



Computational Imaging

Lecture 21: Temporal Encoding IV: Indirect Time-of-flight Imaging II



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点昀技术（Point Spread Technology）



Today's Topic

- Direct-Indirect Separation
- Optimal Coding Functions for Time-of-flight Imaging
- Hamiltonian Coding for Time-of-flight Imaging

Direct-Indirect Separation



Scattering in Real World



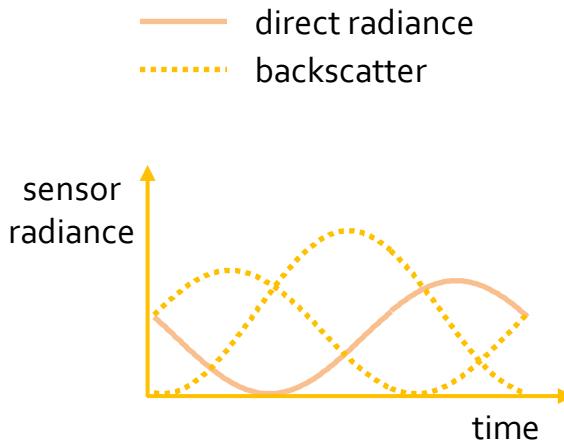
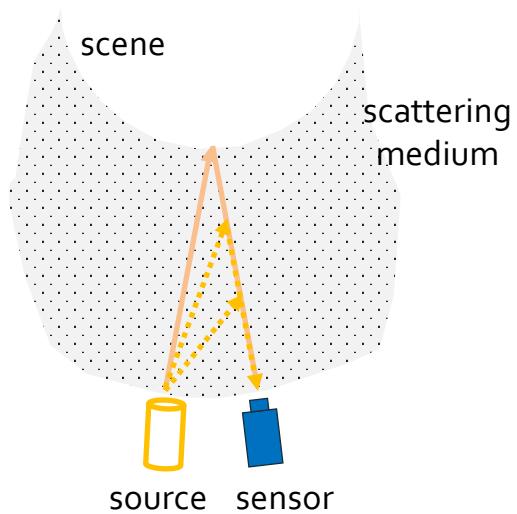
Driving through fog/mist



Driving through a dust storm

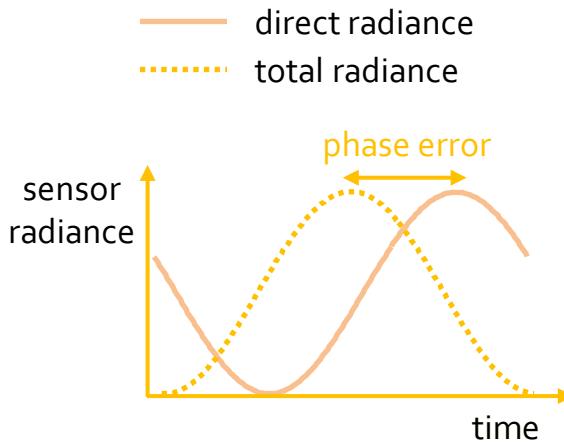
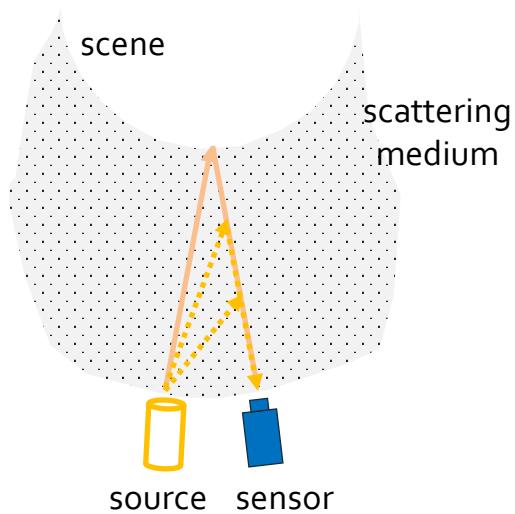


Scattering and ToF Imaging





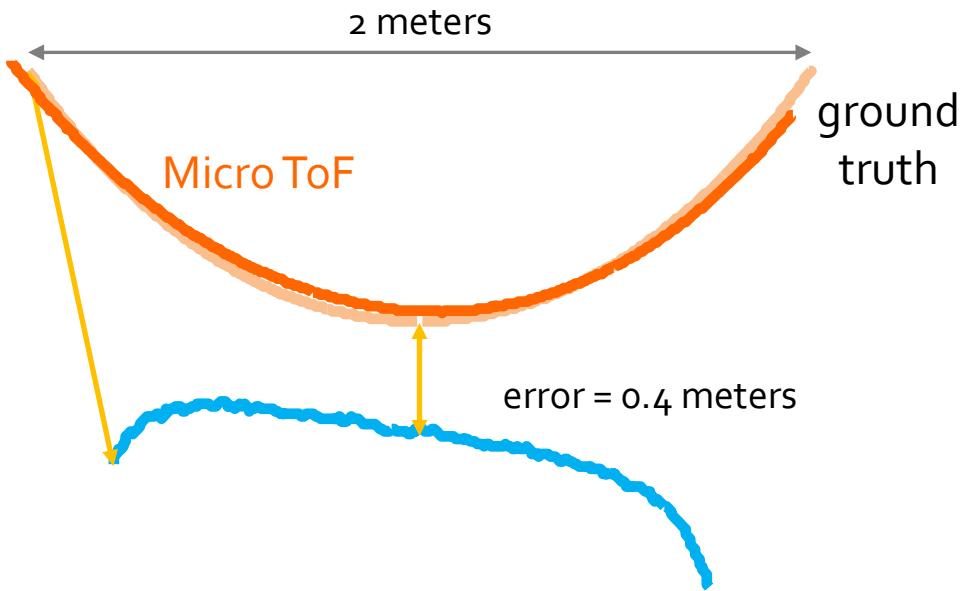
Scattering and ToF Imaging



Scattering Produces Incorrect Phase



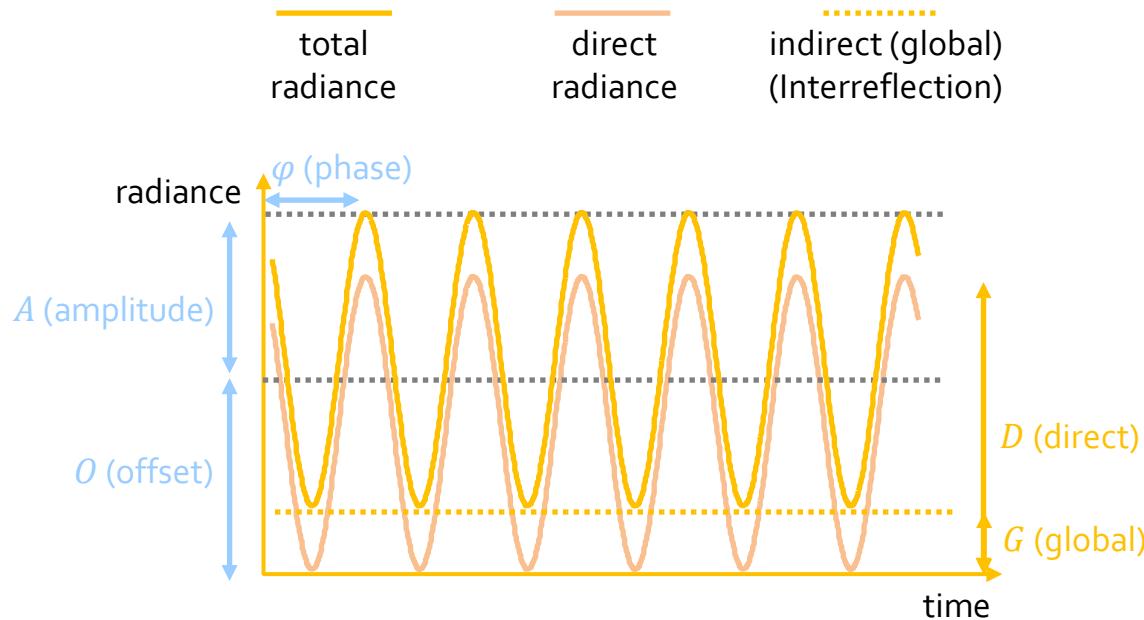
Sphere: Shape Comparison



Micro ToF Achieved High Accuracy Shape



Direct-Indirect Separation

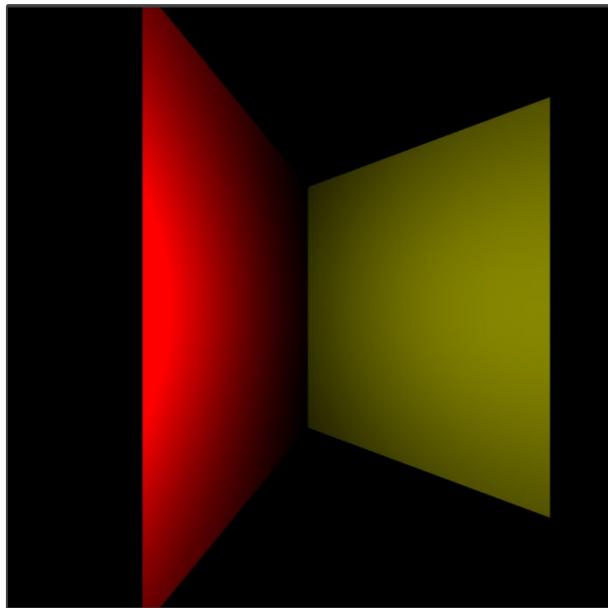


$$D = 2A \quad G = O - A$$

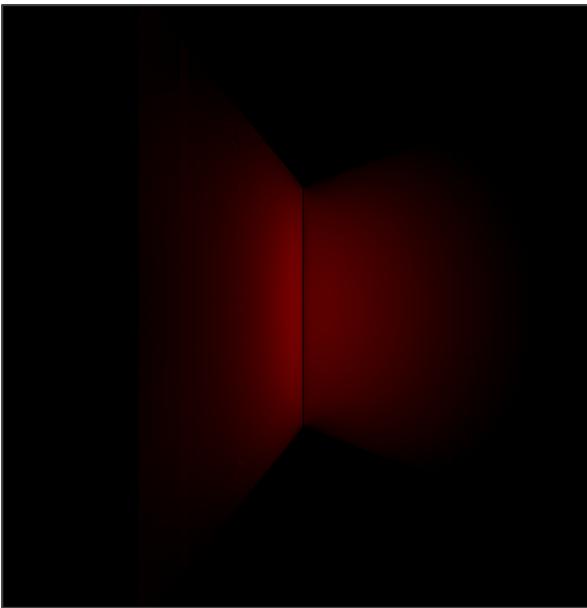
Direct-Global Separation Using Three Measurements



Direct-Indirect Separation



Direct Component

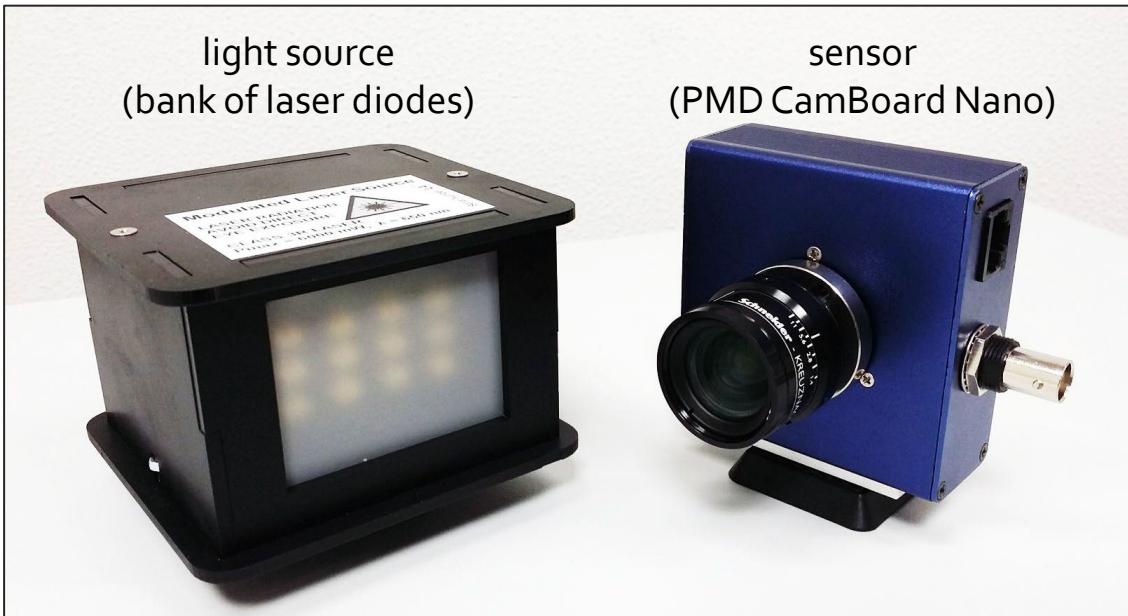


Global Component

Color Bleeding due to
Interreflections



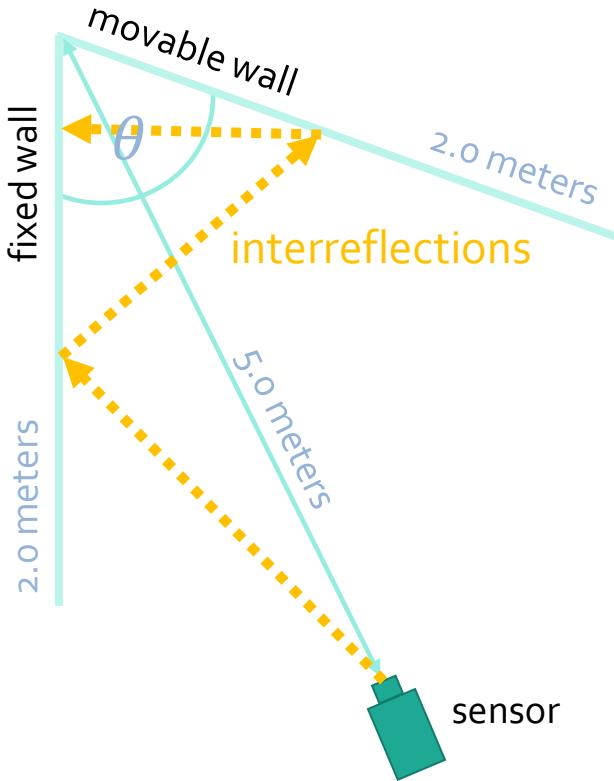
Experimental Setup



Maximum System Modulation Frequency = 125 MHz.

