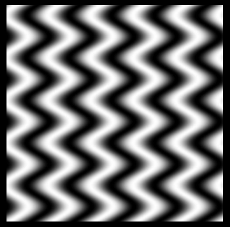


Variants of Separation Method

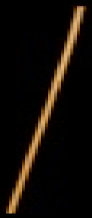
- Coded Structured Light



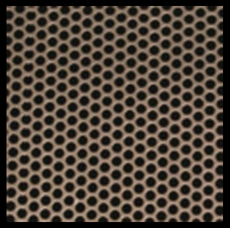
- Shifted Sinusoids



- 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

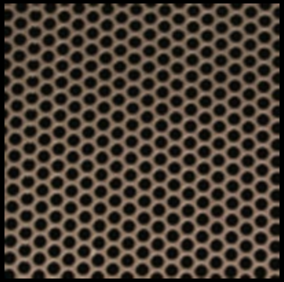
global

Building Corner

Direct

Global

Shower Curtain: Diffuser



Mesh

Shadow

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

direct

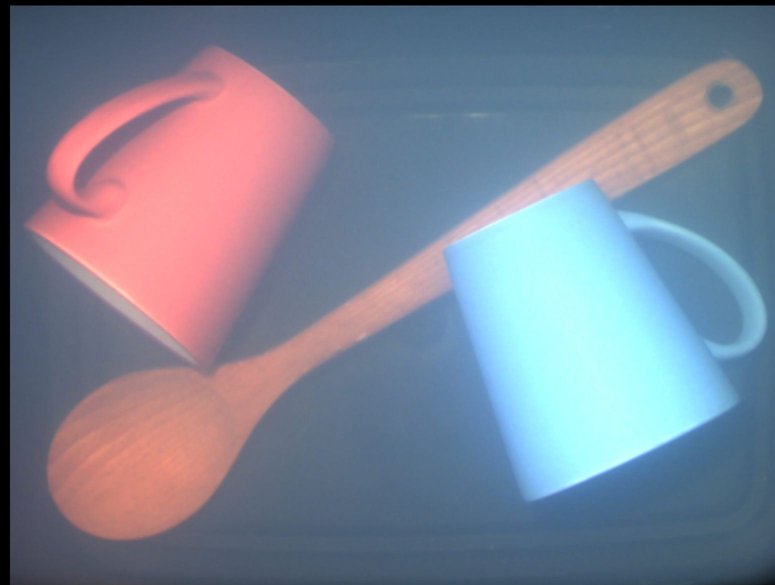
global

Shower Curtain: Diffuser

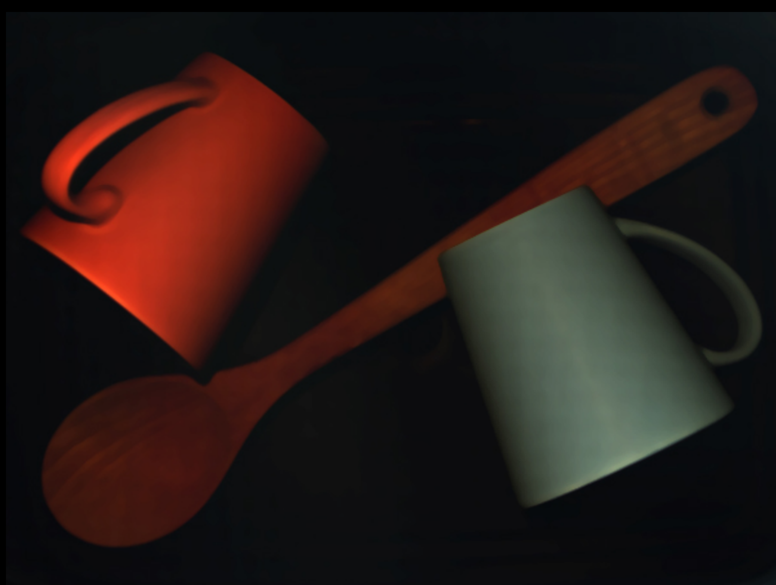
Direct

Global

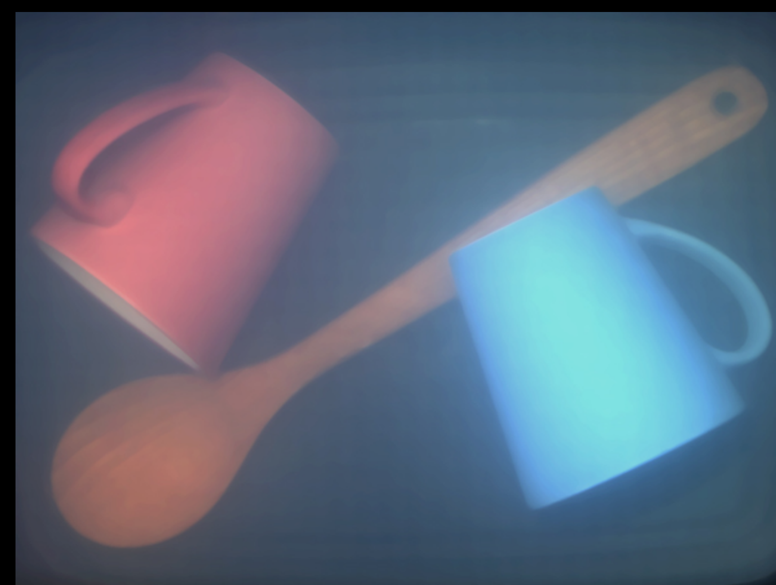
Kitchen Sink: Volumetric Scattering



Volumetric Scattering:
Chandrasekar 50, Ishimaru 78



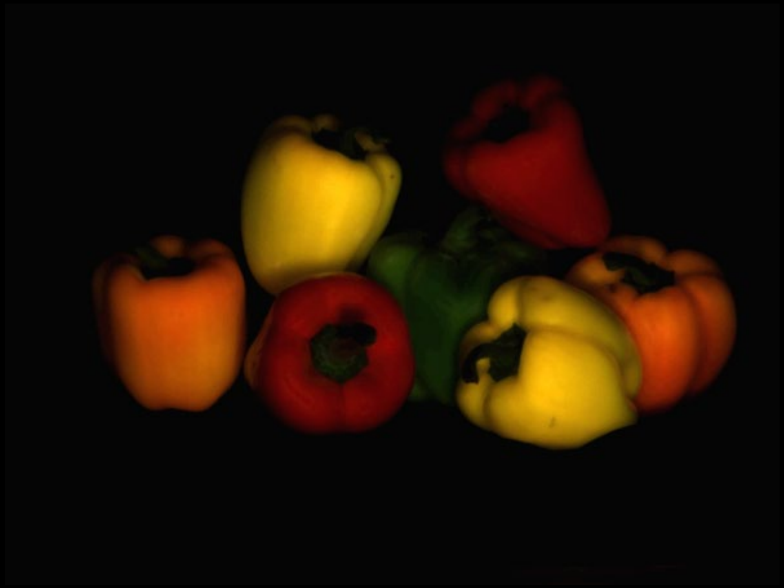
Direct



Global

Peppers: Subsurface Scattering

Direct



Global

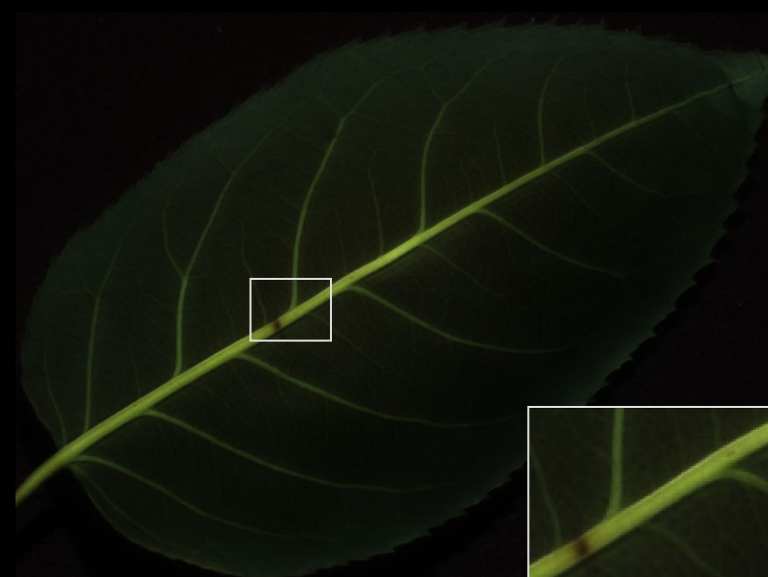
Real Fake

Direct Global

Tea Rose Leaf

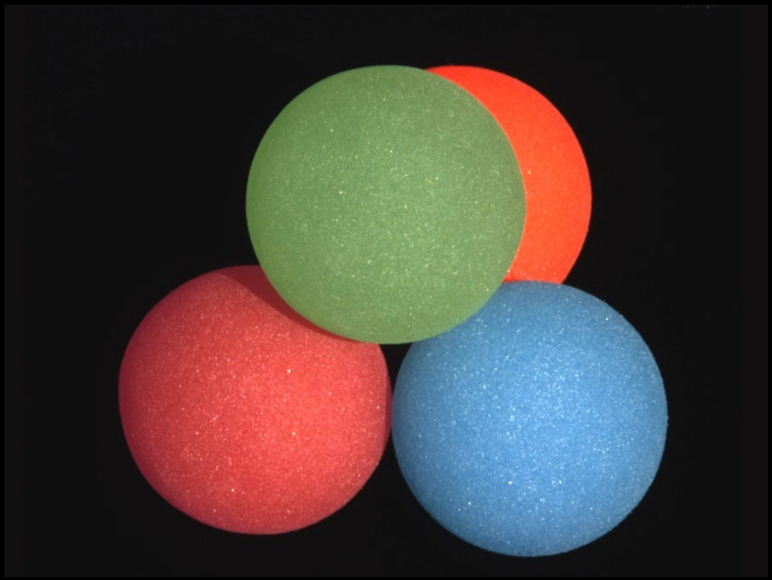
Leaf Anatomy: Purves et al. 03

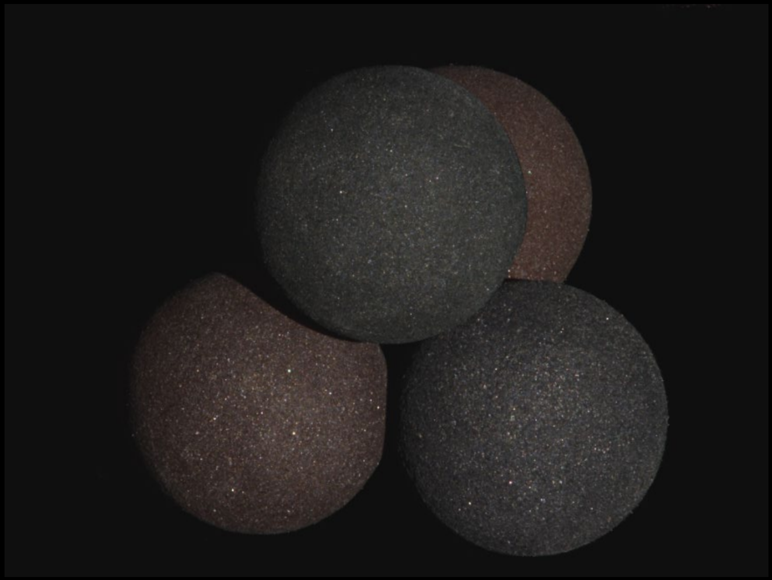
Direct



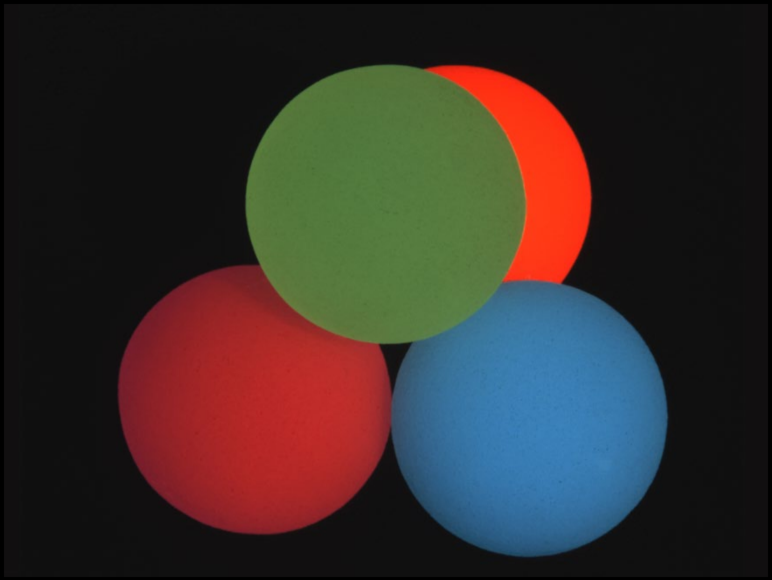
Global

Translucent Rubber Balls





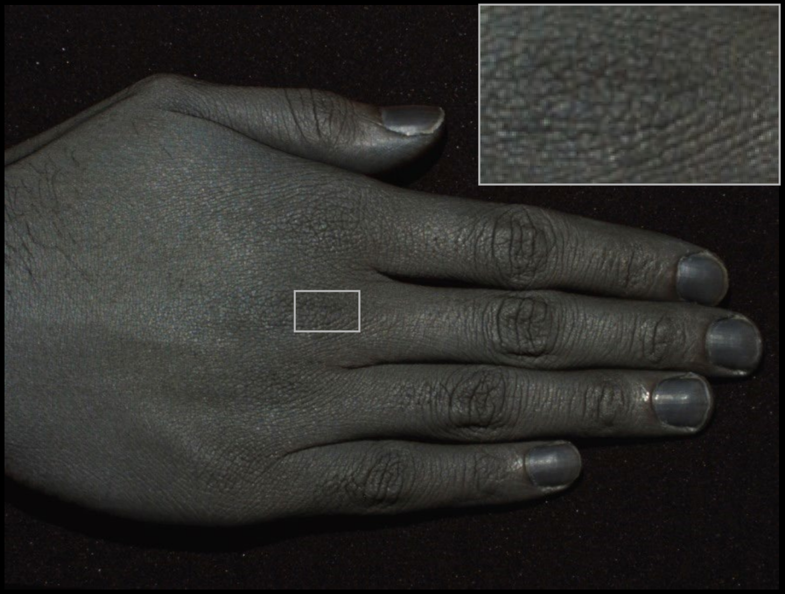
Direct



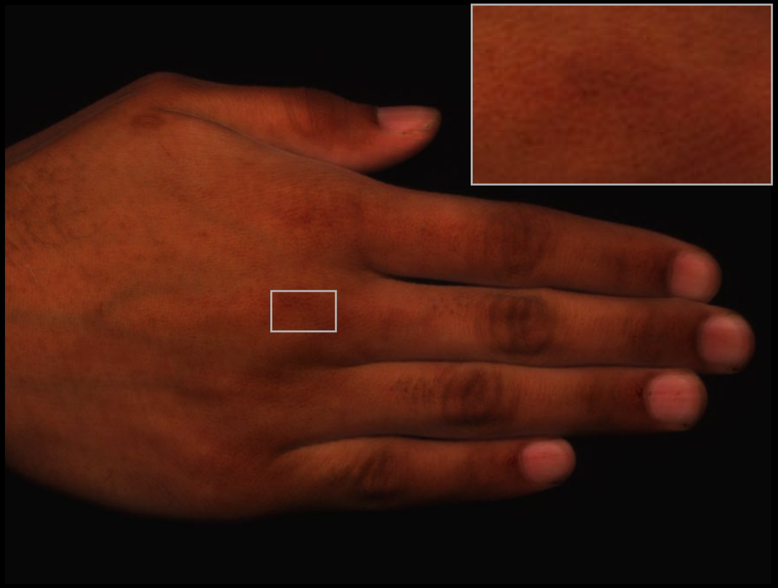
Global

Hand

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



Direct



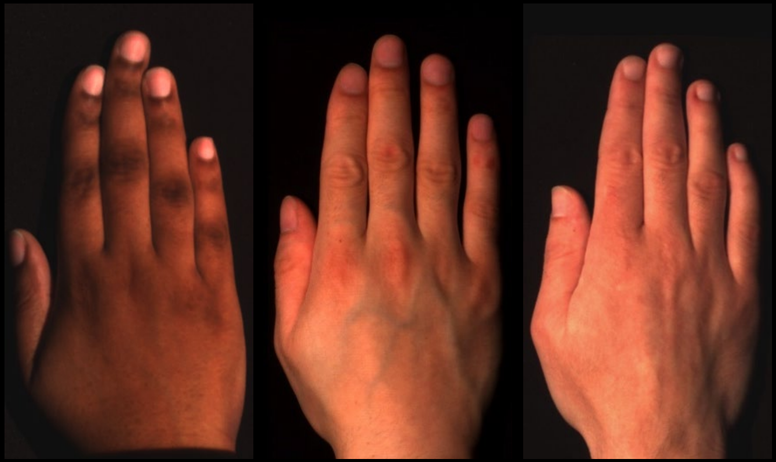
Global

Hands

Afric. Amer. Female — Chinese Male — Spanish Male

Afric. Amer. Female — Chinese Male — Spanish Male

Direct

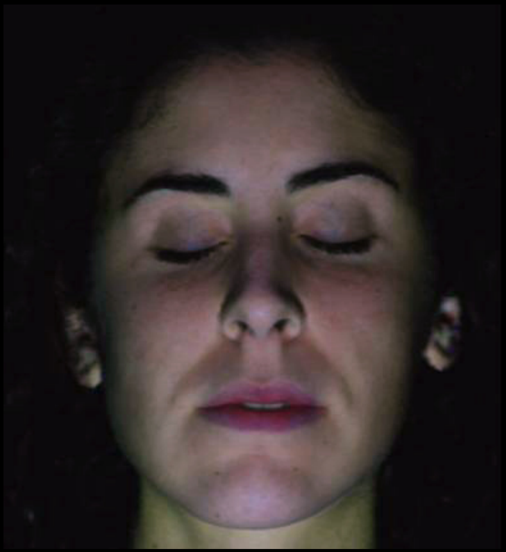


Afric. Amer. Female — Chinese Male — Spanish Male

Global

Face

Direct



Global

Sum

Blonde Hair

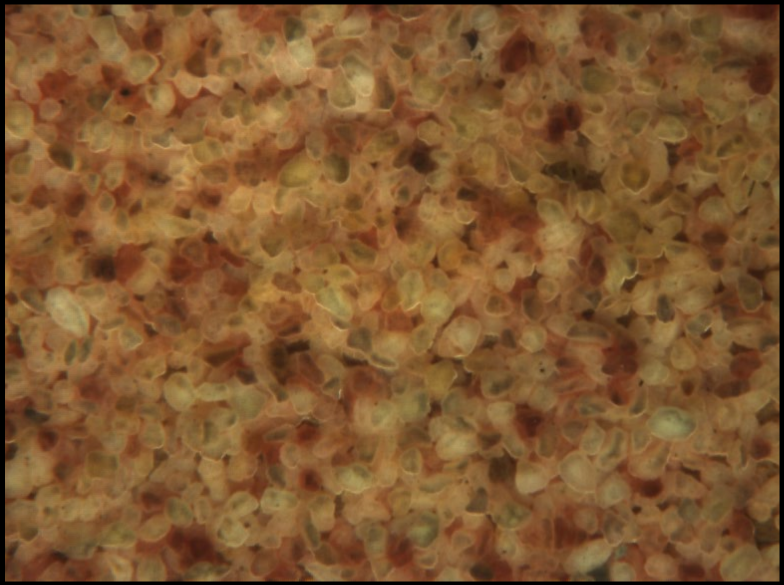
Hair Scattering: Stamm et al. 77, Bustard and Smith 91, Lu et al. 00 Marschner et al. 03

