Compressive Spectral Image Sensing, Processing, and Optimization

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  - CSI + Time-of-Flight imaging
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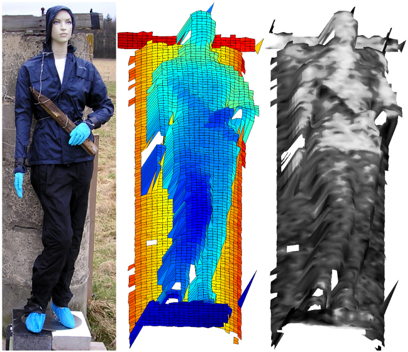
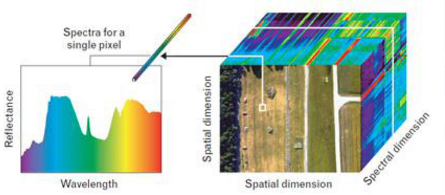
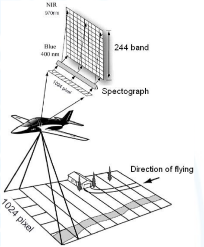


The Spectral Imaging Problem

- Push broom spectral imaging: Expensive, low sensing speed, senses $N \times N \times L$ voxels



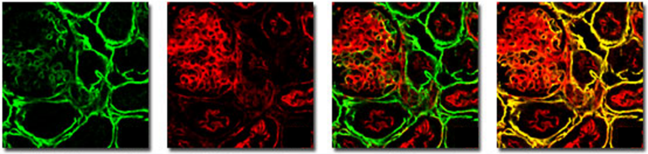


- Optical Filters; Sequential sensing of $N \times N \times L$ voxels; limited by number of colors

Why is this Important?

- Remote sensing and surveillance in the Visible, NIR, SWIR

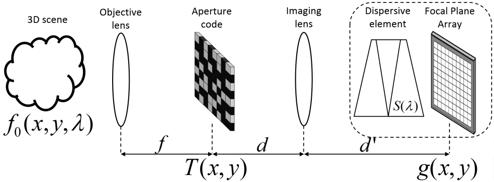
- Devices are challenging in NIR and SWIR due to SWaP

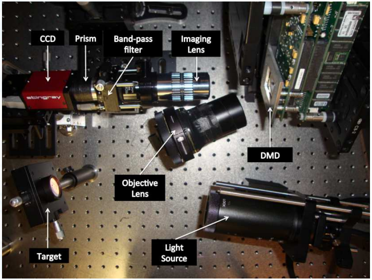


- Medical imaging and other applications

Remarkable Compressive Spectral Imaging Arquitecture

- Coded aperture-based compressive spectral imager (CASSI)
- High compression ratio (Bands:1)
- High fidelity hyperspectral reconstructions





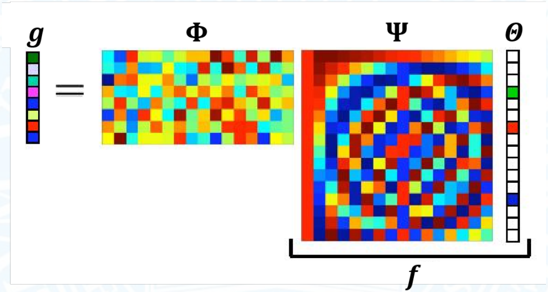
Analog Compressive Measurement

$$g(x,y) = \int T(x+S(\lambda),y) f_0(x+S(\lambda),y,\lambda) d\lambda.$$

Compressive Sensing Fundamentals

CS was introduced by Donoho†, Candès‡, Tao, Romberg...

- Measurements are given by $\mathbf{g} = \mathbf{\Phi}\mathbf{f}$

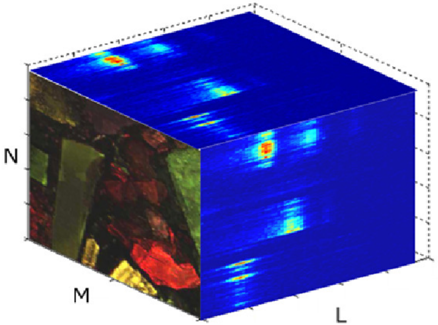


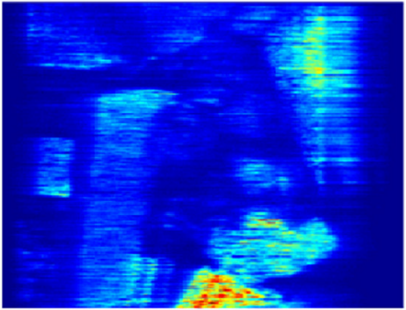
- A sparse solution $\boldsymbol{\theta}$ is recovered from g by solving the inverse problem