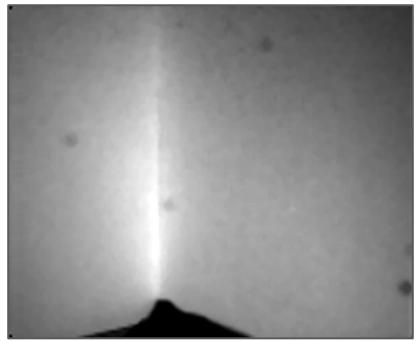


Experiments: V-Groove

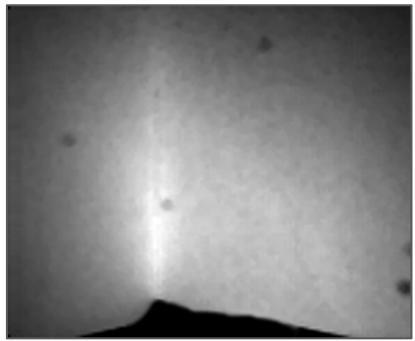




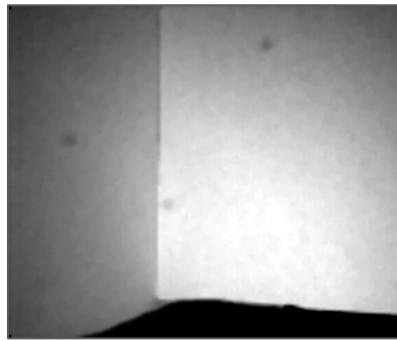
Scene Images Captured By PMD Sensor



apex angle = 45°



apex angle = 60°

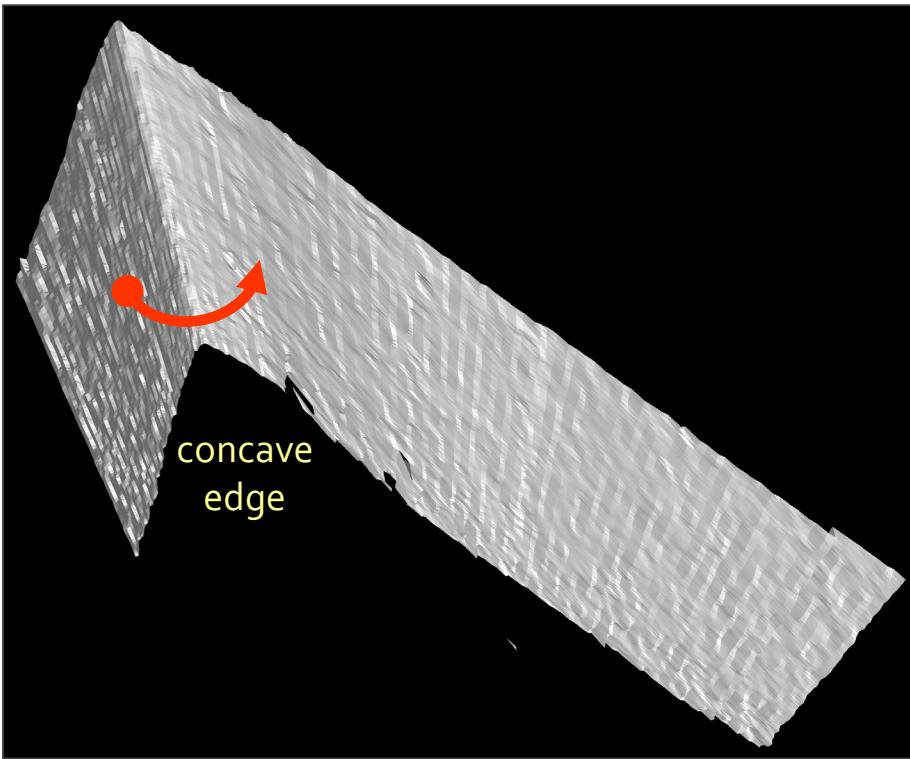


apex angle = 90°

image resolution = 120×165

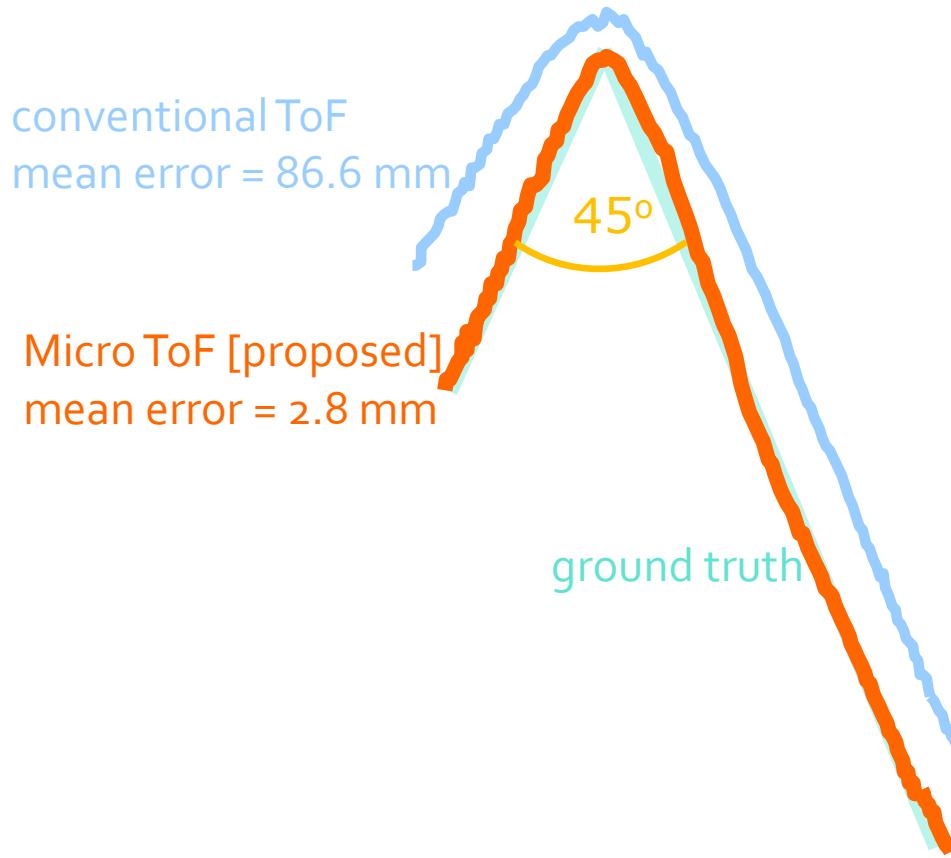


Reconstructed Shape using Micro ToF



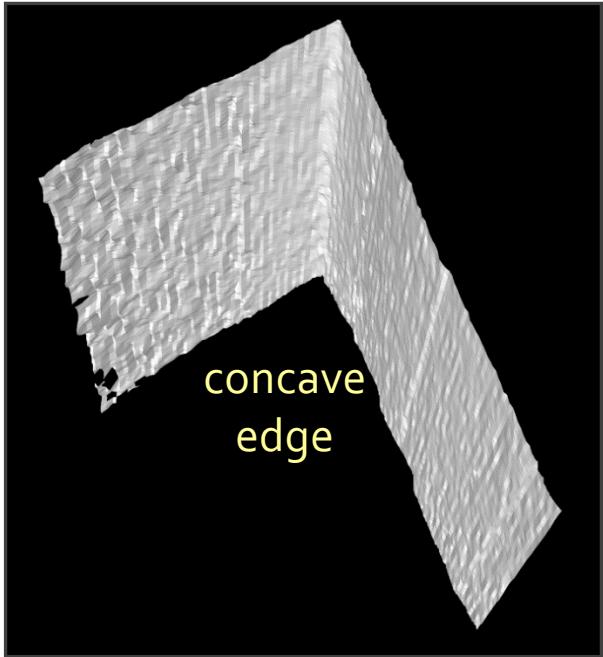


Shape Comparisons

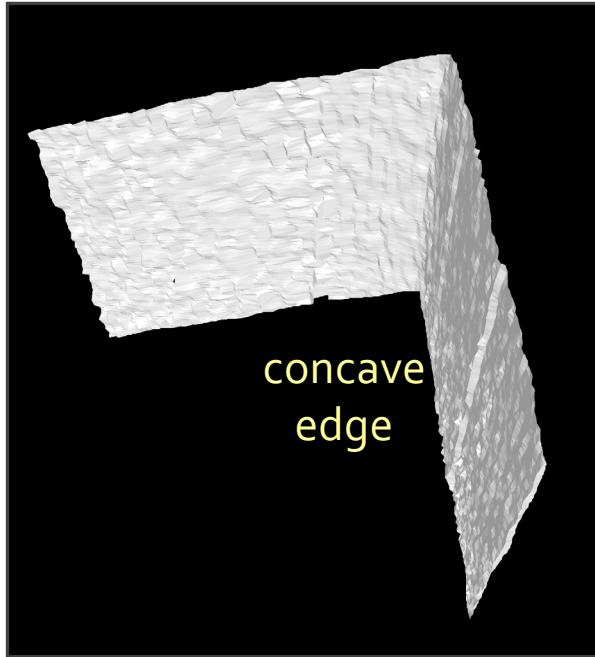




Reconstructed Shapes: Different Angles

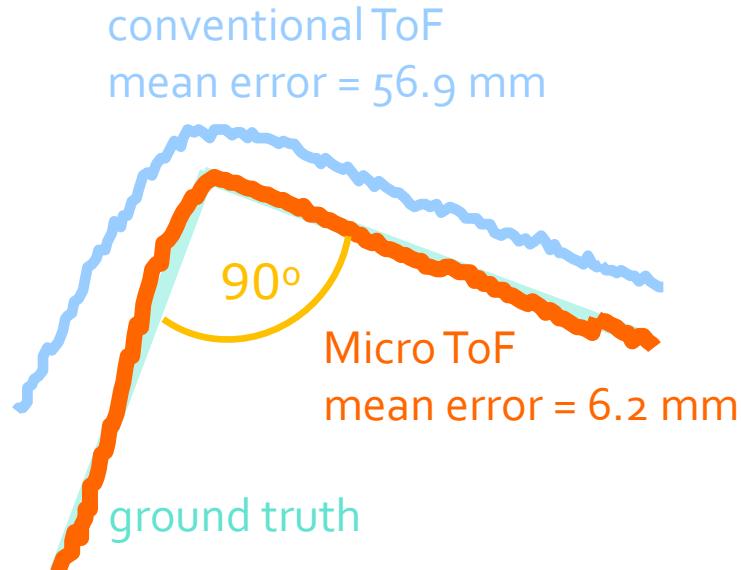
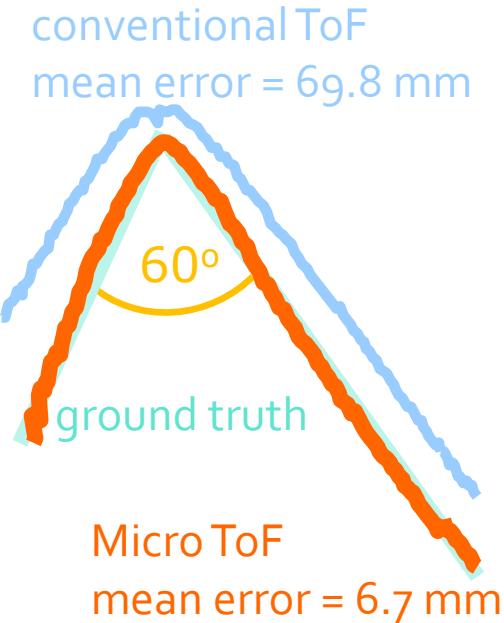


$\theta = 60^\circ$



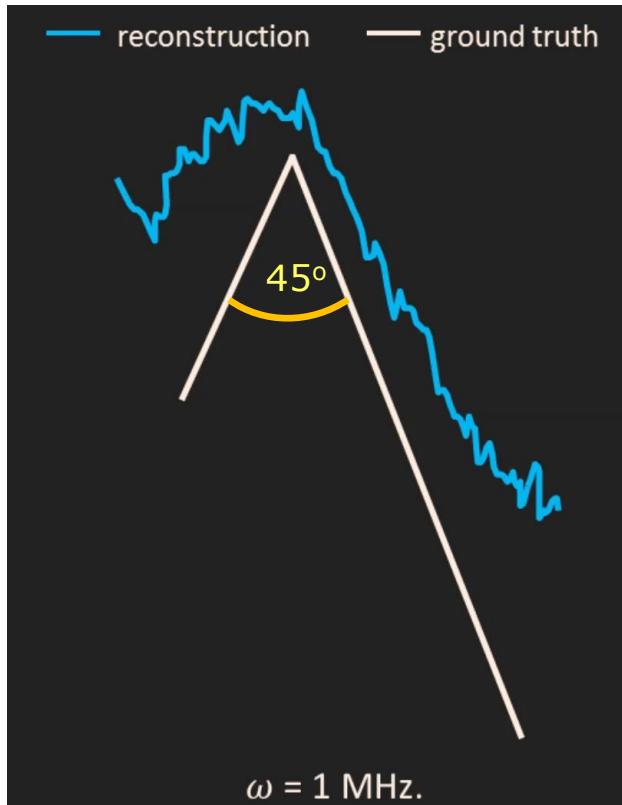
$\theta = 90^\circ$

Shape Comparisons



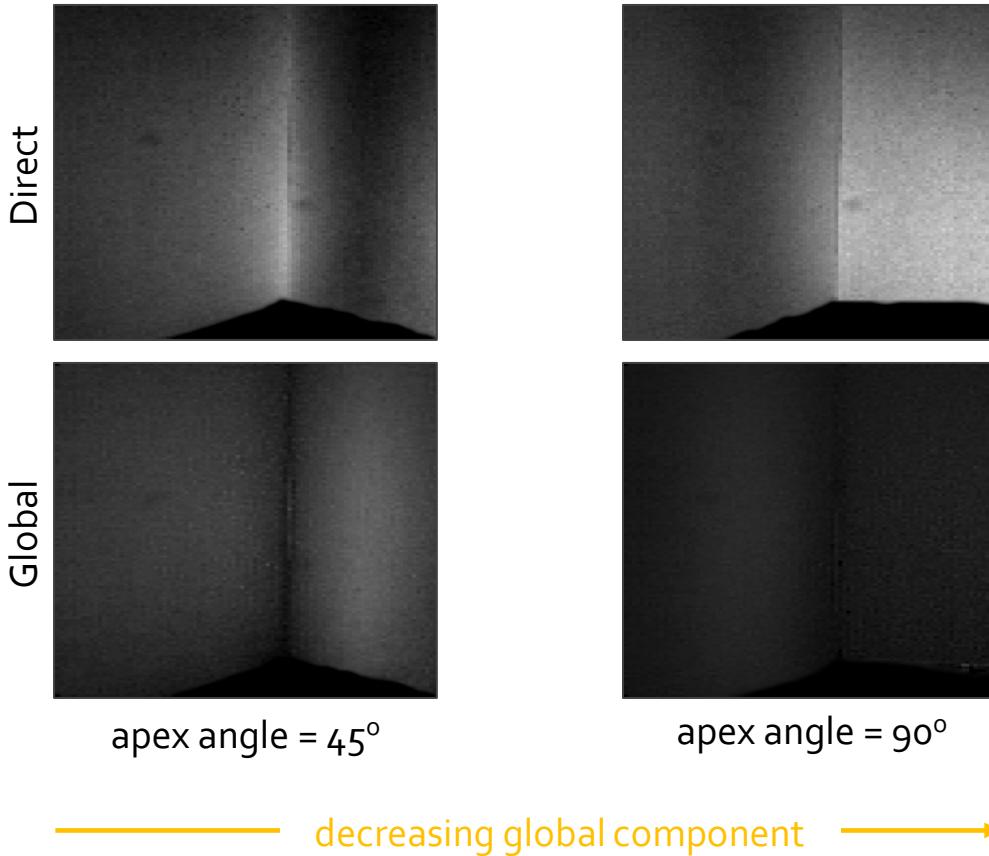


Recovered Shape vs. Frequency





Direct-Global Separation Vs. Apex Angle



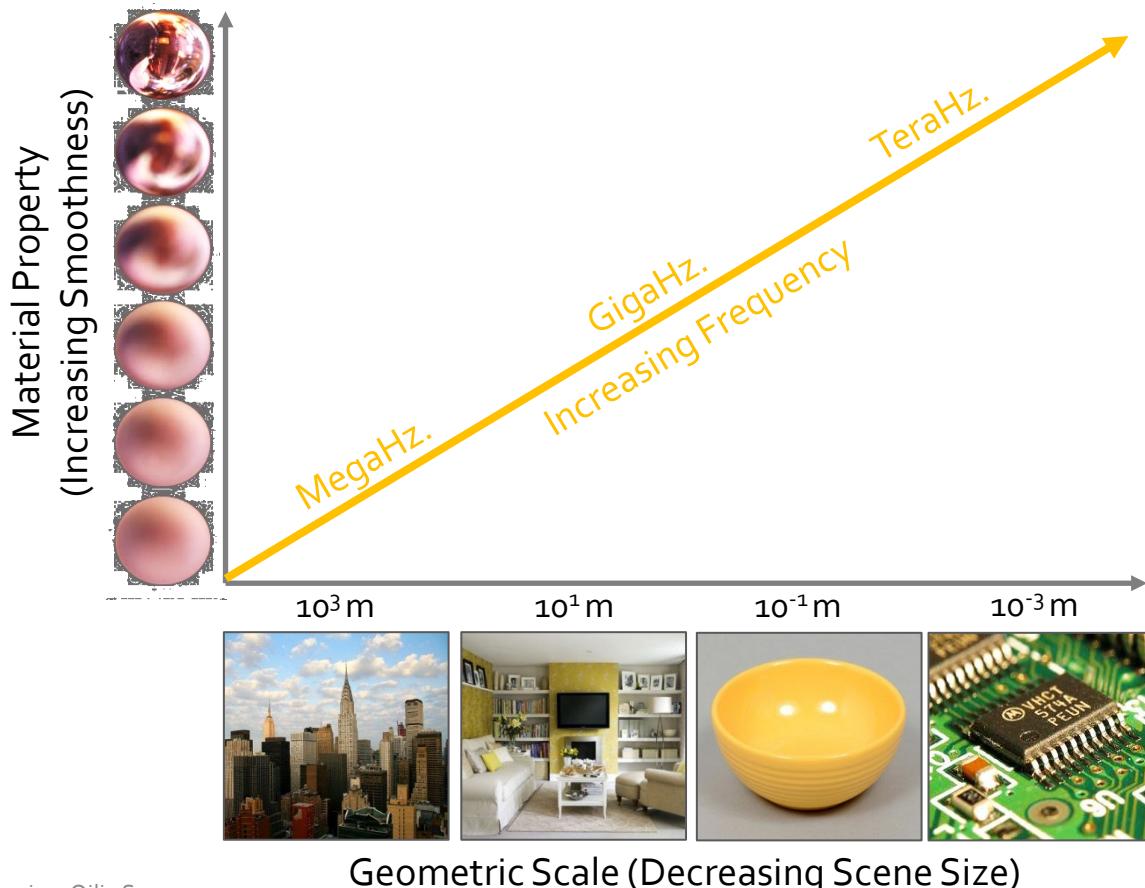


Summary

- Indirect Illumination Hurts Time-of-Flight Imaging
- Use High Frequencies that are Slightly Different