Direct

Global

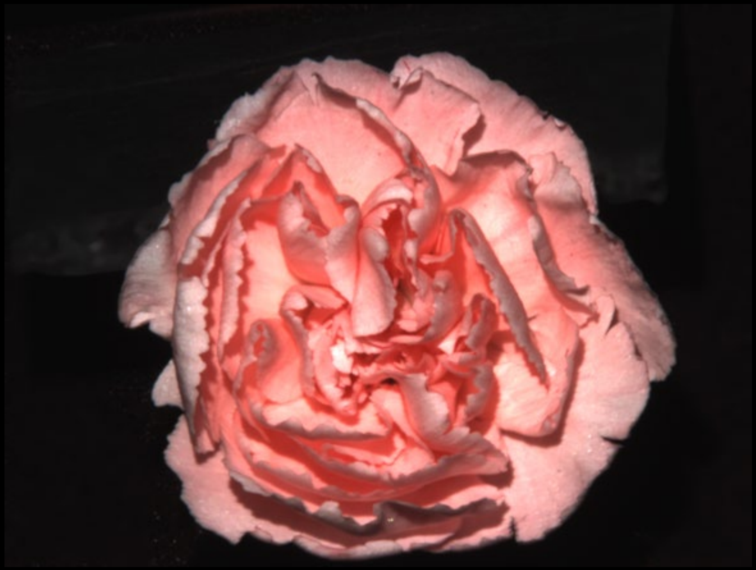
Pebbles: 3D Texture

Direct

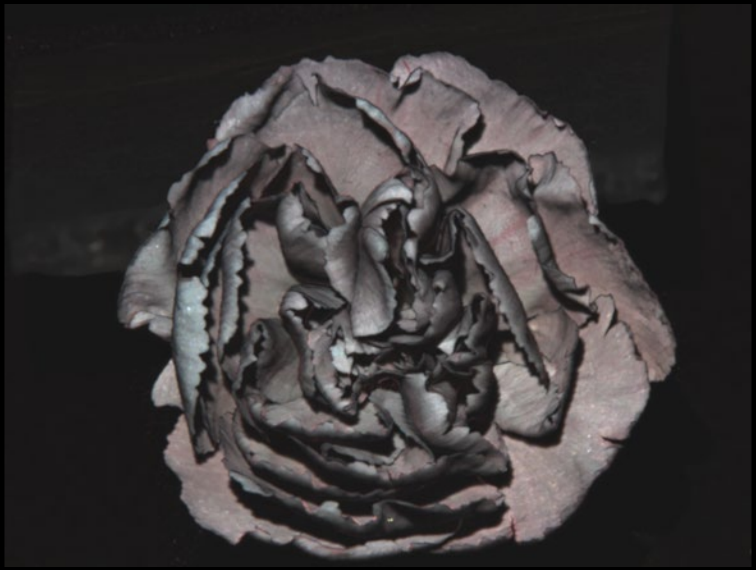


Global

Pink Carnation



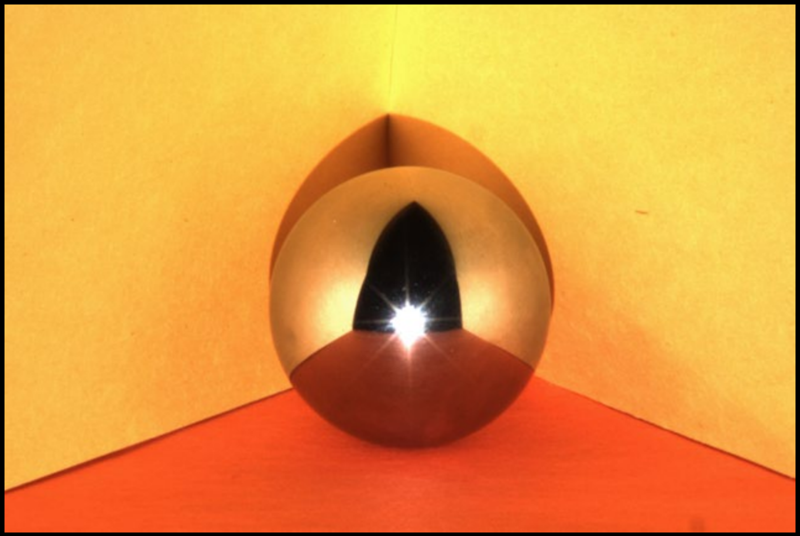
Spectral Bleeding: Funt et al. 91

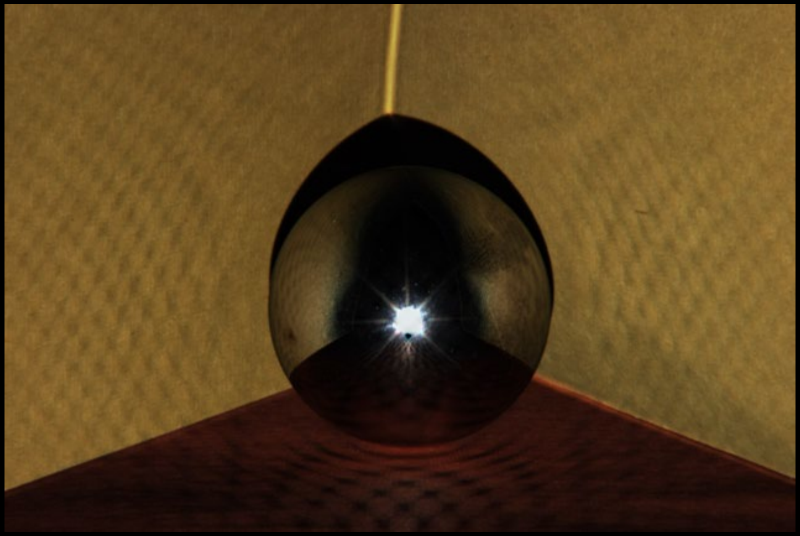


Direct

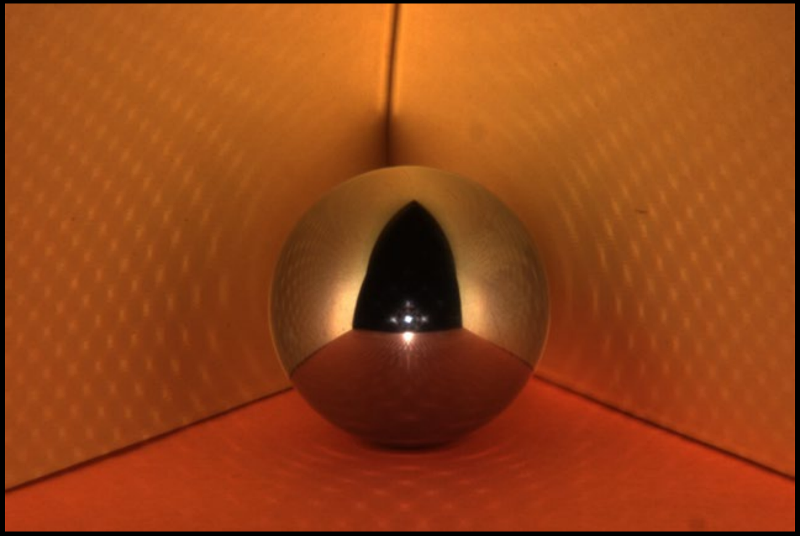
Global

Mirror Ball: Failure Case





Direct

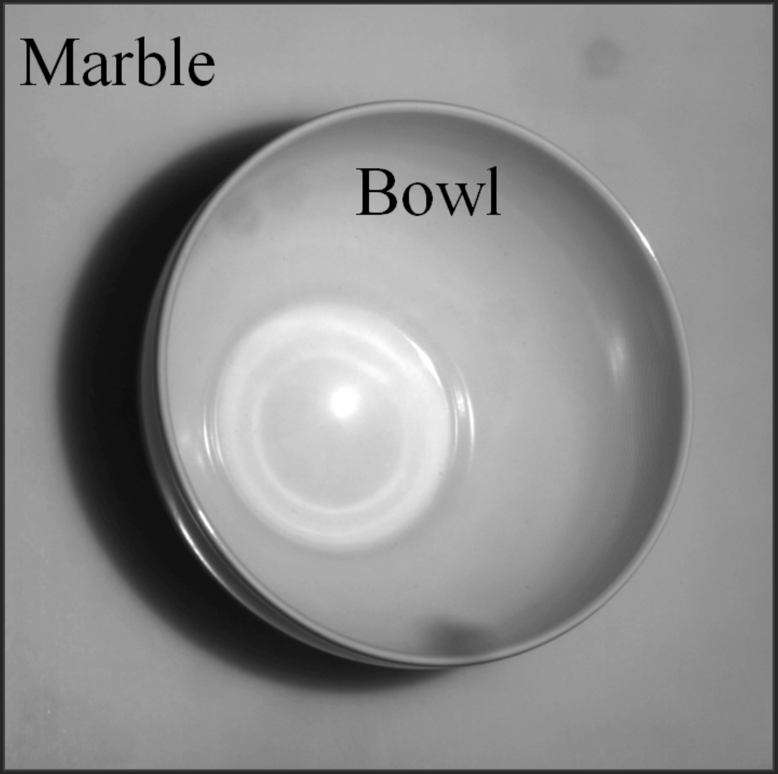


Global

Application to structured light

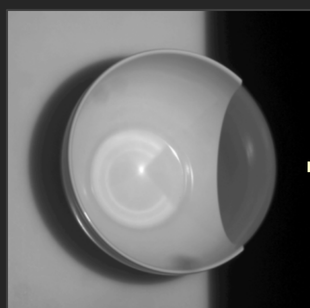
Why is global illumination a problem?

Bowl on a Marble Slab

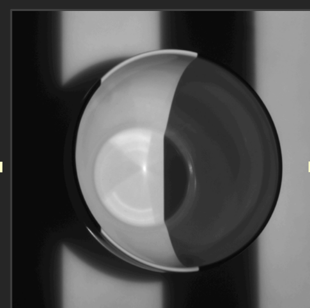


Captured images under conventional Gray codes

Lowest Frequency Illumination → Highest Frequency Illumination

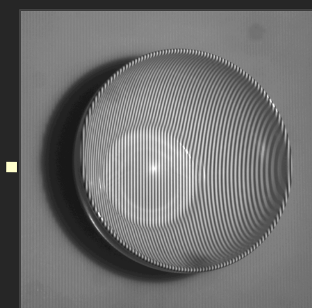


Pattern 1



Pattern 4

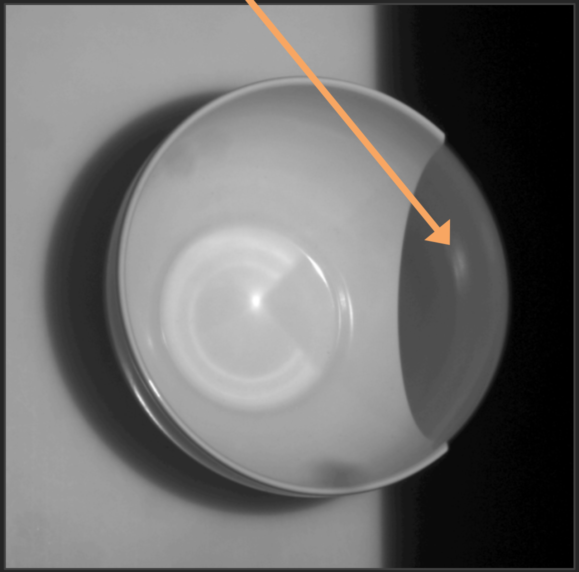
Pattern 7



Pattern 10

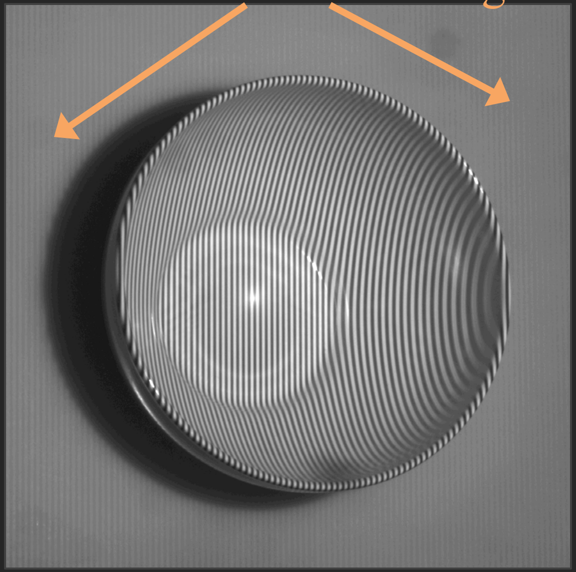
Issues due to global illumination effects

Strong Inter-reflections



Low-frequency pattern

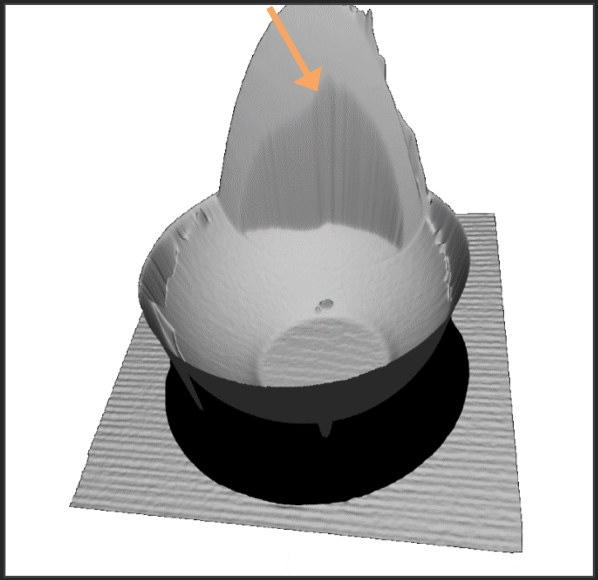
Blurring due to
Sub-surface Scattering



High-frequency pattern

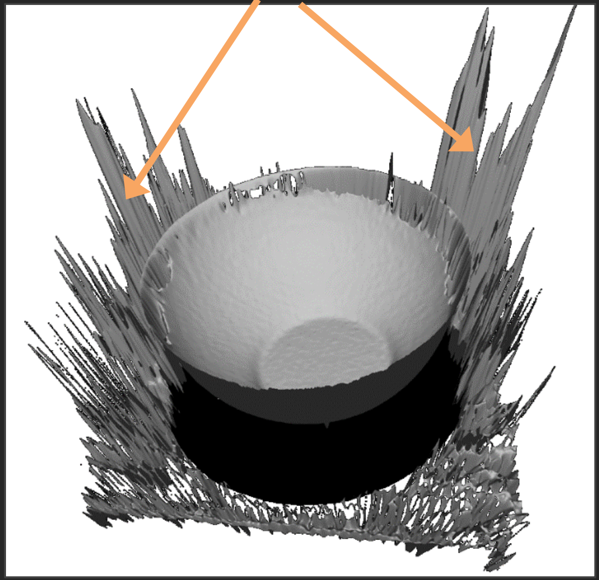
3D Visualizations: State of the Art

Errors due to
interreflections



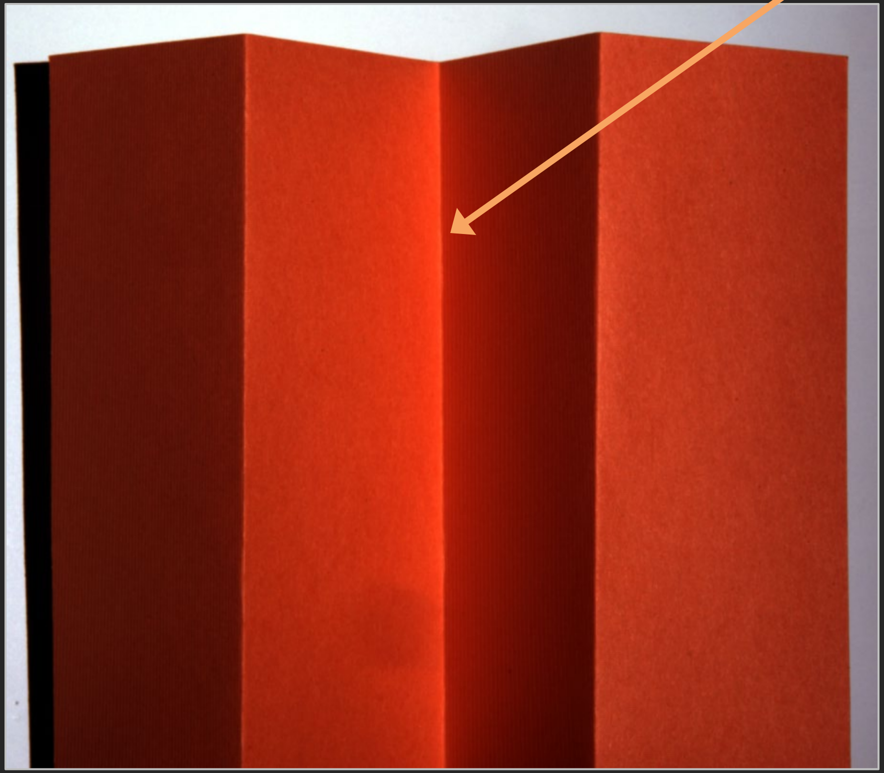
Conventional Gray
(11 images)

Errors due to
sub-surface scattering

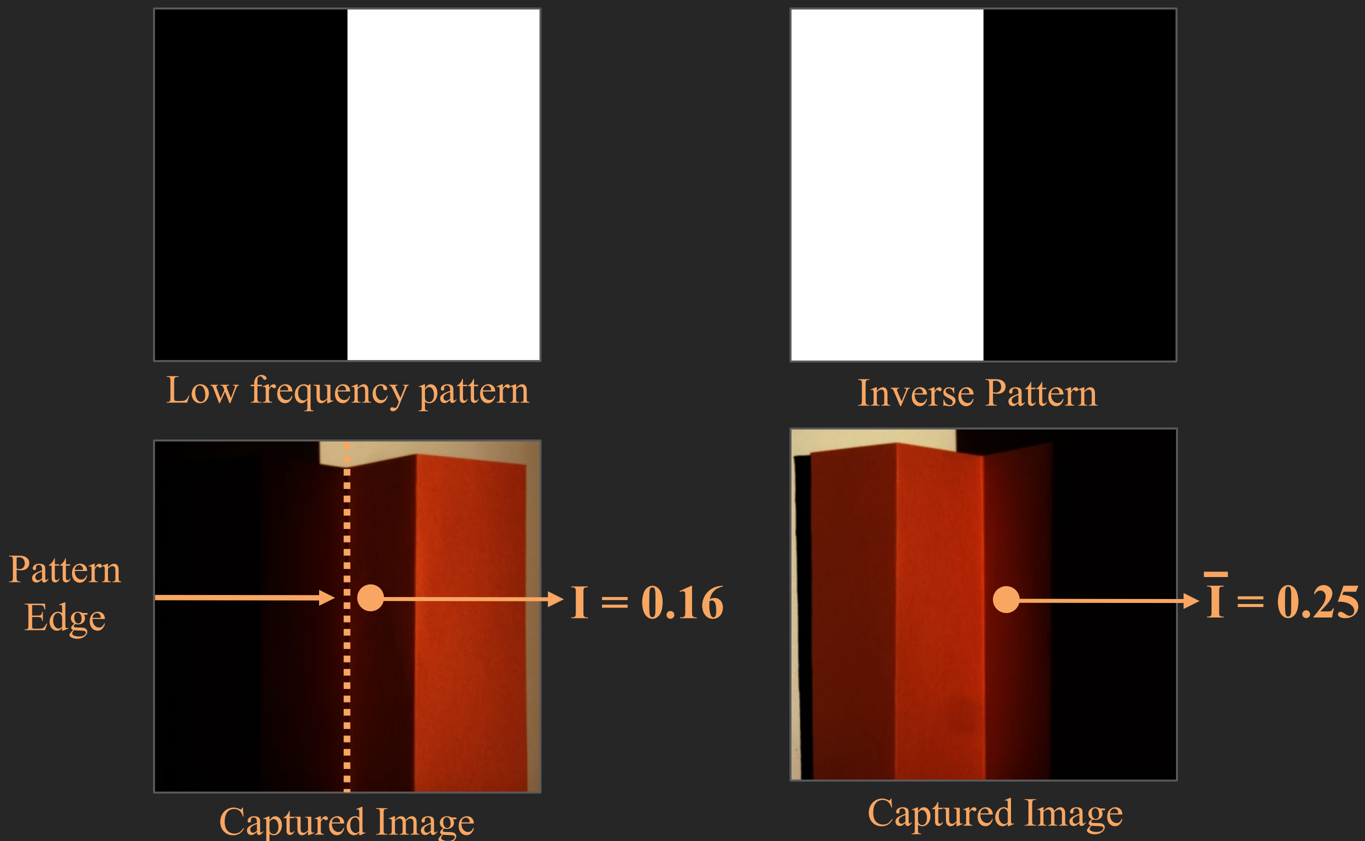


Modulated Phase-Shifting
(162 images)

V-Groove Scene

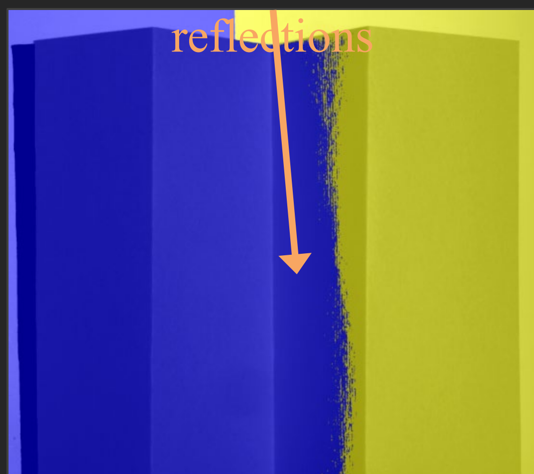


Conventional Gray codes

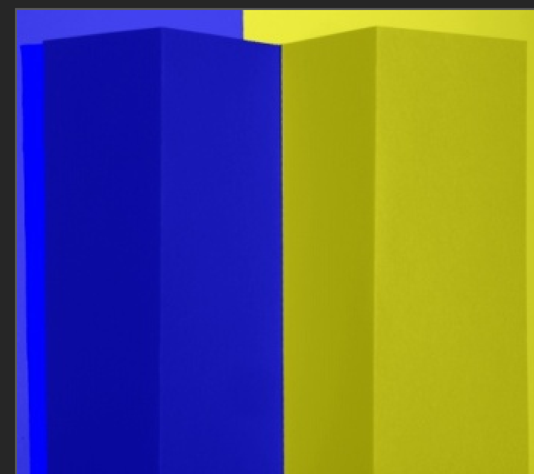


Binarization error

Errors due to inter-reflections



Incorrect Binarization

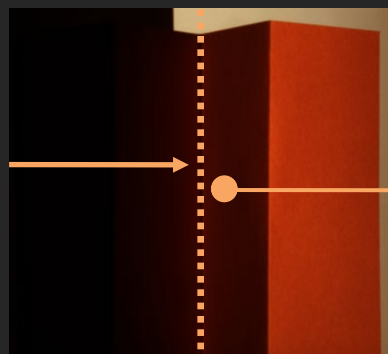


Ground-truth Binarization

One (illuminated) Zero (not-illuminated)

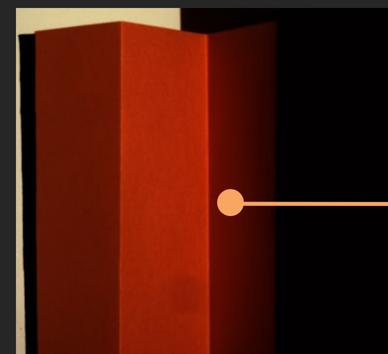
Low-frequency patterns

Pattern Edge



$I = 0.16$

Captured Image



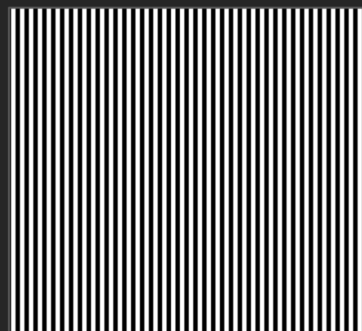
$\bar{I} = 0.25$

Captured Image

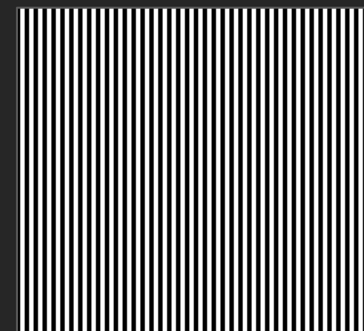
$$I = \text{Direct} + \alpha \,.\, \text{Global} \qquad \bar{I} = (1 - \alpha)\,.\,\text{Global}$$

