Virtual Scanning

Unsupervised Non-line-of-sight Imaging from Irregularly Undersampled Transients

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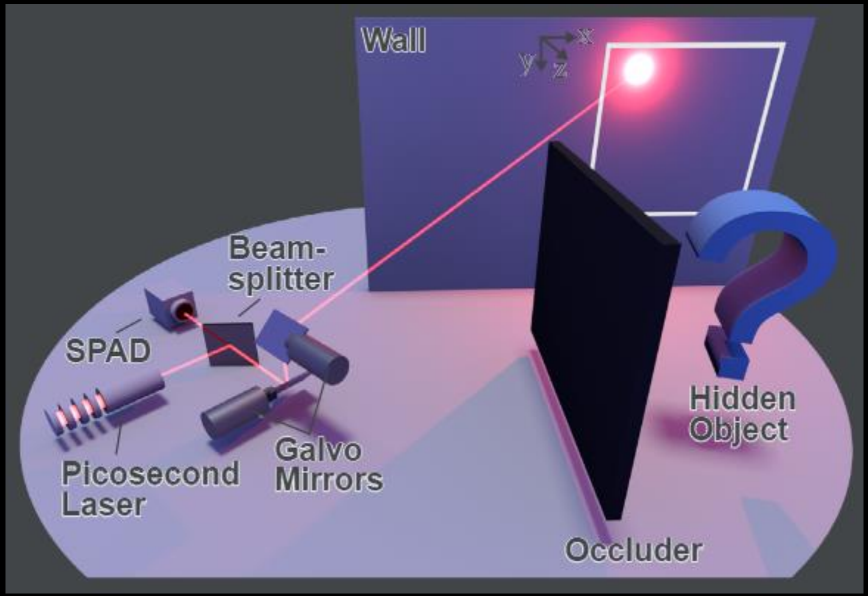
Non-line-of-sight Imaging (NLOS imaging)

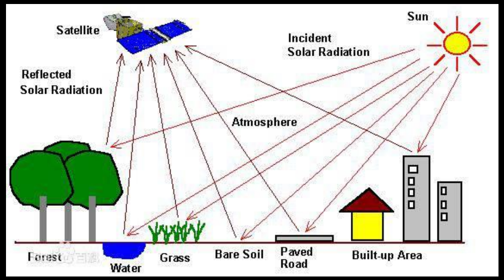


Typical System[1]

Limited relay surface

Challenge Task

Rescue Operations



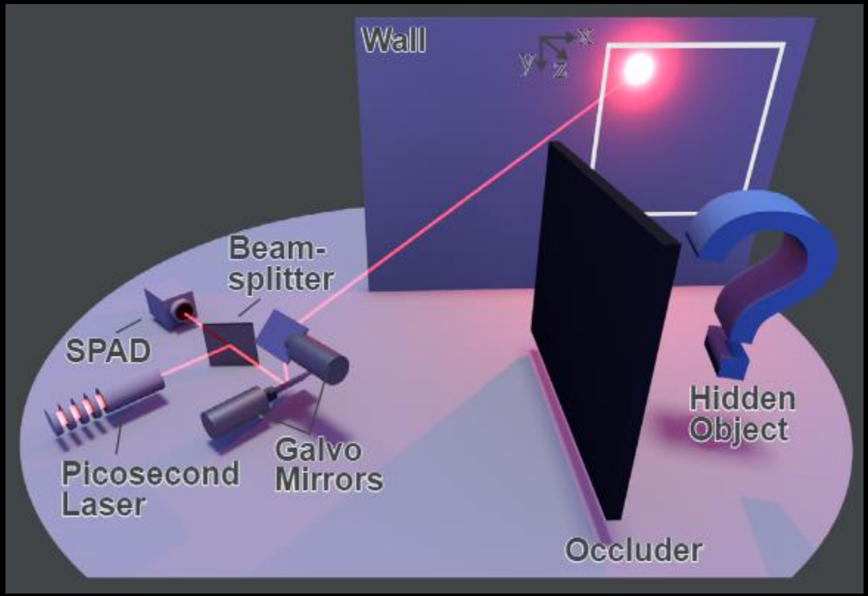
Remote Sensing

Autonomous Driving

Medical Imaging

[1] Wave-Based Non-Line-of-Sight Imaging using Fast f −k Migration

Non-line-of-sight Imaging (NLOS imaging)



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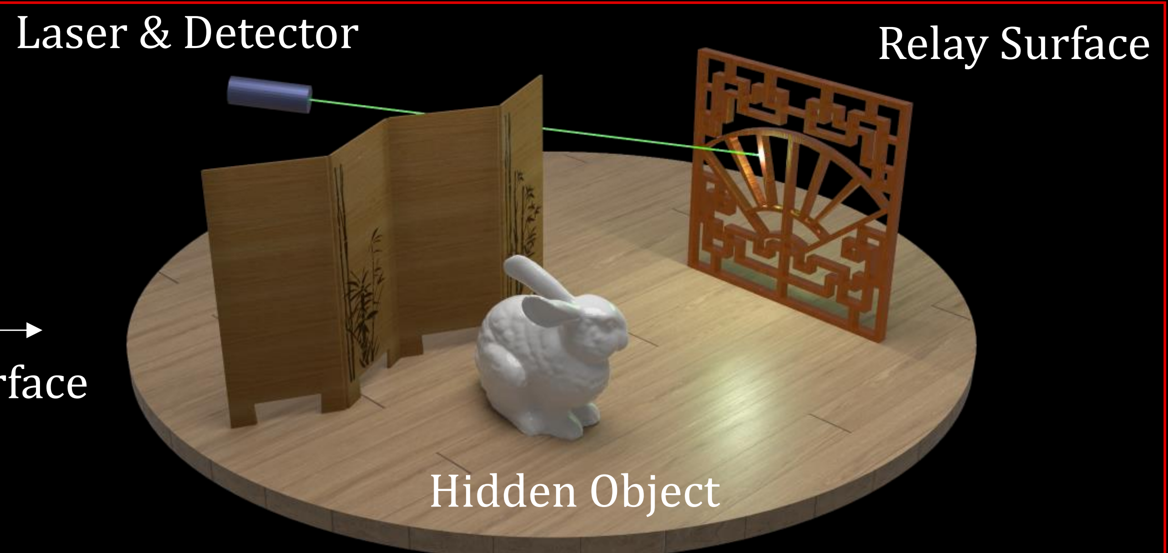
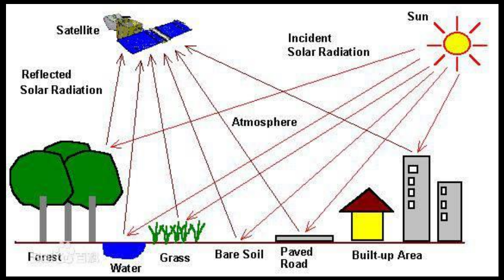


Challenge Task

Rescue Operations



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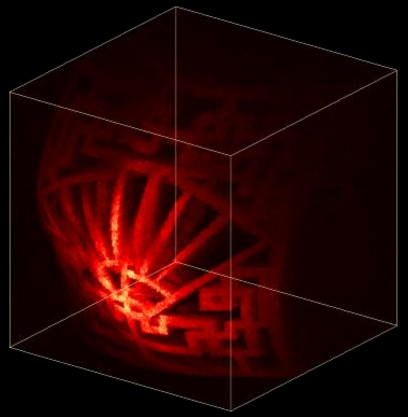
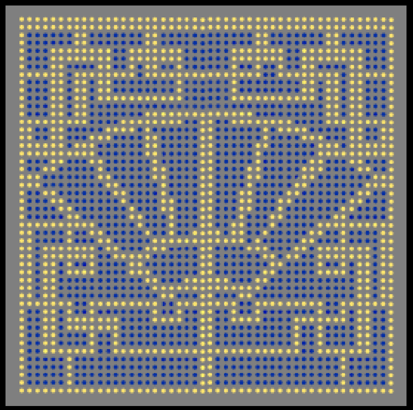
Non-line-of-sight Imaging from Irregularly Undersampled Transient

