Snapshot Lidar: Fourier embedding of amplitude and phase for single-image depth reconstruction

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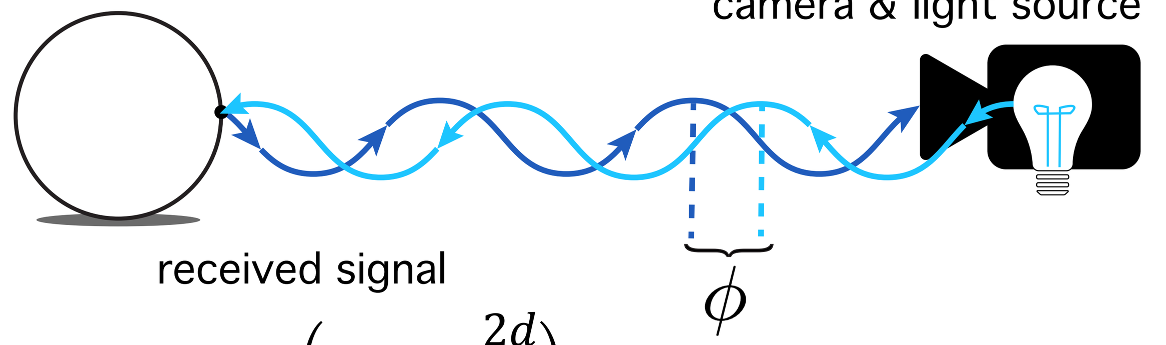
Amplitude-Modulated Continuous Wave Time-of-Flight (AMCWToF)



light signal
$e(t) = \sin \omega t$

camera signal
$s(t) = \sin(\omega t + \theta)$

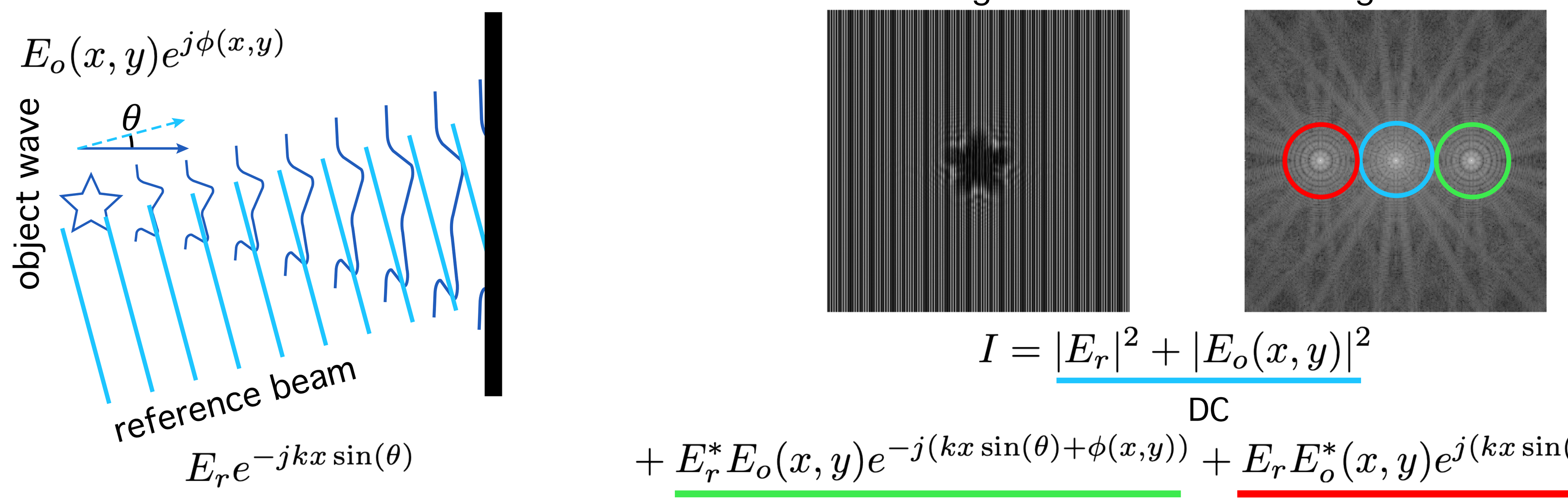
received signal
$r(t) = A \sin\left(\omega t - \omega \frac{2d}{c}\right)$