$$\alpha \sim= 0,\ \text{Direct} < \text{Global} \quad => \quad I < \bar{I}$$

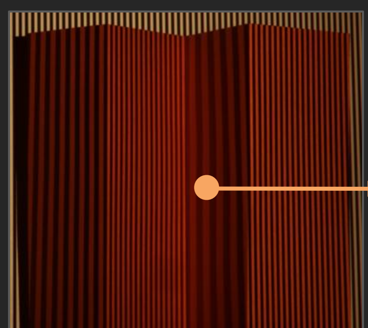
High-frequency patterns



Pattern

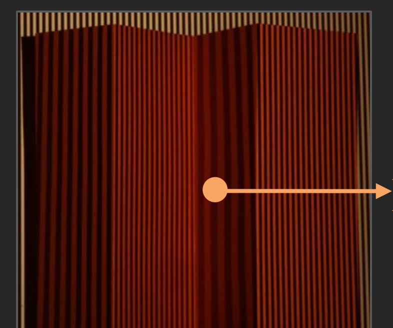


Inverse Pattern



$\mathbf{I = 0.25}$

Captured Image

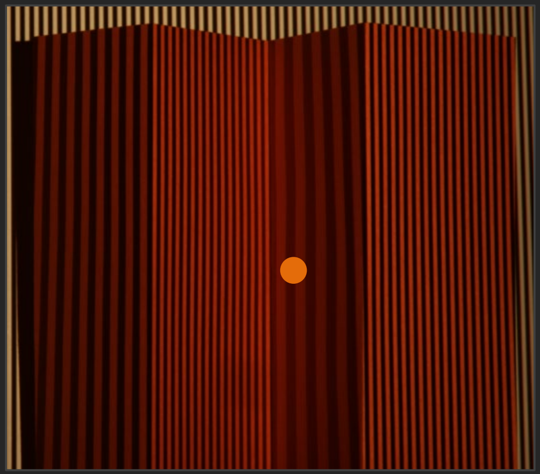


$\mathbf{\bar{I} = 0.16}$

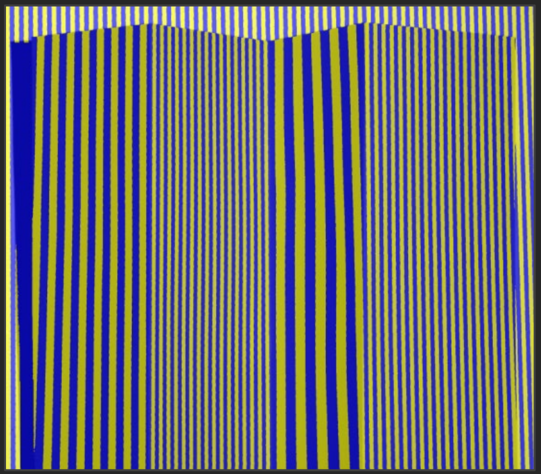
Captured Image

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

High-frequency Patterns are Decoded Correctly



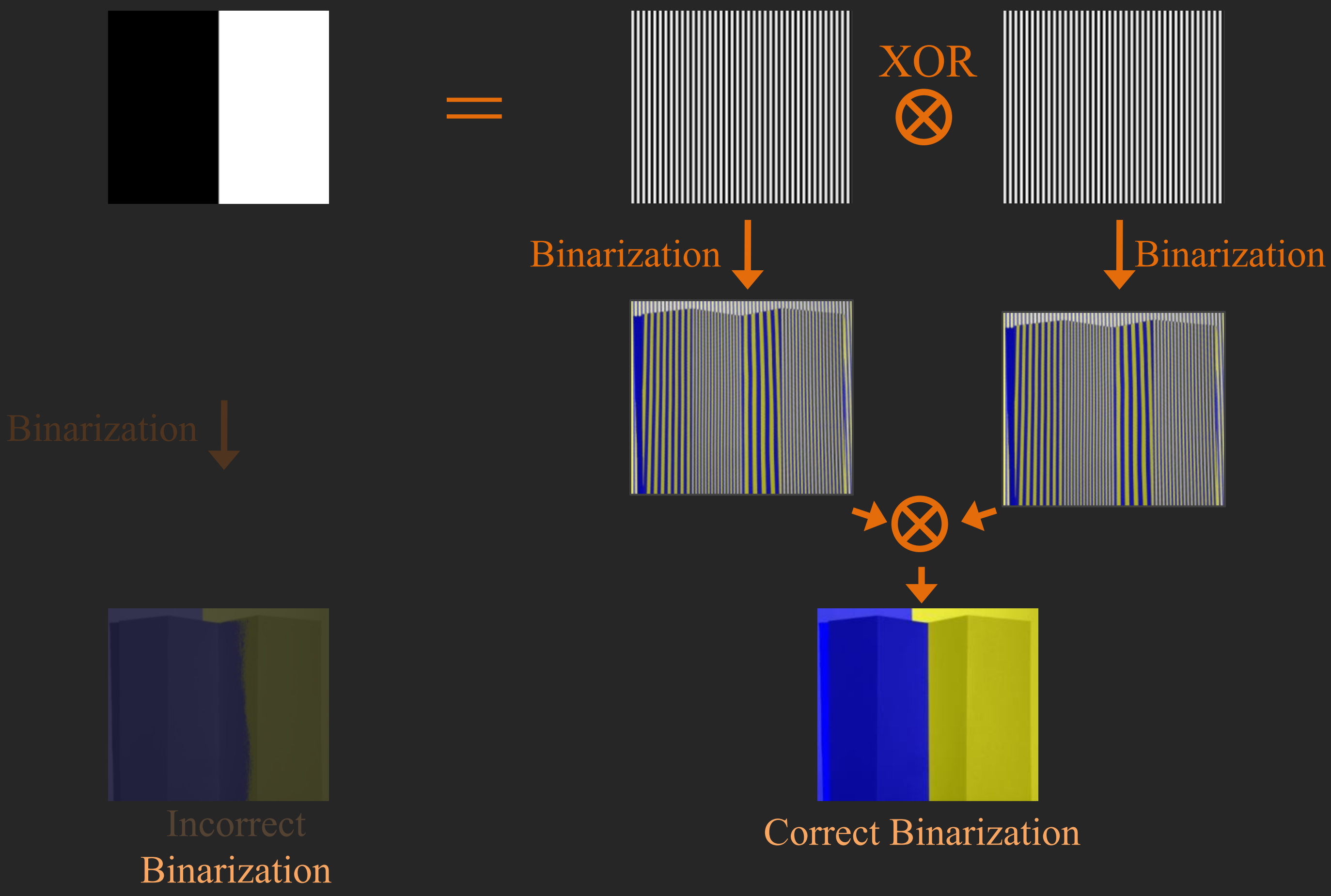
Captured Image



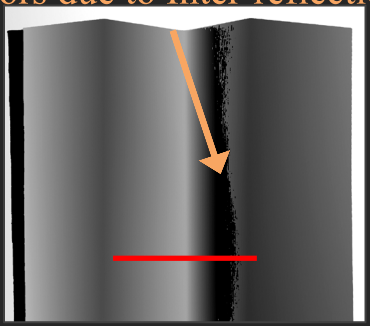
Binary Decoding

Logical Coding and Decoding

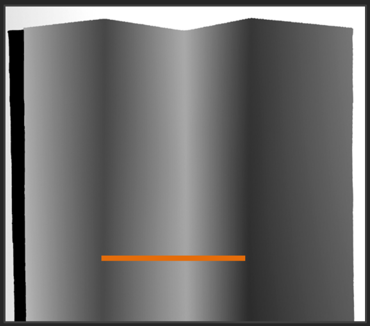
Logical Coding and Decoding



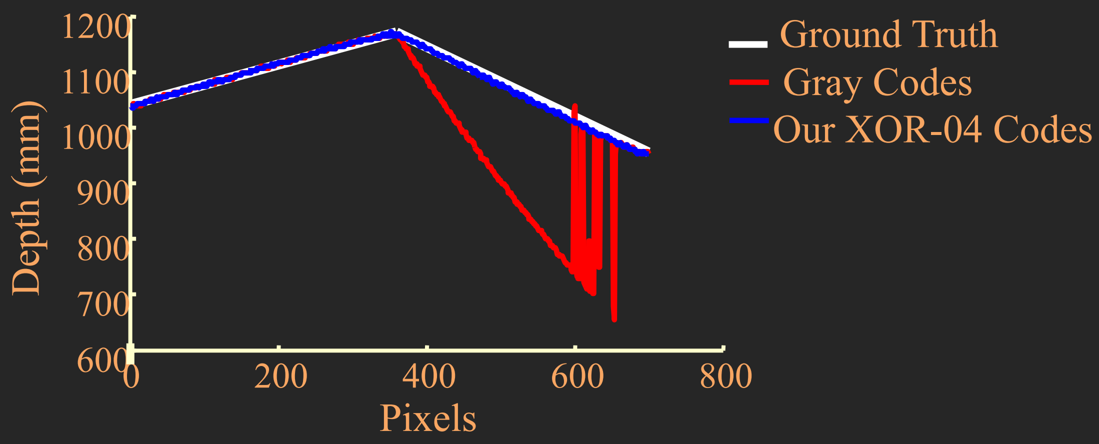
Depth Map Comparison



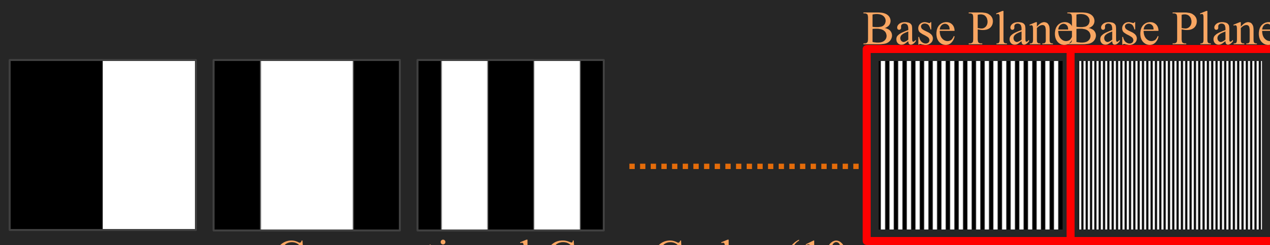
Conventional Gray Codes (11 images)



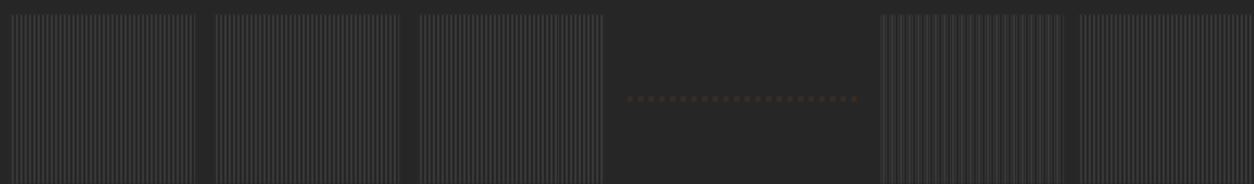
Our XOR-04 Codes (11 images)



Making the Logical XOR Codes



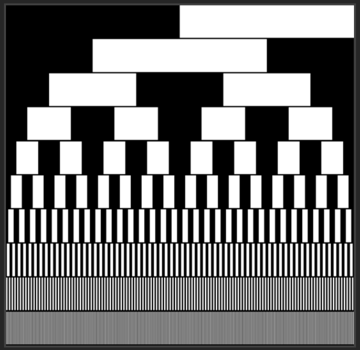
Conventional Gray Codes (10 patterns)



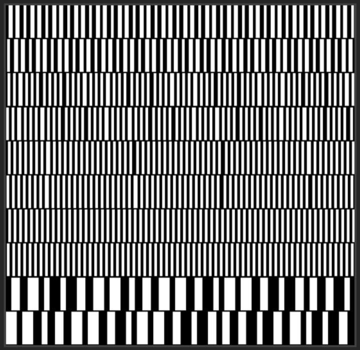
XOR of Last Pattern with Patterns 1-9 → *XOR-02 Codes (10 patterns)*

XOR of Second-last Pattern with Patterns 1-8 → *XOR-04* Codes (10 patterns)

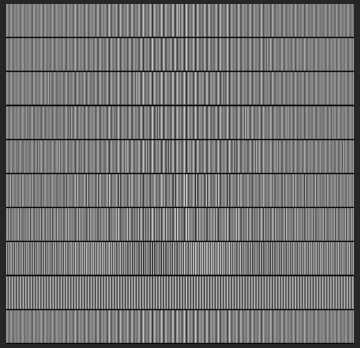
Ensemble of Codes for General Scenes



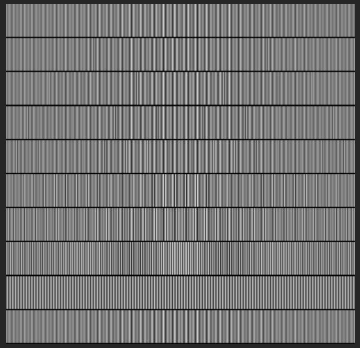
Conventional Gray (10 images)



Max min-SW Gray (10 images)

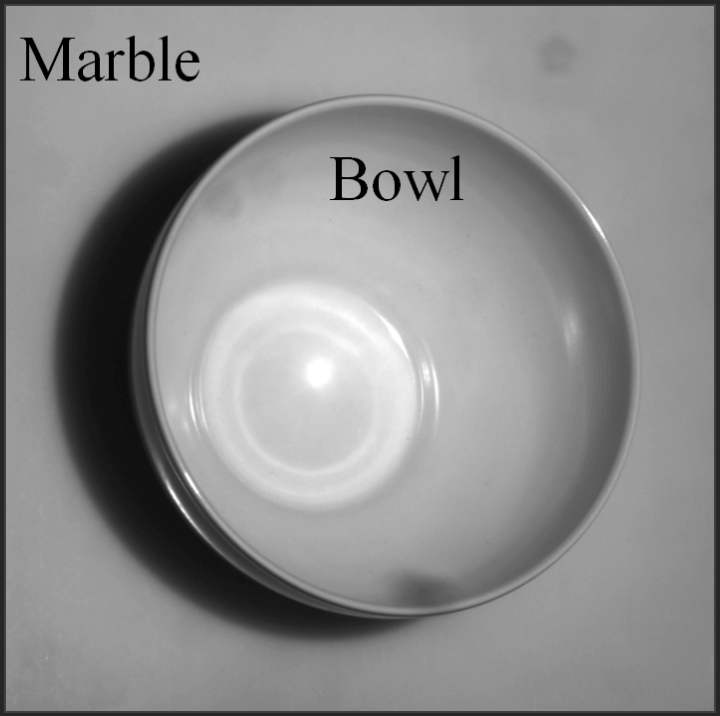


XOR-04 (10 images)

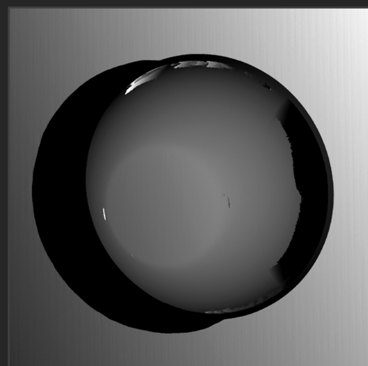


XOR-02 (10 images)

Reconstructing General Scenes

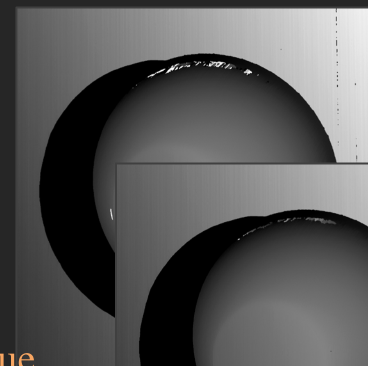


Ensemble of Codes for General Scenes

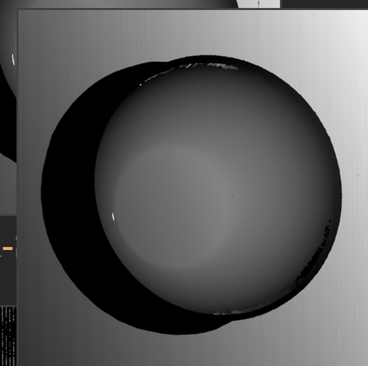


Conventional Gray (10 images)

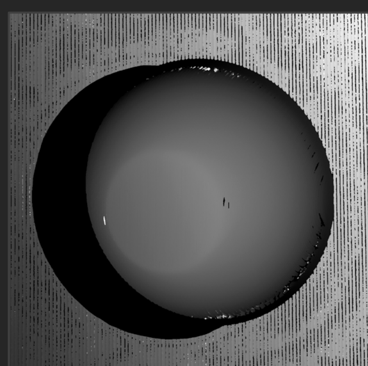
Return the consistent value



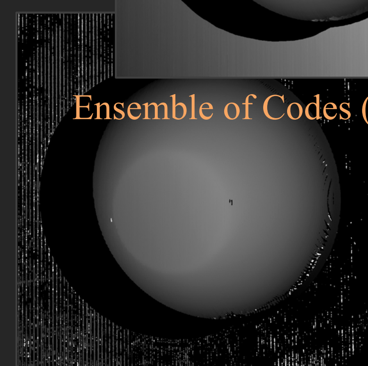
Max min-



Ensemble of Codes (41 images)

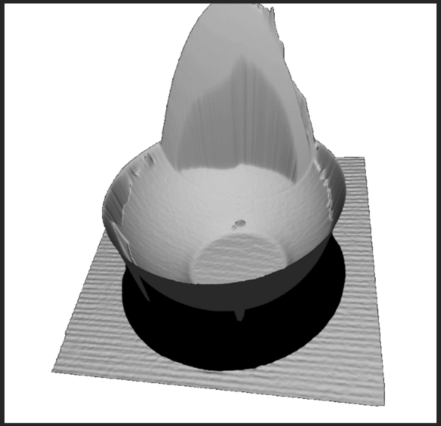


XOR-04 (10 images)

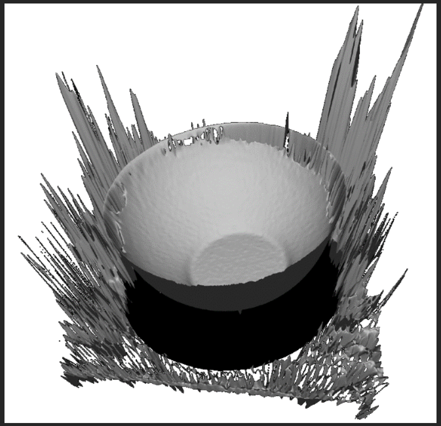


XOR-02 (10 images)

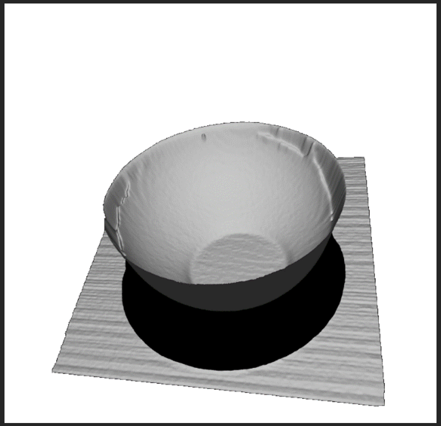
Shape Comparison



Conventional Gray
(11 images)



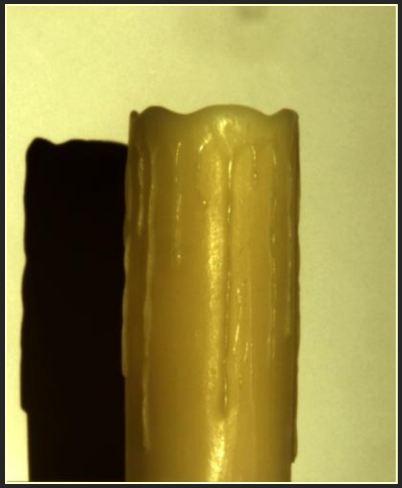
Modulated Phase-Shifting
(162 images)



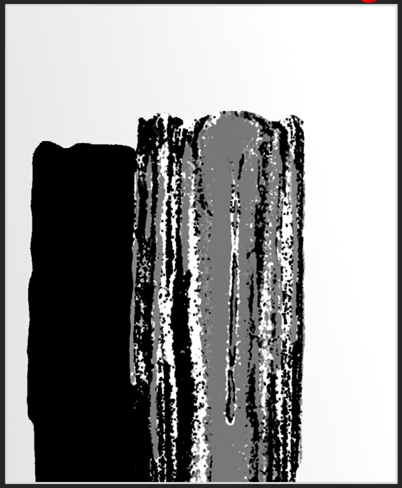
Our Technique
(41 images)

Translucent Wax Candle

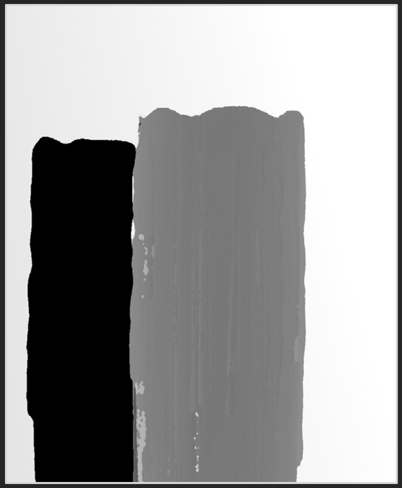
Errors due to strong sub-surface scattering



Scene



Modulated Phase-Shifting (162 images)

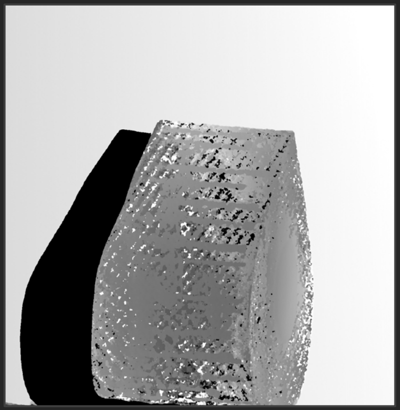


Our Ensemble Codes (41 images)

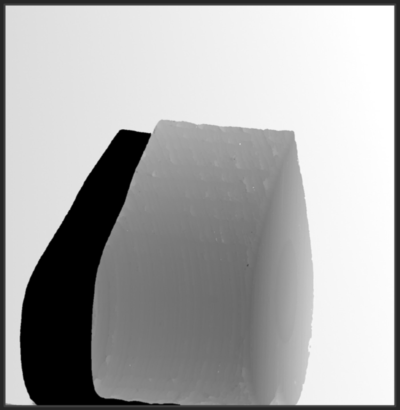
Translucent Wax Object

Errors due to strong
sub-surface scattering

Scene



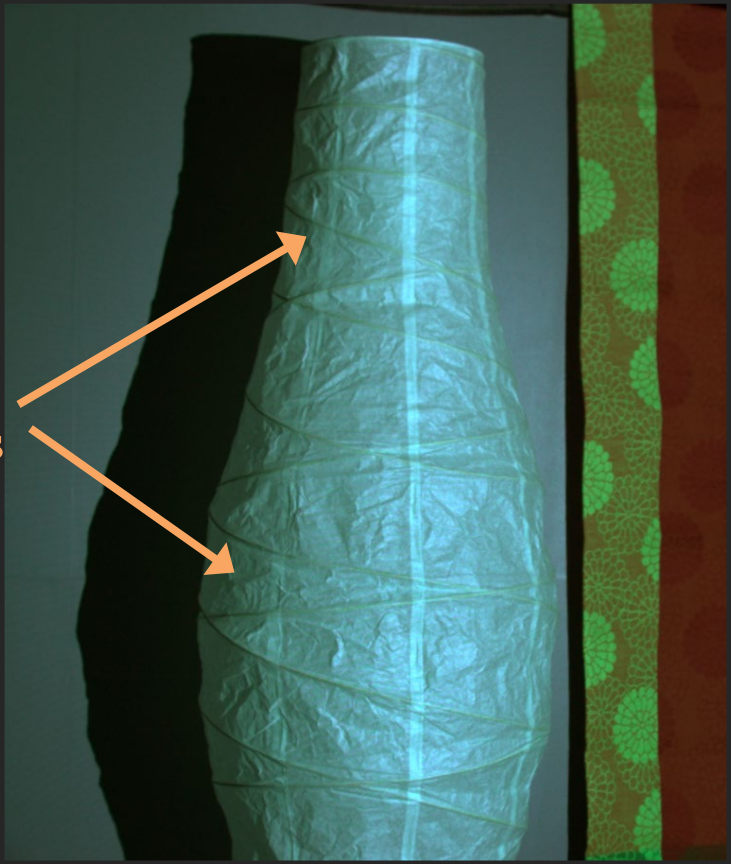
Modulated Phase-
Shifting (162 images)



Our Ensemble Codes
(41 images)

Ikea Lamp

Diffusion +
Inter-reflections

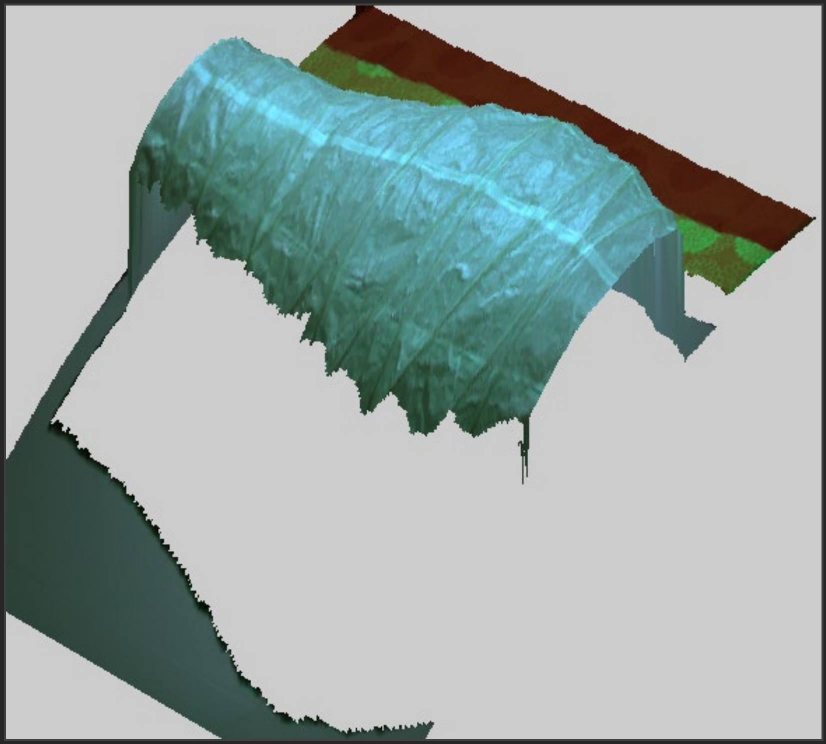


Depth-Map Comparison

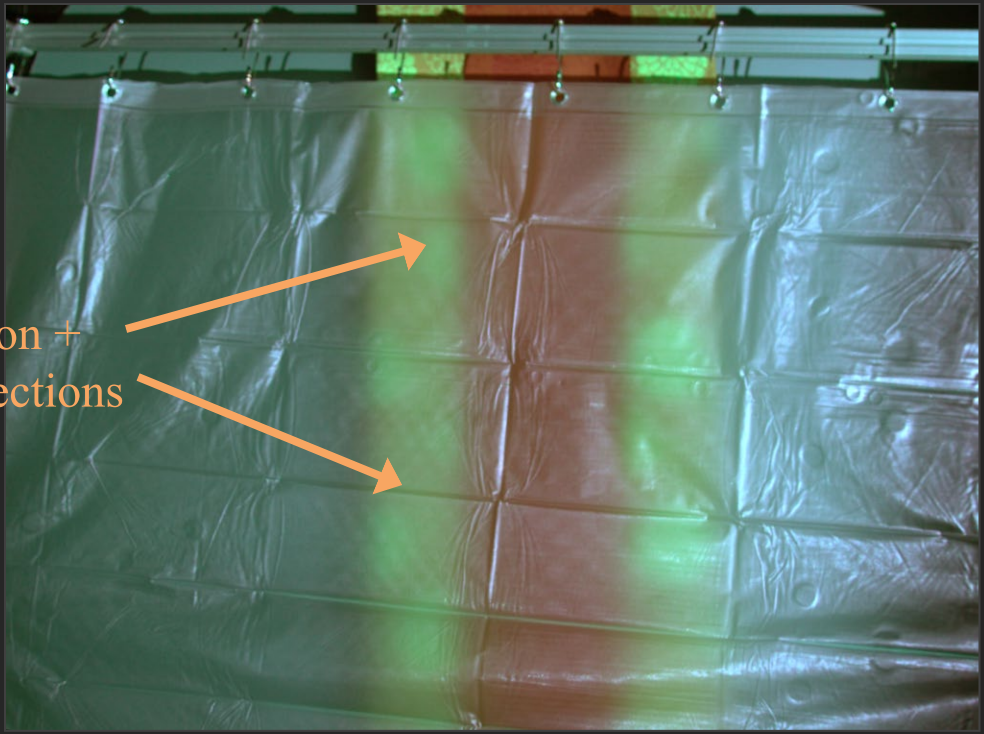
Regular Gray Codes (11 images)

Our Ensemble Codes (41 images)

3D Visualization using our ensemble codes

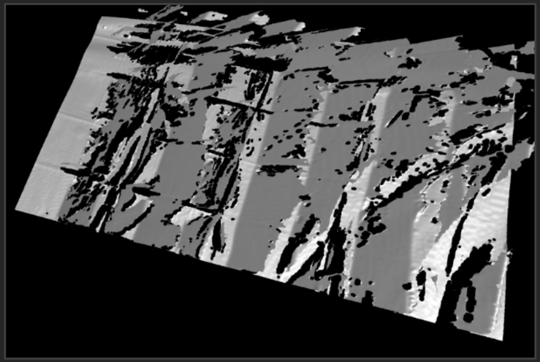


Shower Curtain

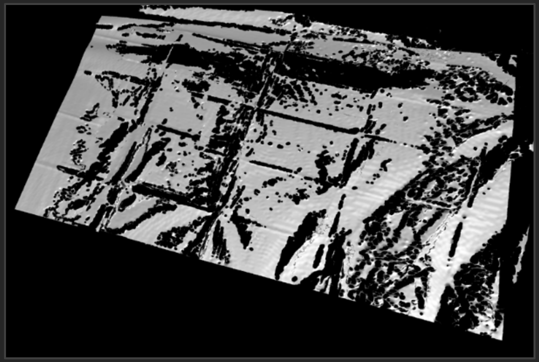


Goal is to reconstruct the shape of the shower-curtain. Shape of the curtain is planar because it was taped to the rod to avoid movement while capture.