Laser & Detector

Relay Surface



Zero padded
Undersampled Transient



Scannable Points

Nonlinear Forward Model

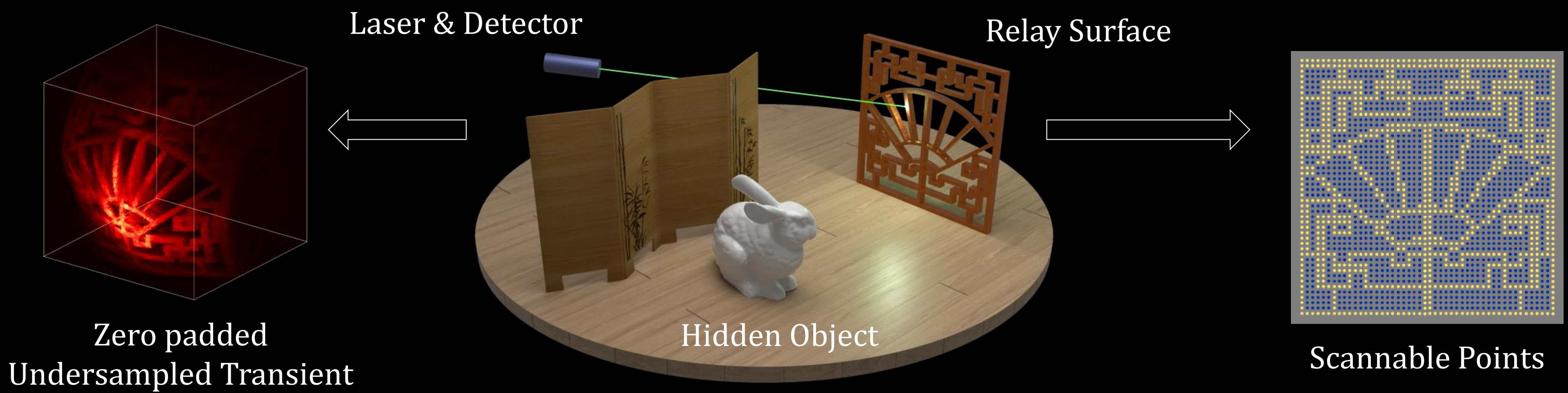
$$\tau(p,t) = \int_Q \frac{\kappa(q)}{\|p-q\|^4} \cdot \delta(2\|p-q\| - tc)dq$$

Model Simplification

Linear Forward Model

$$u = H\rho$$

Non-line-of-sight Imaging from Irregularly Undersampled Transient



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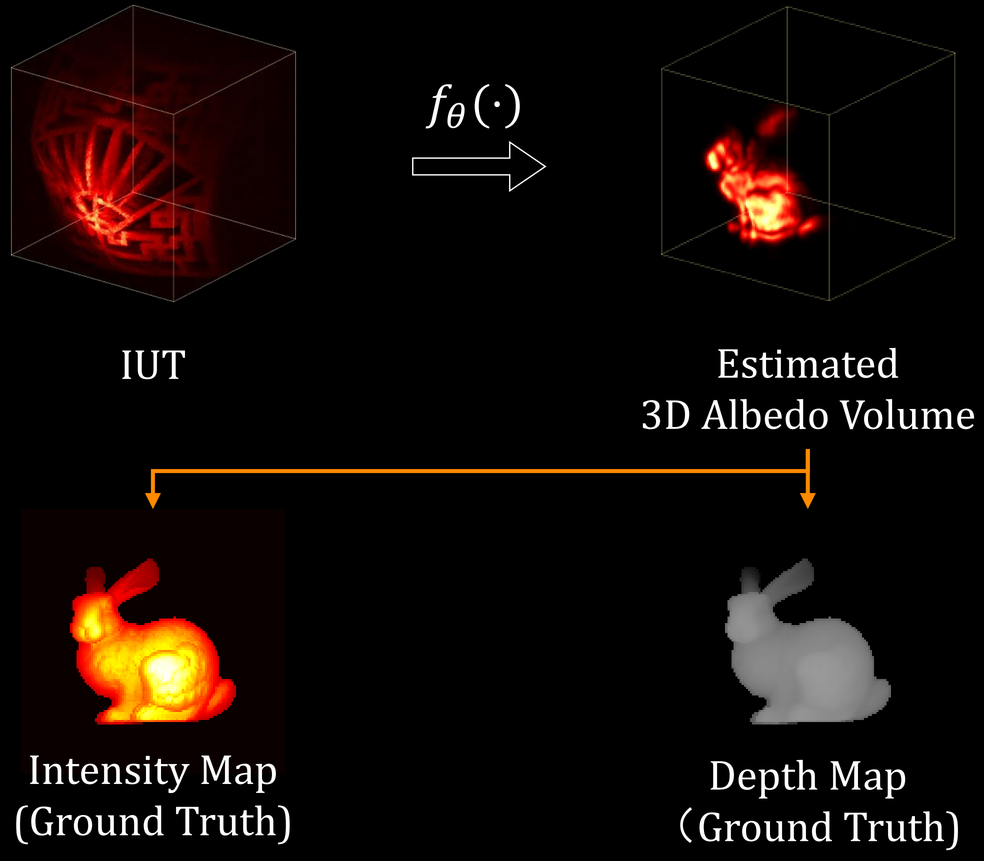
Motivation

To solve the challenge inverse problem: $\rho = \arg\min_{\rho} ||u - H\rho||_2^2$