$\phi = \omega \frac{2d}{c}$ depth

measurement

$$m_\theta = \int_0^T s(t) r(t) \mathrm{d}t = \frac{A}{2}\cos(\theta - \phi)$$

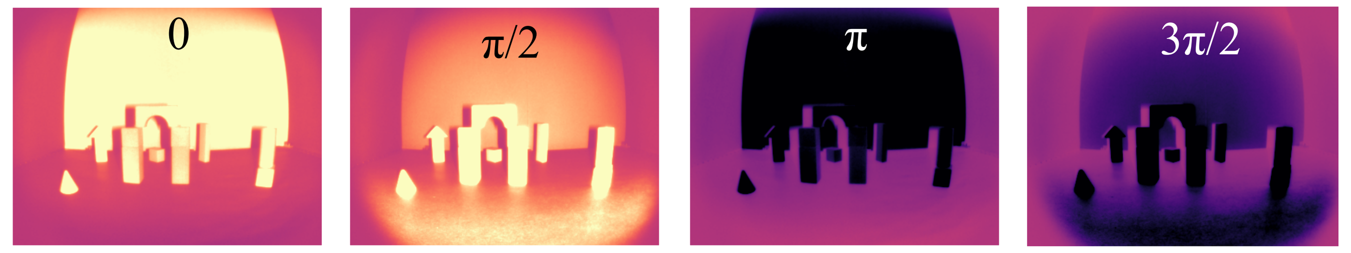
Off-axis Holography



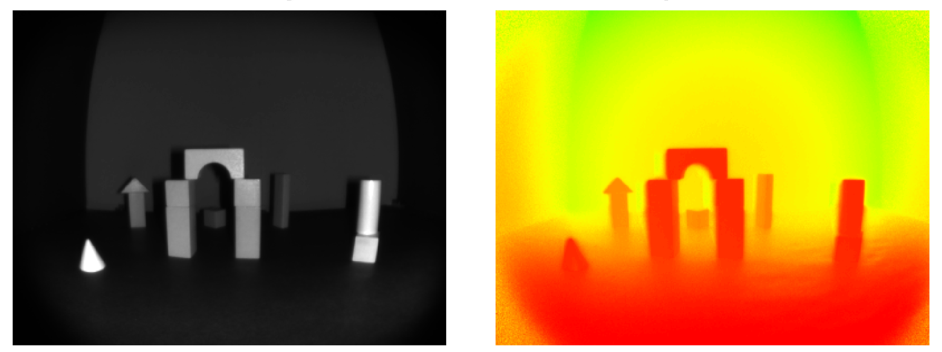
$$I = \underbrace{|E_r|^2 + |E_o(x,y)|^2}_{\text{DC}} + \underbrace{E_r^* E_o(x,y) e^{-j(kx\sin(\theta)+\phi(x,y))}}_{\text{shifted hologram}} + \underbrace{E_r E_o^*(x,y) e^{j(kx\sin(\theta)+\phi(xy))}}_{\text{shifted twin}}$$

Conventional Method

$s(t) = \sin(\omega t + \boxed{\theta})$ $0, \pi/2, \pi, 3\pi/2$



capture 4 measurements sequentially: m_0 $m_{\pi/2}$ m_π $m_{3\pi/2}$



calculate amplitude and phase

$$A = \frac{1}{2}\sqrt{(m_0 - m_\pi)^2 + (m_{\frac{3\pi}{2}} - m_{\frac{\pi}{2}})^2} \qquad \phi = \tan^{-1}\left(\frac{m_{\frac{3\pi}{2}} - m_{\frac{\pi}{2}}}{m_0 - m_\pi}\right)$$

- requires 4 images
- susceptible to motion blur
- slow

Snapshot Method (Proposed)

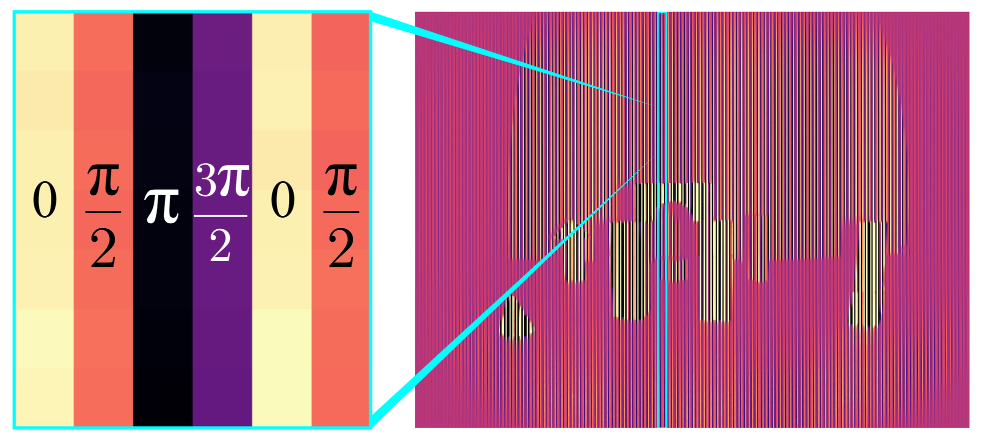
$s(t) = \sin(\omega t + \boxed{\theta})$ kx