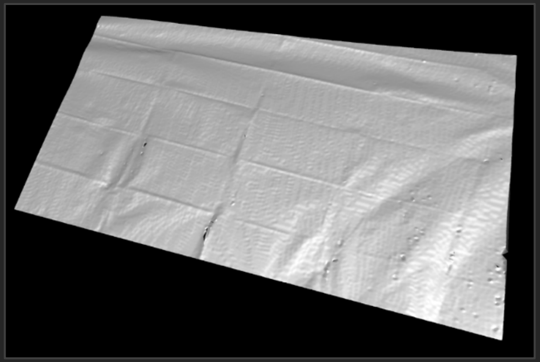
Shape Comparisons



Regular Gray Codes (11 images)

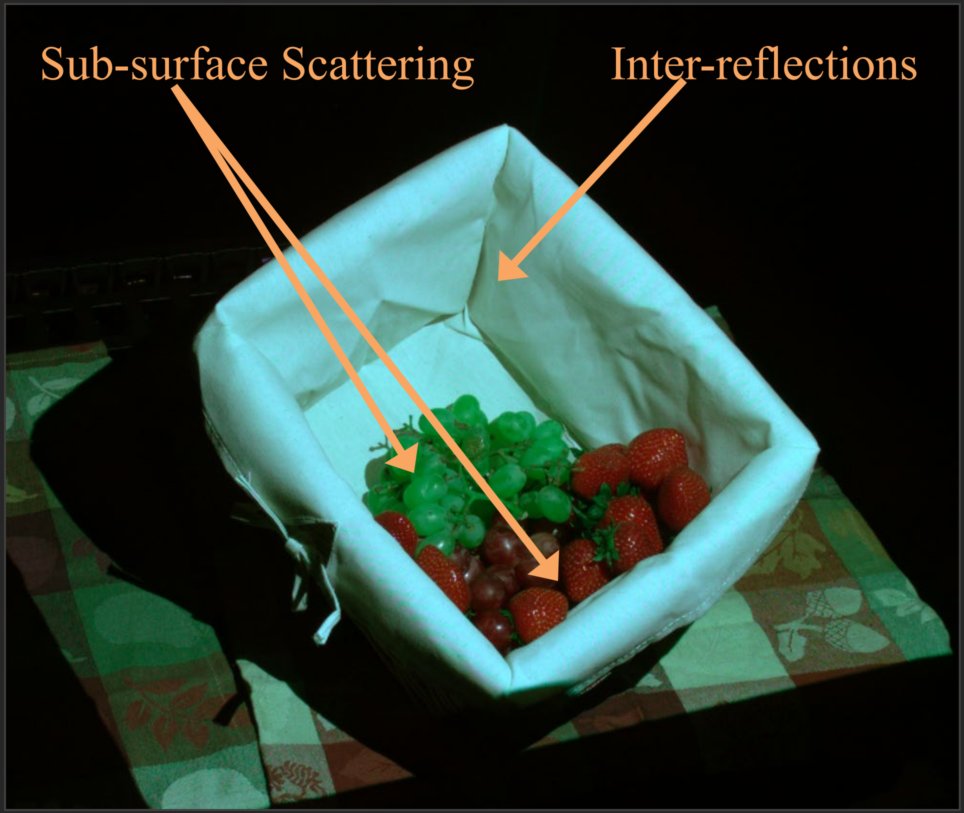


Phase-Shifting (18 images)

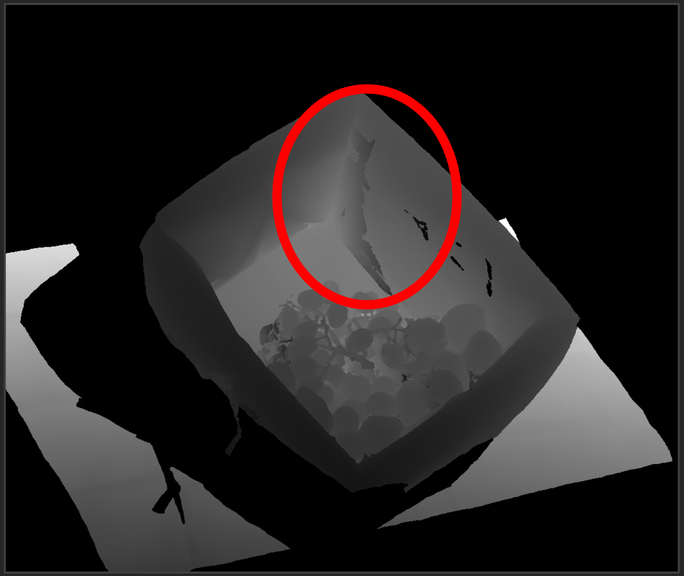


Our XOR Codes (11 images)

Fruit Basket: Multiple Effects



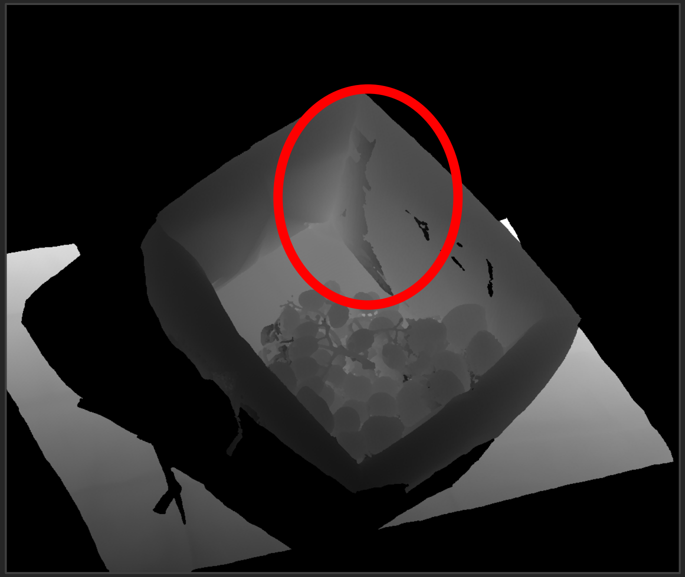
Depth-maps with previous state of the art



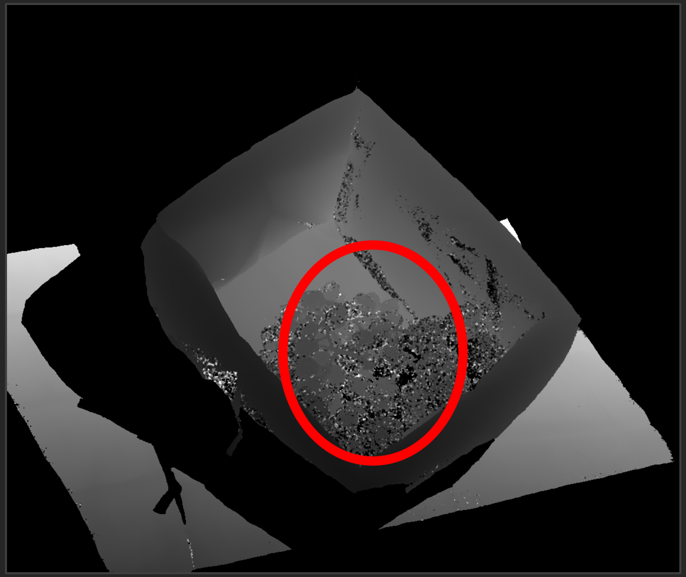
Regular Gray (11 images)

Phase-Shifting (18 images)

Depth-maps with previous state of the art

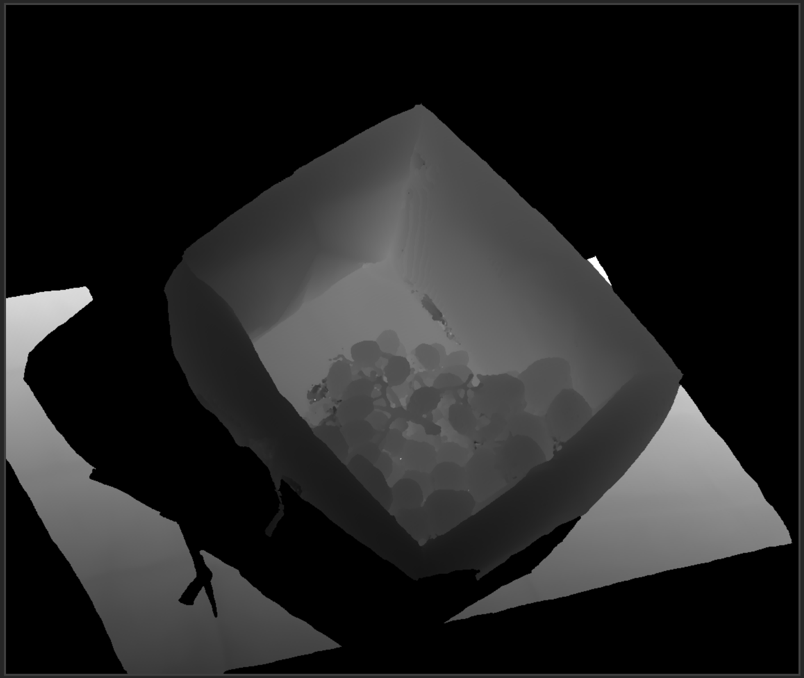


Regular Gray (11 images)



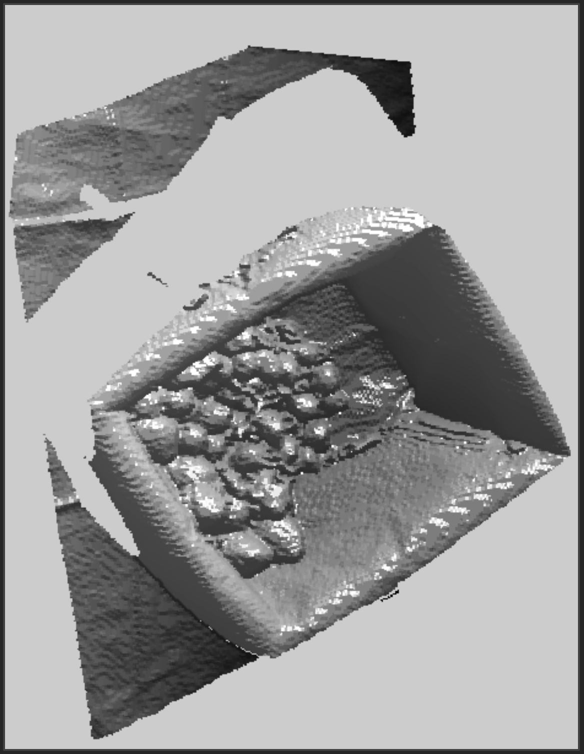
Modulated Phase-Shifting (162 images)

Depth-maps with our Ensemble Codes



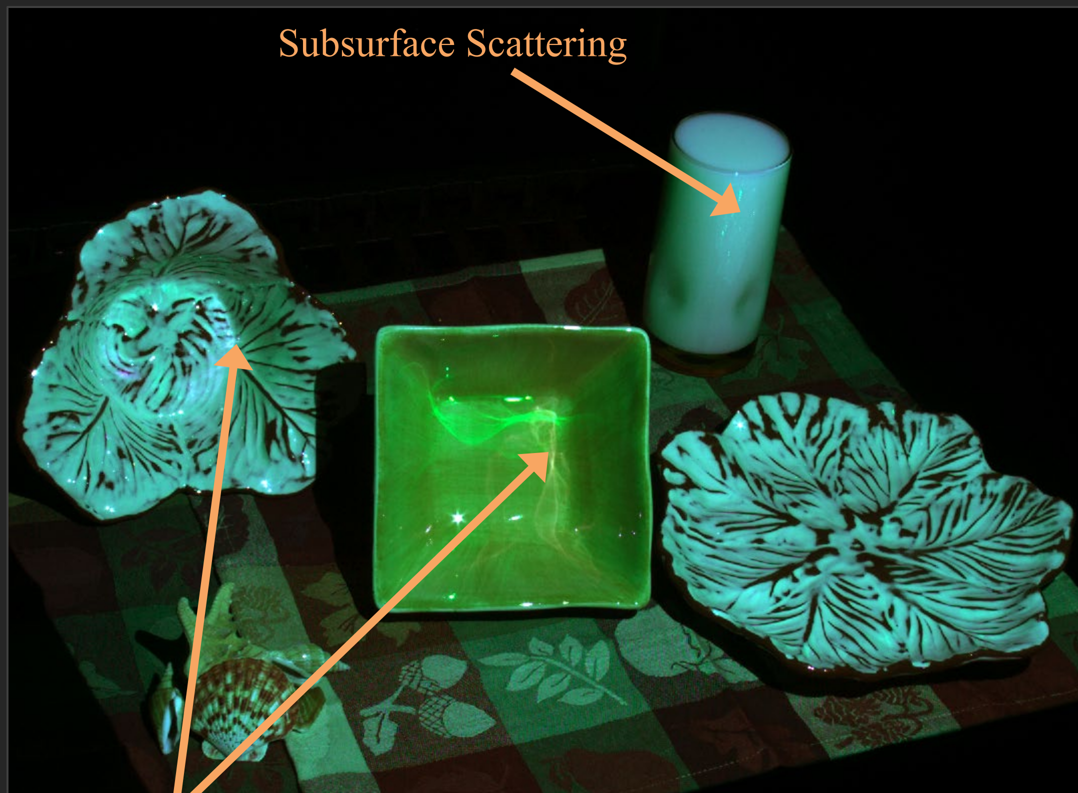
Our Ensemble Codes (41 images)

3D Visualizations with our ensemble codes

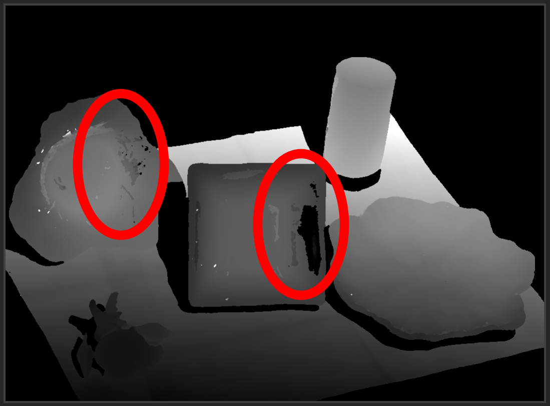


3D Visualization with our ensemble codes

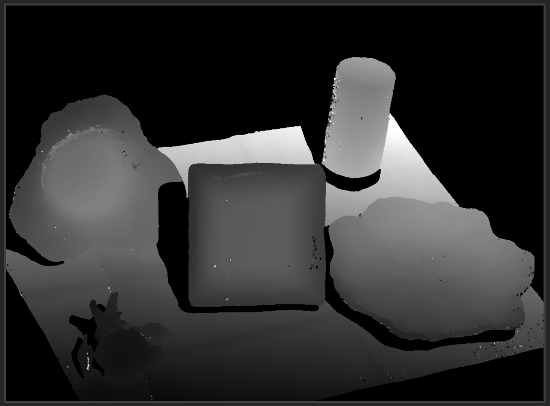
Bowls and Milk: Multiple Effects



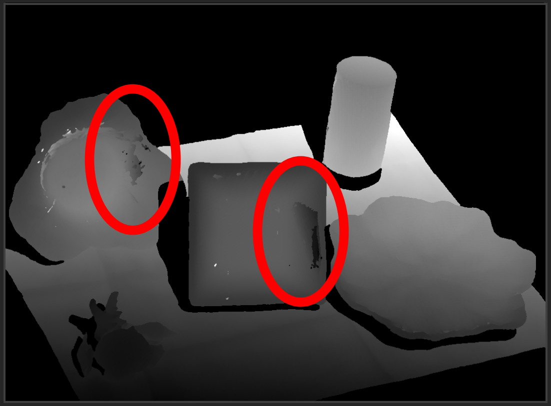
Interreflections



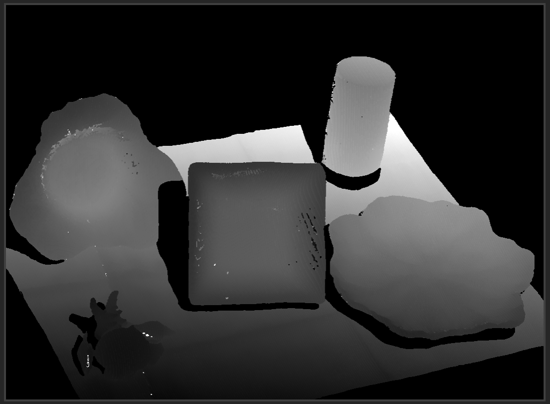
Phase-Shifting (18 images)



Modulated Phase-Shifting (162 images)

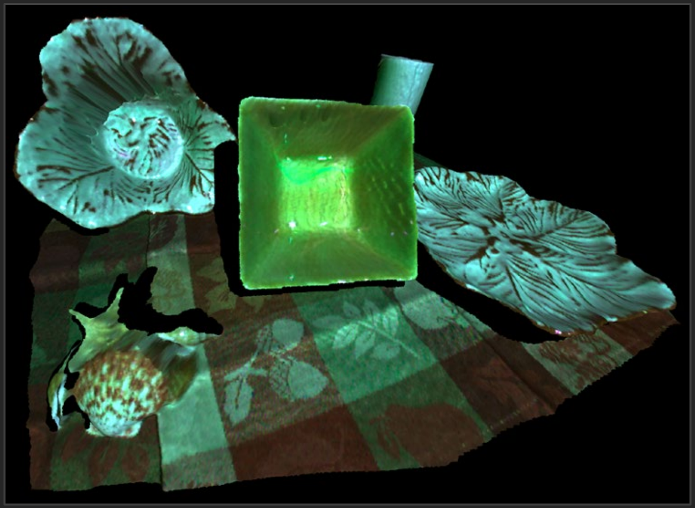


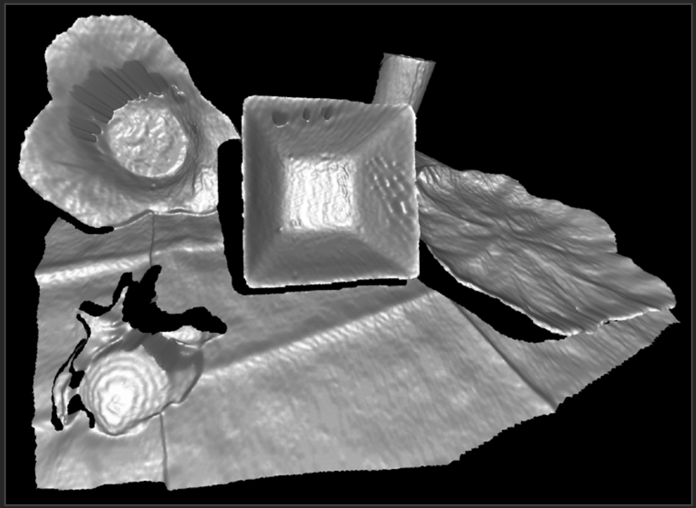
Regular Gray Codes (11 images)



Our XOR Codes (11 images)

3D Visualizations with our ensemble codes





Flower-Vase

Diffusion

Sub-surface Scattering

Comparison

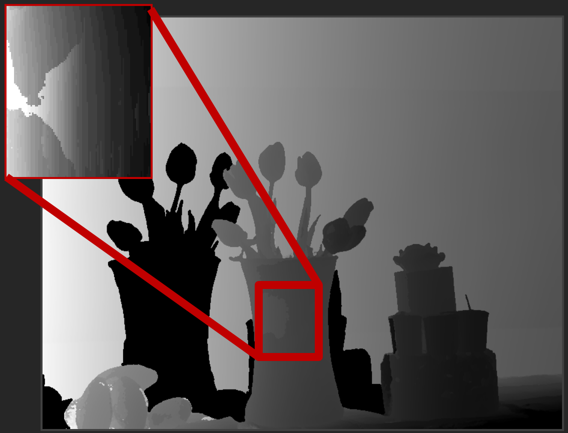
Phase-Shifting (18 images)

Regular Gray Code (11 images)

Modulated Phase-Shifting (162 images)

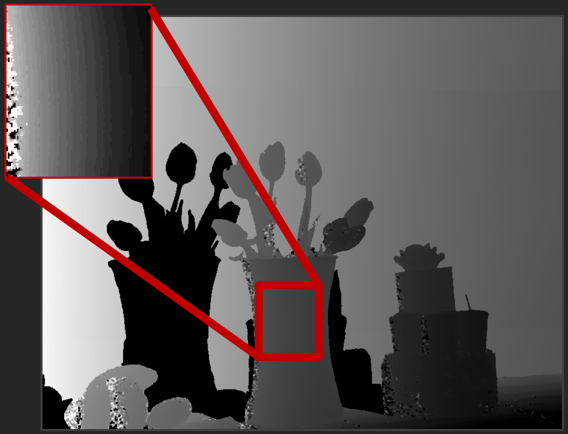
Our Ensemble Codes (41 images)

Comparison

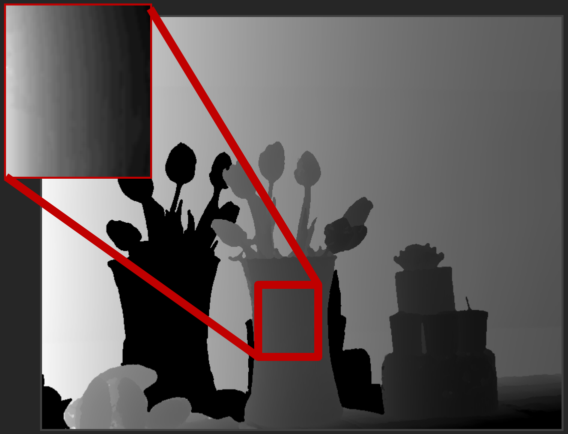


Phase-Shifting (18 images)

Regular Gray Code (11 images)



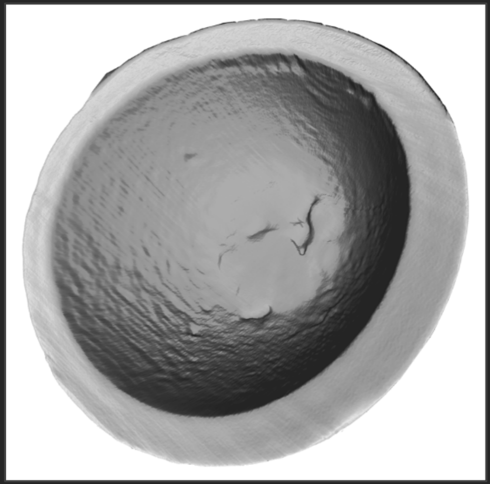
Modulated Phase-Shifting (162 images)



Our Ensemble Codes (41 images)