$$\hat{\boldsymbol{\theta}} = \min_{\boldsymbol{\theta}} \|\boldsymbol{\theta}\|_1 \text{ s.t. } \mathbf{g} = \mathbf{\Phi}\mathbf{\Psi}\boldsymbol{\theta}.$$

† Donoho. IEEE Trans. on Information Theory. December 2006.
‡ Candès, Romberg and Tao. IEEE Trans. on Information Theory. April 2006.

Compressive Measurements





Datacube

$$\mathbf{f} = \boldsymbol{\Psi}\boldsymbol{\theta}$$

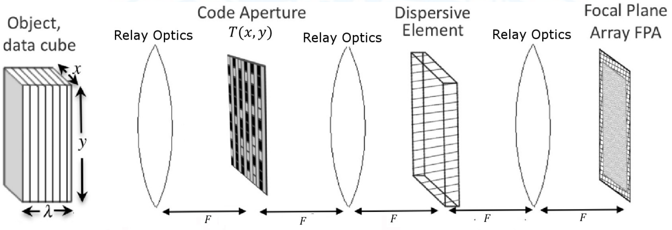
Compressive Measurements

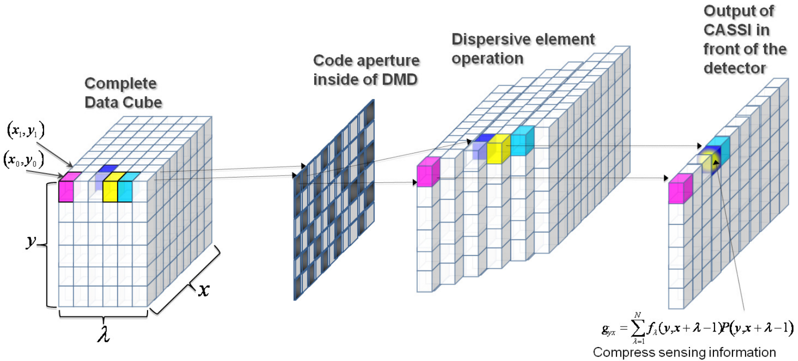
$$\mathbf{g} = \boldsymbol{\Phi}\boldsymbol{\Psi}\boldsymbol{\theta} + \mathbf{w}$$

Underdetermined system of equations

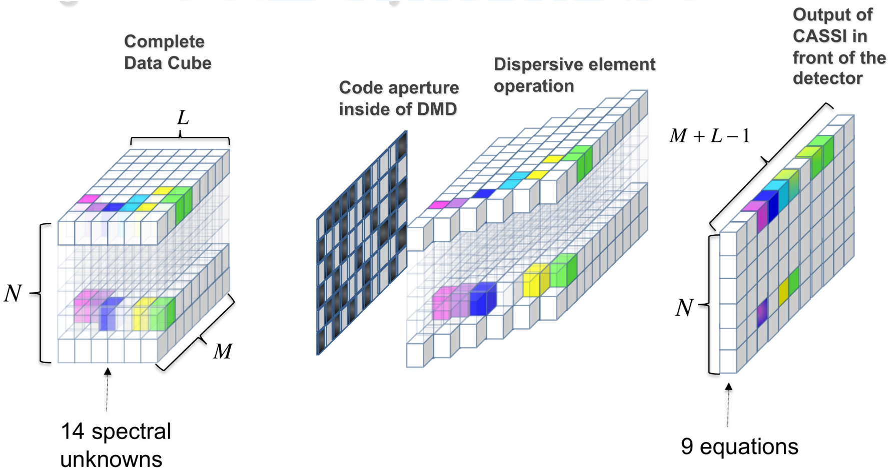
$$\hat{\mathbf{f}} = \boldsymbol{\Psi}\{\min_{\boldsymbol{\theta}} \|\mathbf{g} - \boldsymbol{\Phi}\boldsymbol{\Psi}\boldsymbol{\theta}\|_2 + \tau\|\boldsymbol{\theta}\|_1\}$$

CASSI: Principles of Operation





CASSI: Sensing+Compressive System



Undetermined system of equations: $N \times M \times L$ Unknowns and $N(M + L - 1)$ Equations.