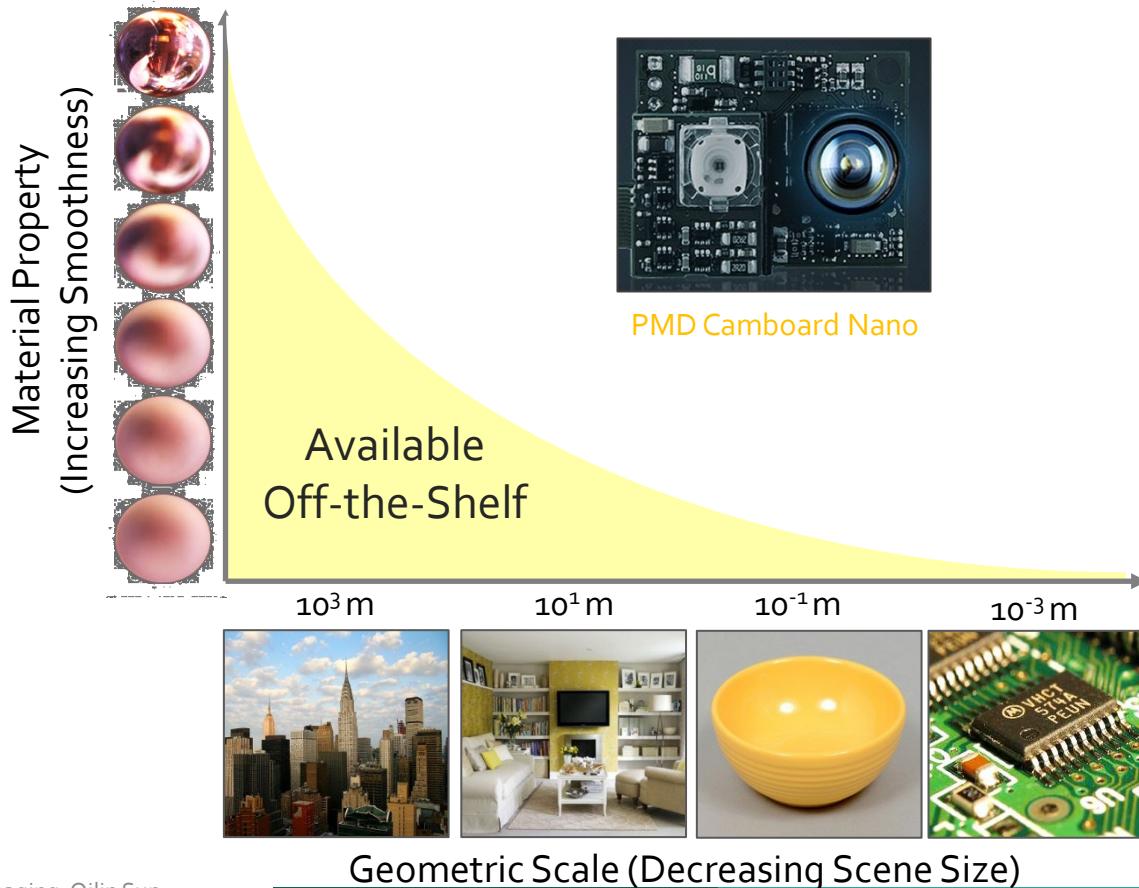


How High Should The Frequency Be?



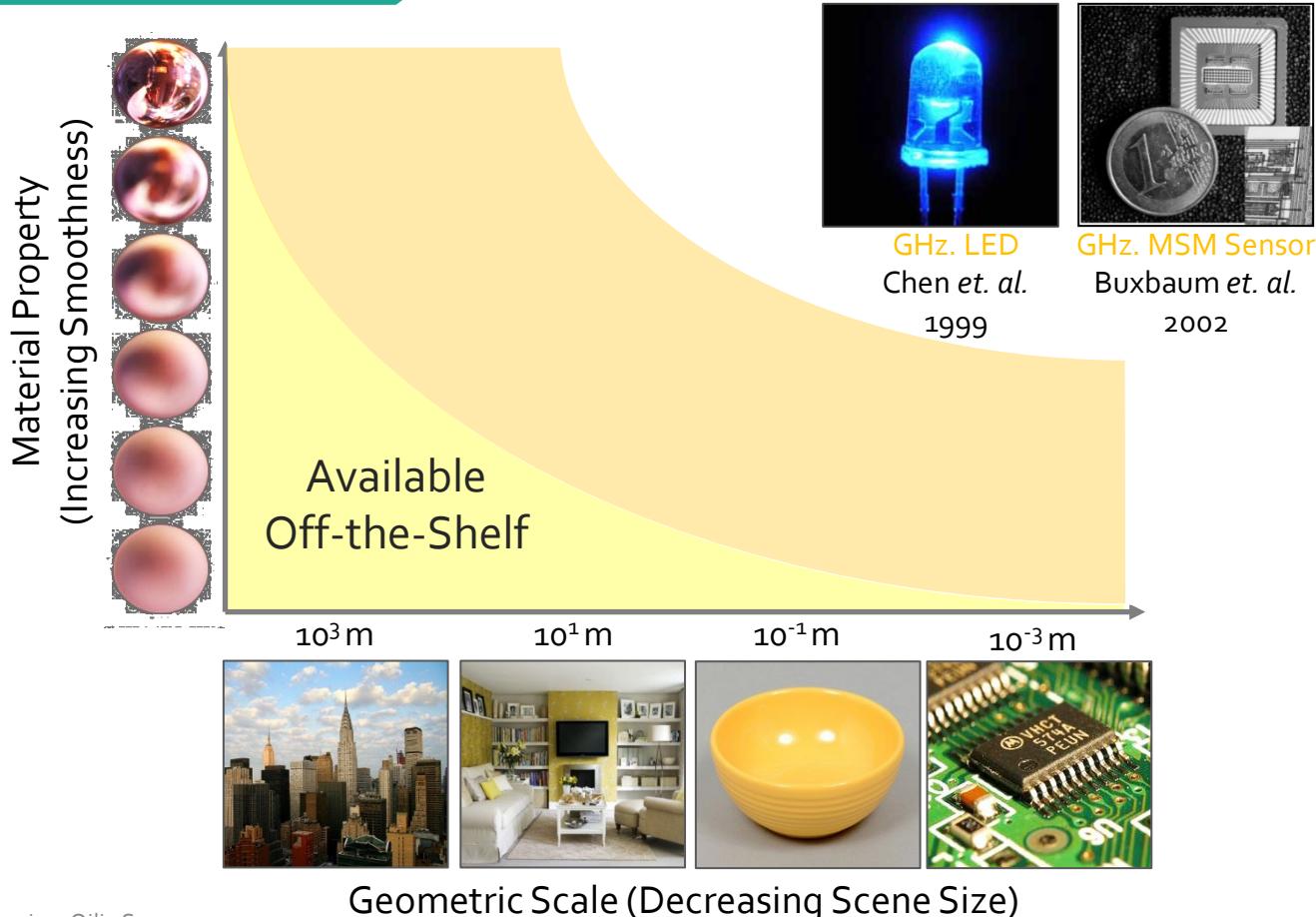


Technology (Devices) Required



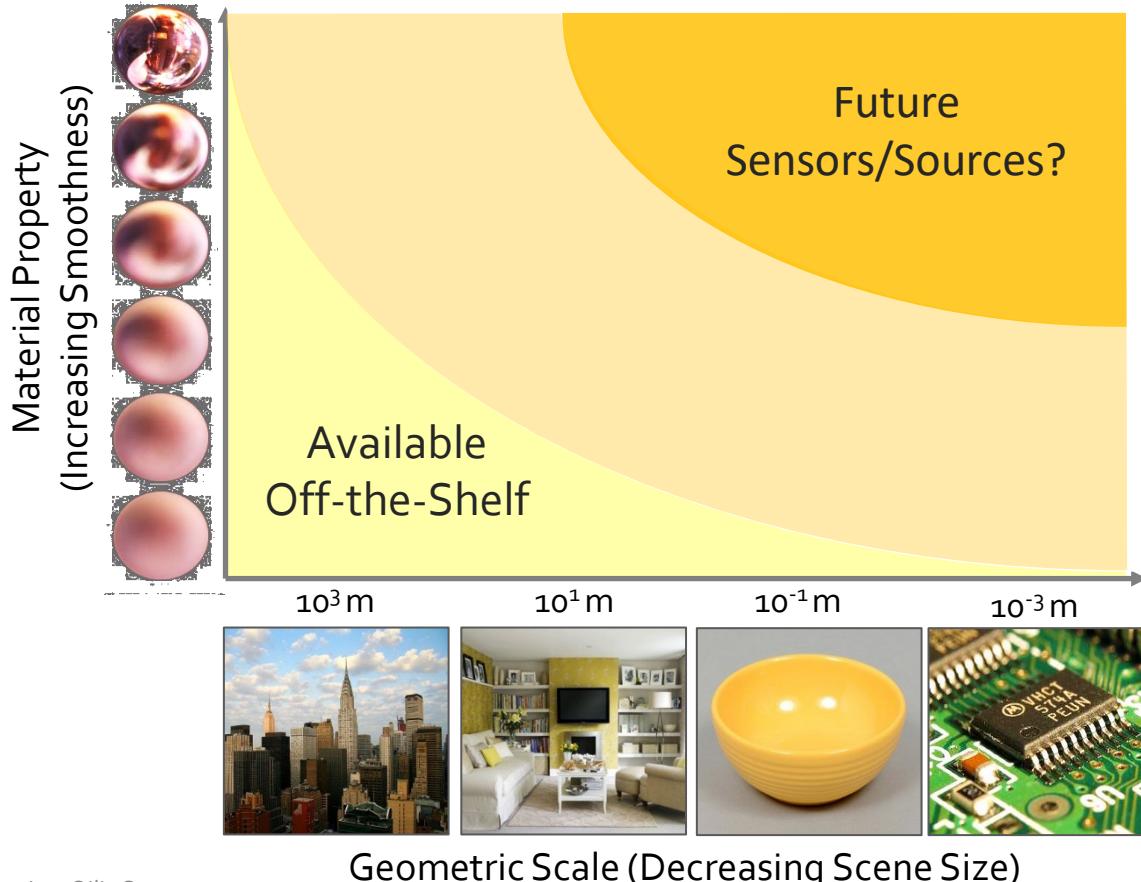


Technology (Devices) Required



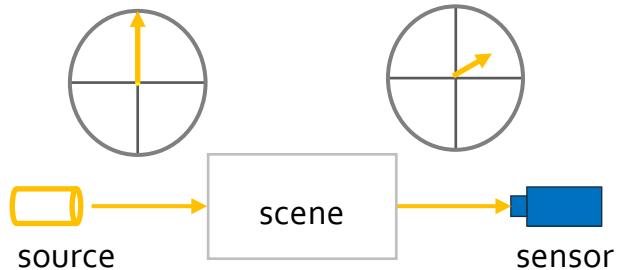


Technology (Devices) Required

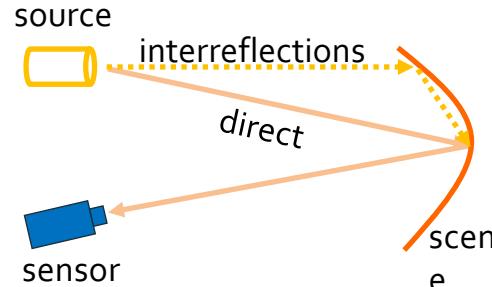




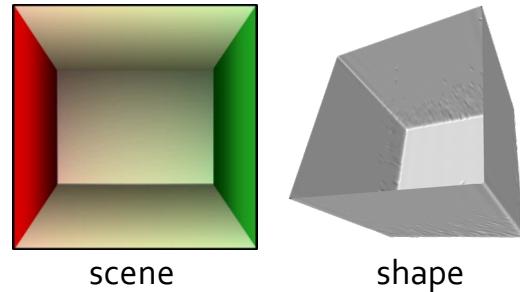
Conclusion



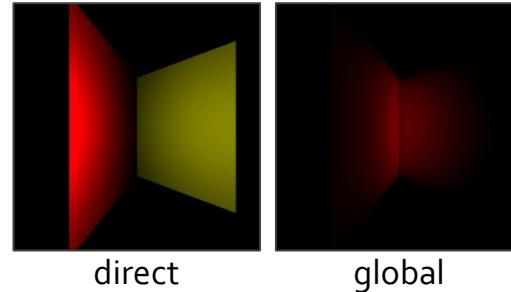
Phasor Light Transport



Generalization of C-ToF Imaging



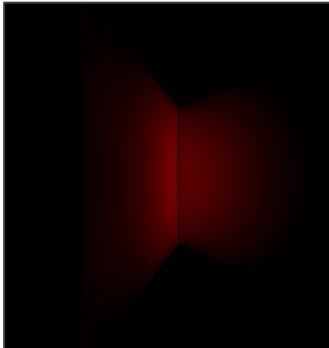
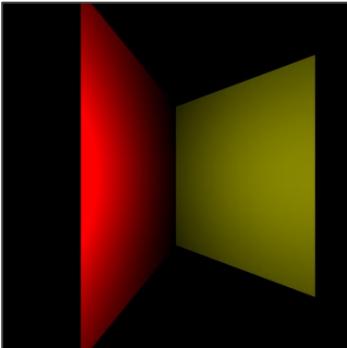
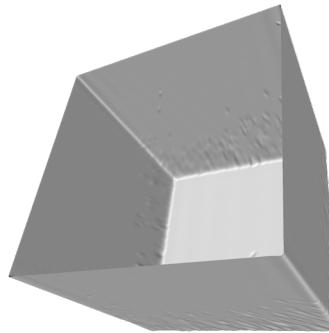
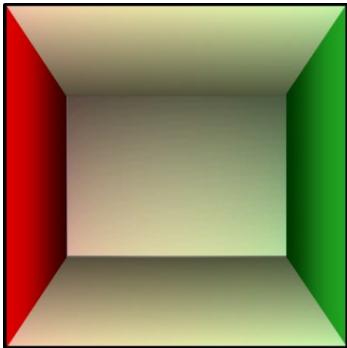
Shape Recovery



Fast Light Transport Analysis

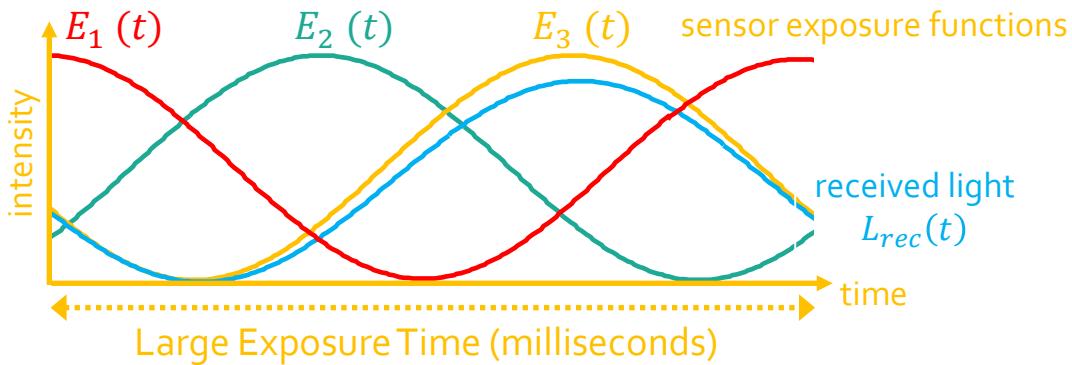


Questions



Optimal Coding Functions for Time-of-flight Imaging

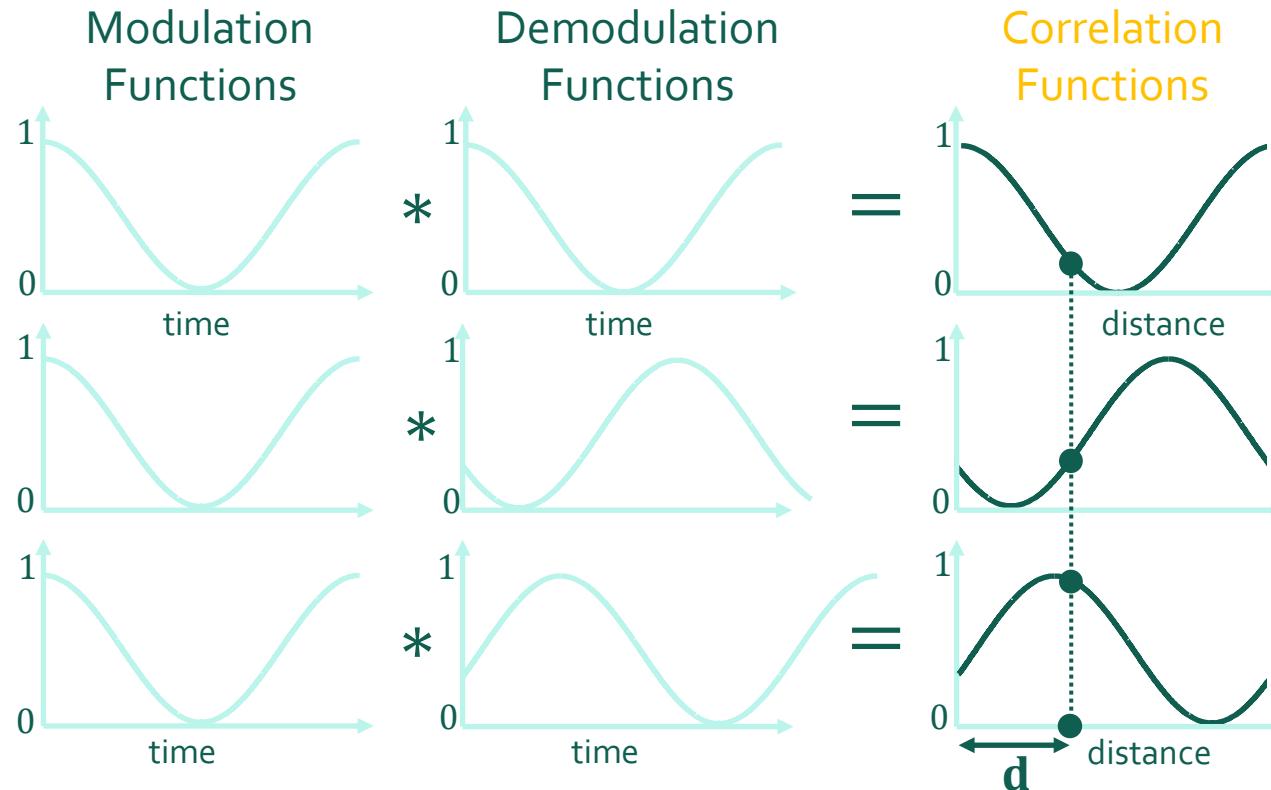
Recall: Measuring Phase-Shift: Correlation