Multiple Global Illumination Effects

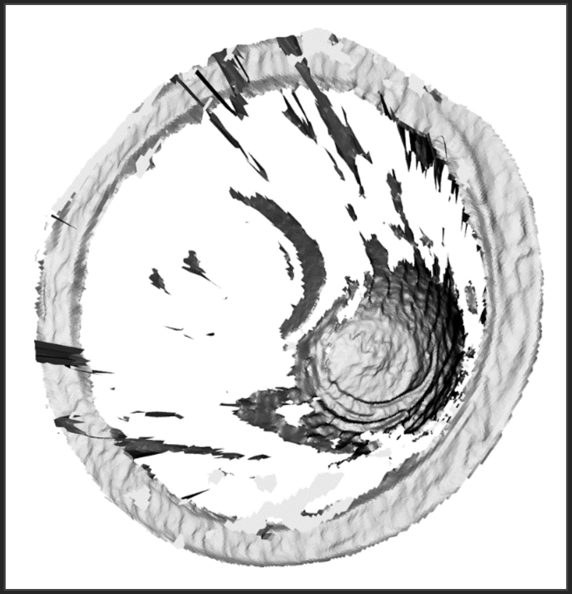
Wax Bowl



Shape Using Ensemble Codes

Multiple Global Illumination Effects

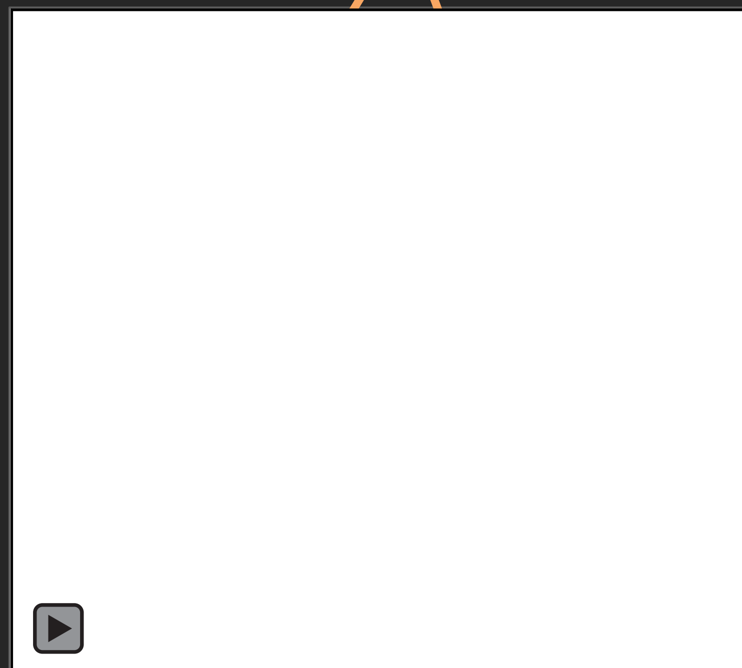
Deep Wax Container



Shape Using Ensemble Codes

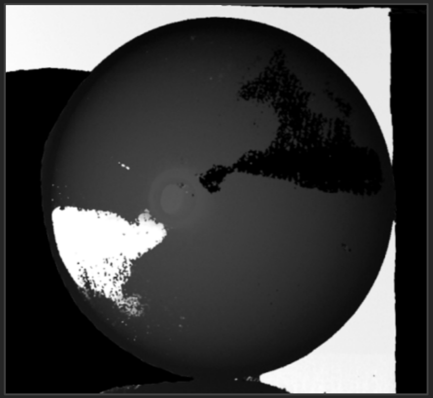
Lamp made of shiny brushed metal

Strong and high-frequency inter-reflections



Depth Map Comparison

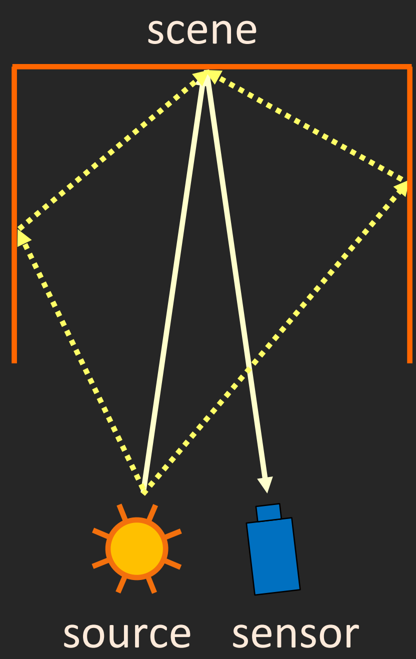
Regular Gray (11 images)

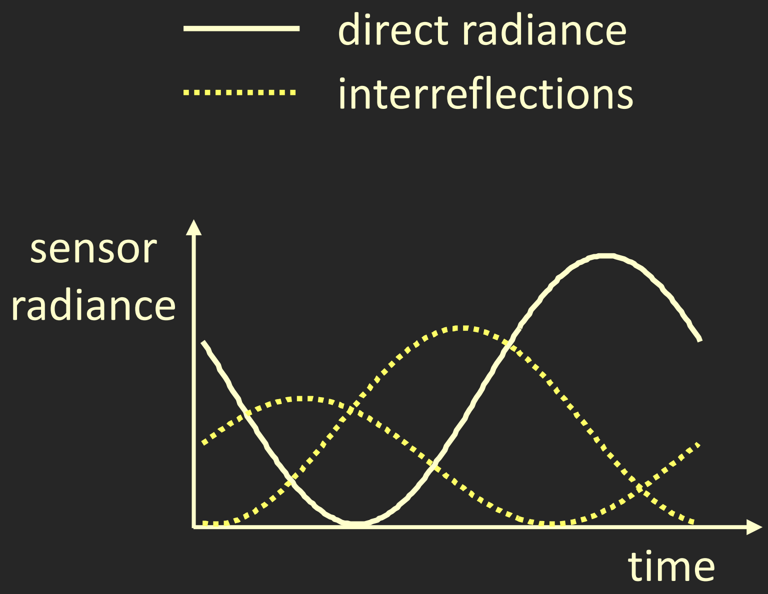


Our Ensemble Codes (41 images)

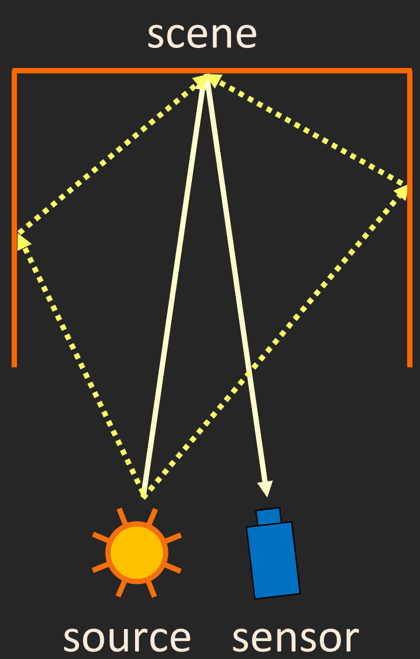
Application to time-of-flight imaging

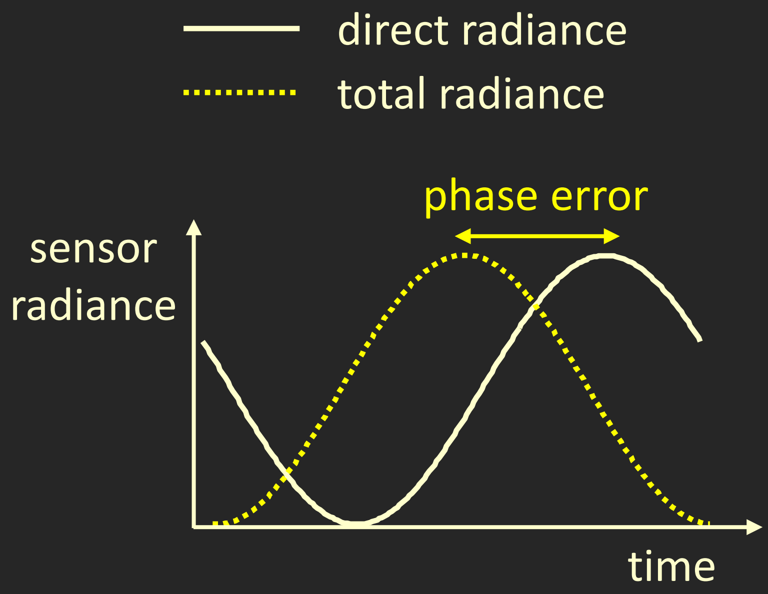
Interreflections and ToF Imaging





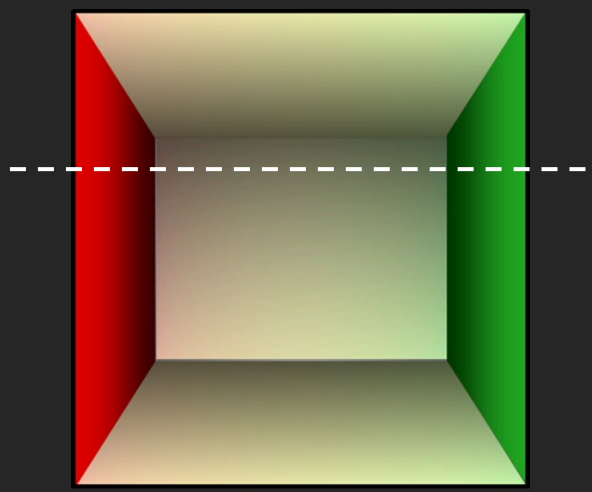
Interreflections and ToF Imaging

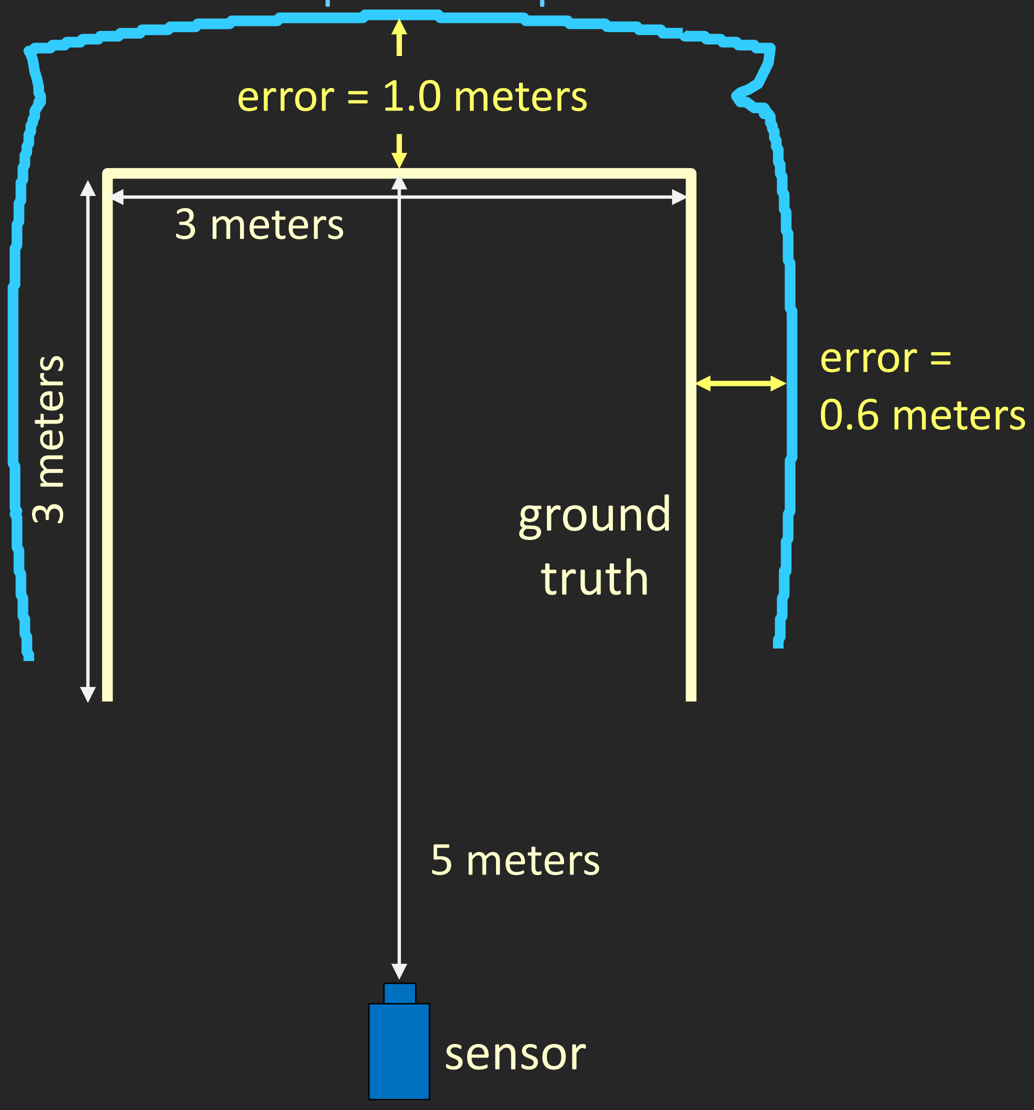




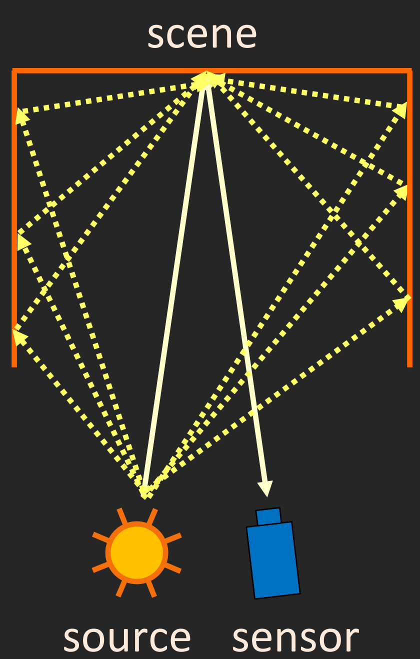
Interreflections Produce Incorrect Phase

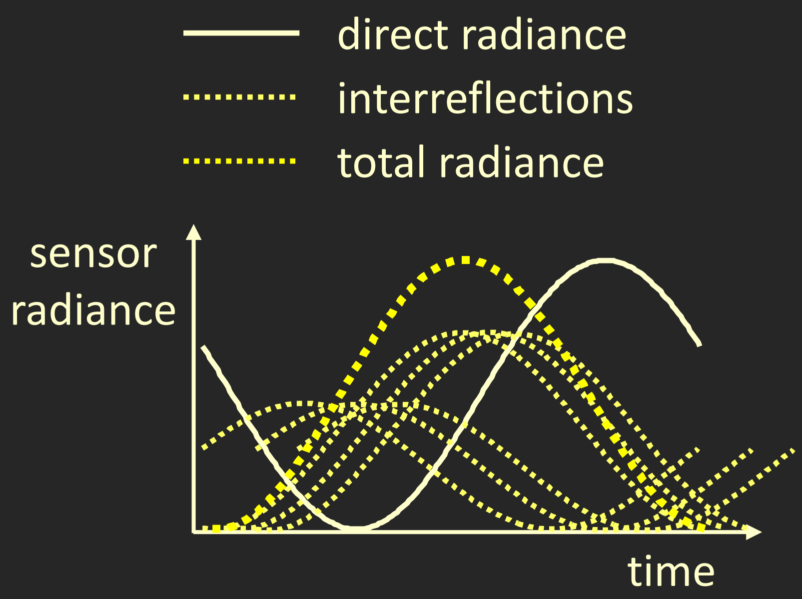
Errors in Shape Recovery


camera view



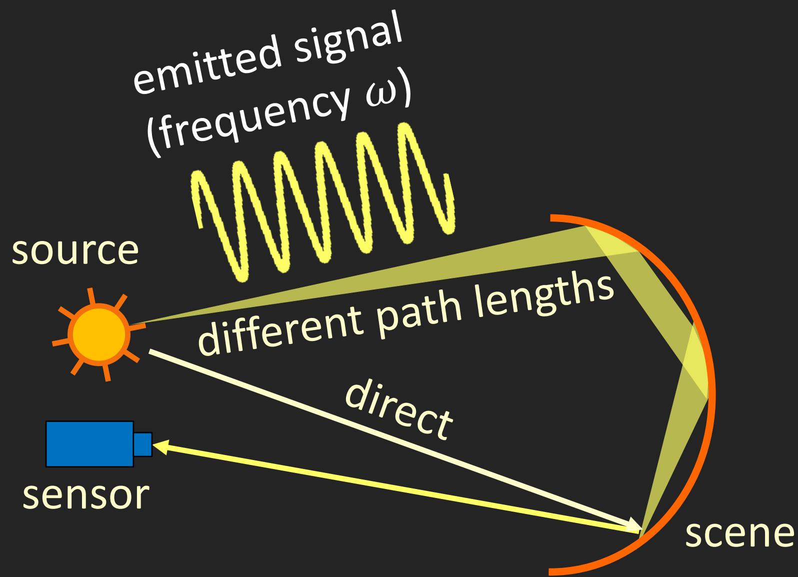
Multipath Interference: Existing Work

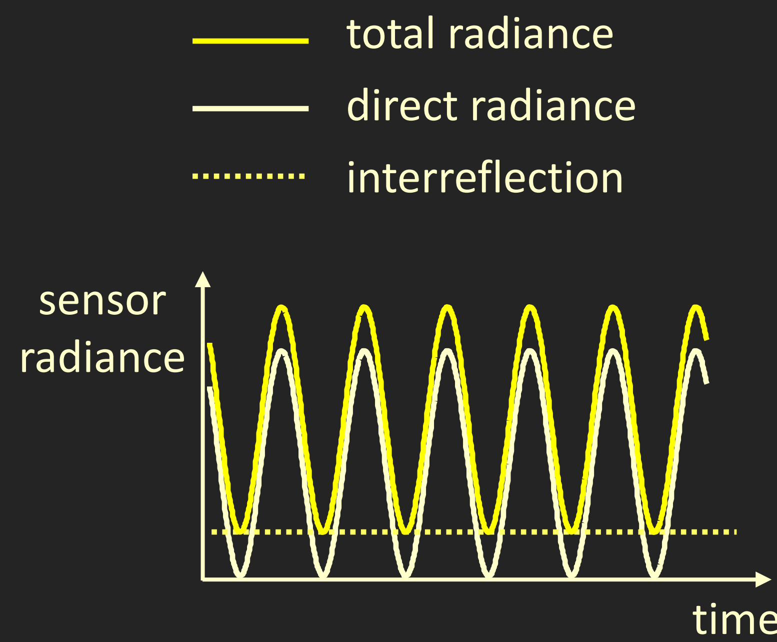




How To Separate Different Components?

Interreflections vs. Modulation Frequency



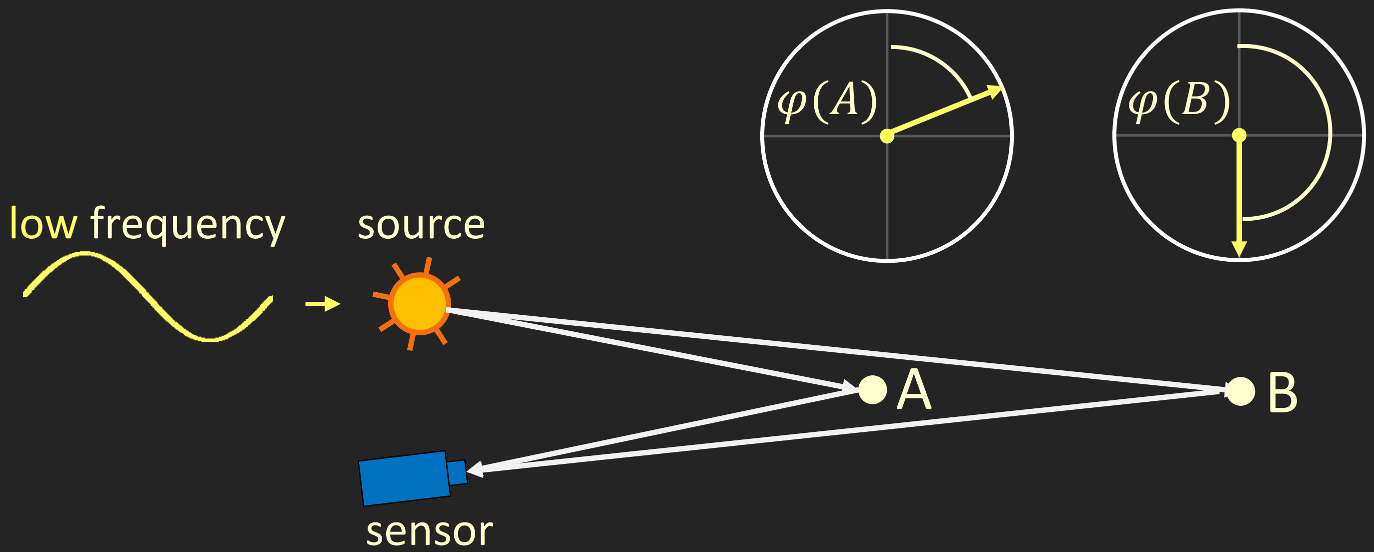


For High Temporal Frequency

Interreflection Component Constant

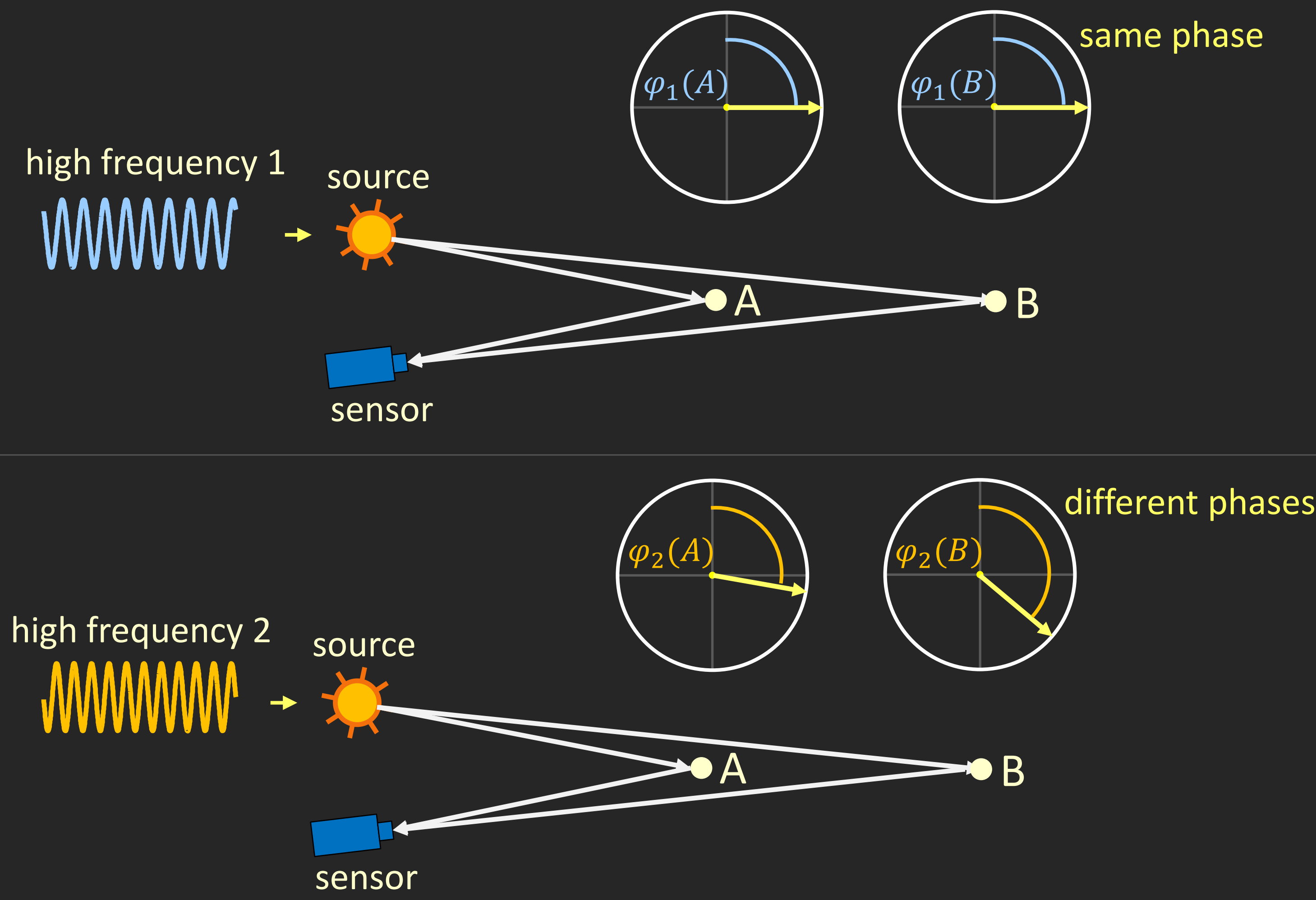
Interreflections Do Not Affect Phase

Phase Ambiguity



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

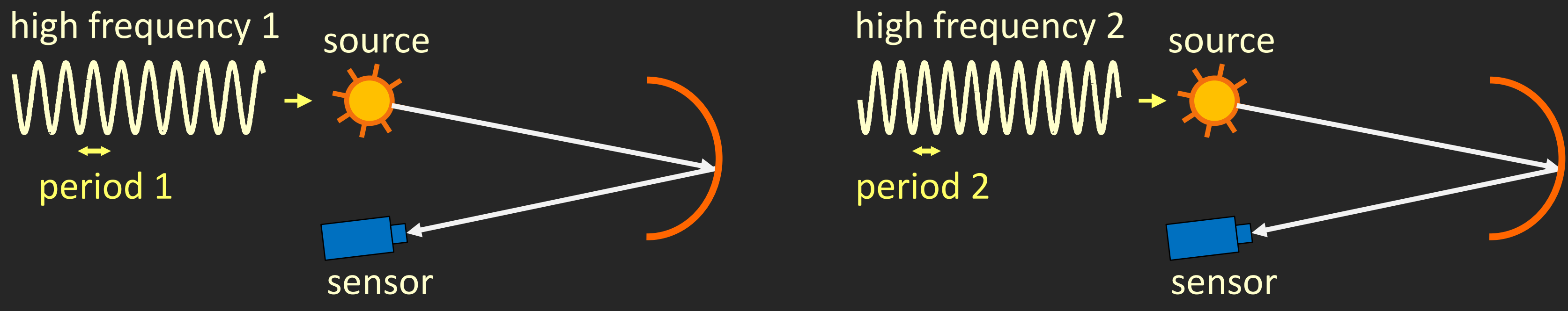
Disambiguating Phase



Compute Phases at Two High Frequencies

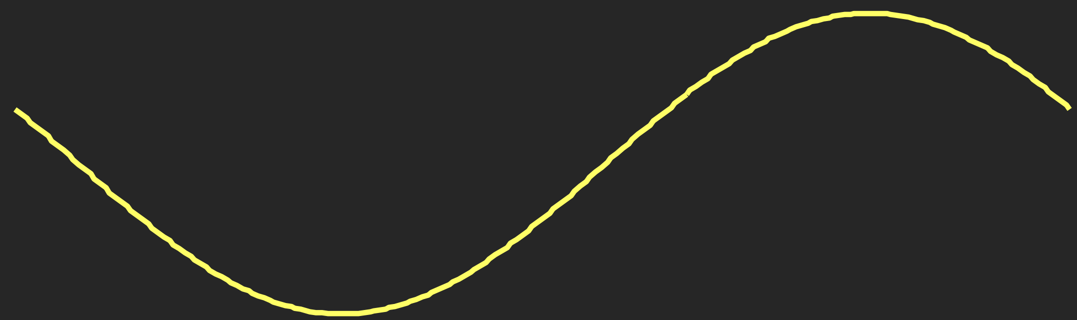
[Jongenelen *et al.* 2010, 2011]