CASSI: Computational Model

A single shot compressive measurement across the FPA:

$$G_{nm} = \sum_{i=0}^{L-1} F_{i(n+m)m} T_{i(n+m)} + w_{in}$$

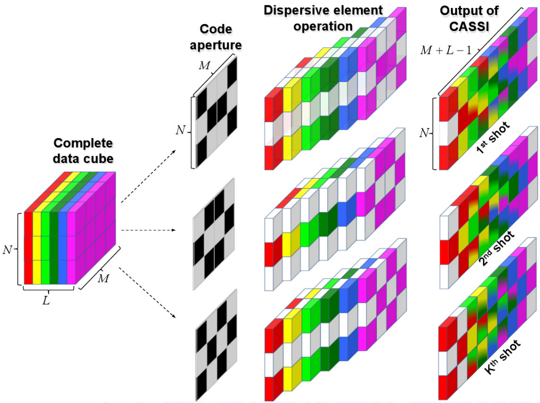
- F is the $N \times M \times L$ datacube
- T is the binary code aperture
- w is the sensing noise

In vector form, the FPA measurement can be written as

$$\mathbf{g} = \mathbf{H}\mathbf{f} + \mathbf{w}$$

- $\mathbf{H}$ accounts for the coded aperture and the dispersive element.

CASSI: Multishot Matrix Model



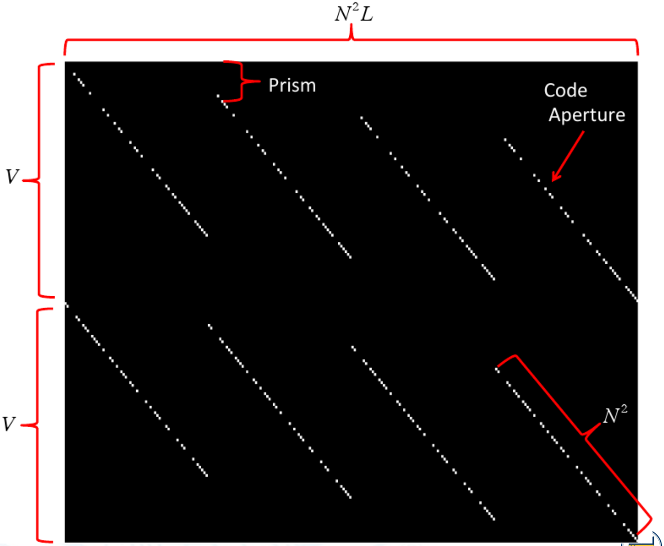
$$\begin{bmatrix} \mathbf{g}^0 \\ \mathbf{g}^1 \\ \vdots \\ \mathbf{g}^{k-1} \end{bmatrix} = \begin{bmatrix} \mathbf{H}_0 \\ \mathbf{H}_1 \\ \vdots \\ \mathbf{H}_{k-1} \end{bmatrix} \mathbf{f},$$

$$\mathbf{g} = \mathbf{H}\mathbf{f}, \mathbf{H} \in \{0, 1\}$$

- Multi-shot coding done by using multiple coded apertures or a Digital-Micromirror-Device (DMD)

CASSI: Forward Operator $\mathbf{H}$

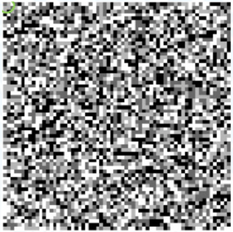
- Data cube: $N \times N \times L$
- Spectral bands: L
- Spatial resolution: $N \times N$
- Sensor size $N \times (N + L - 1)$
- $V = N(N+L-1)$



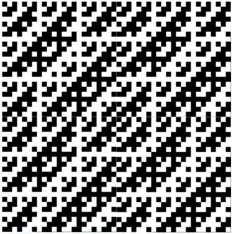
Performance of Different Coded Apertures