- Correlation 1: $I_1 = \text{High Signal-to-Noise Ratio} \left[\int E_1(t) \times L_{rec}(t) dt \right]$
- Correlation 2: $I_2 = \text{Real Time Capture} \left[\int E_2(t) \times L_{rec}(t) dt \right] \rightarrow \text{phase } \varphi_{rec}$
- Correlation 3: $I_3 = \int E_3(t) \times L_{rec}(t) dt \rightarrow \text{offset } O_{rec}$
- $\qquad\qquad\qquad \text{amplitude } A_{rec}$



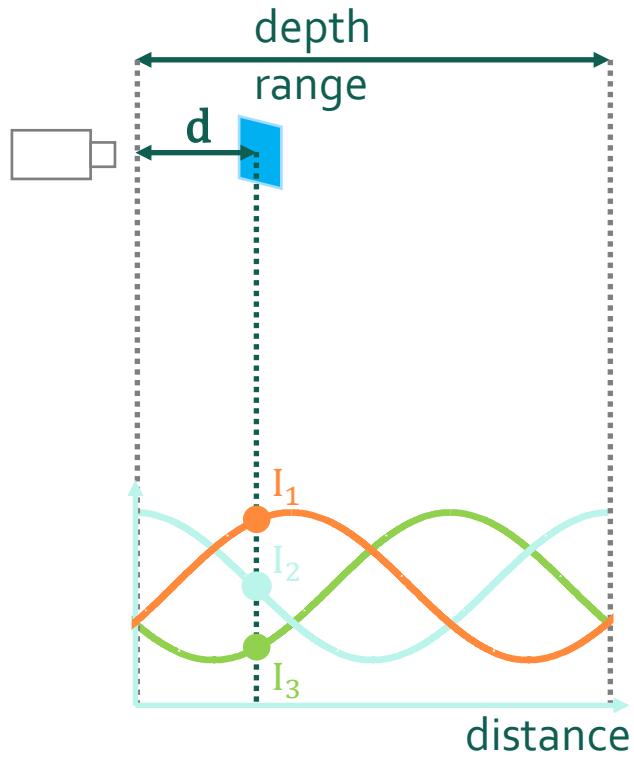
Measuring Phase-Shift: Correlation



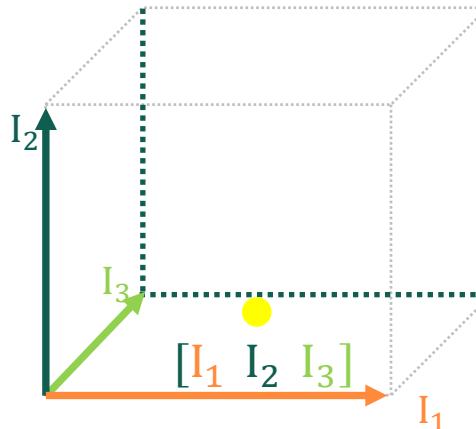
Correlation of two sinusoids is a sinusoid



Mapping of Depth to Intensities



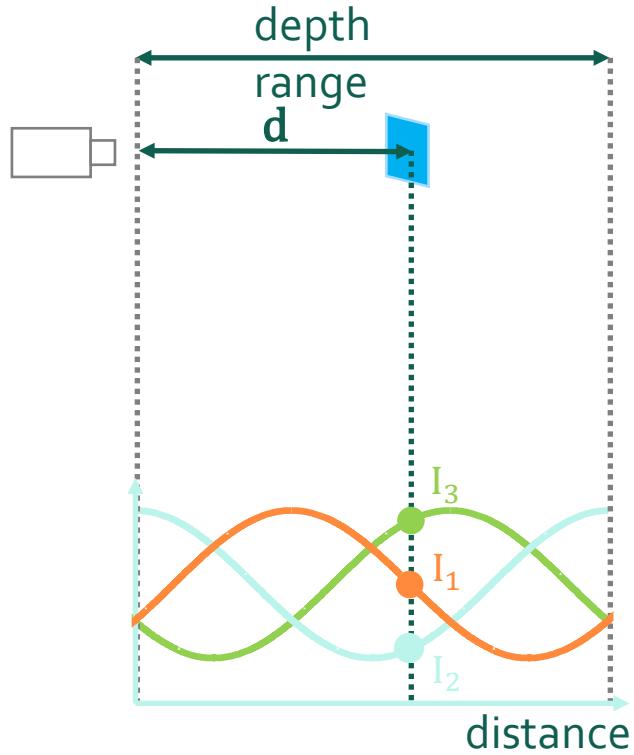
Correlation Functions



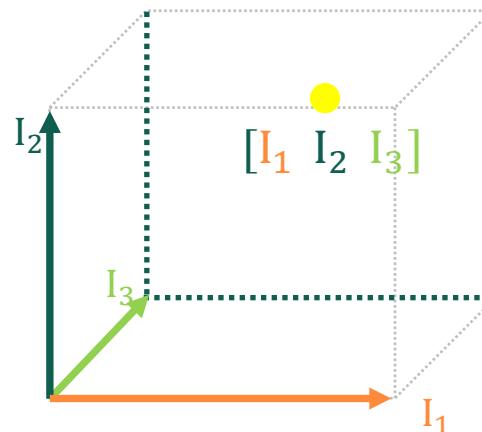
3D Intensity Space



Mapping of Depth to Intensities



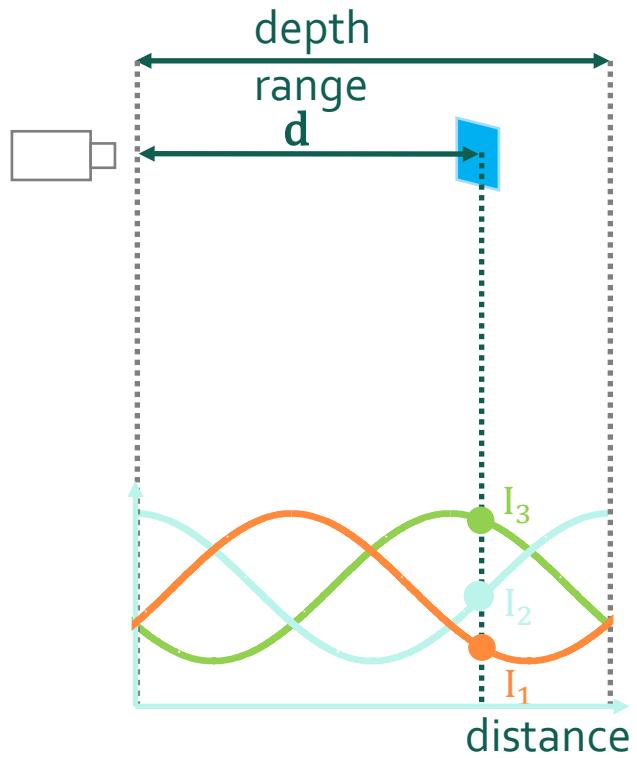
Correlation Functions



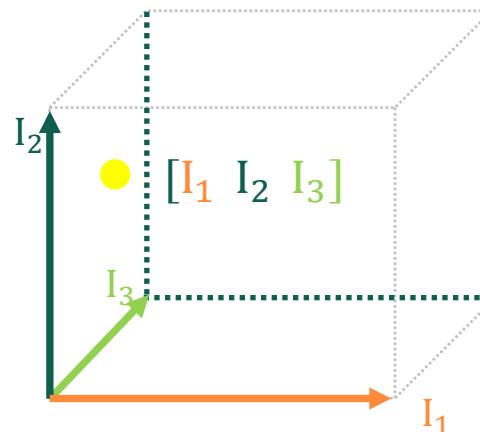
3D Intensity Space



Space of All Possible Intensities

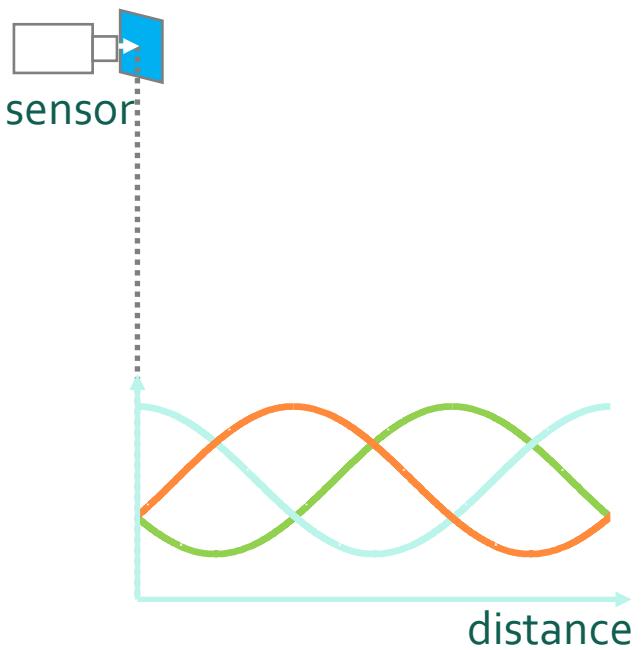


Correlation Functions



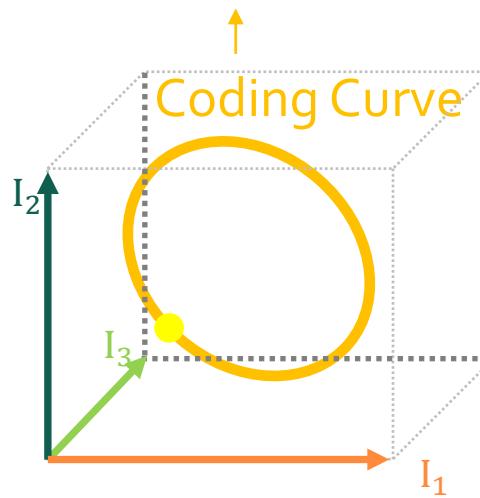
3D Intensity Space

Space of All Possible Intensities



Correlation
Functions

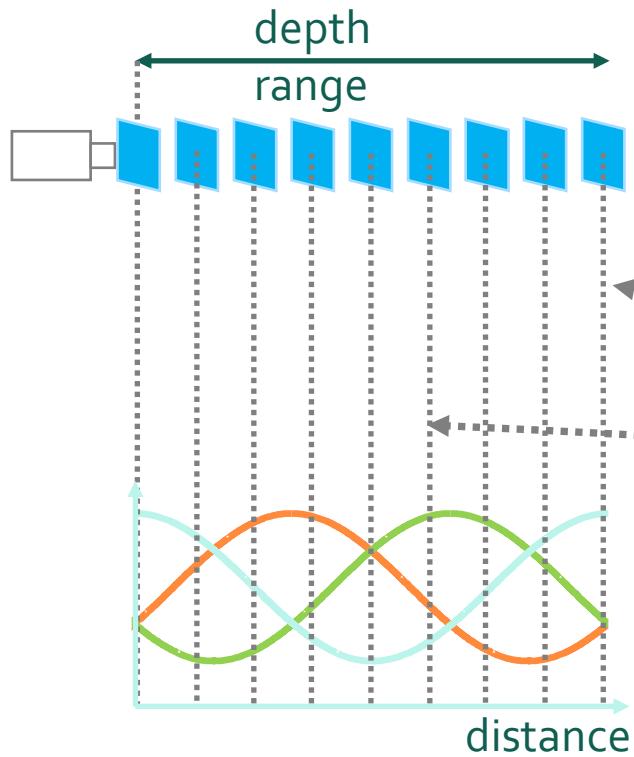
Mapping from depths to measured intensities



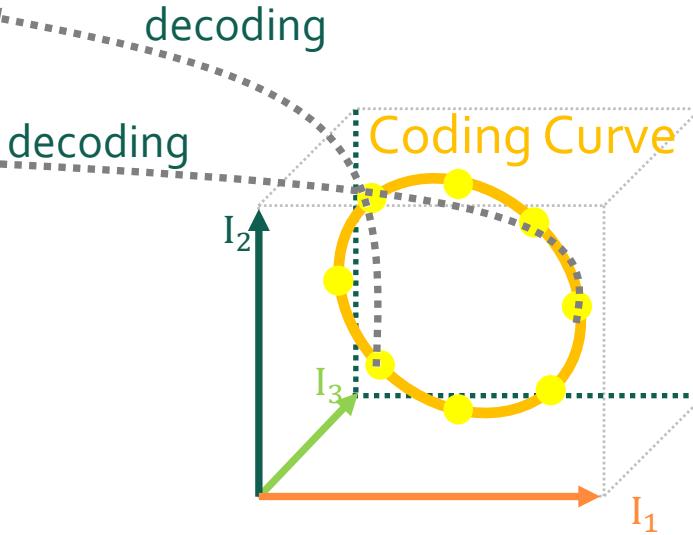
3D Intensity Space



Decoding: From Intensities to Depths



Correlation Functions

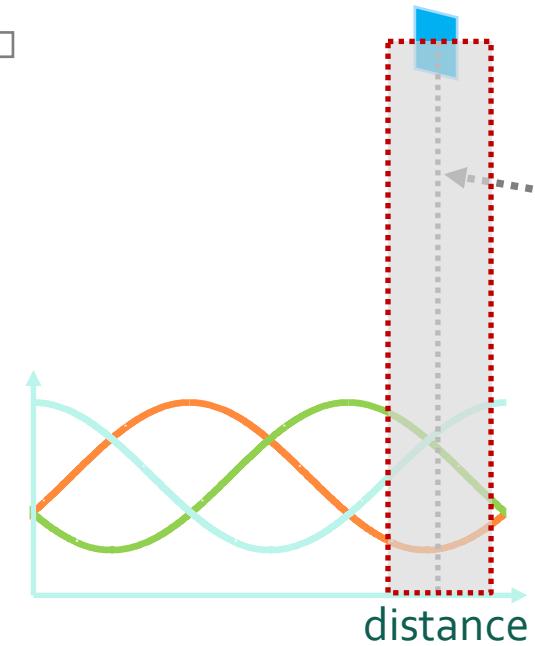


3D Intensity Space



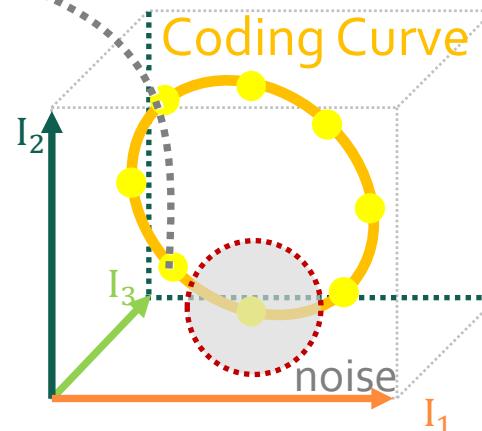
Effect of Noise on Decoding

large depth uncertainty → low depth resolution



Correlation Functions

decoding



3D Intensity Space

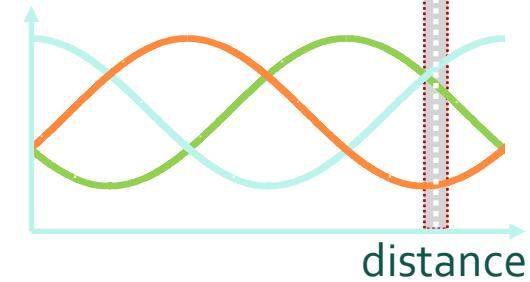


Increasing the Size of Intensity Space

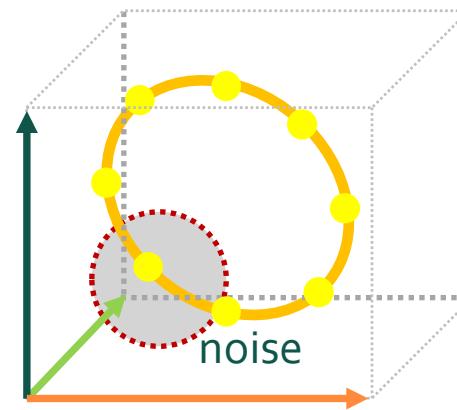
small depth uncertainty → high depth resolution