Micro Time-of-Flight Imaging



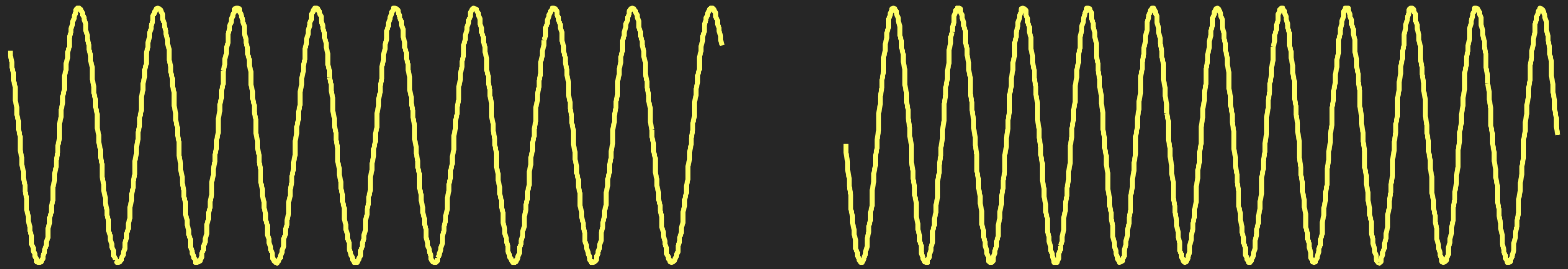
Modulation Signals With Micro (Small) Periods

Conventional vs. Micro ToF Imaging



Conventional ToF Shifting: One Low Frequency

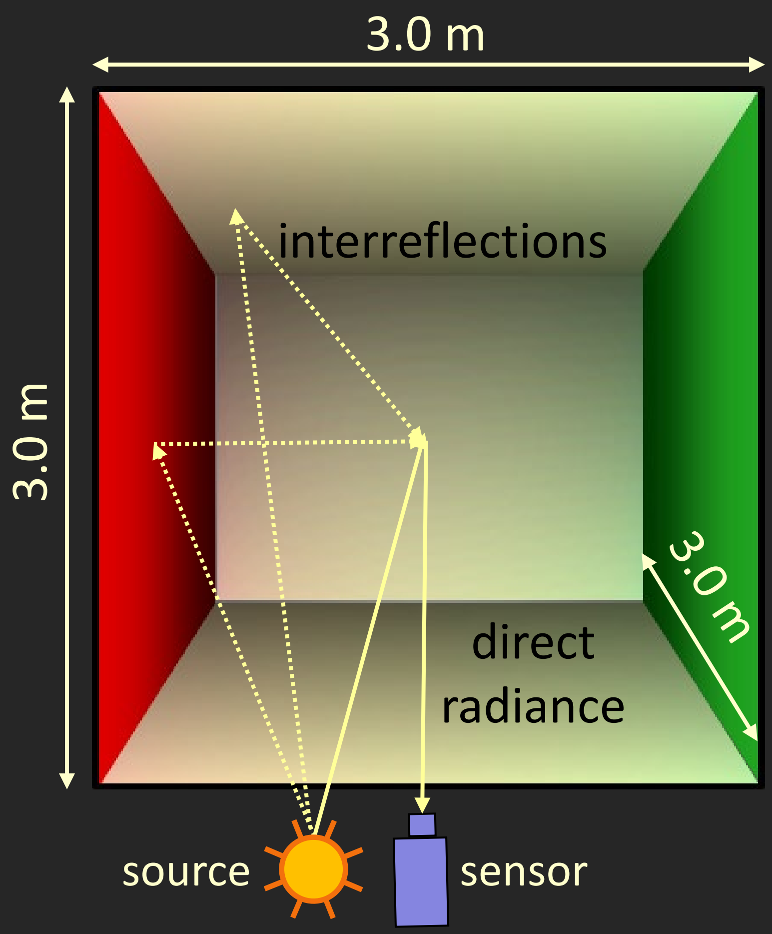
Three Measurements



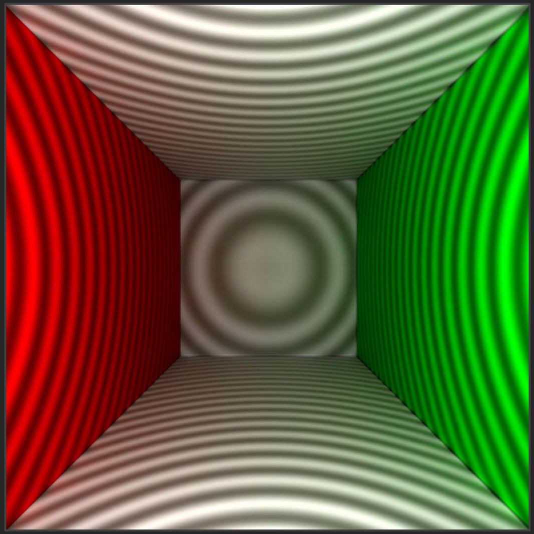
Micro ToF Shifting: Two High Frequencies

Four Measurements

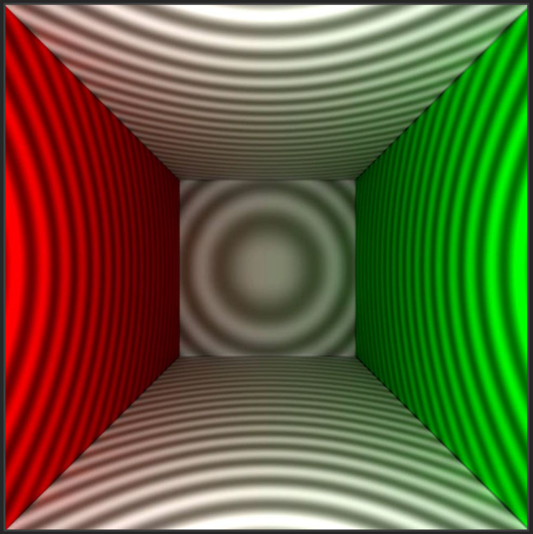
Simulations: Cornell Box



Cornell Box: Input Images



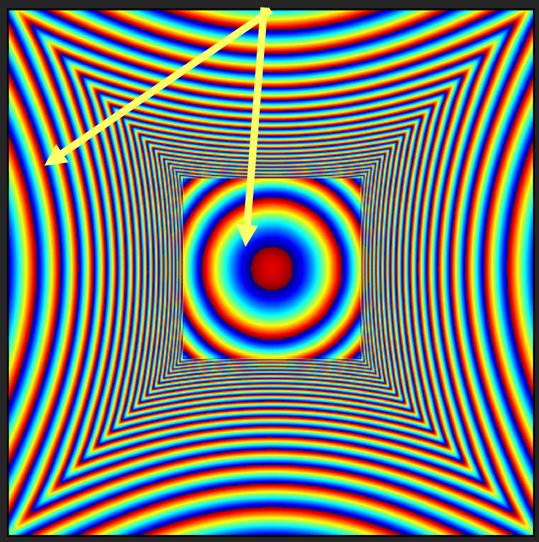
957 MHz.



930 MHz.

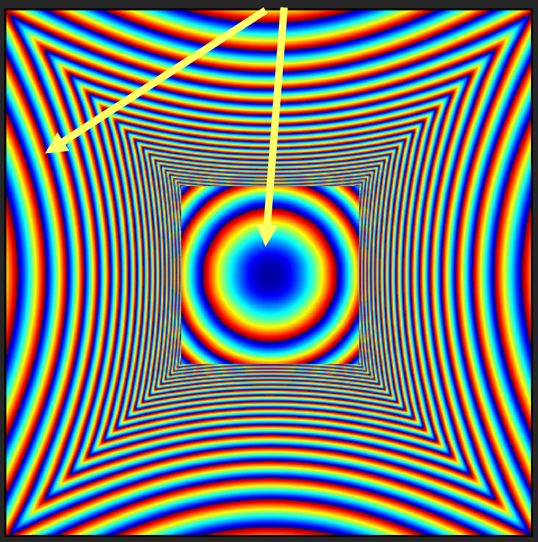
Cornell Box: Phase Maps

ambiguities



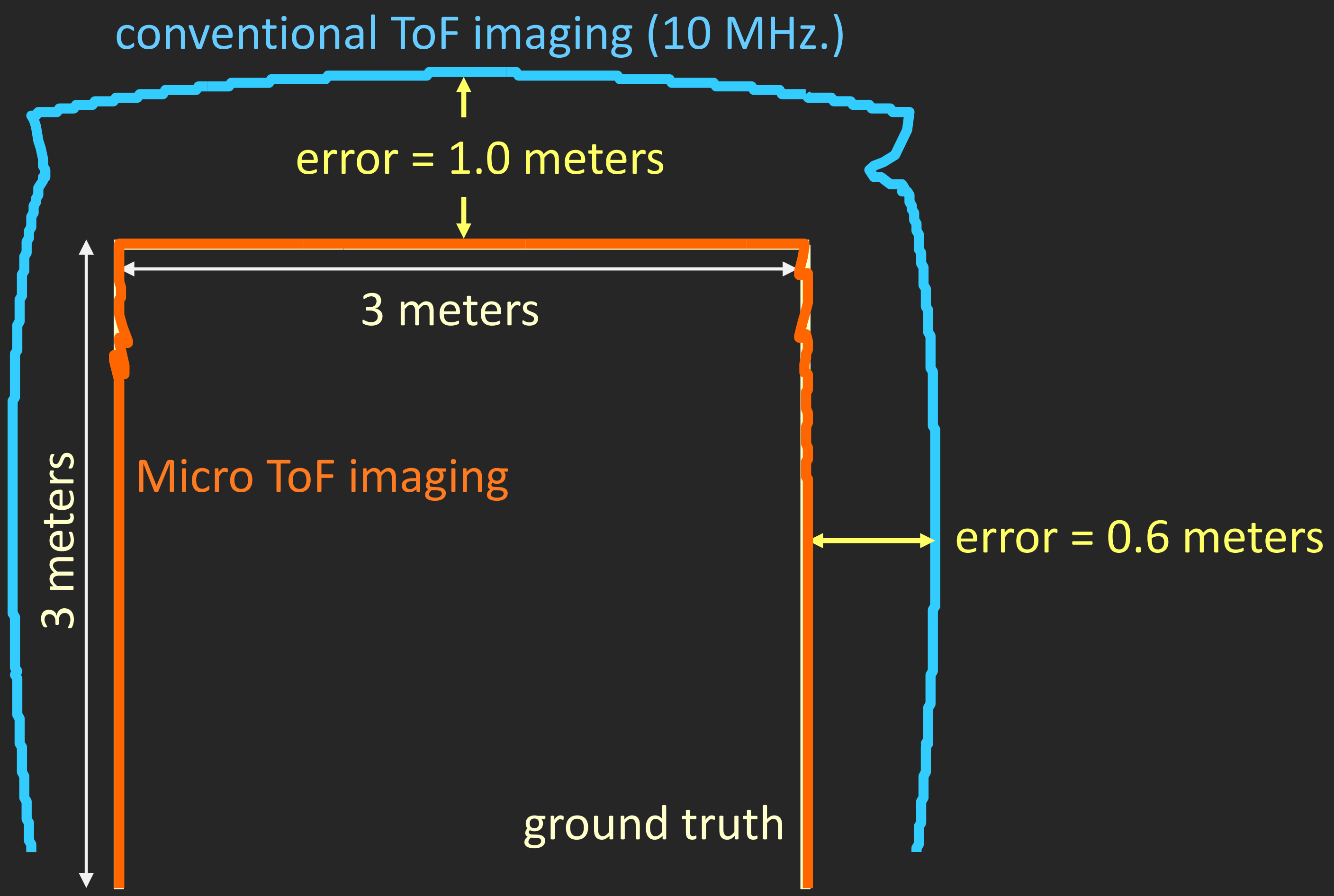
957 MHz.

ambiguities



930 MHz.

Cornell Box: Shape Comparison



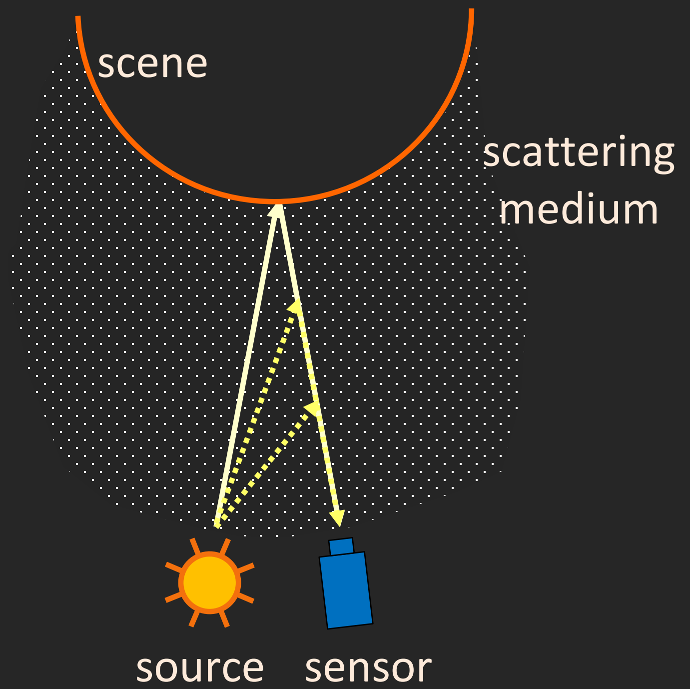
Scattering in Real World

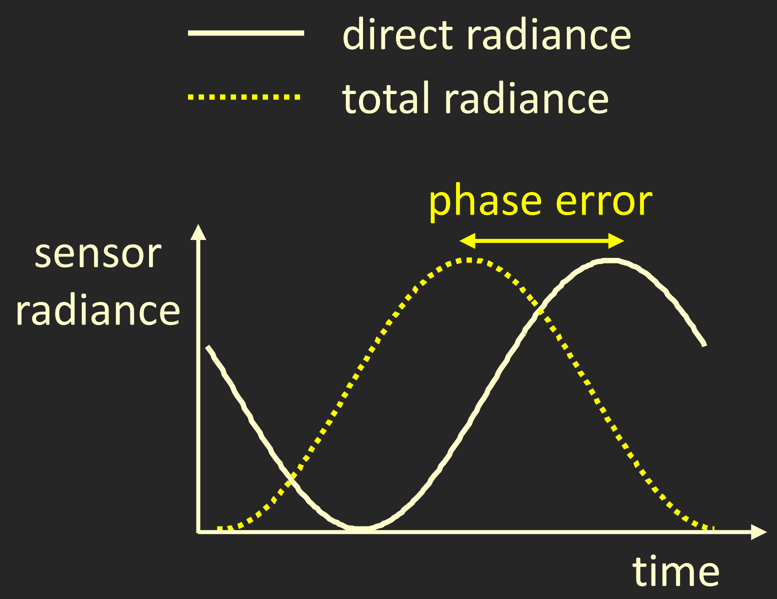
Driving through fog/mist

Driving through a dust storm

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

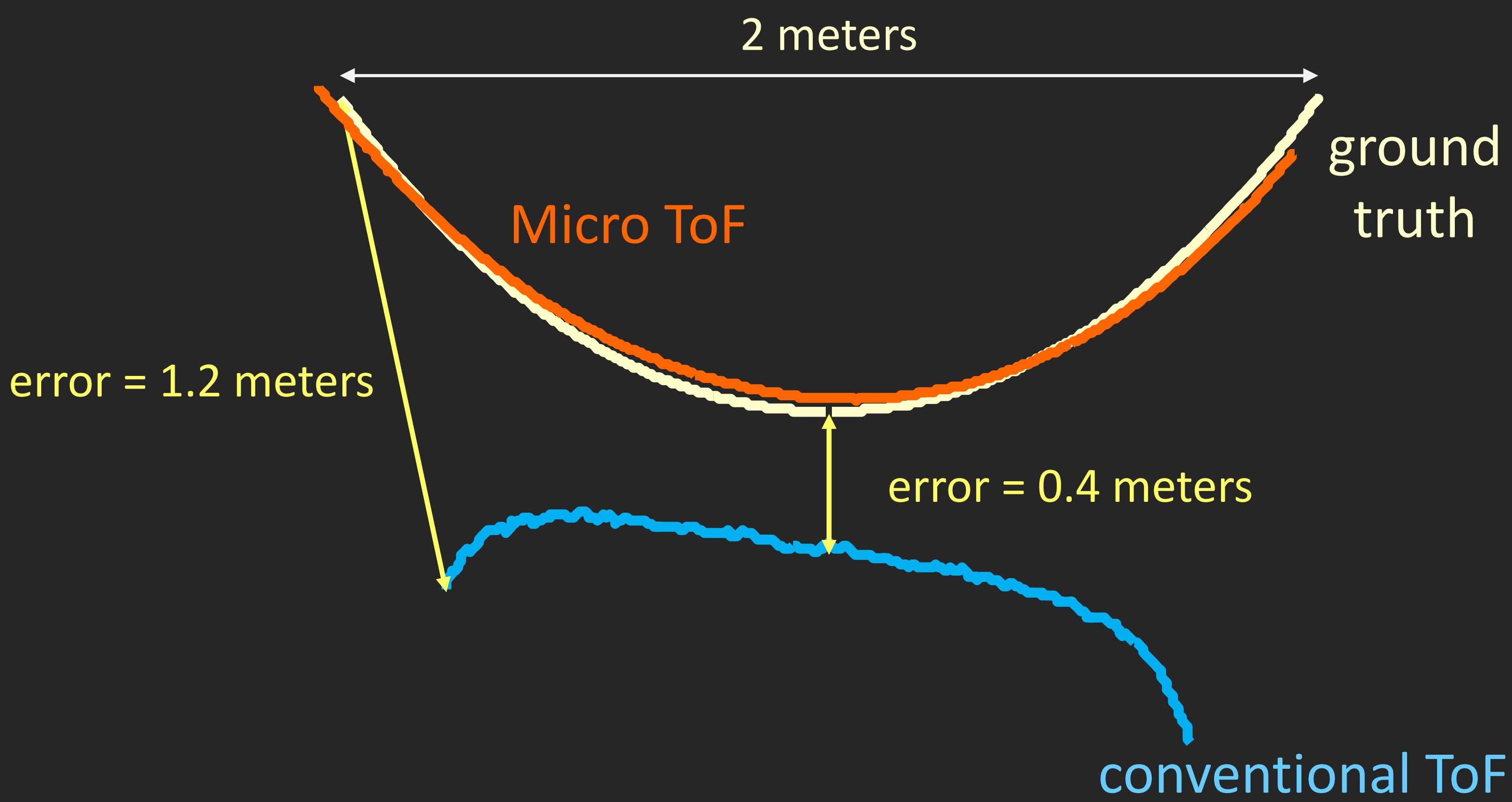
Scattering and ToF Imaging





Scattering Produces Incorrect Phase

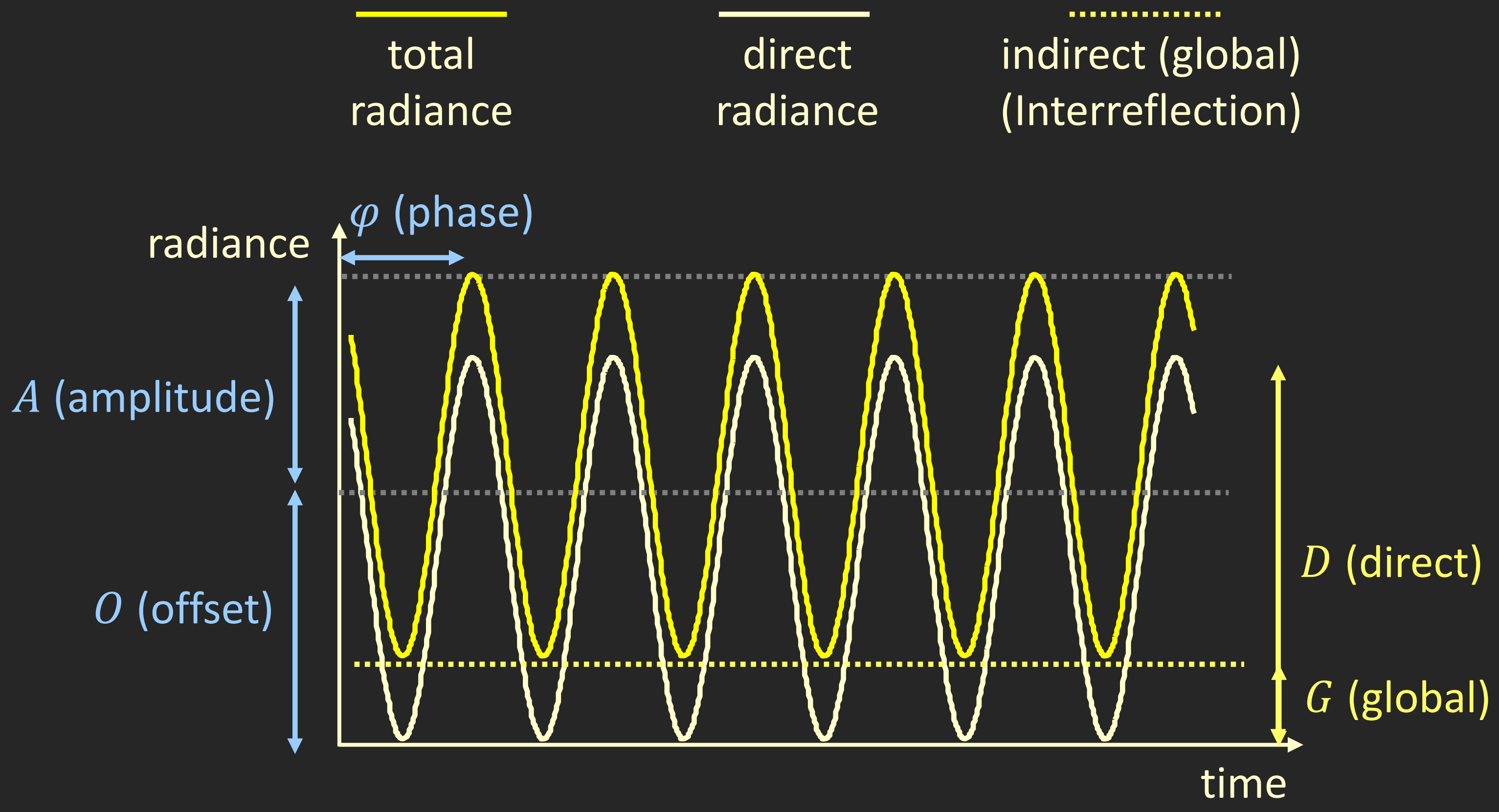
Sphere: Shape Comparison



Micro ToF Achieves High Accuracy Shape

Depth is Underestimated

Direct-Indirect Separation

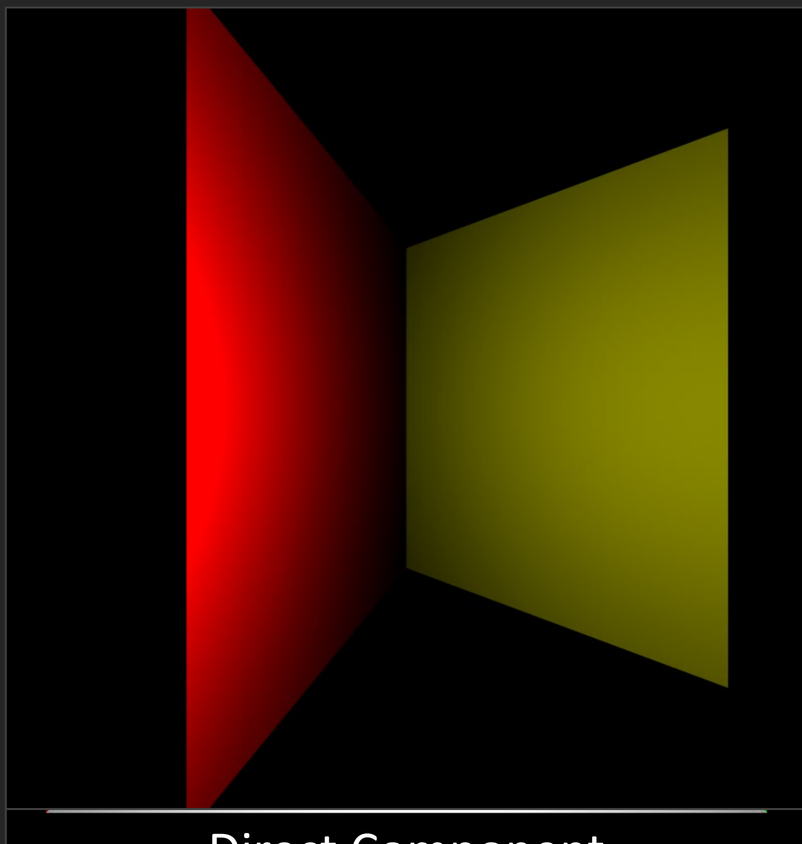


$$D = 2A \quad G = O - A$$

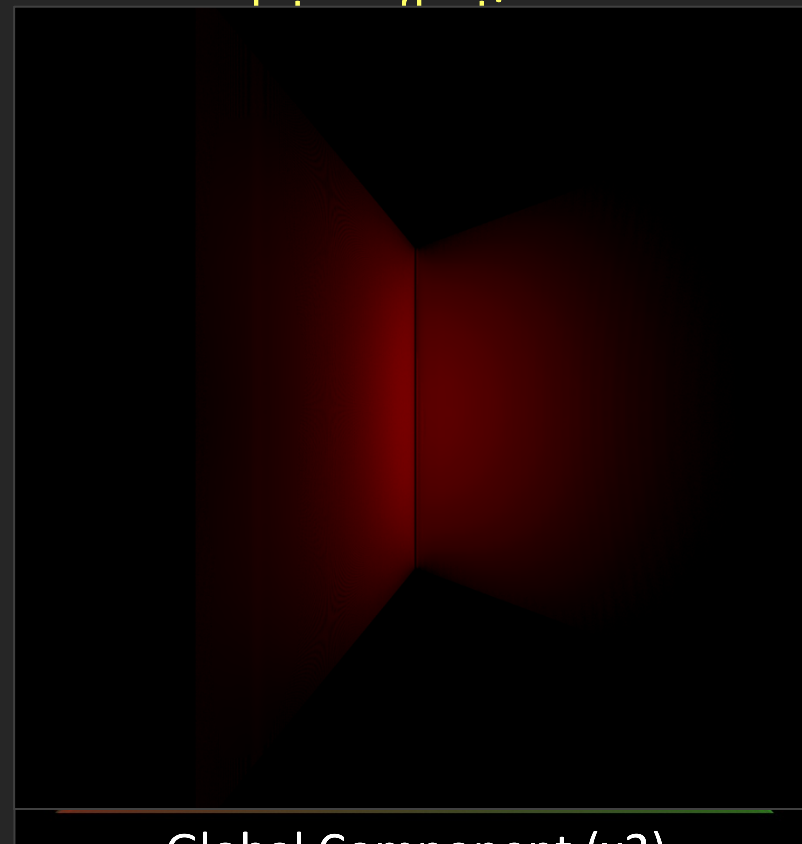
Direct-Global Separation Using Three Measurements