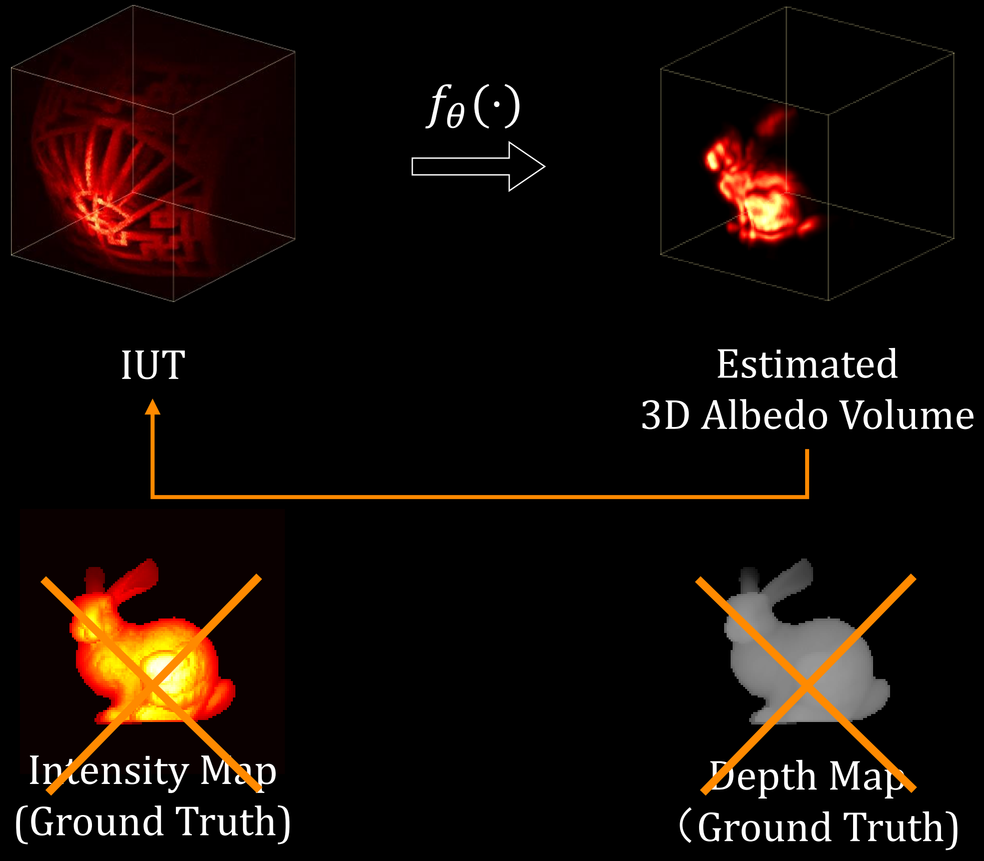
Supervised Learning

$\mathbb{E}_u \left|\left|f_\theta(u) - \rho_{gt}\right|\right|_2^2$



Unsupervised Learning

$\mathbb{E}_u ||H f_\theta(u) - u||_2^2$



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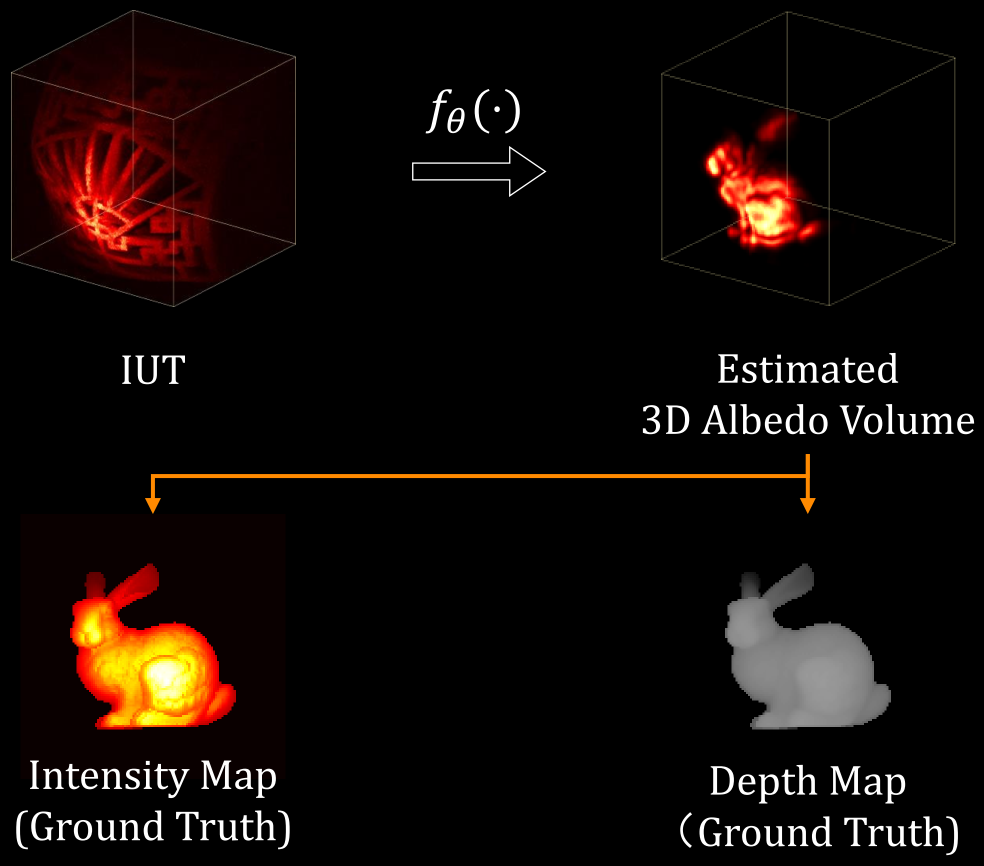
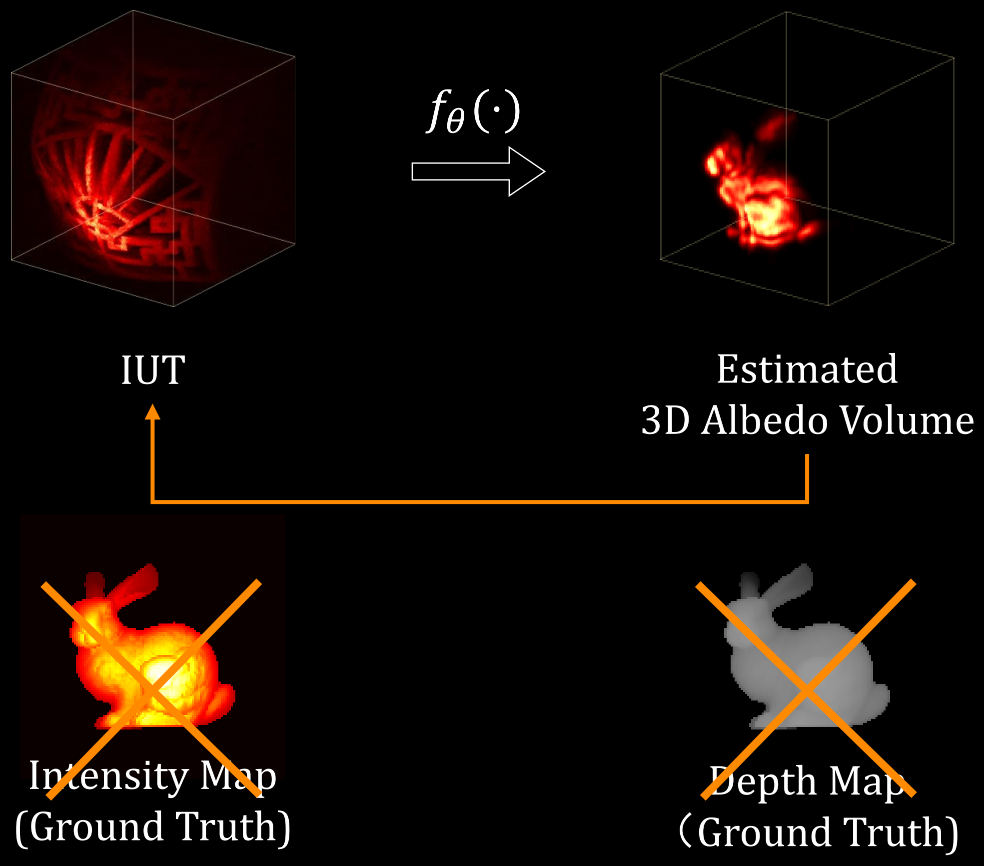


Unsupervised Learning

$$\mathbb{E}_u \left|\left| H f_\theta(u) - u \right|\right|_2^2$$

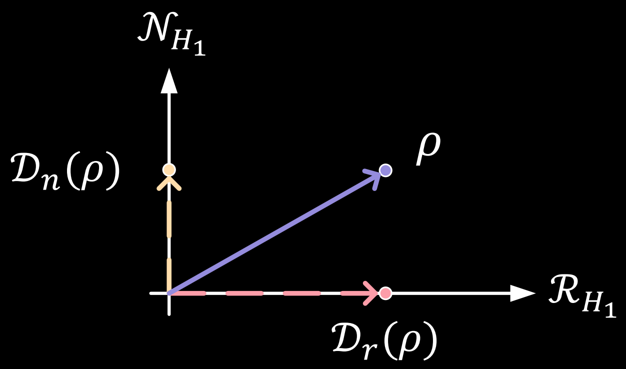


Motivation

Measurement Consistency (MC) is not enough for unsupervised learning.