Fixed Light Source Power
and Scene Brightness



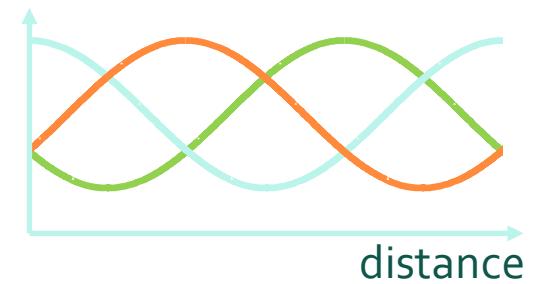
Correlation Functions



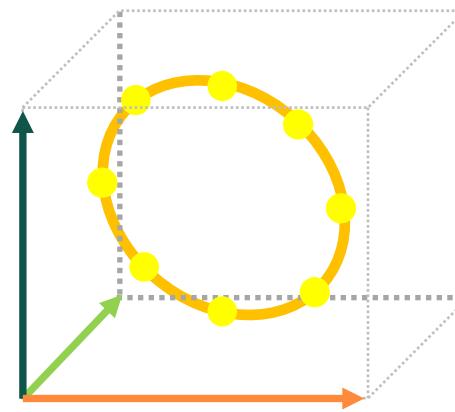
3D Intensity Space



Key Idea: Longer Coding Curves



Correlation Functions



3D Intensity Space

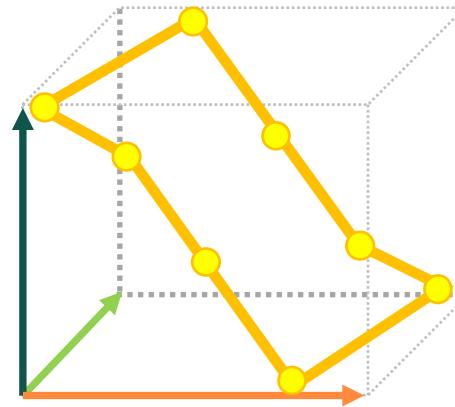


Key Idea: Longer Coding Curves



Correlation Functions

Longer Coding Curve

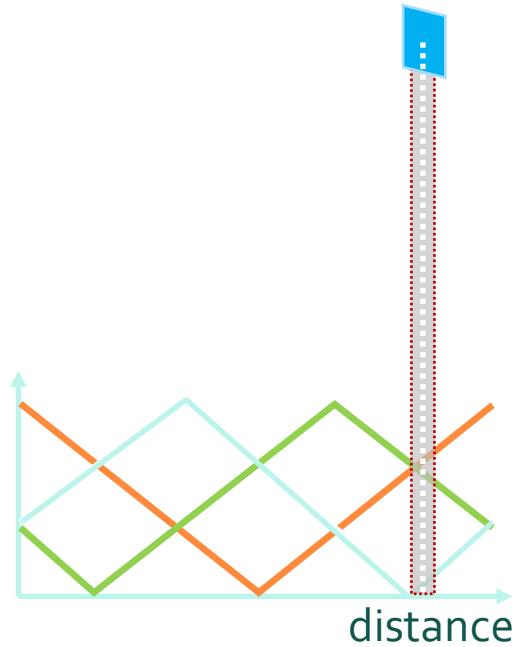


3D Intensity Space



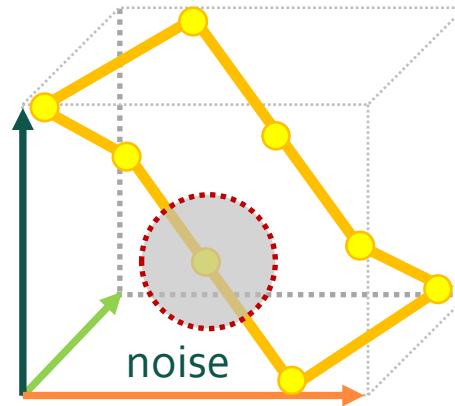
Key Idea: Longer Coding Curves

small depth uncertainty → high depth resolution



Correlation Functions

Longer Coding Curve



3D Intensity Space



Theoretical Expression for Depth Resolution

$$\chi = \frac{\text{depth resolution} \times \text{mean signal} \times \text{coding curve length}}{\text{image noise} \times \sigma_I \times d_{range}}$$

χ

depth resolution
(higher the better)

mean signal

coding curve length

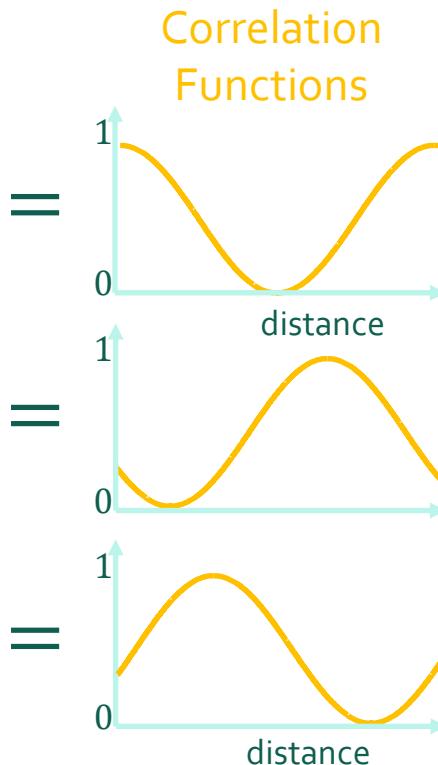
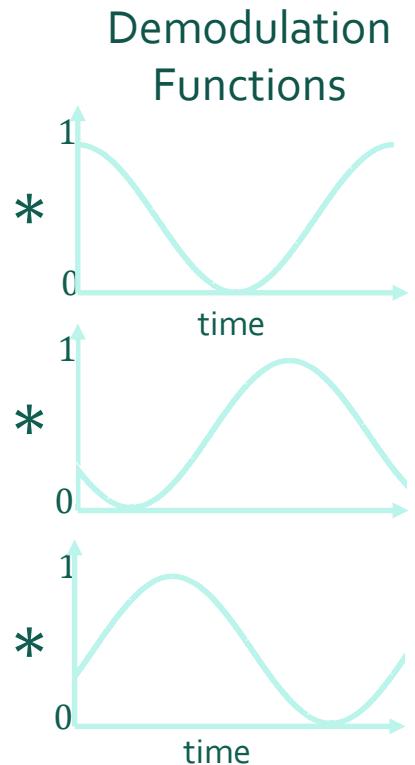
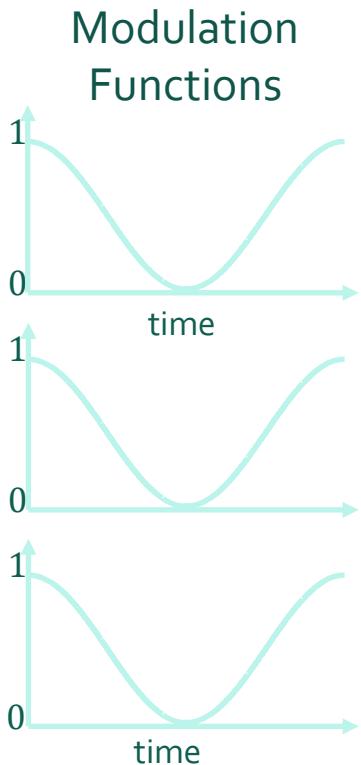
image noise

σ_I

d_{range}

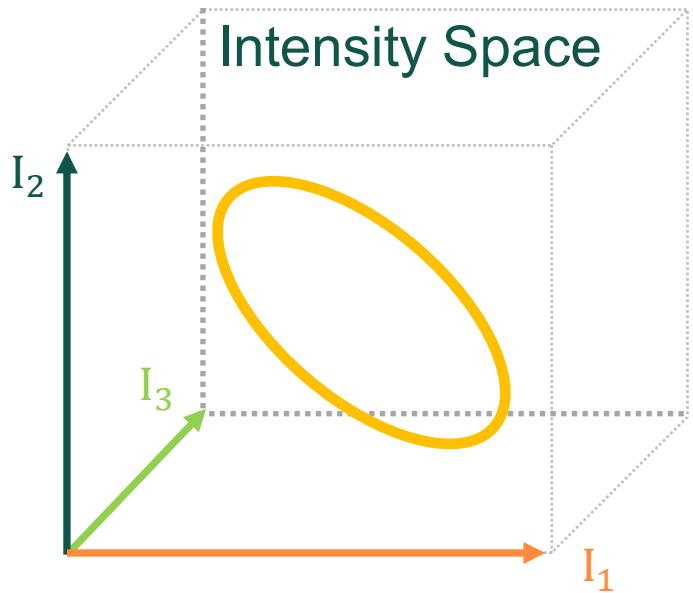
Unified Expression For Analyzing All CW-ToF Methods

E.g., Conventional Sinusoidal Coding





E.g., Conventional Sinusoidal Coding



Coding Curve:

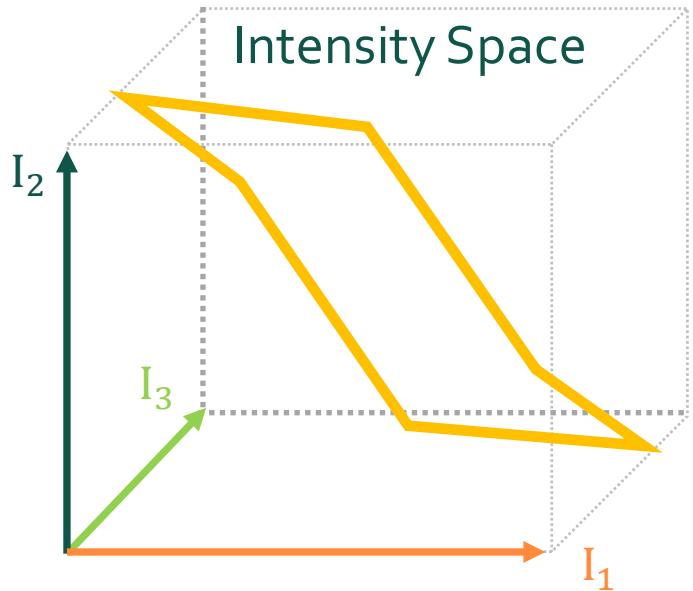
Circle of radius $\frac{1}{4} \sqrt{\frac{K}{2}}$

(K = number of measurements)

$$\text{Curve Length} = \frac{\pi}{2} \sqrt{\frac{K}{2}}$$



E.g., Square Coding



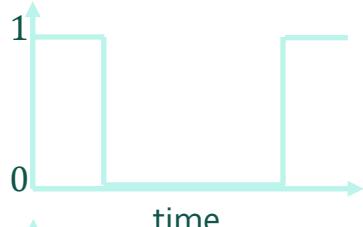
Coding Curve:
Non-planar ($2K$) polygon

$$\text{Side length} = \frac{1}{\sqrt{K}}$$

$$\text{Curve Length} = 2\sqrt{K}$$

E.g., Square Coding

Modulation Functions



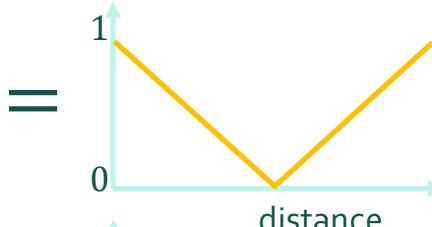
time

Demodulation Functions

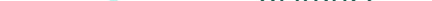


time

Correlation Functions



distance

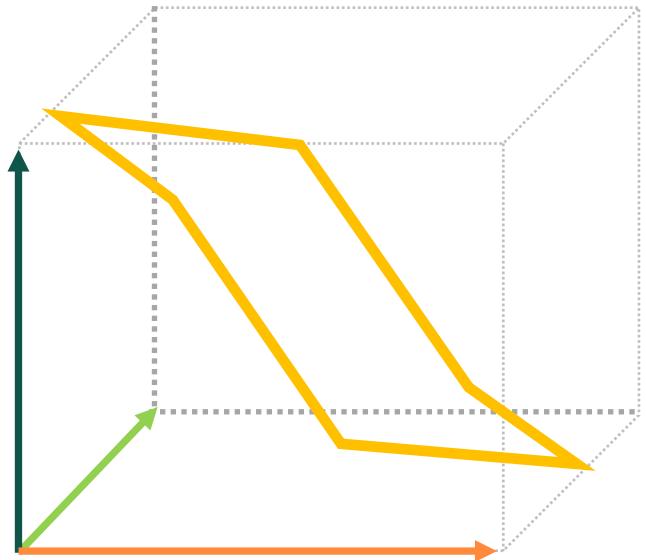


distance

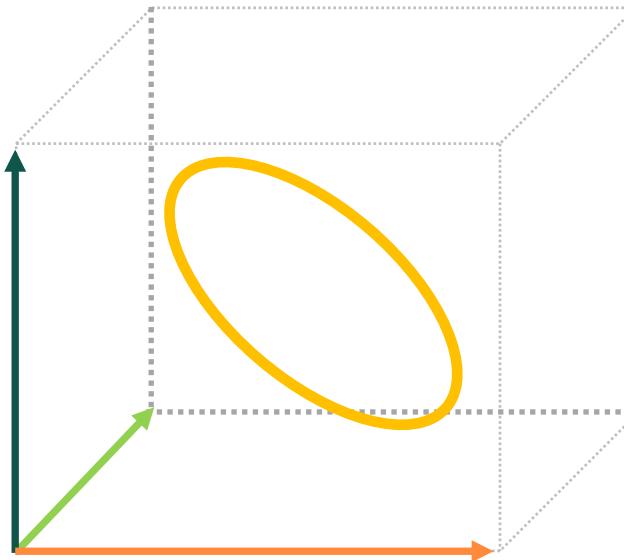


Comparison

Square Coding



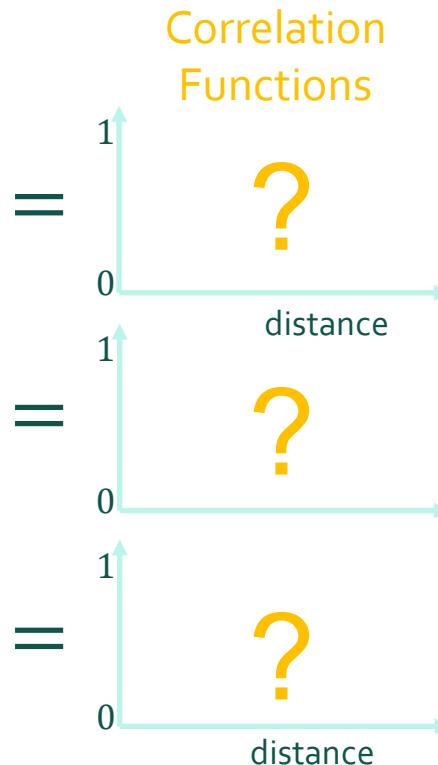
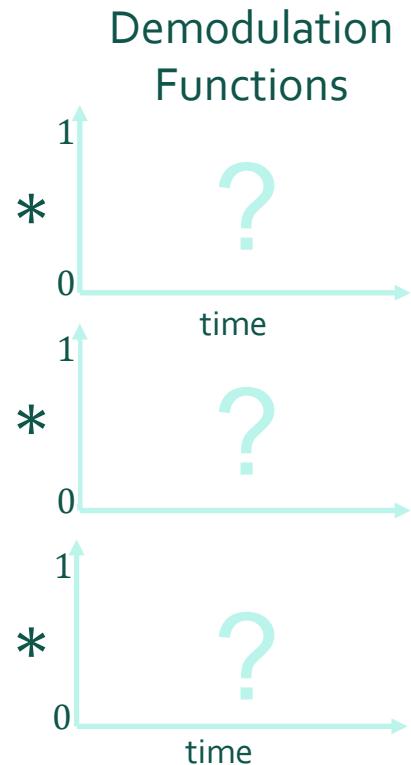
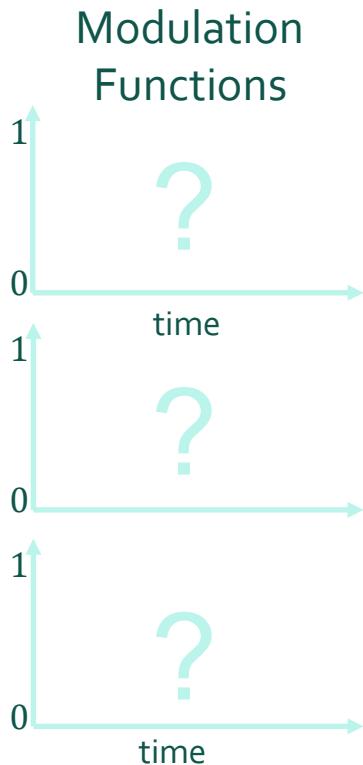
Sinusoid Coding