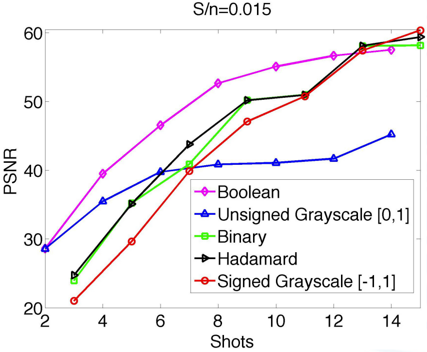
Binary

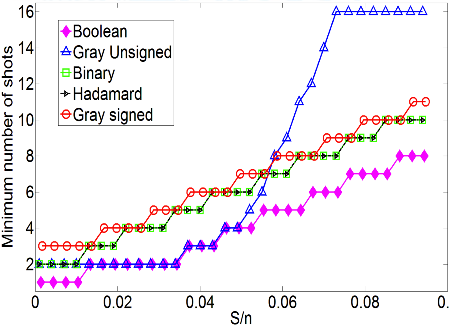
Grayscale



Hadamard

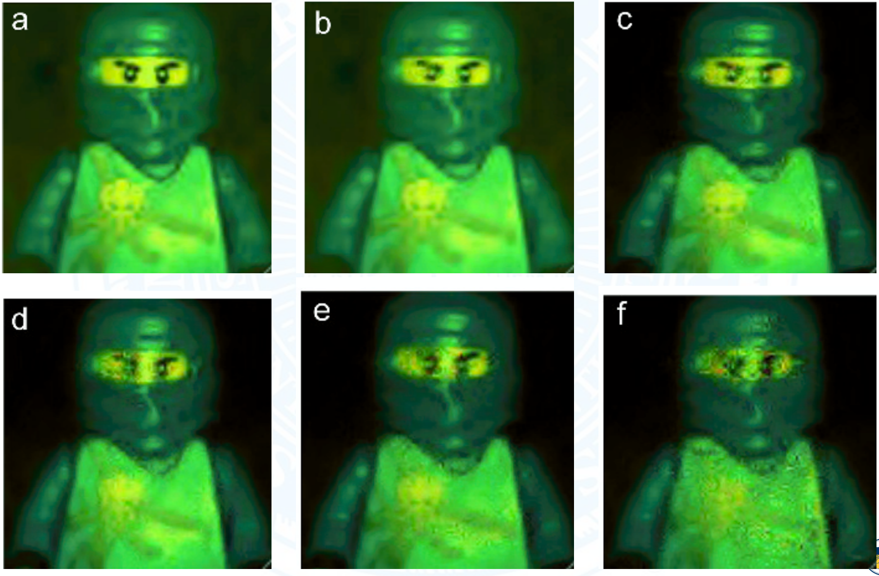






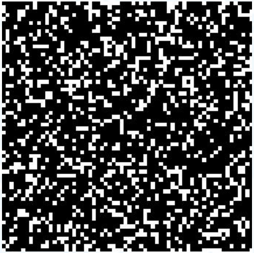
Reconstructions

Original | Boolean | Unsigned grayscale

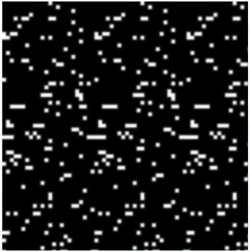


Binary | Hadamard | Signed grayscale

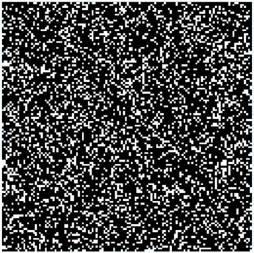
Broad Family of Coded Apertures



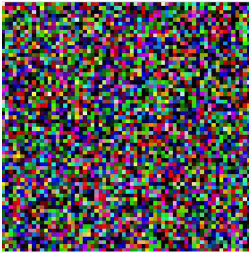
(a) Boolean



(b) Spectral Selective

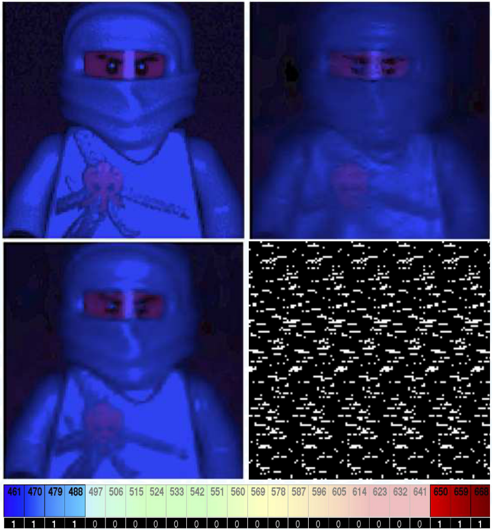


(c) Super-resolution



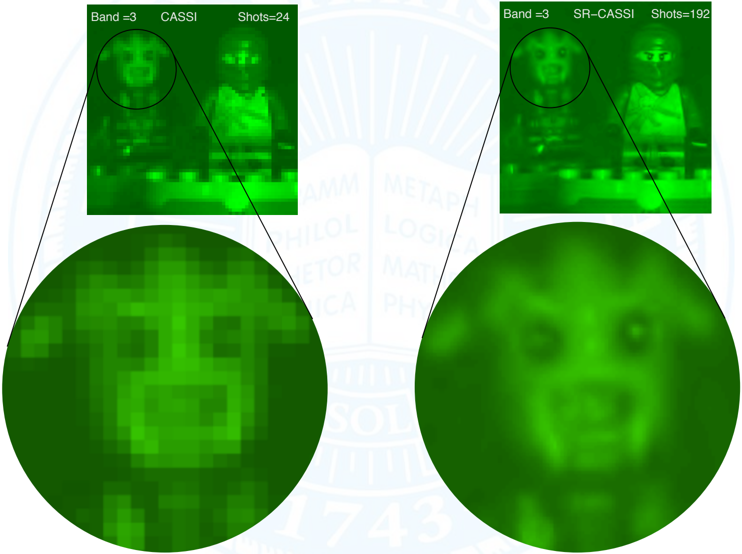
(d) Colored

Coded Apertures for Spectral Selectivity