$$\mathbb{E}_u \| H f_\theta(u) - u \|_2^2$$

Range-Null Space Decomposition



$$\rho = \underbrace{H^\dagger H \rho}_{\text{range-space component}} + \underbrace{(I - H^\dagger H)\rho}_{\text{null-space component}}$$

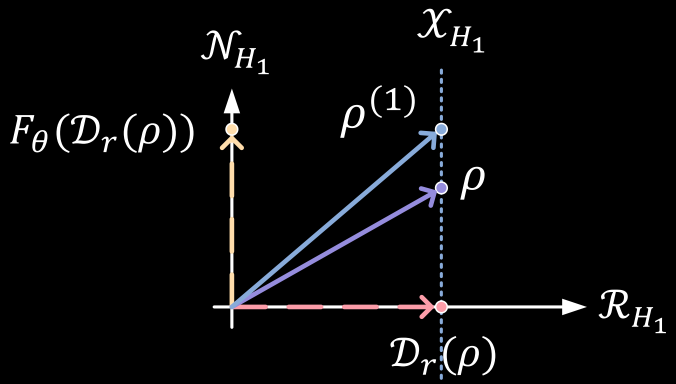
$$\mathcal{R}_H : \mathcal{D}_r(\rho) = H^\dagger H \rho$$

$$\mathcal{R}_H = \{H^\top u, u \in \mathbb{R}^{st}\}$$

$$\mathcal{N}_H : \mathcal{D}_n(\rho) = (I - H^\dagger H)\rho$$

$$\mathcal{N}_H = \{v \in \mathbb{R}^{l^2 z} \mid Hv = 0\}$$

Unsupervised learning with MC Loss



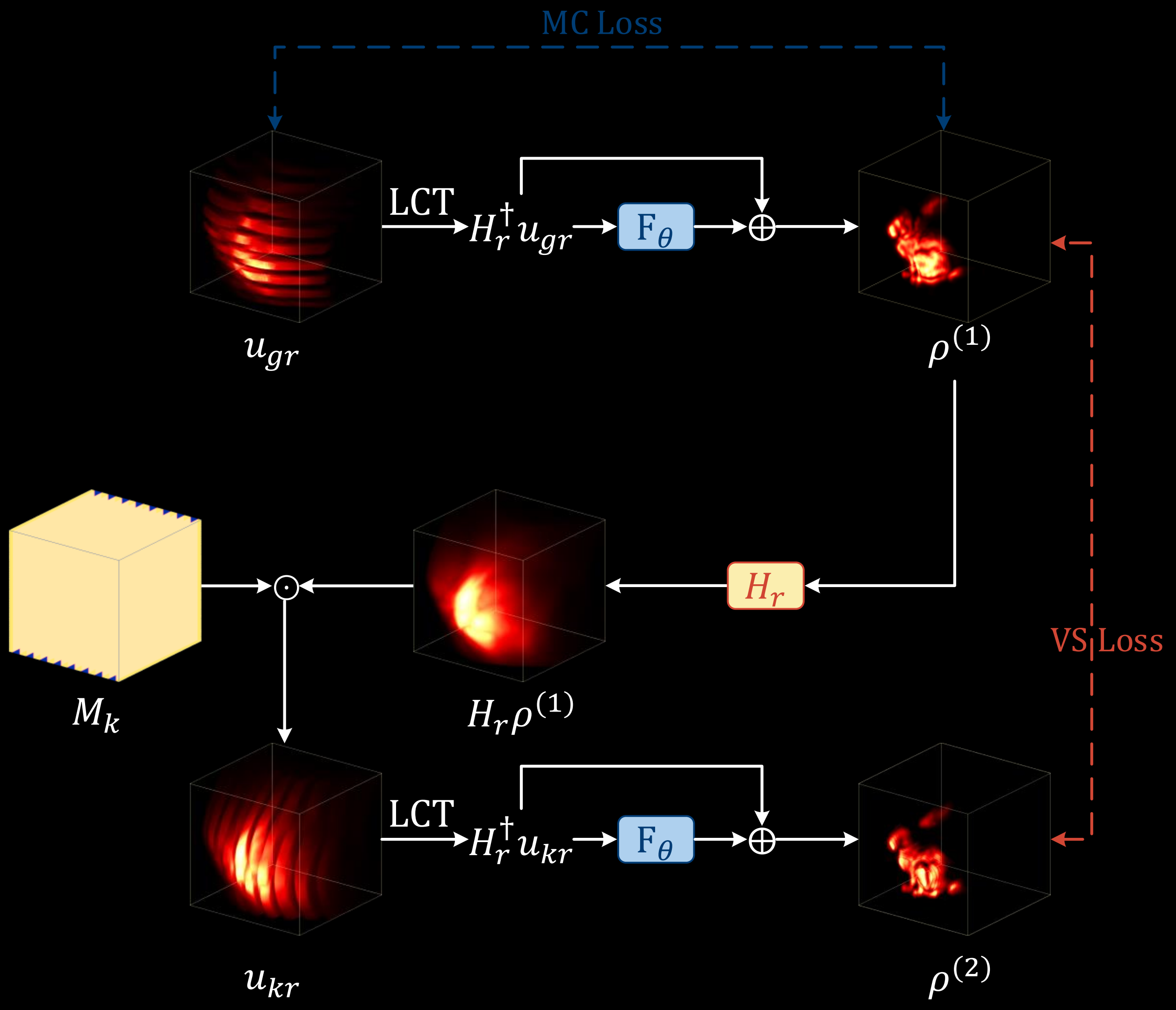
$$\mathcal{X}_{H_1} = \{v \mid H_1^\dagger H_1 v = \mathcal{D}_r(\rho), \mathcal{D}_r(\rho) \in \mathcal{R}_{H_1}\}$$

$$\rho^{(1)} = f_\theta(u) = \mathcal{D}_r(\rho) + F_\theta(\mathcal{D}_r(\rho)) = \mathcal{D}_r(\rho) + v_n, \forall v_n \in \mathcal{N}_H$$

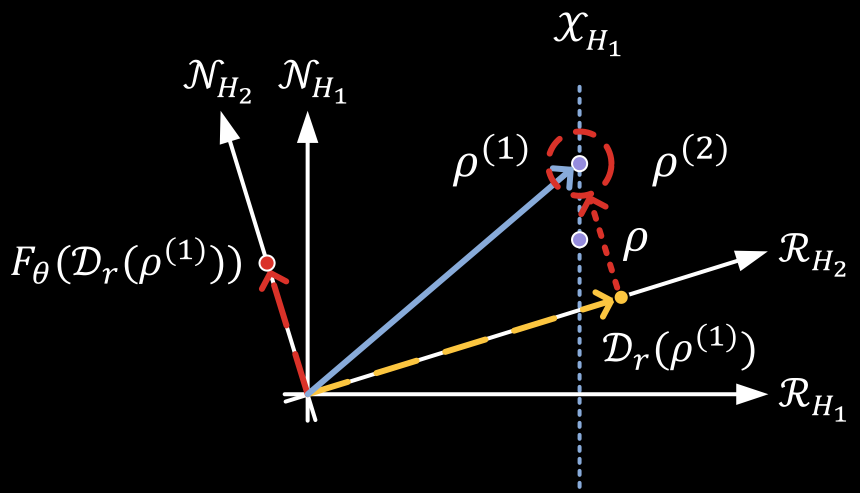
$$H(\mathcal{D}_r(\rho) + v_n) = H H^\dagger H \rho + H v_n = u$$