Resolution of square coding $\frac{4\sqrt{2}}{2\sqrt{K}} \cong 1.8$ times
Curve Length compared to sinusoid coding $\frac{\pi}{2\sqrt{2}} \sqrt{K}$



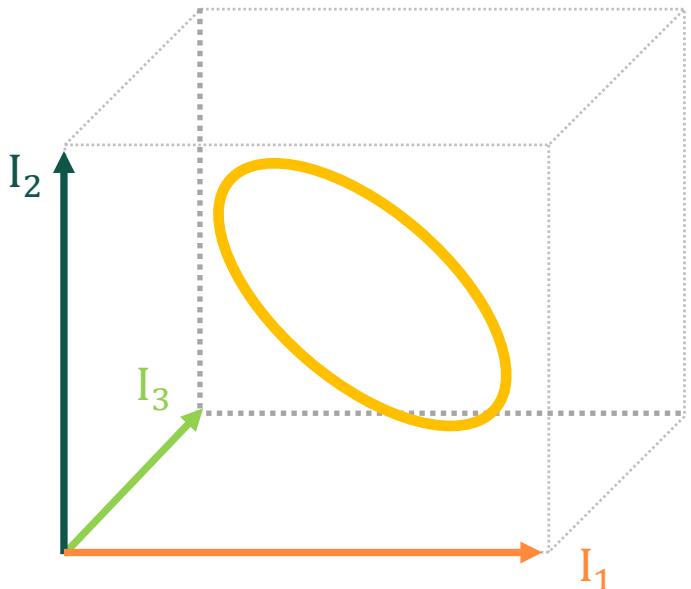
Towards Optimal Time-of-Flight Coding





Towards Optimal Time-of-Flight Coding

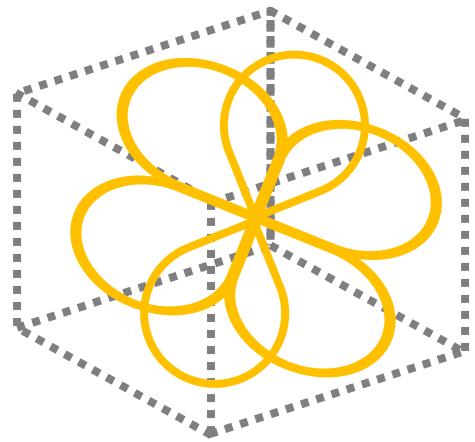
Intensity Space



Optimize in the Space of Coding Curves

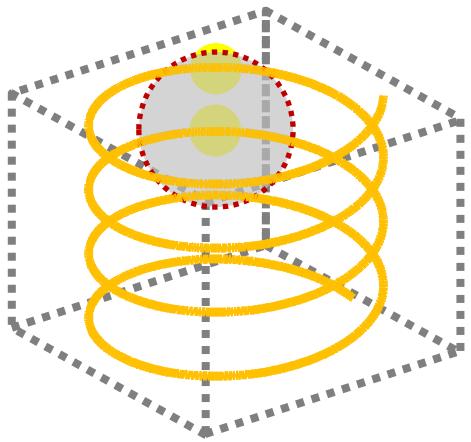


Long Coding Curves



Self-Intersecting

Depths to Intensities
Mapping Not Unique



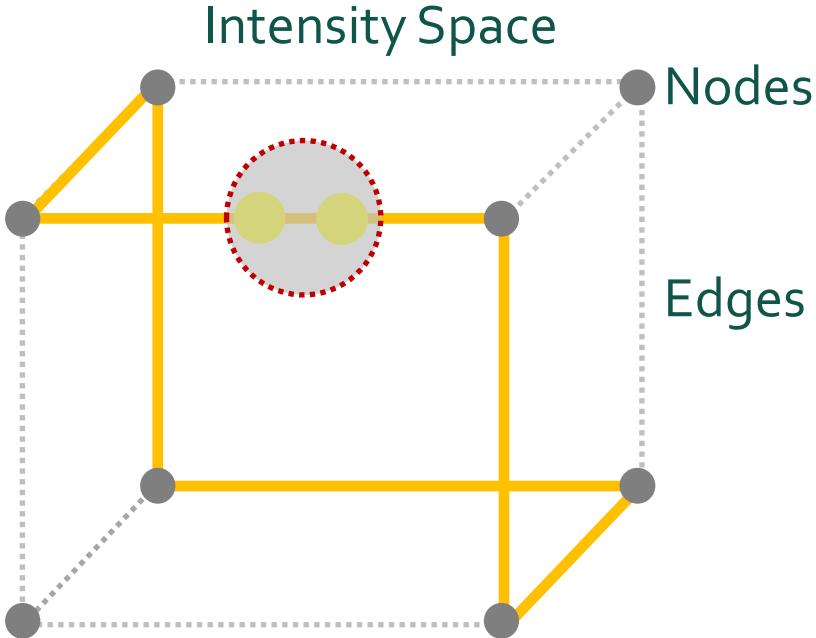
Not Locality Preserving

Small Noise Can Result
in Large Depth Errors

Hamiltonian Coding for Time-of-flight Imaging



Hamiltonian Cycle on Hypercube

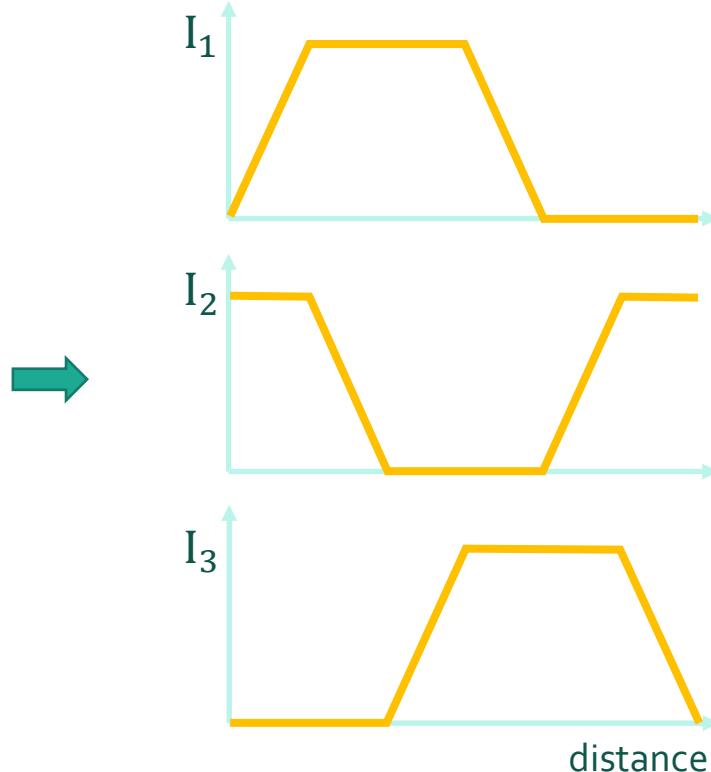
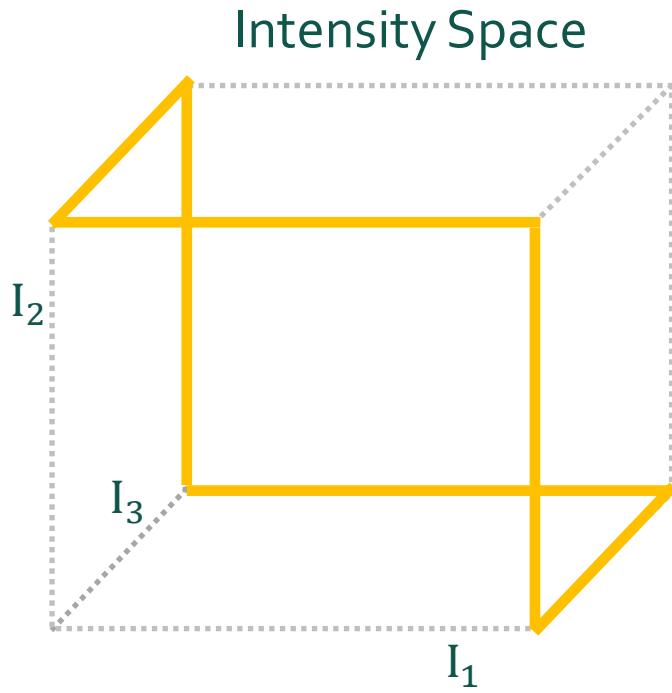


Coding Curve: Hamiltonian Cycle on Hypercube Graph

Long and Locality Preserving
Curve Lengthy = 2^K

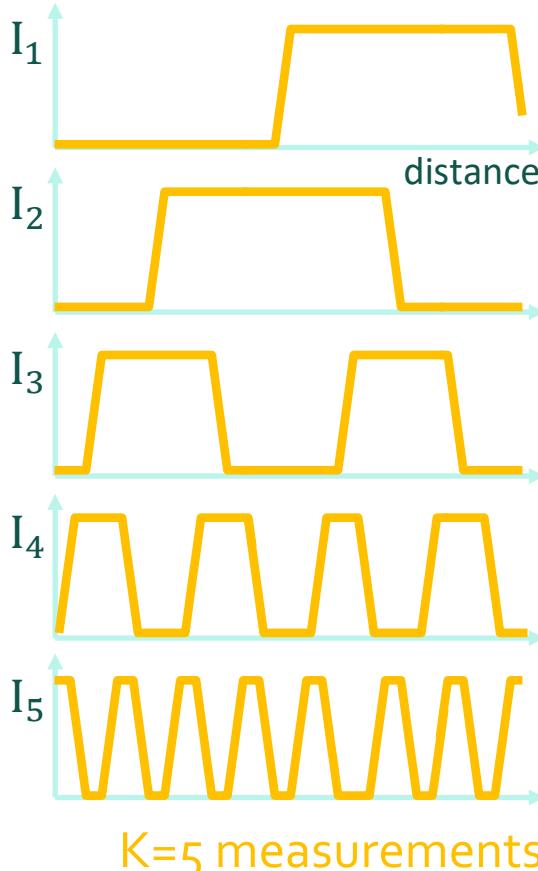
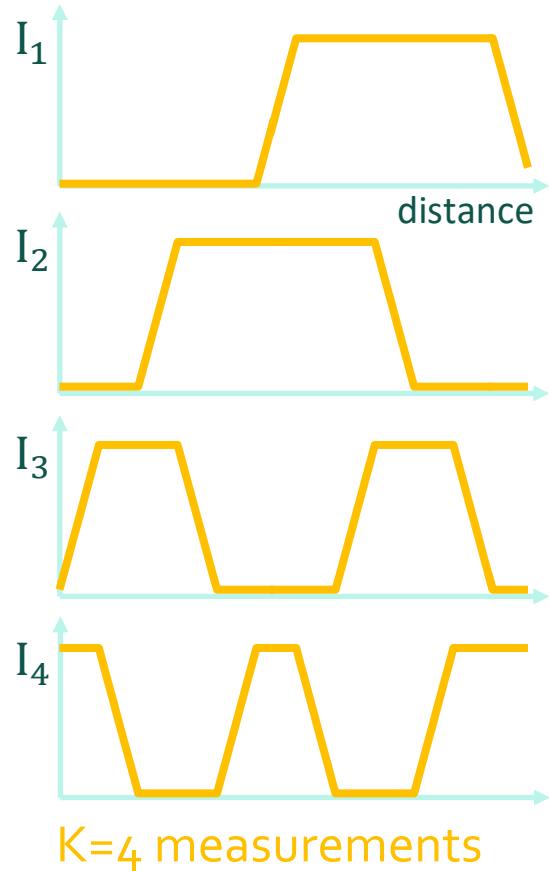


Hamiltonian Coding





Higher Order Hamiltonian Coding



Relationship to Gray Codes

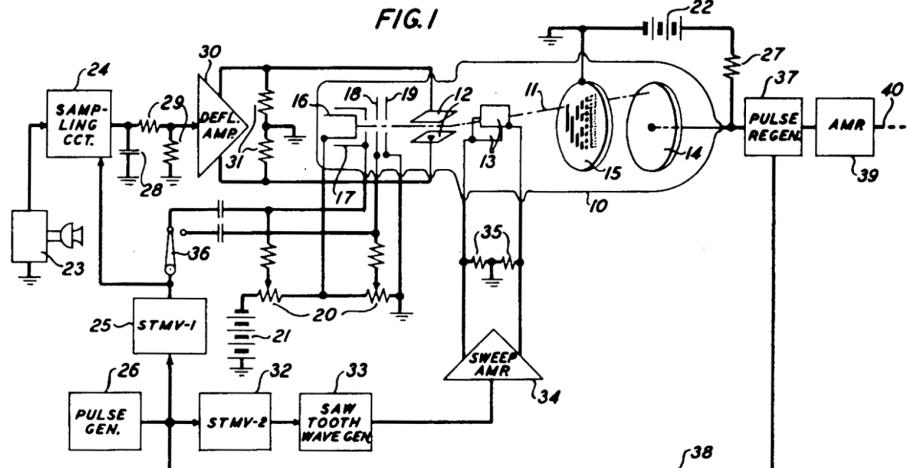
March 17, 1953

F. GRAY
PULSE CODE COMMUNICATION

2,632,058

Filed Nov. 13, 1947

4 Sheets-Sheet 1



Noise Robust Communication

Gray Codes

[000]

[001]

[011]

[010]

[110]

[111]

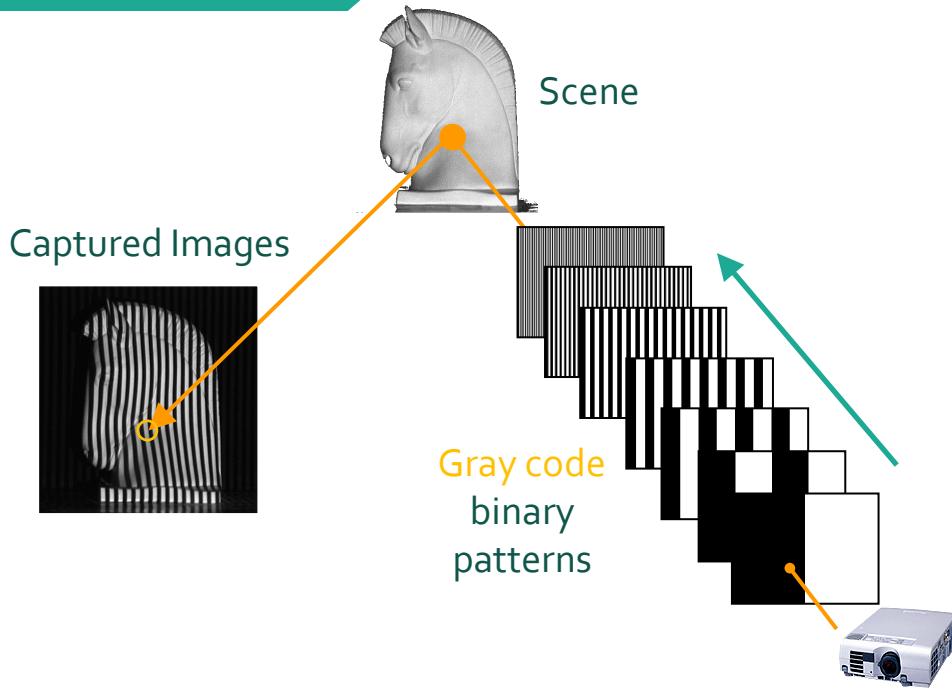
[101]

[100]

Hamming Distance Between Consecutive Codes = 1



Relationship to Gray Codes



Gray Codes

[000]

[001]

[011]

[010]

[110]

[111]

[101]