define ToF hologram as

$$\boxed{\mathcal{I}(x,y) = A(x,y)e^{-j\phi}}$$

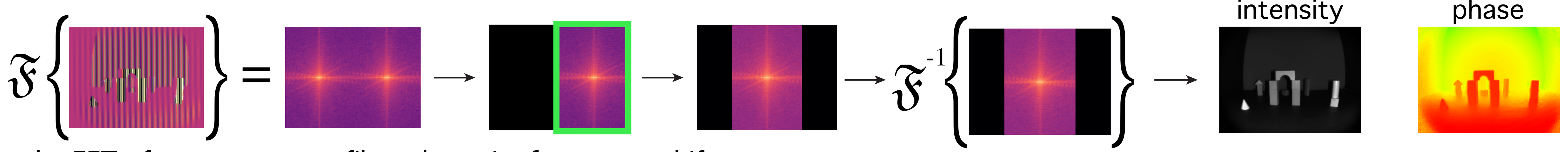
measurement becomes:

$$m_{kx} = \frac{A(x,y)}{2}\cos(kx - \phi(x,y)) = \frac{A(x,y)}{4}[e^{j(kx-\phi)} + e^{-j(kx-\phi)}]$$



capture image with spatially varying θ

$$\mathfrak{F}_{m_{kx}}(\omega_x, \omega_y) = \frac{1}{4}(\underbrace{\mathcal{I}(\omega_x - k, \omega_y)}_{\text{shifted hologram}} + \underbrace{\mathcal{I}^*(k - \omega_x, \omega_y)}_{\text{shifted twin}})$$



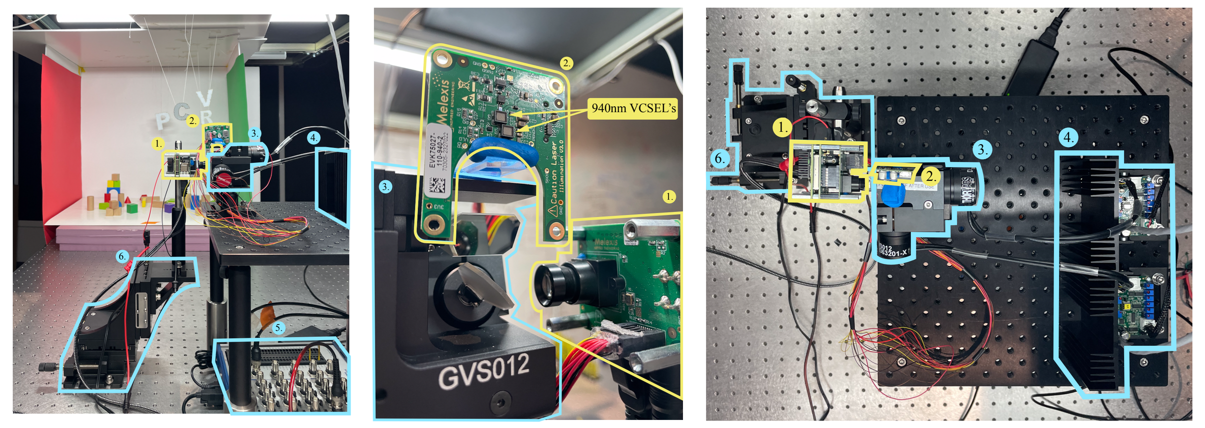
take FFT of measurement, filter the twin, frequency shift to center

reconstruct from inverse FFT

- inspired by off-axis holography
- embeds ToF hologram in Fourier space
- 4x lower bandwidth