Virtual Scanning: learn to recover null-space component

Virtual Scanning Process



Recover Null-space Component



$$\rho^{(1)} = f_\theta(u_{gr}) = H_r^{\dagger} u_{gr} + F_\theta(H_r^{\dagger} u_{gr})$$

$$\rho^{(2)} = f_\theta(H_r \rho^{(1)} \odot M_k)$$

VS Loss

$$\rho^{(2)} \rightarrow \rho^{(1)}$$

Equal to

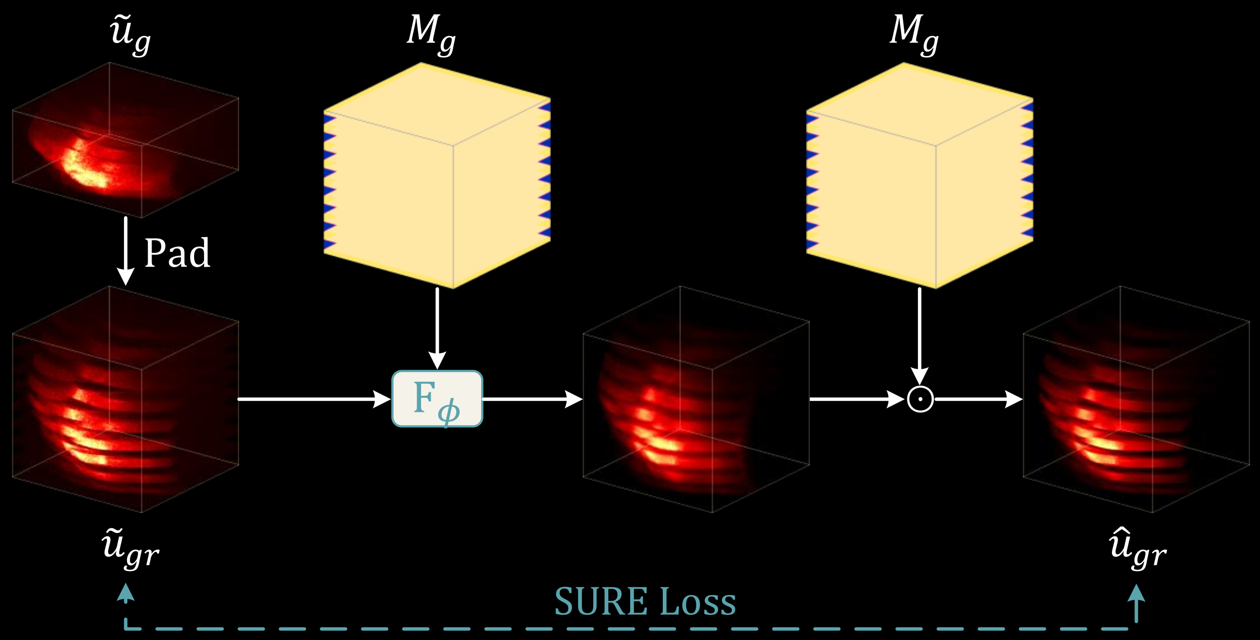
$$F_\theta\left(\mathcal{D}_r\left(\rho^{(1)}\right)\right) + \mathcal{D}_r\left(\rho^{(1)}\right) \rightarrow \mathcal{D}_n\left(\rho^{(1)}\right) + \mathcal{D}_r\left(\rho^{(1)}\right)$$

$$F_\theta\left(\mathcal{D}_r\left(\rho^{(1)}\right)\right) \rightarrow \mathcal{D}_n\left(\rho^{(1)}\right)$$

SURE-based Denoiser

The noise model of NLOS imaging

$$\tilde{u} \sim Poisson(u + b)$$



- Our SURE-denoiser considers the physical detector model of NLOS, which works in a low-photon condition.
- The denoiser can be also trained without paired data.

Stein's Unbiased Risk Estimation (SURE) framework can derive the unbiased estimator of supervised loss function

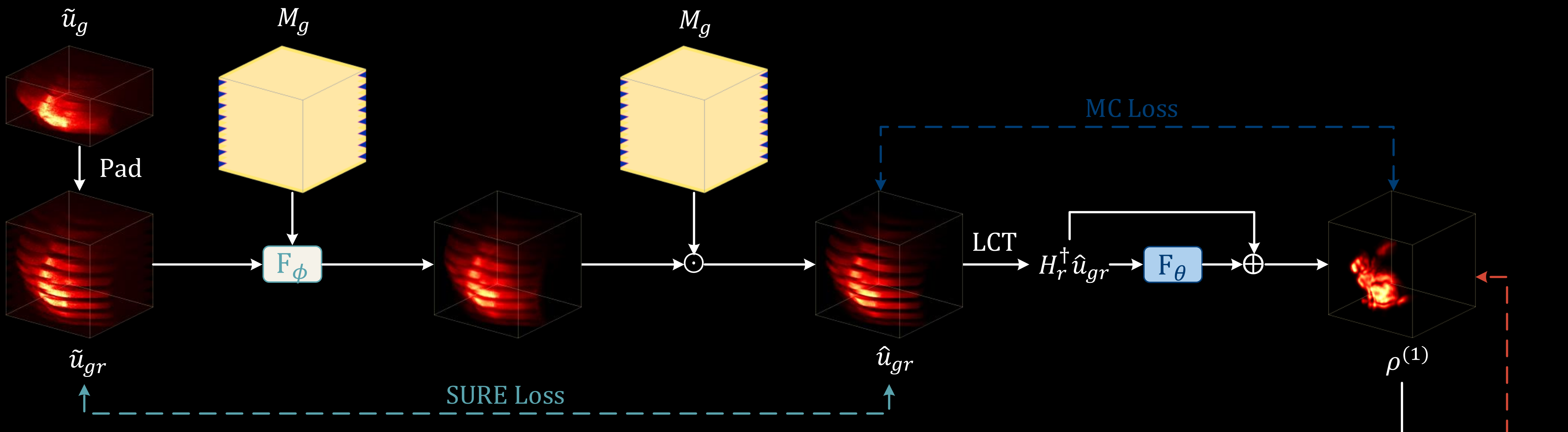
$$\mathbb{E}_{\{\tilde{u},u\}}\left\{\sum_{j=1}^{J}\frac{1}{st}\|u_j - F_\phi(\tilde{u}_j)\|^2\right\} = \mathbb{E}_u\left\{\sum_{j=1}^{J}\frac{1}{st}\mathbb{E}_{\tilde{u}|u}\|u_j - F_\phi(\tilde{u}_j)\|^2\right\}$$

The unsupervised learning SURE-based loss function

$$\sum_{j=1}^{J}\frac{1}{st}\{\|\tilde{u}_j - F_\phi(\tilde{u}_j)\|^2 - (\mathbf{1} + b)^\top \tilde{u}_j +$$

$$2b^\top F_\phi(\tilde{u}_j) + \frac{2}{\varepsilon}(e_j \odot \tilde{u}_j)^\top (F_\phi(\tilde{u}_j + \varepsilon e_j) - F_\phi(\tilde{u}_j))\}$$