Direct-Global Separation

Color Bleeding due to

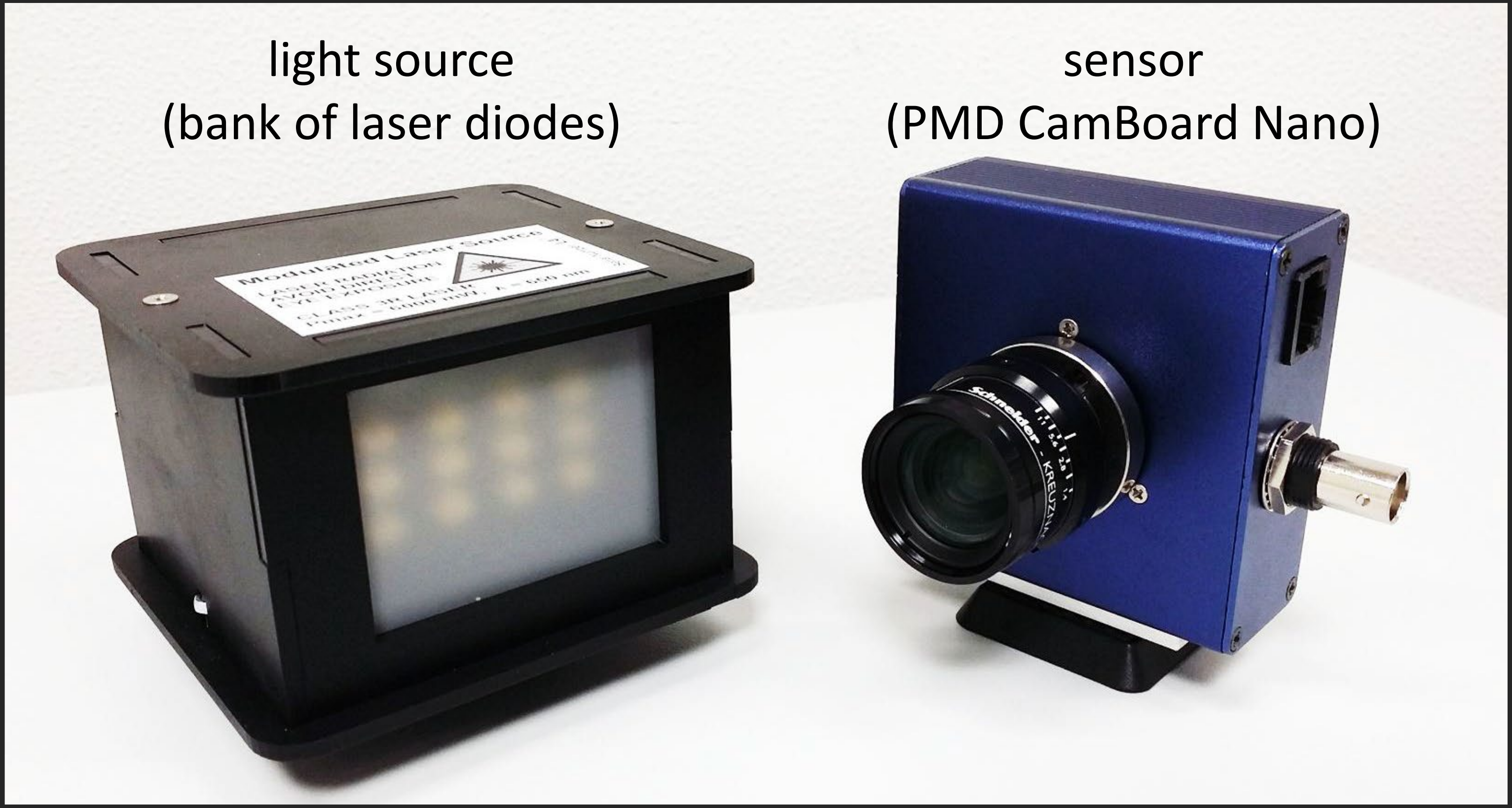


Direct Component
Direct Component



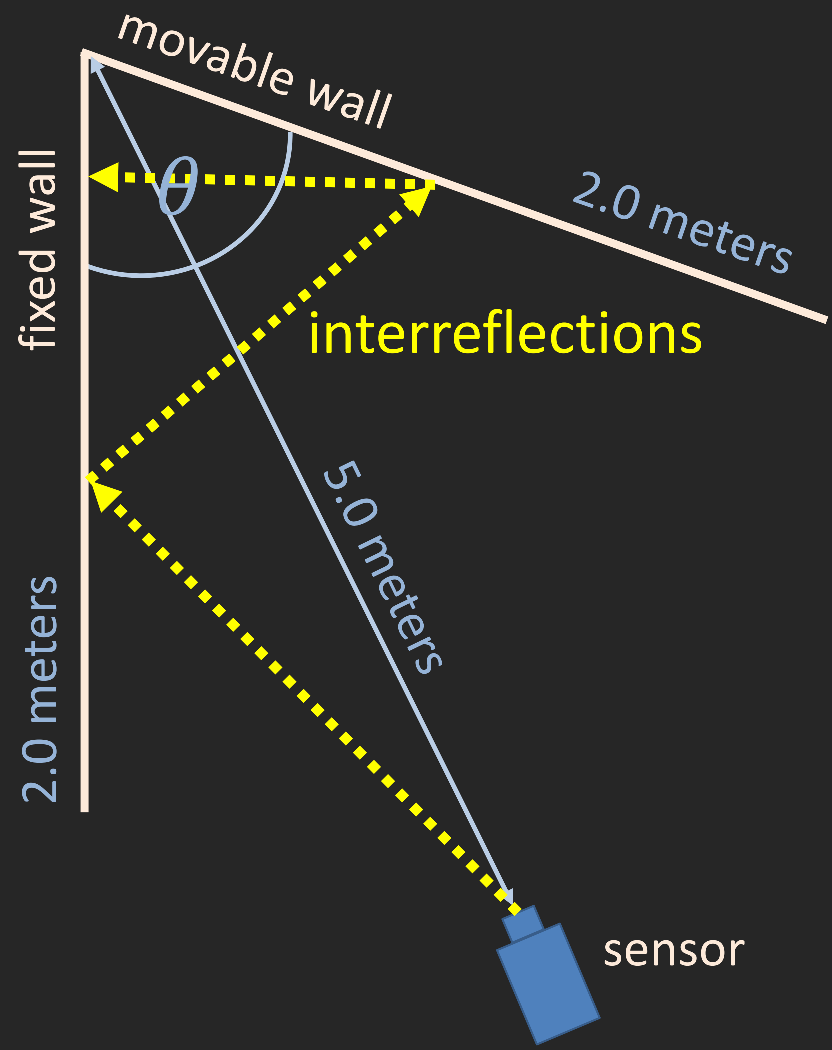
Global Component (x2)
Global Component (x2)

Experimental Setup

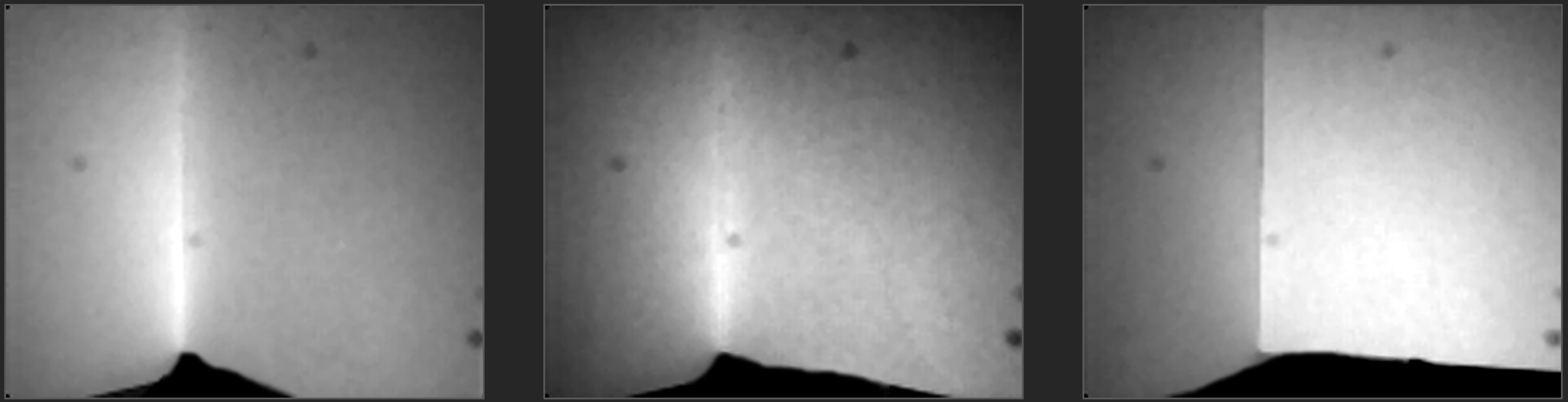


Maximum System Modulation Frequency = 125 MHz.

Experiments: V-Groove



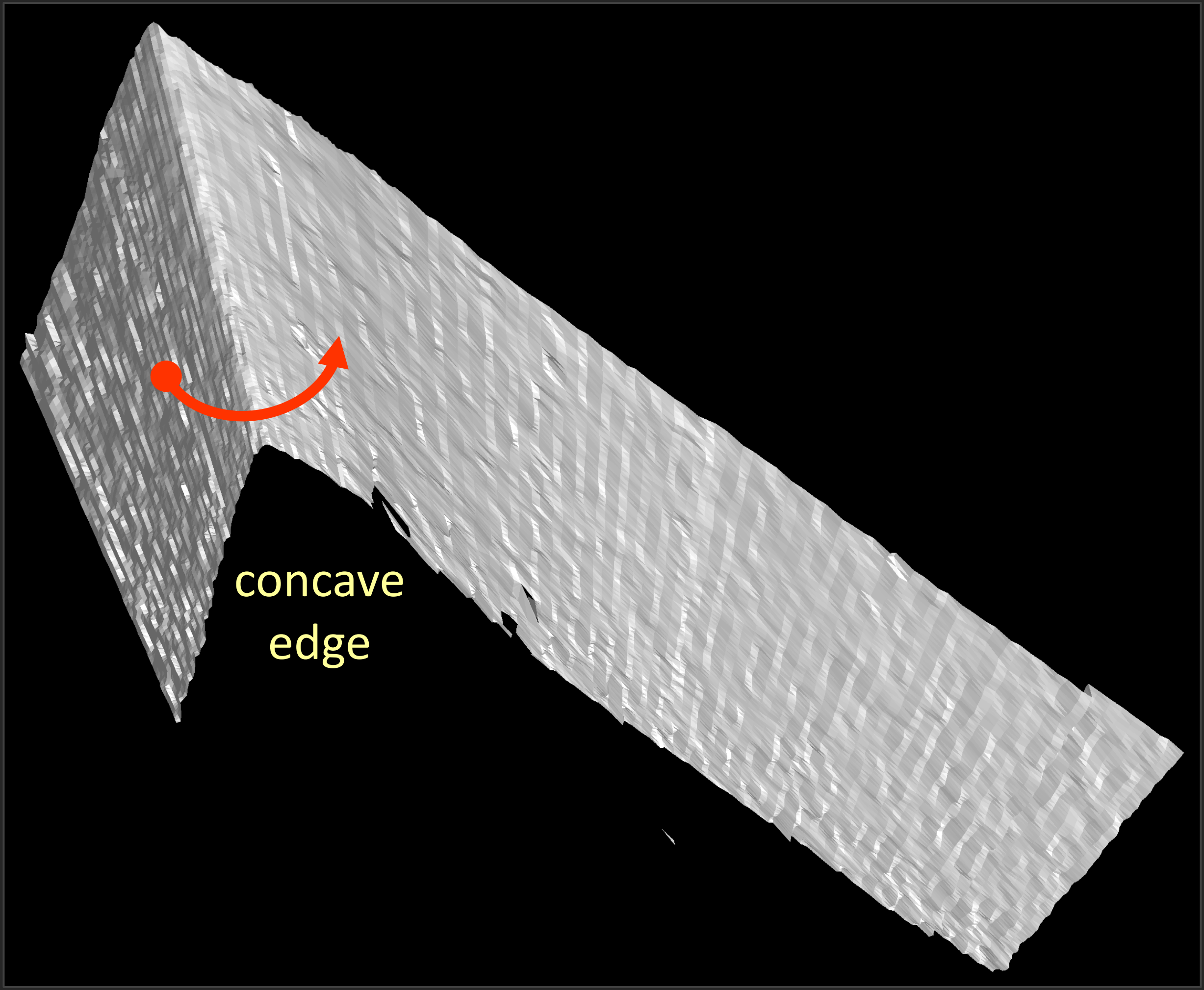
Scene Images Captured By PMD Sensor



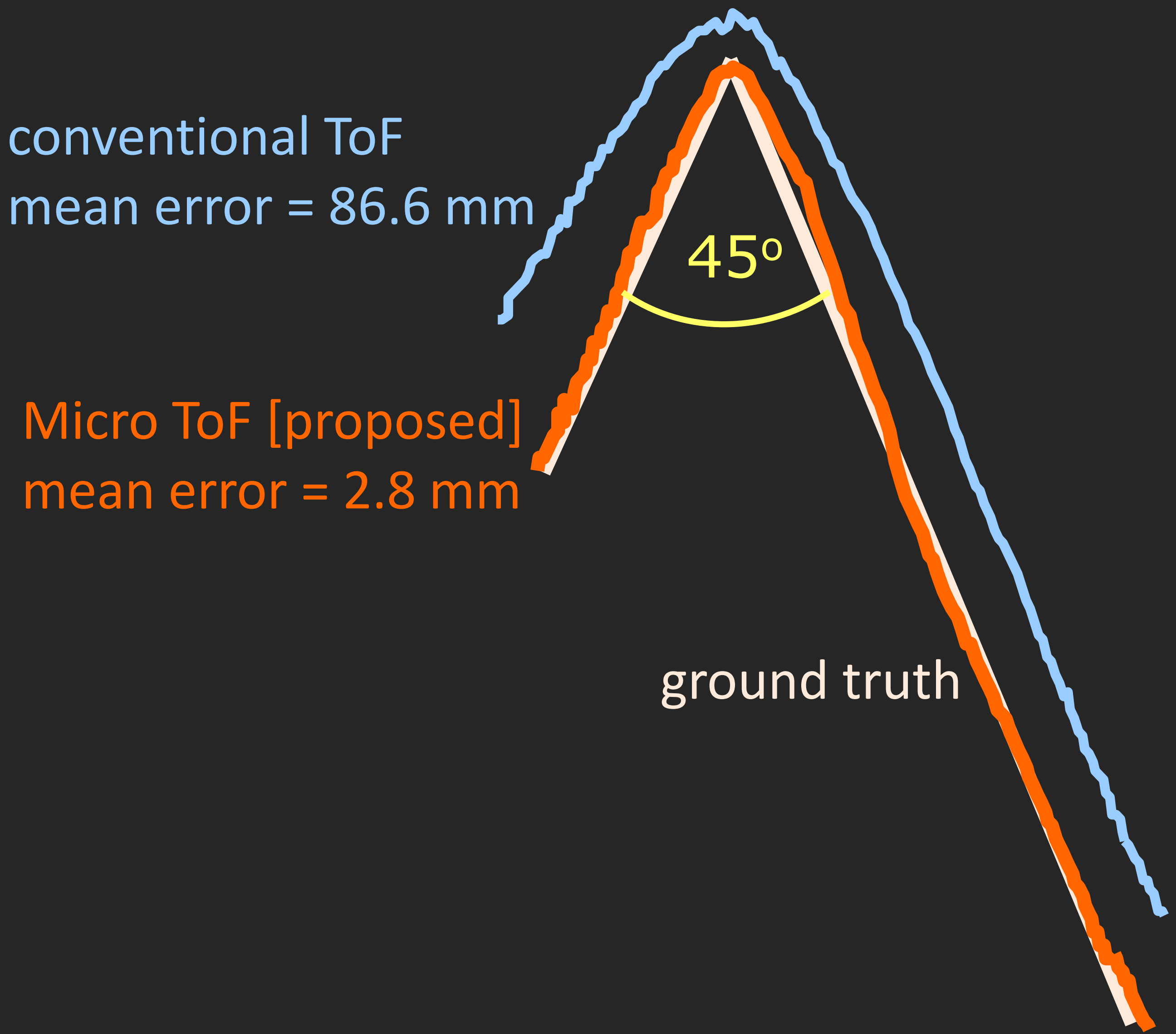
apex angle = 45° apex angle = 60° apex angle = 90°