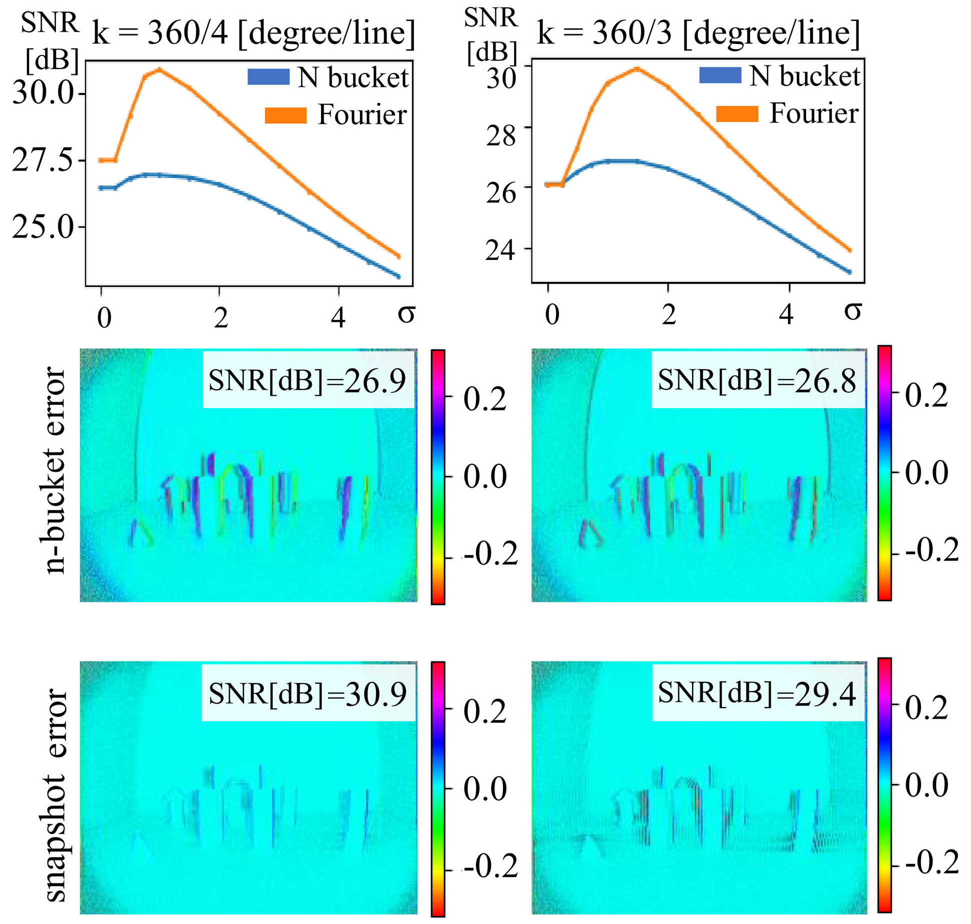
Results

hardware setup



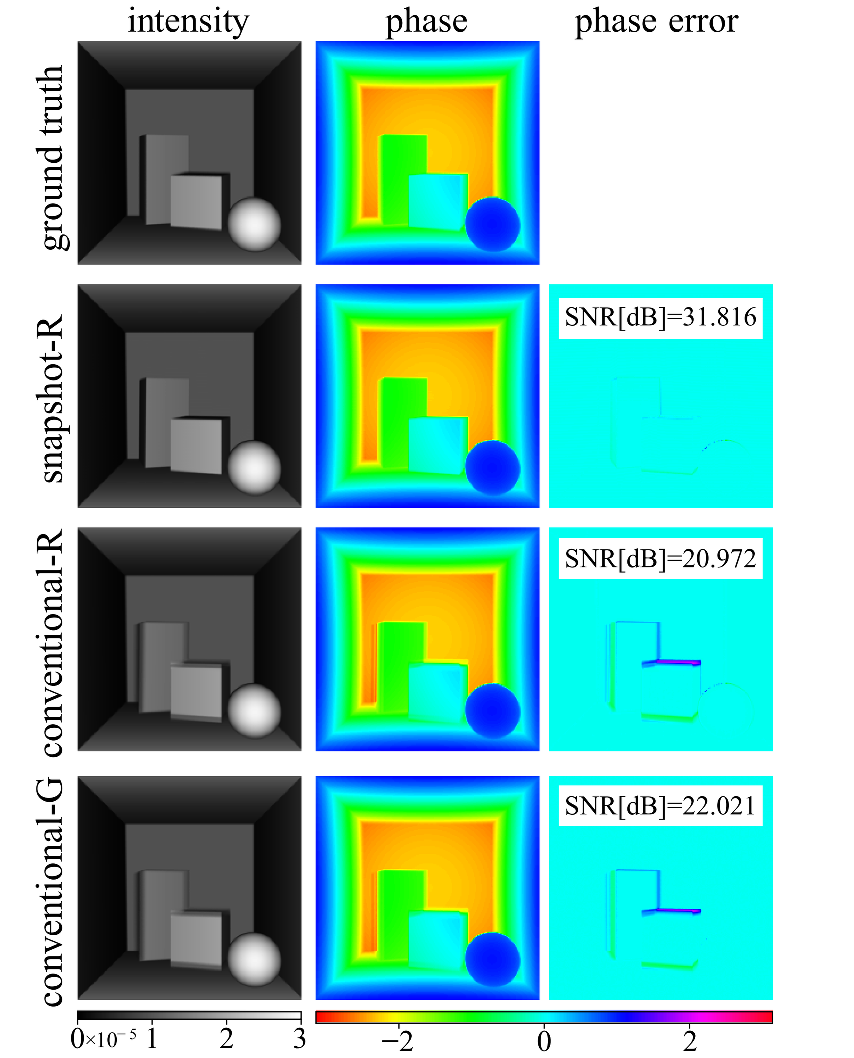
1.MLX75027-110-940-2 main boards
2.MLX75027-110-940-2 illumination board, 940nm
3.Thorlabs GVS012 2-axis galvo
4.Galvo system equipment (heatsinks, controllers, etc)
5.NI DAQ USB6363
6.Thorlabs XYZ stage