Training Details



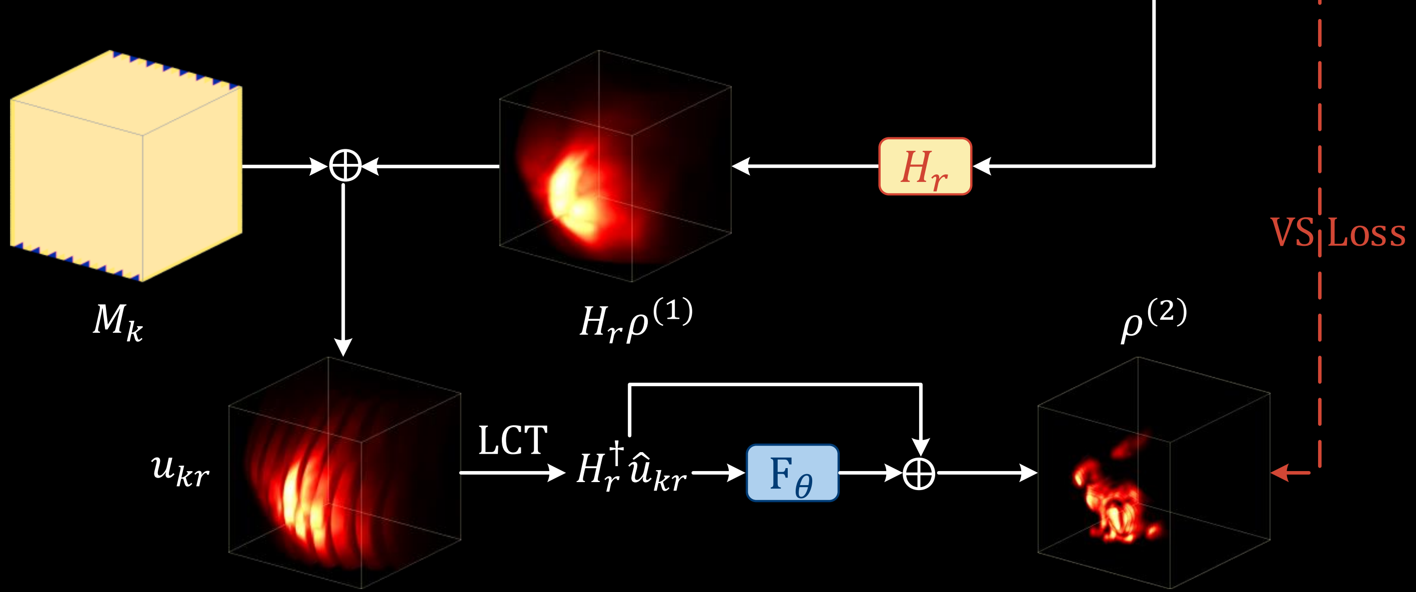
- First stage

$$\mathcal{L}_{\text{SURE}} = \mathbb{E}_{\{i,g\}}\Big\{\frac{1}{st}\|\tilde{u}_{i,g} - F_\phi(\tilde{u}_{i,g})\|_2^2 - \frac{1}{st}(\mathbf{1}+b)^\top \tilde{u}_{i,g} + \frac{2}{st}b^\top F_\phi(\tilde{u}_{i,g}) + \frac{2}{st\varepsilon}(e_{i,g}\odot \tilde{u}_{i,g})^\top\big(F_\phi(\tilde{u}_{i,g}+\varepsilon e_{i,g}) - F_\phi(\tilde{u}_{i,g})\big)\Big\}$$

- Second stage

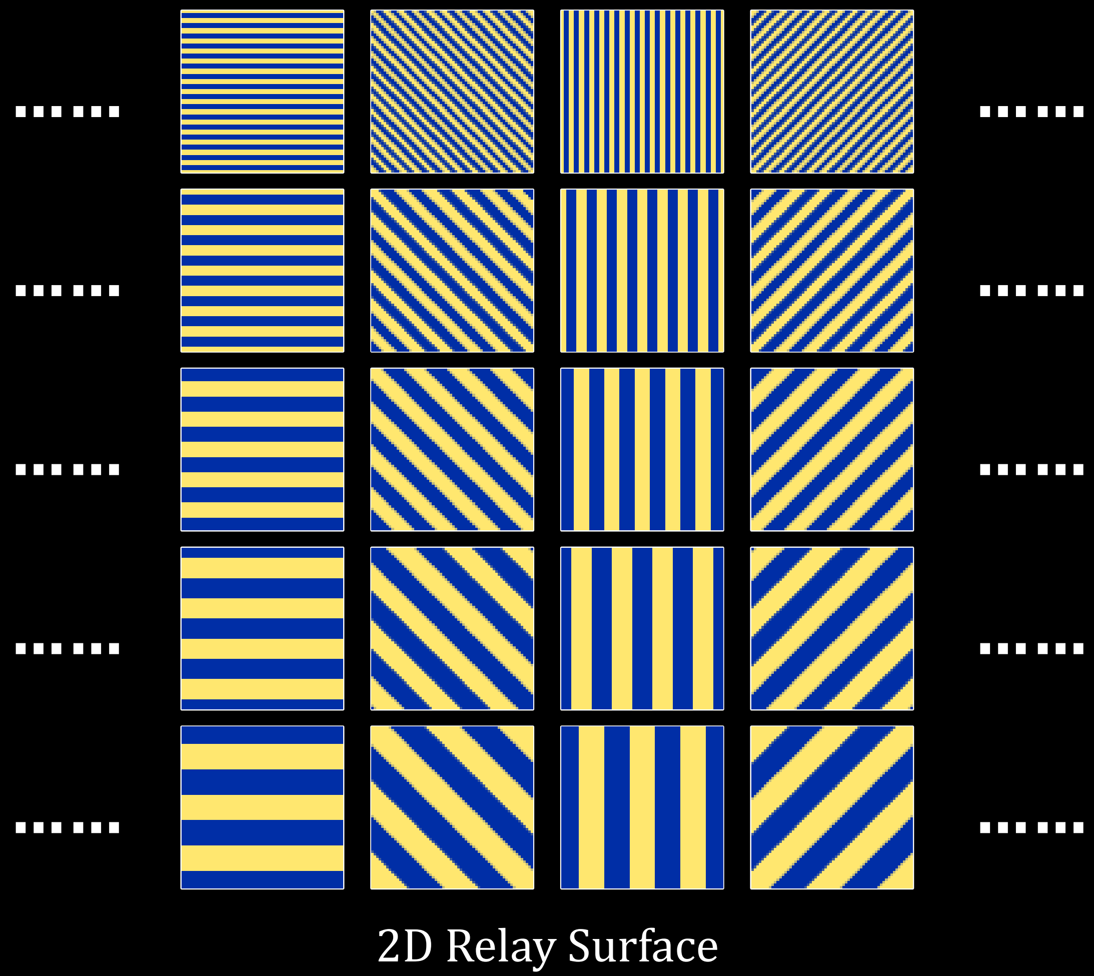
$$\mathcal{L}_{\text{VS}} = \mathbb{E}_{\{i,g\}}\|f_\theta(\hat{u}_{i,g}) - f_\theta(H_k(f_\theta(\hat{u}_{i,g}))\|_2^2$$