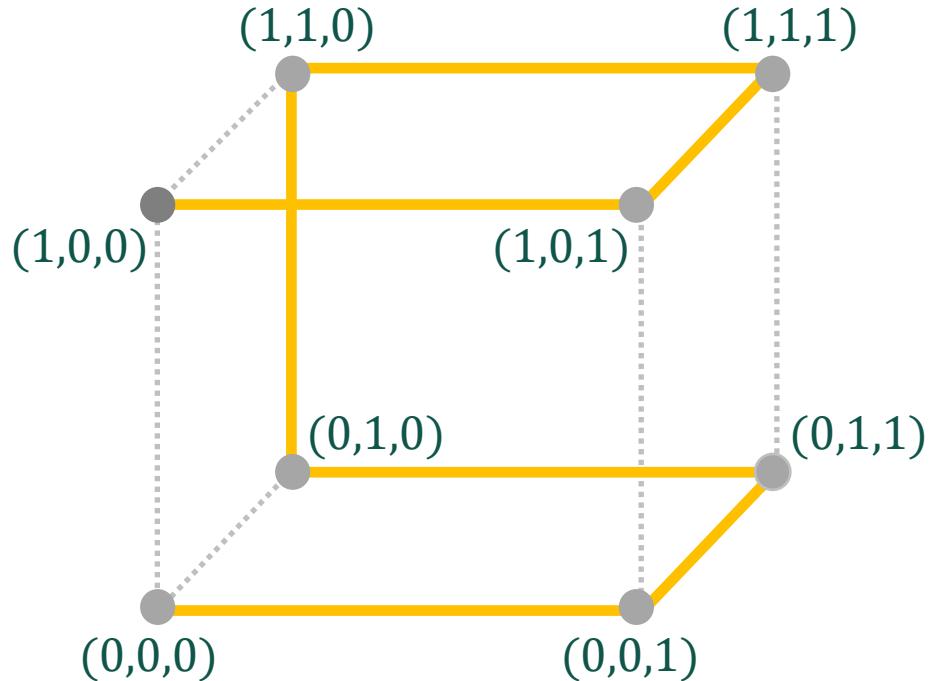
[100]

Robust Structured Light 3D Imaging

Hamming Distance Between Consecutive Codes = 1



Relationship to Gray Codes



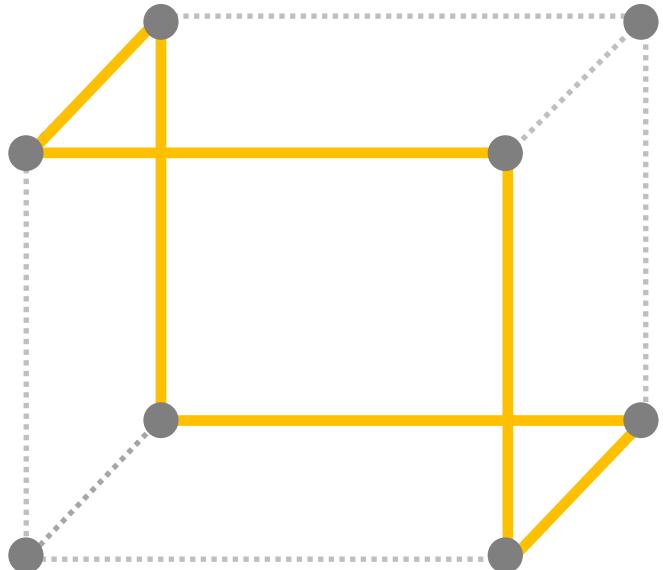
Gray Codes

[000]
[001]
[011]
[010]
[110]
[111]
[101]
[100]

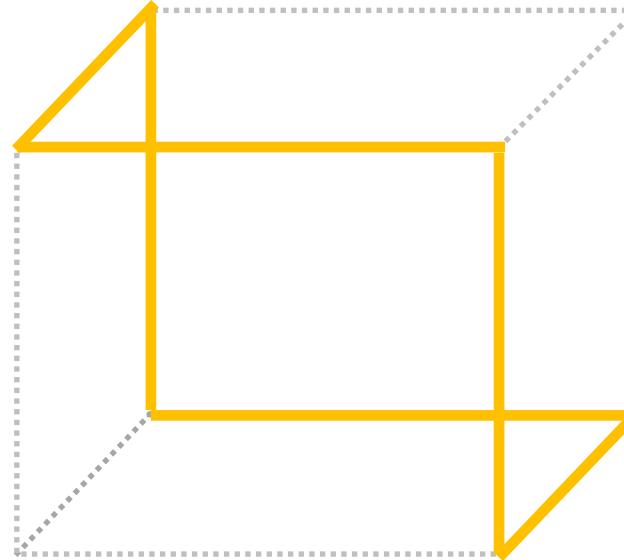
Hamming Distance Between Consecutive Codes = 1



Hamiltonian Codes vs. Gray Codes



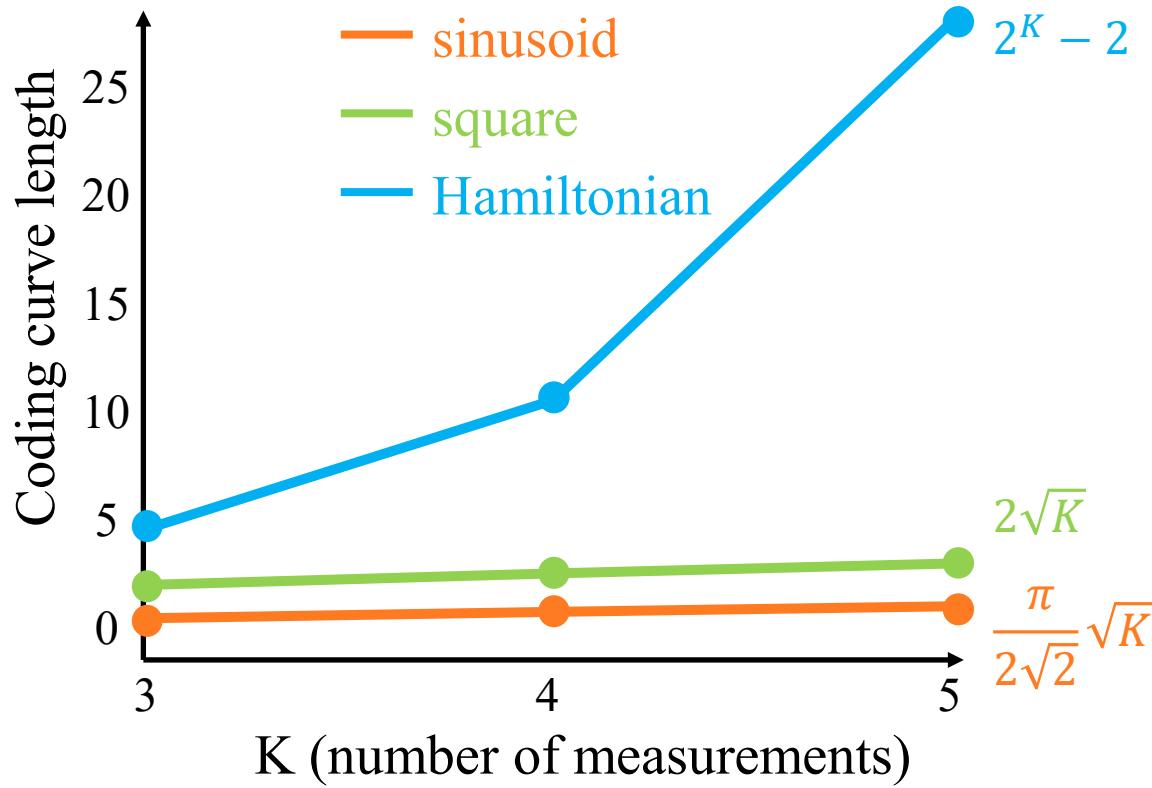
Gray Codes
Discrete



Hamiltonian Codes
Continuous

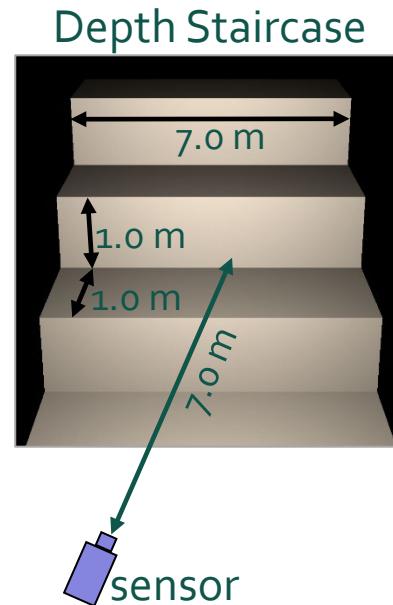
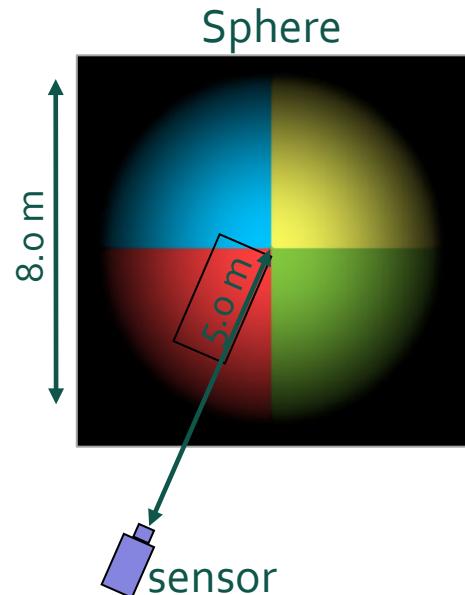
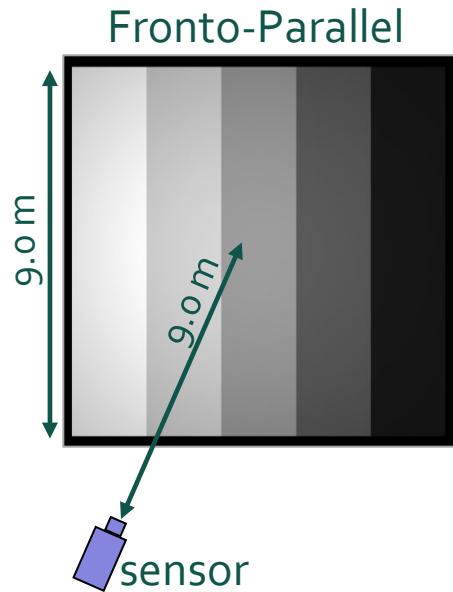


Comparison: Coding Curve Lengths





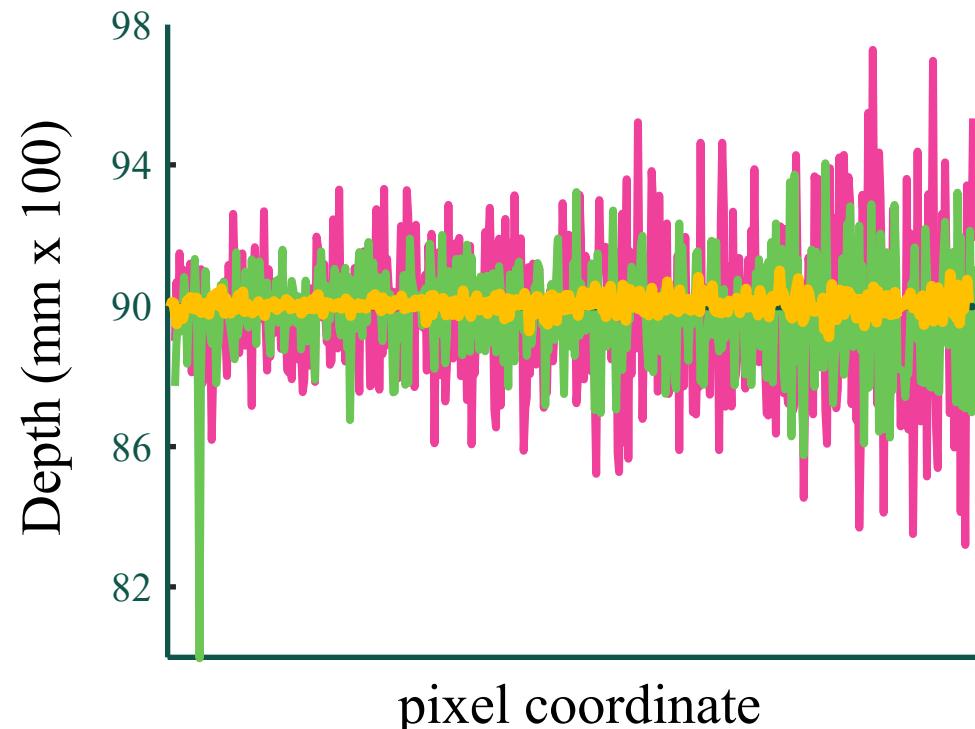
Simulation Results





Comparisons (K=5, Strong Noise)

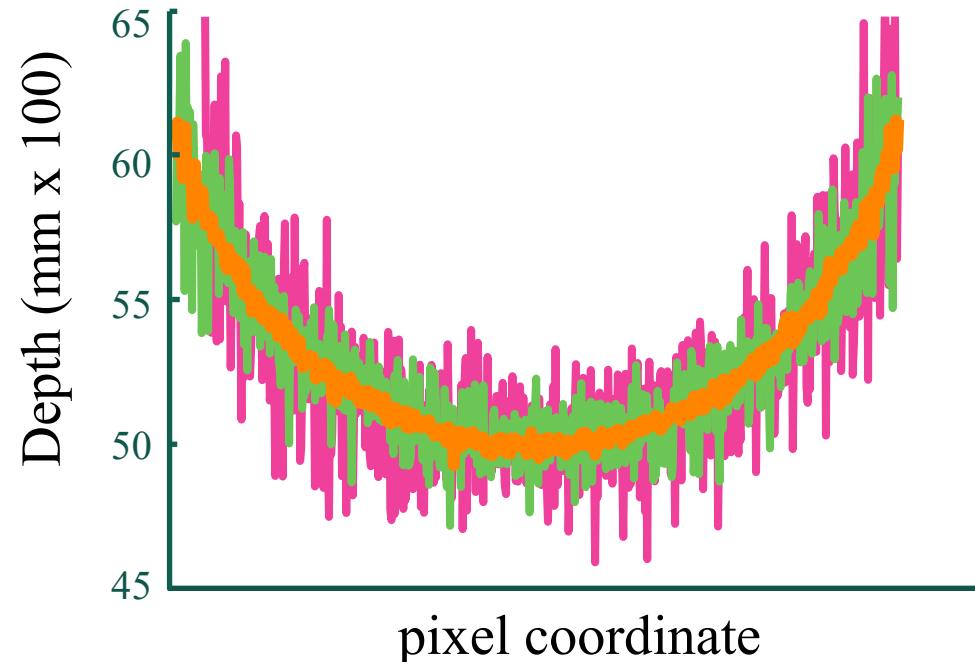
— sinusoid coding (err = 206.7 mm) — square coding (err = 136.1 mm) — Hamiltonian coding (err = 23.4 mm) — Ground truth





Comparisons (K=5, Strong Noise)

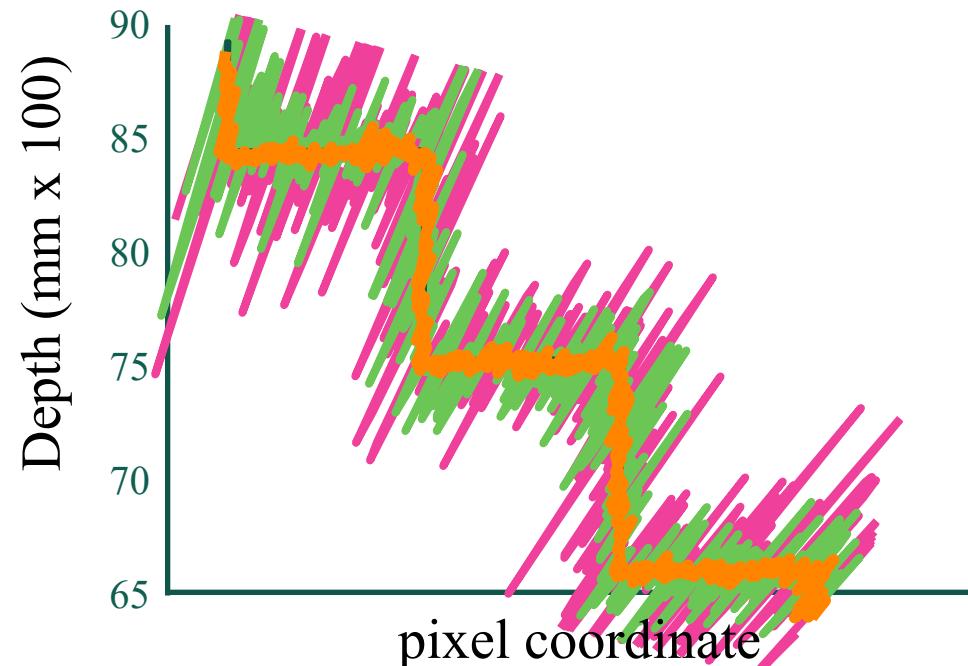
— sinusoid coding (err = 202.9 mm) — square coding (err = 128.8 mm) — Hamiltonian coding (err = 24.4 mm) — Ground truth





Comparisons (K=5, Strong Noise)