image resolution = 120 x 165

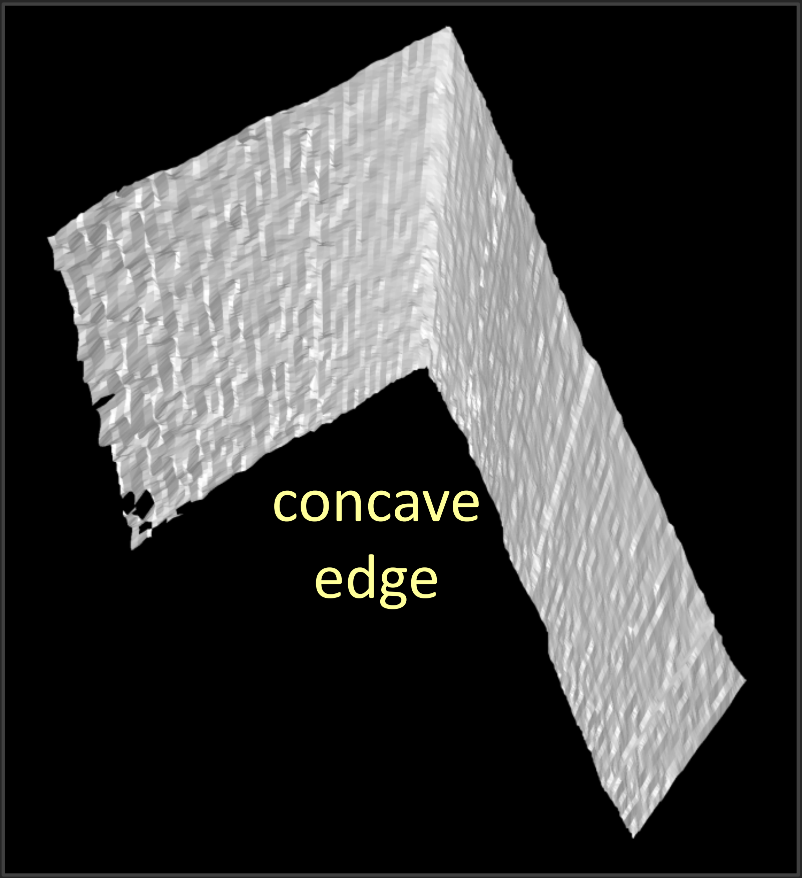
Reconstructed Shape using Micro ToF



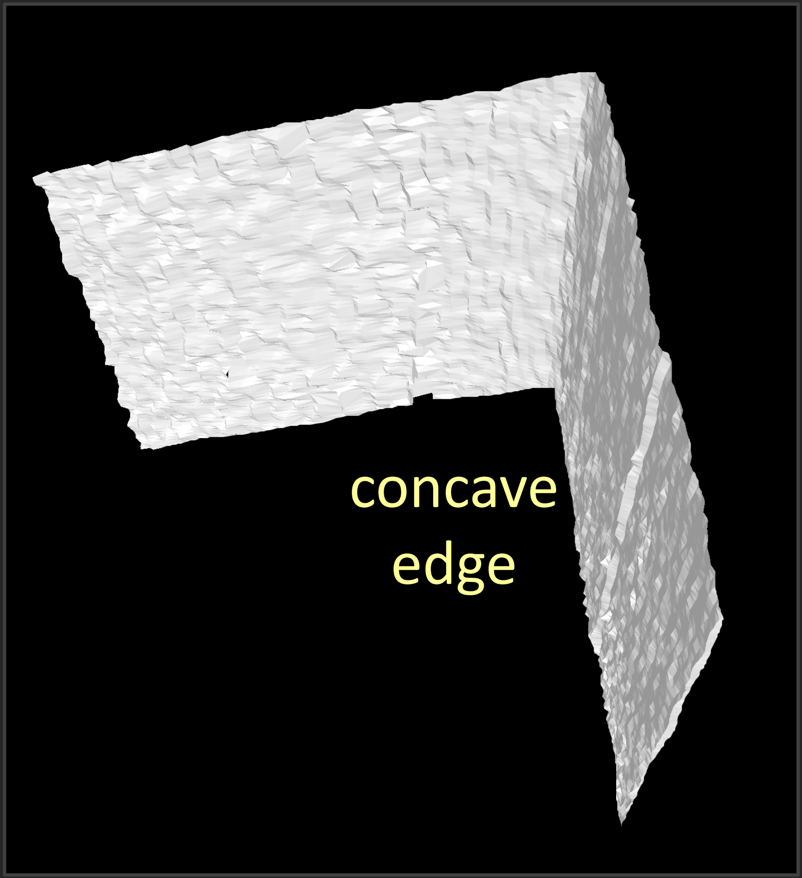
Shape Comparisons



Reconstructed Shapes: Different Angles

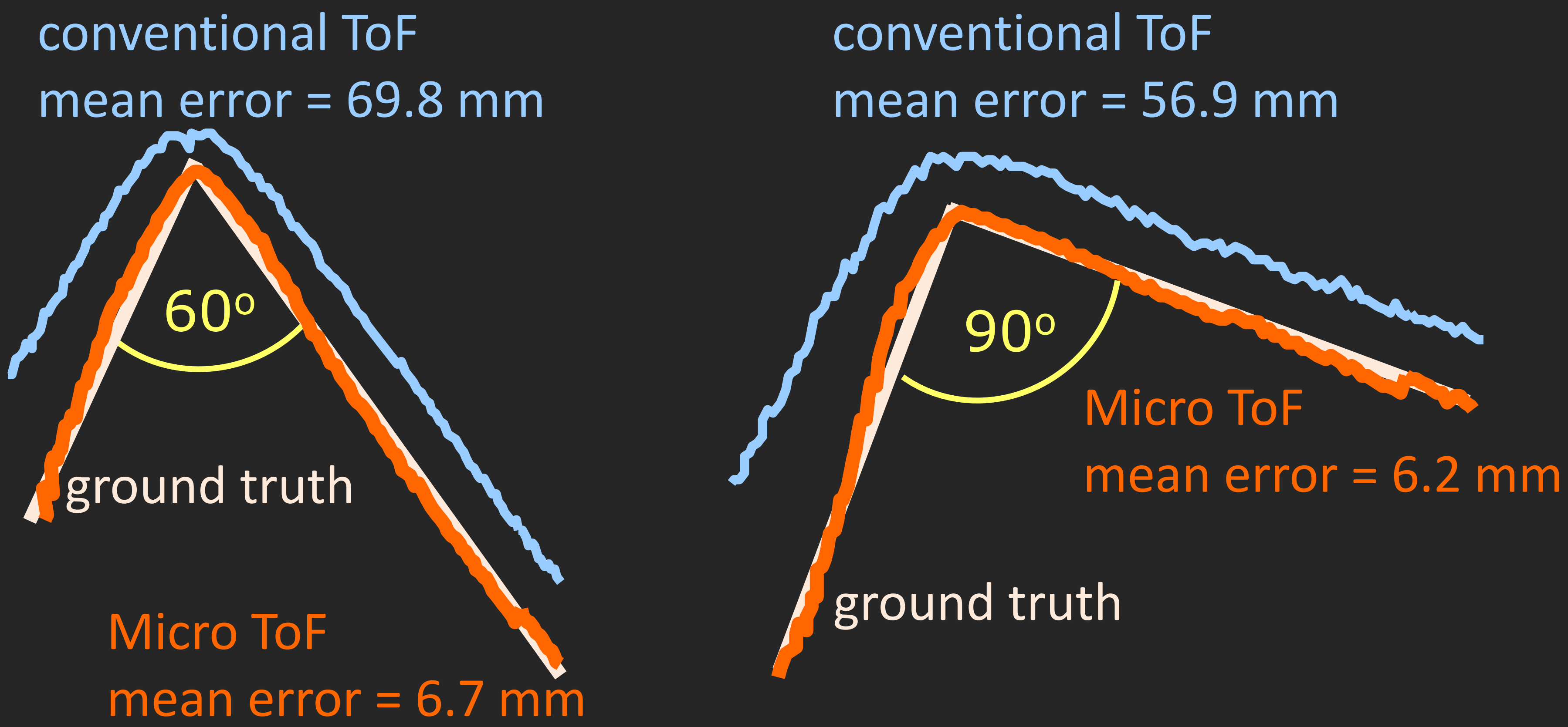


$\theta = 60°$

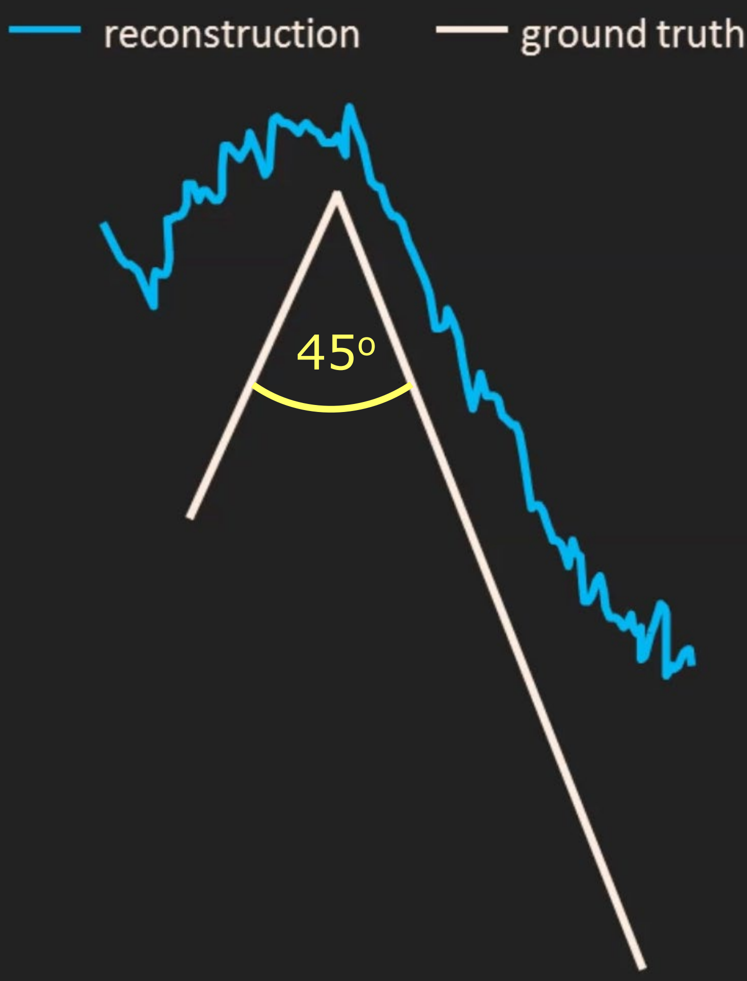


$\theta = 90°$

Shape Comparisons



Recovered Shape vs. Frequency

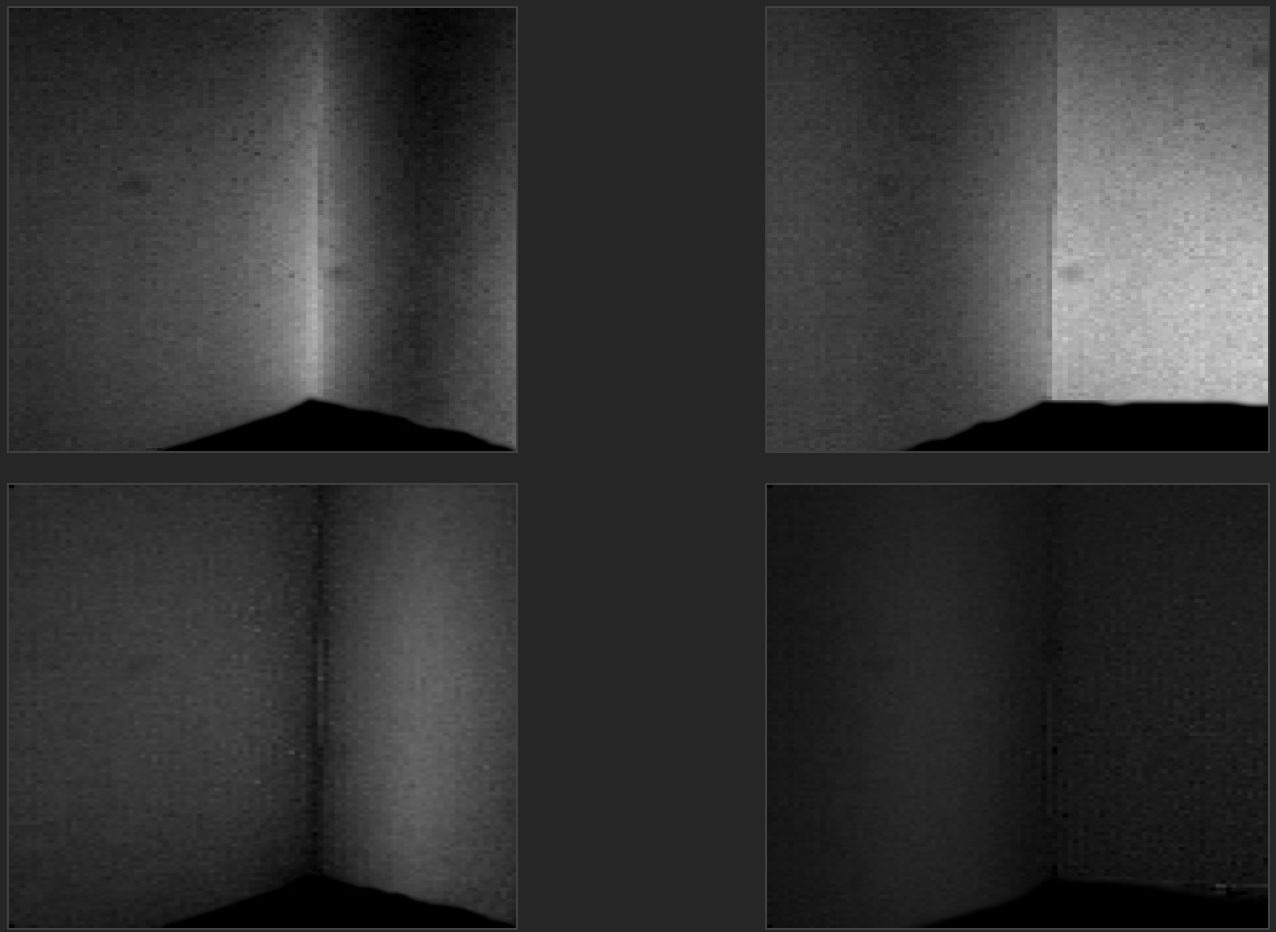


ω = 1 MHz.

Direct-Global Separation Vs. Apex Angle

Direct

Global

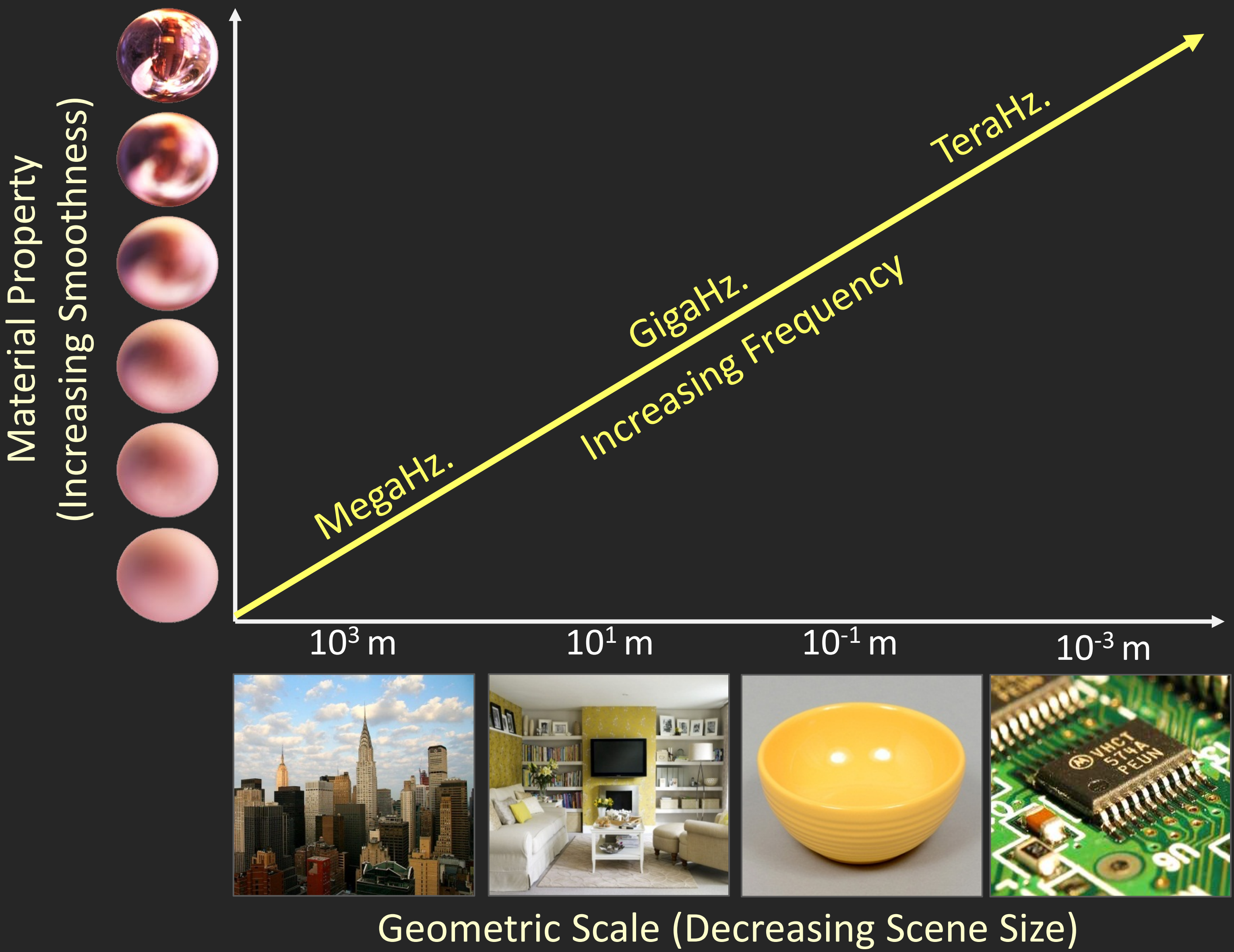


apex angle = 45°

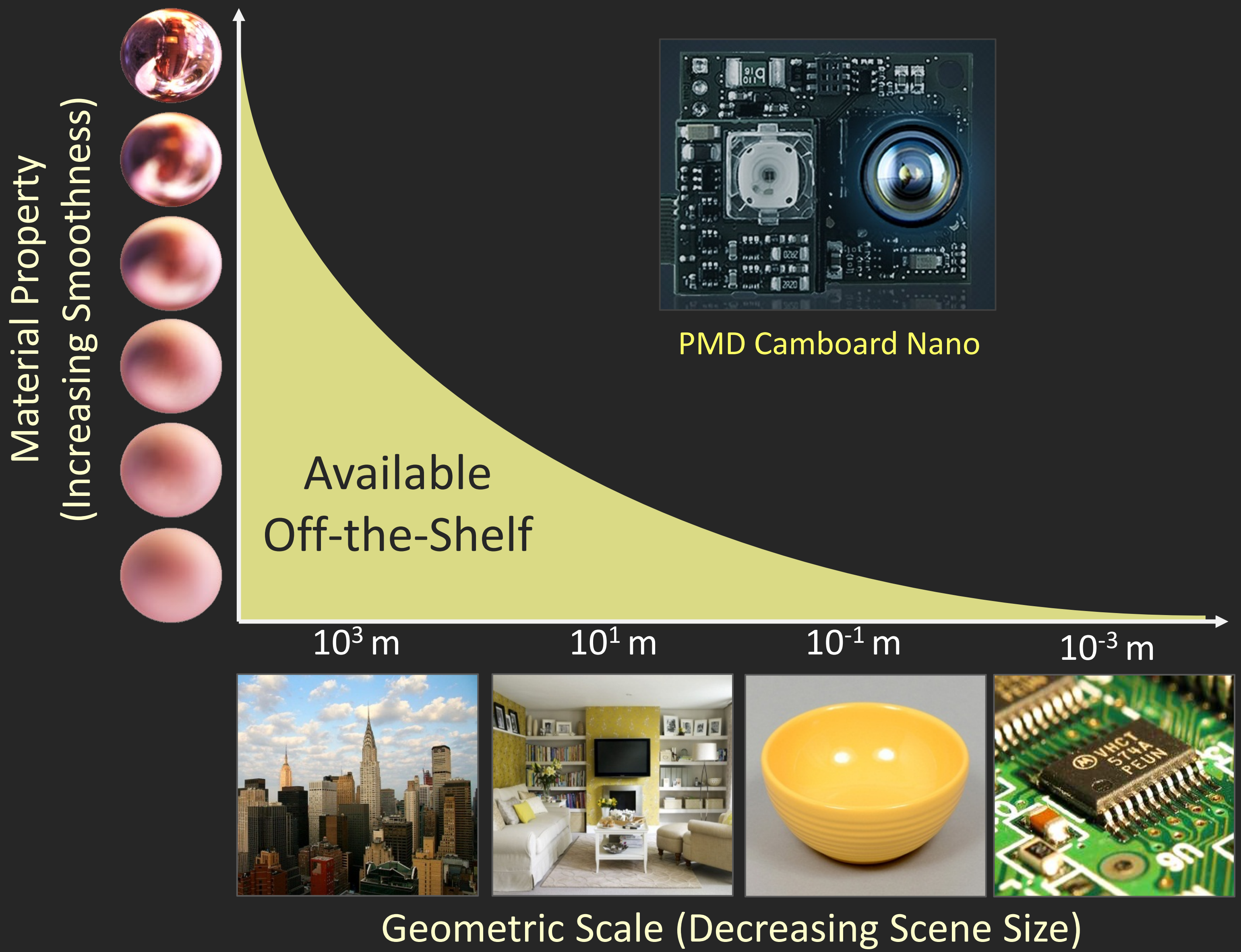
apex angle = 90°

decreasing global component →

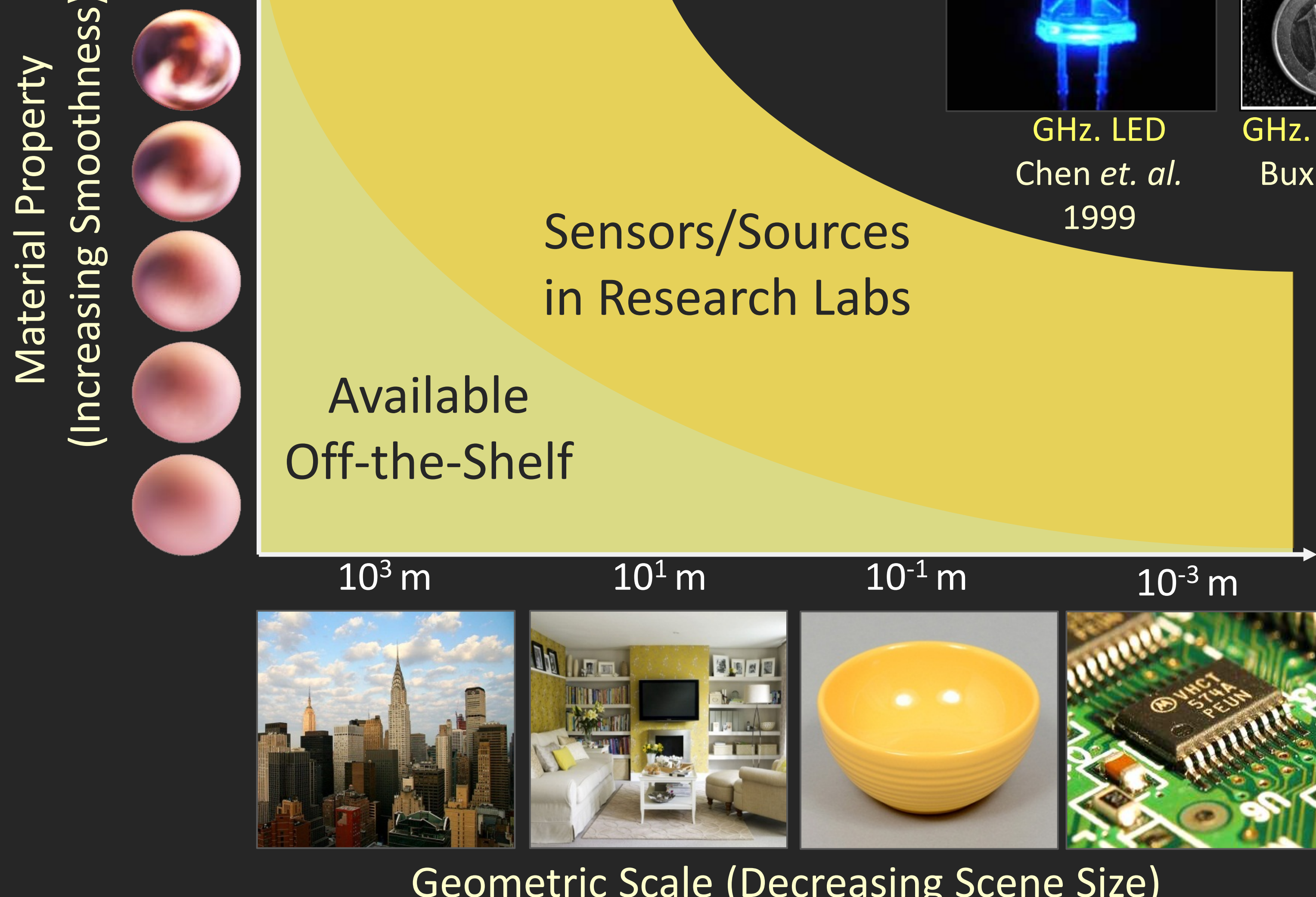
How High Should The Frequency Be?



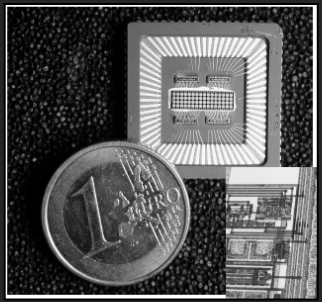
Technology (Devices) Required



Technology (Devices) Required

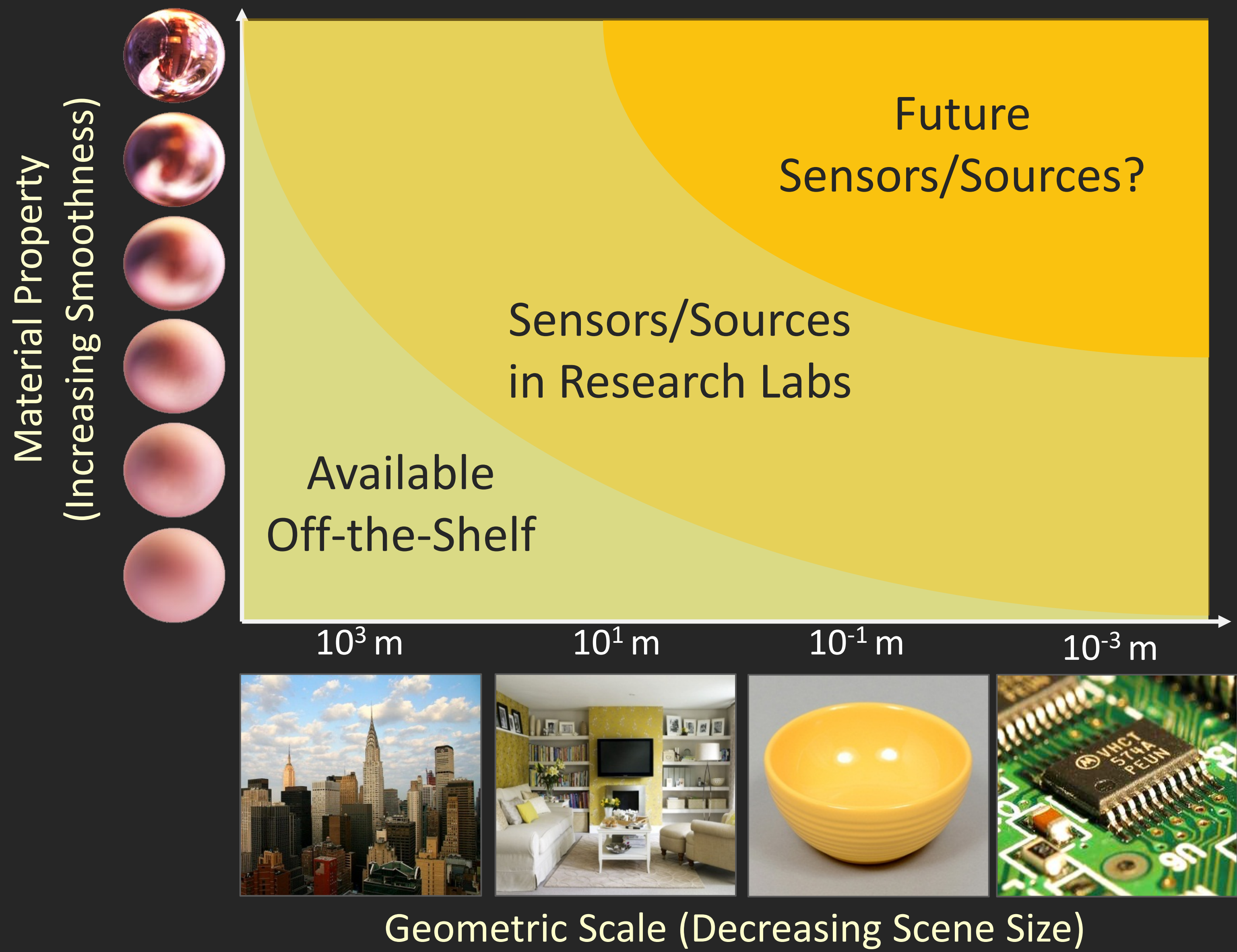


GHz. LED
Chen *et. al.*
1999



GHz. MSM Sensor
Buxbaum *et. al.*
2002

Technology (Devices) Required



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.
- Durand et al., “A frequency analysis of light transport,” SIGGRAPH 2005.
  This paper more formally discusses the notion of light transport frequency, and the frequency characteristics of different light transport effects (specular versus diffuse reflections, hard versus smooth shadows).