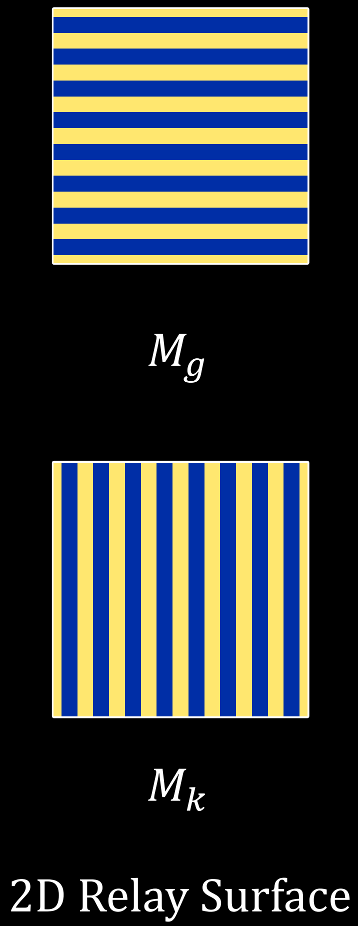
$$\mathcal{L}_{\text{MC}} = \mathbb{E}_{\{i,g\}}\|\hat{u}_{i,g} - H_g(f_\theta(\hat{u}_{i,g}))\|_2^2$$

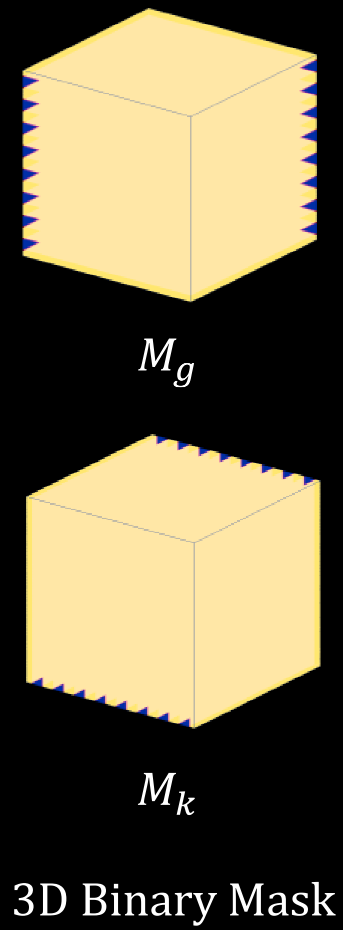


Experiment Setup

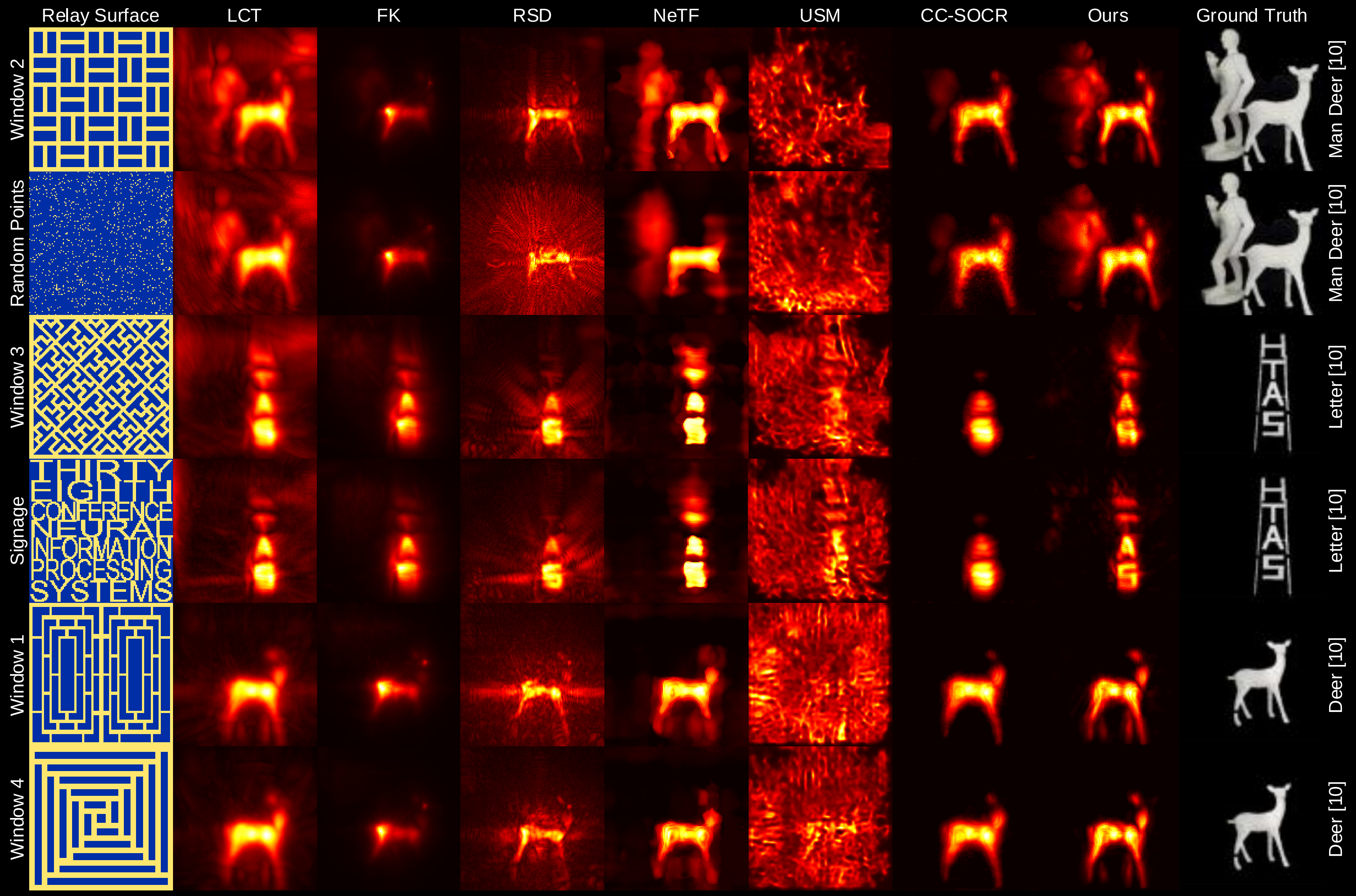
- How to create a group of forward operators