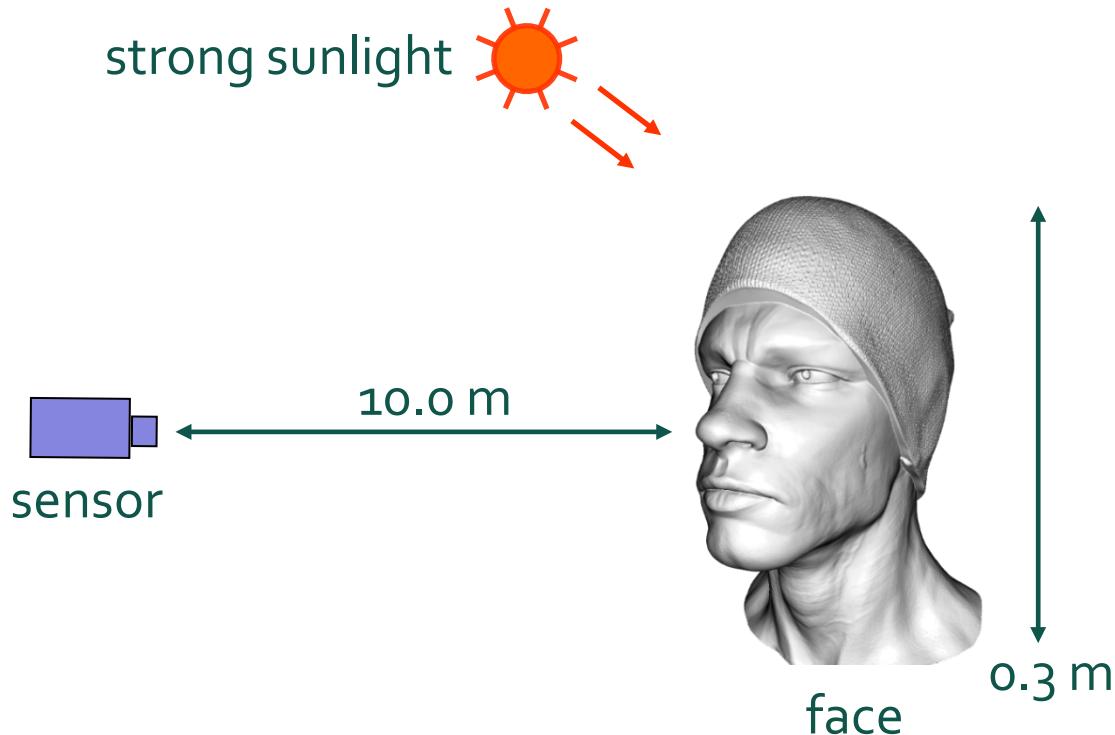
— sinusoid coding (err = 340.4 mm) — square coding (err = 219.6 mm) — Hamiltonian coding (err = 41.0 mm) — Ground truth



Scene

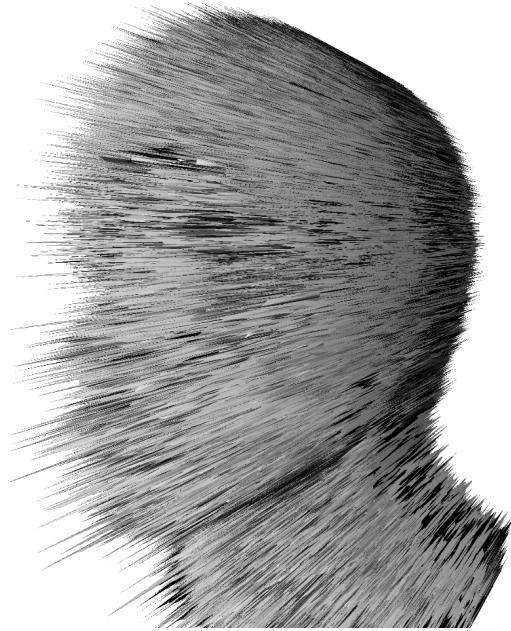


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The Chinese University of Hong Kong, Shenzhen



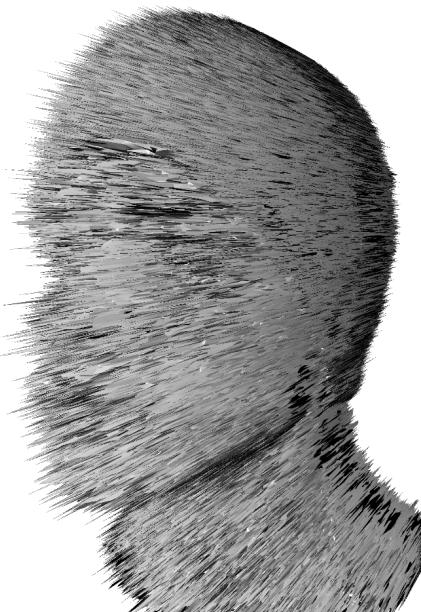


Comparison (Raw 3D Shape, No Processing)



sinusoid coding
(5 images)

error = 14.51 mm



square coding
(5 images)

error = 8.07 mm

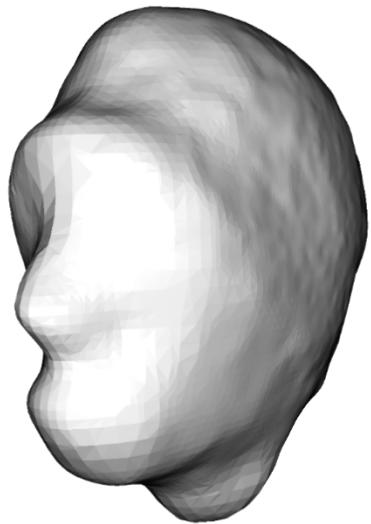


Hamiltonian Coding
(5 images)

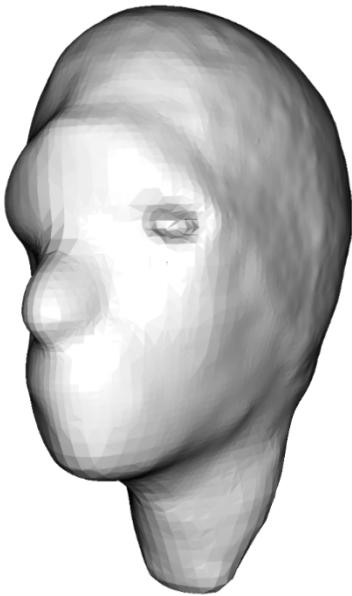
error = 1.46 mm



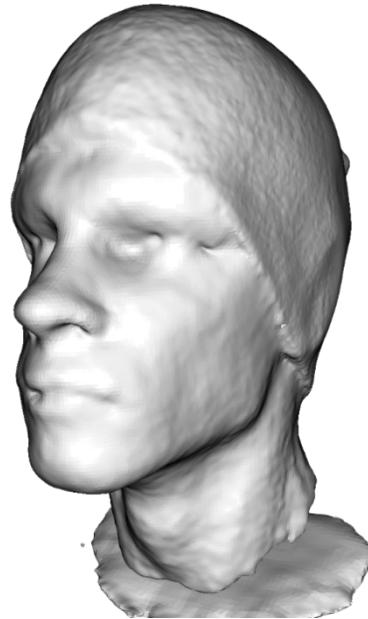
Comparison (After Remeshing)



sinusoid coding
(5 images)



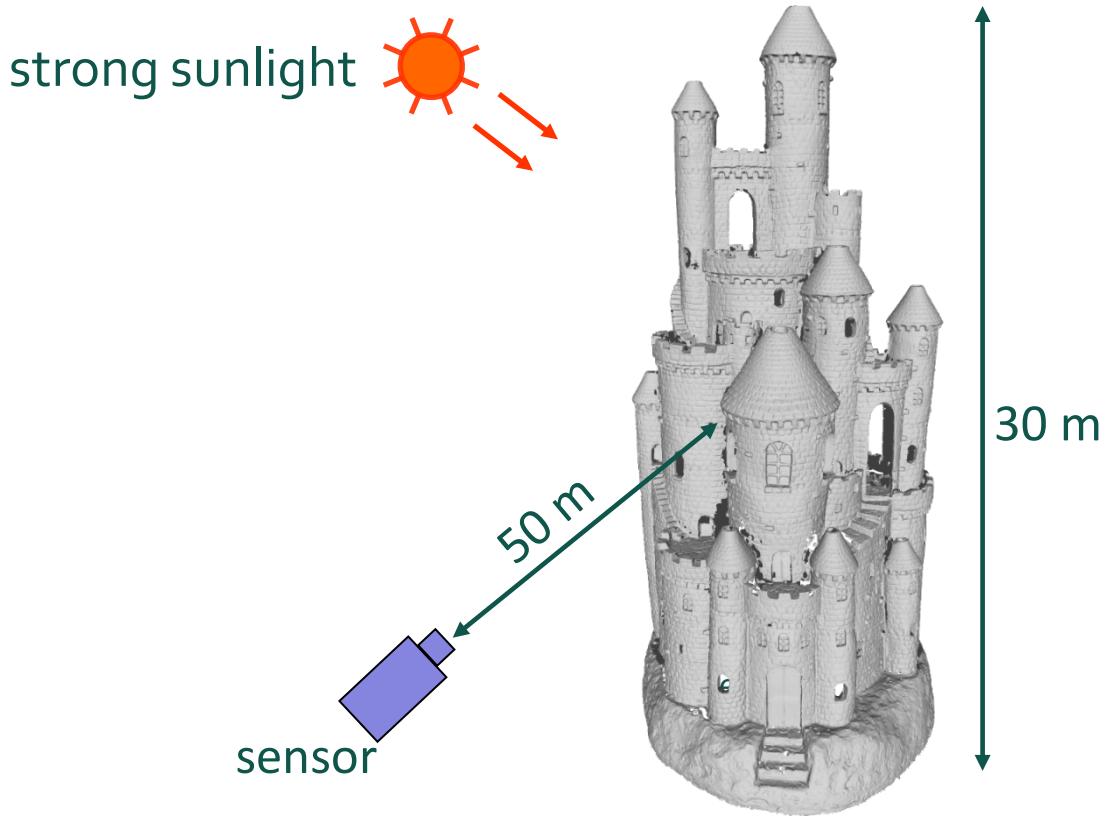
square coding
(5 images)



Hamiltonian Coding
(5 images)



Scene: Long Distance 3D Imaging





Comparison

error = 42.7 cm



sinusoid coding

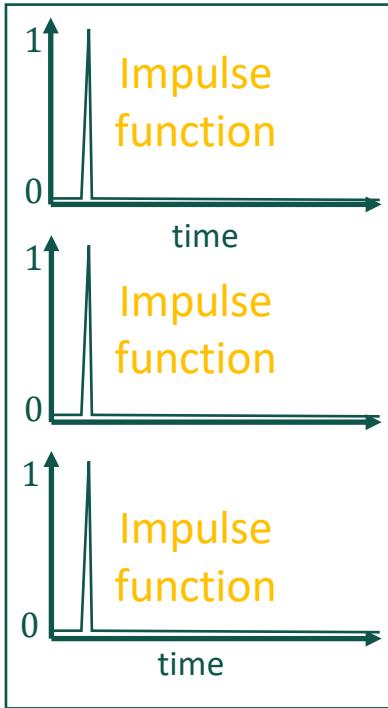
error = 4.0 cm



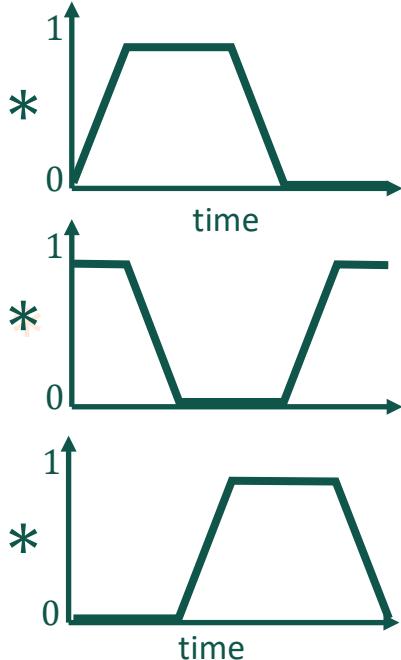
Hamiltonian Coding

Current Implementation

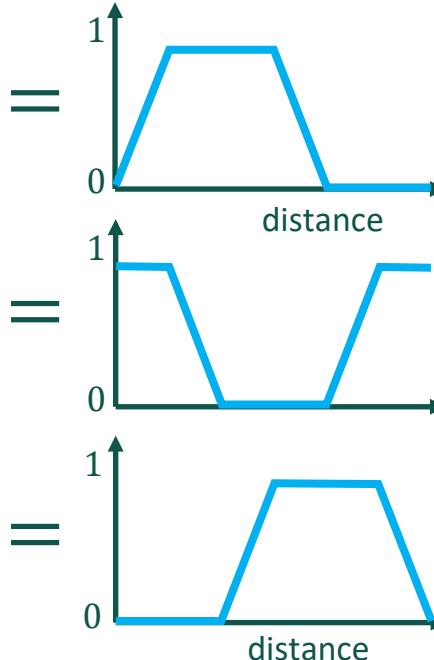
Inefficient



Modulation



Demodulation

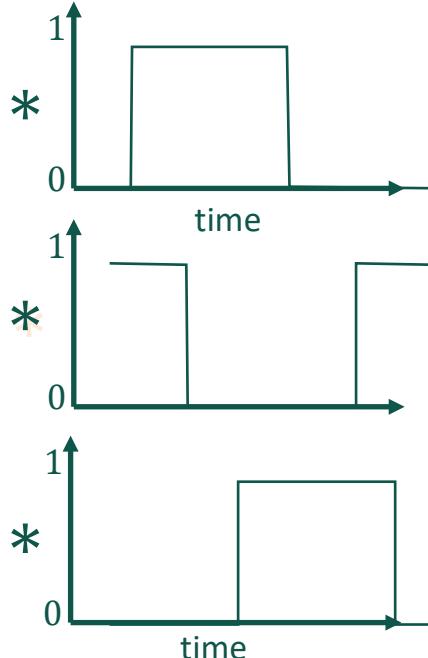
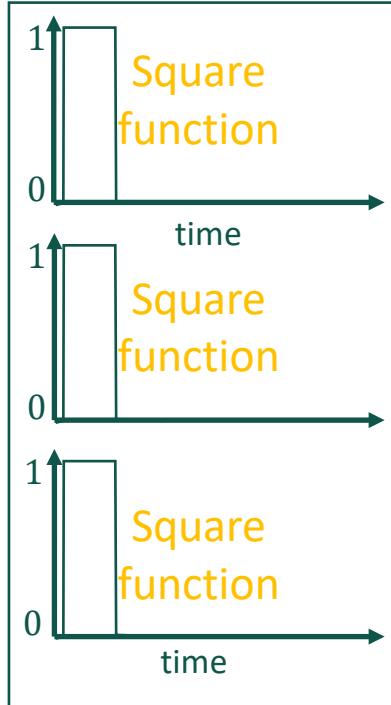


Correlation



Practical Implementation

Practical

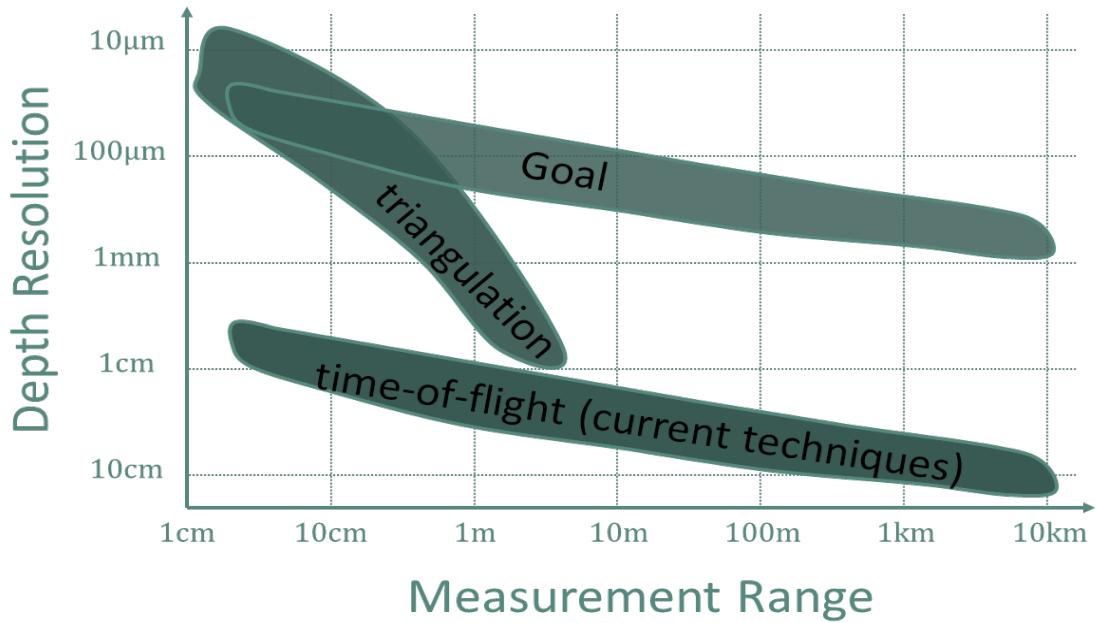


Modulation

Demodulation

Correlation

Range vs. Resolution: 3D Imaging





Today's Topic

- Direct-Indirect Separation
- Optimal Coding Functions for Time-of-flight Imaging
- Hamiltonian Coding for Time-of-flight Imaging



Thank You!



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点昀技术（Point Spread Technology）