n-bucket reconstruction technique vs. snapshot

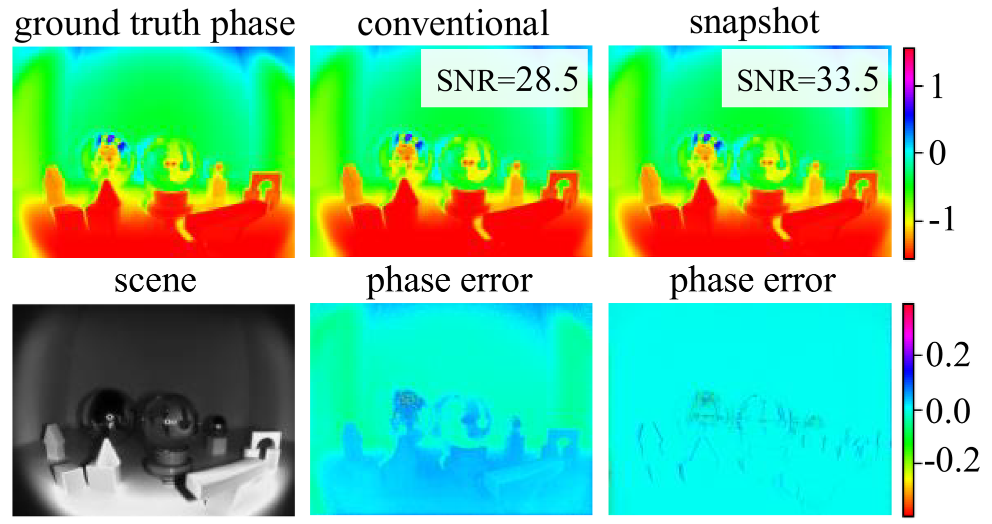


conventional vs. snapshot technique for a moving scene

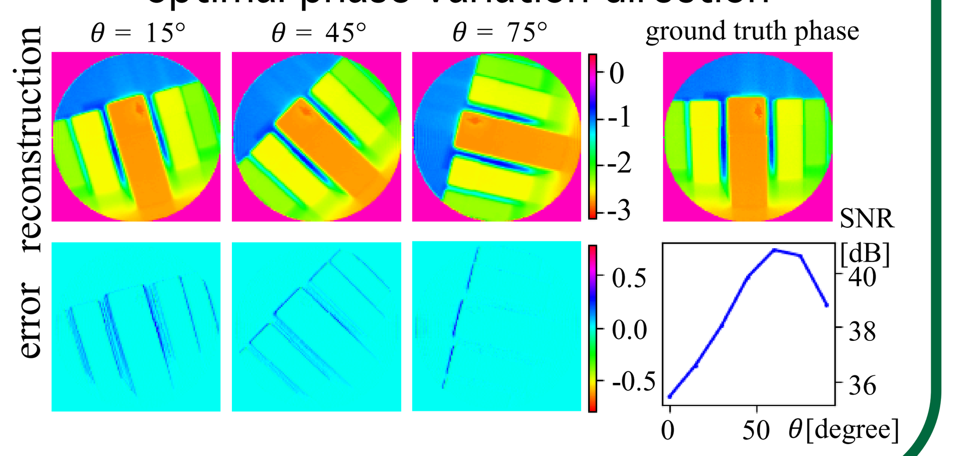
-G = global shutter -R = rolling shutter



robustness to local error



optimal phase variation direction



The authors thank Jeremy Klotz for his help with the hardware prototype. This research is partially supported by a Burke Research Initiation Award.