Results on public real-world dataset



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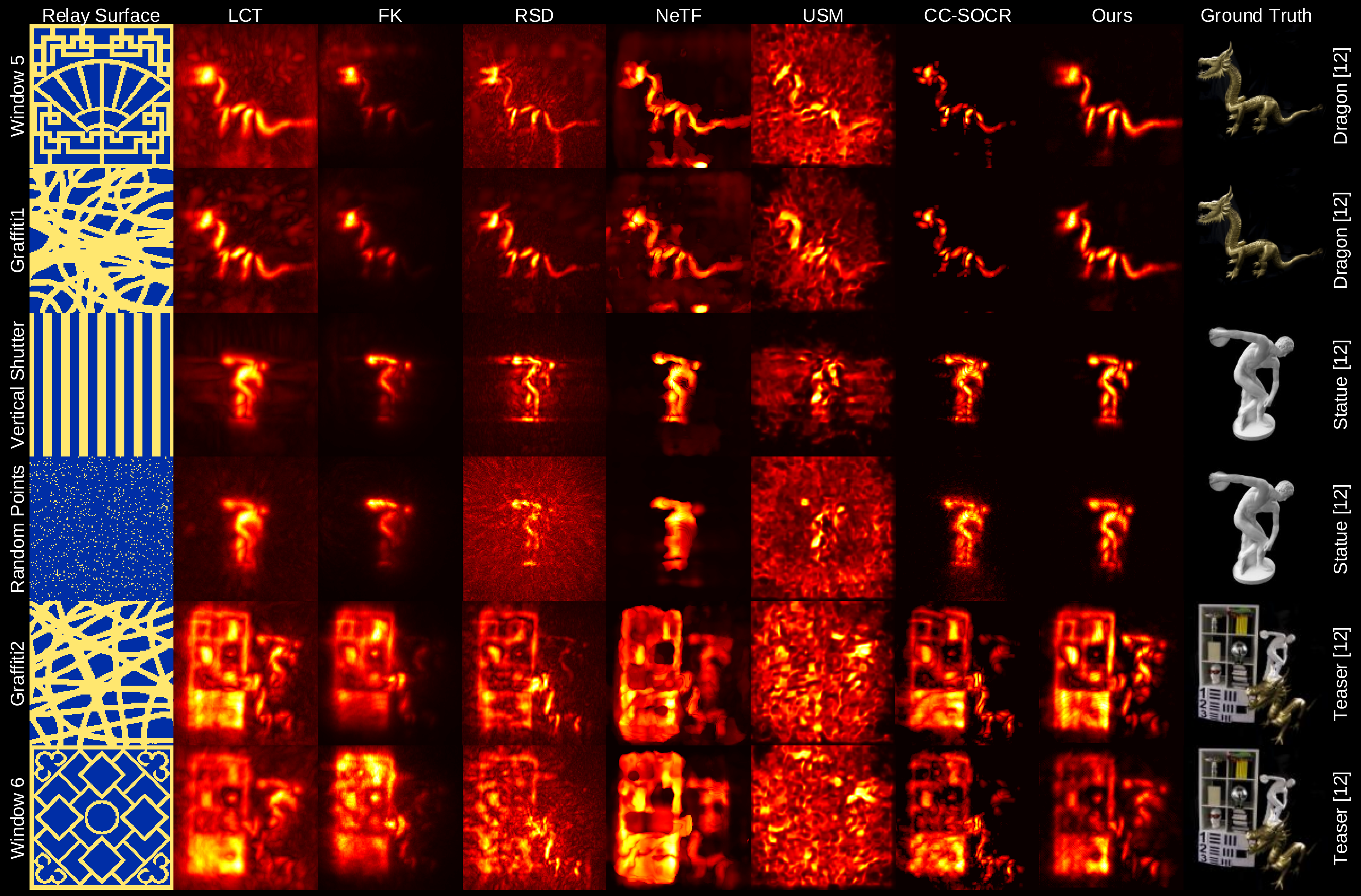
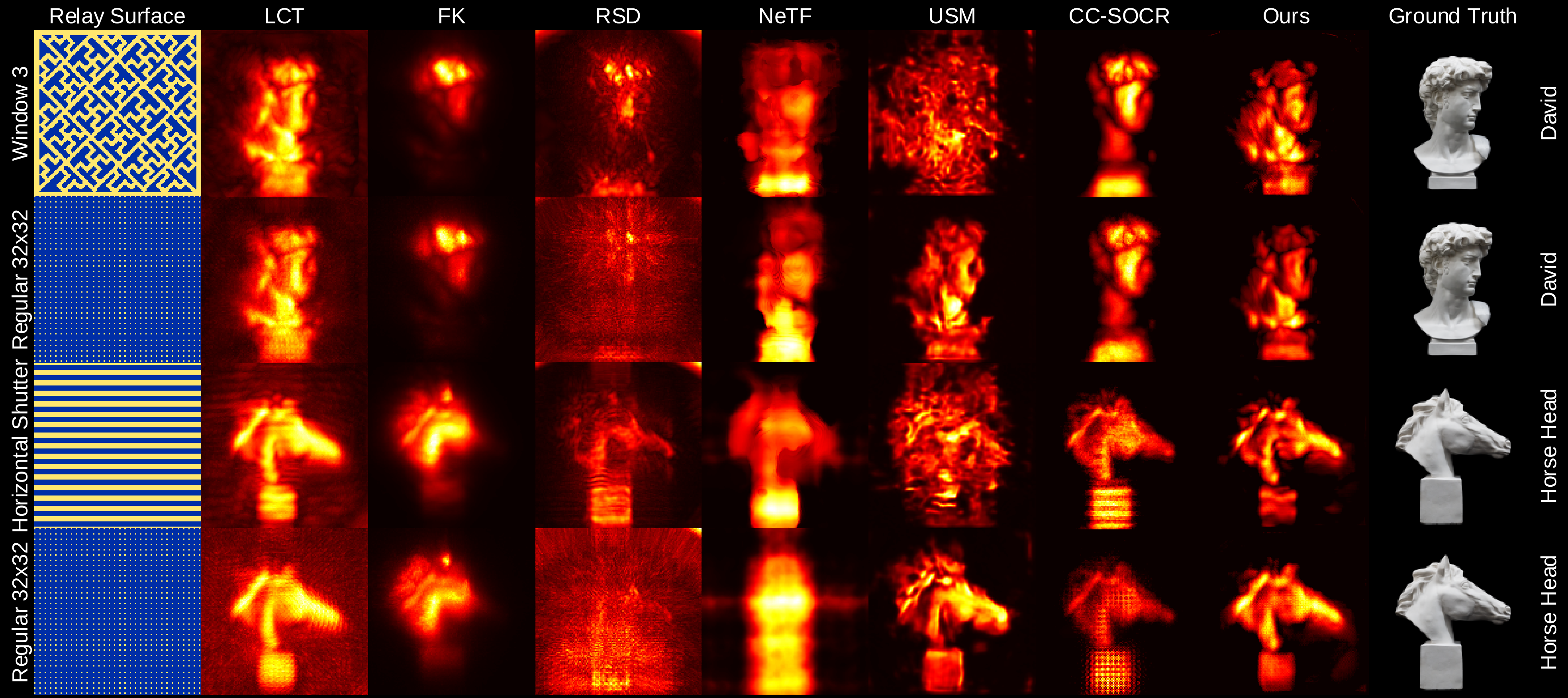


Results on self-captured real-world dataset

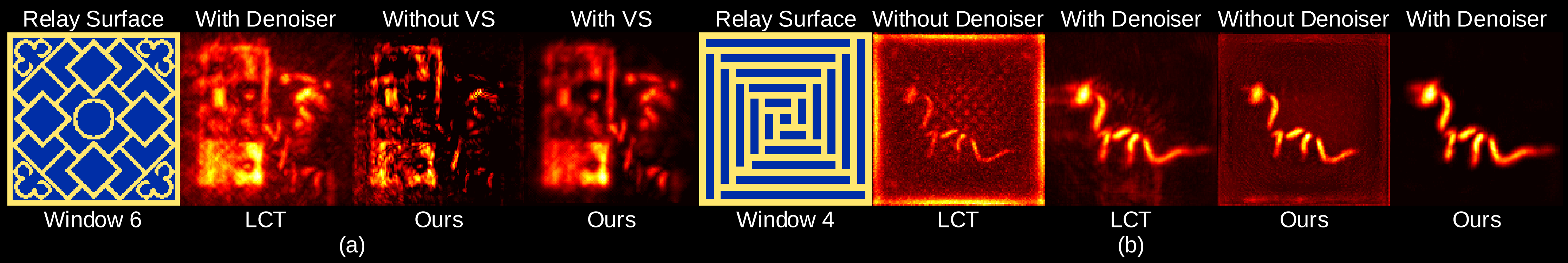


Inference Time

Method	LCT	FK	RSD	NeTF	USM	CC-SOCR	Ours
Runtime(CPU)	0.81 s	1.52 s	0.94 s	N/A	2.34 s	7.73 h	2.24 s
Runtime(GPU)	0.09 s	0.15 s	0.12 s	0.69 h	0.24 s	N/A	0.18 s

Ablation Study

Qualitative Results



Quantitative Results

SURE-based denoiser	Virtual Scanning Process	PSNR (dB)
×	√	18.69
√	×	19.63
√	√	20.52

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