(Top-left) The desired image. Reconstructions: (Top-right) random codes (26.92 dB), (Middle-left) selective codes (31.02 dB). (Middle-right) Spectral selective coded aperture. (Bottom) Wavelengths of desired bands.

Coded Apertures for Super-Resolution

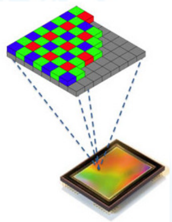


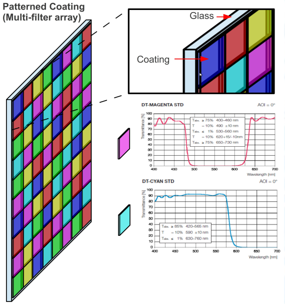
(Left) CASSI reconstruction (Right) Super-resolved reconstruction

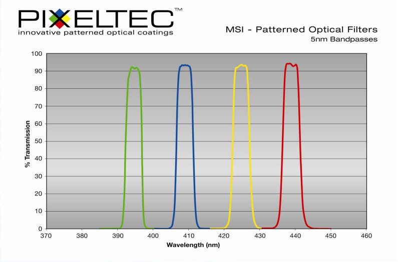
Colored Coded Aperture Spectral Imaging

Patterned coating combines micro-lithography with optical coating technology.

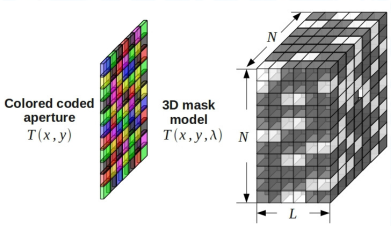
- Precision patterned coating and patterns
- Sub-pixel alignment accuracy
- Ultraviolet, visible, NIR, SWIR
- Multi-filter arrays on monolithic substrates



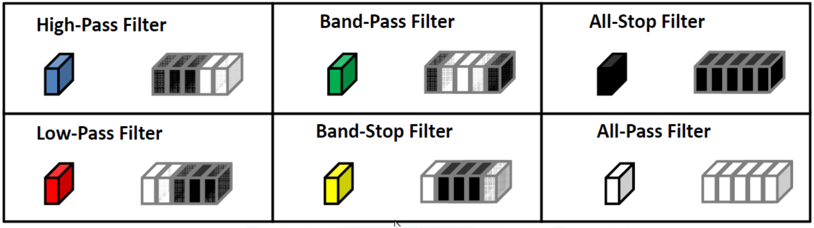




Colored coded aperture model

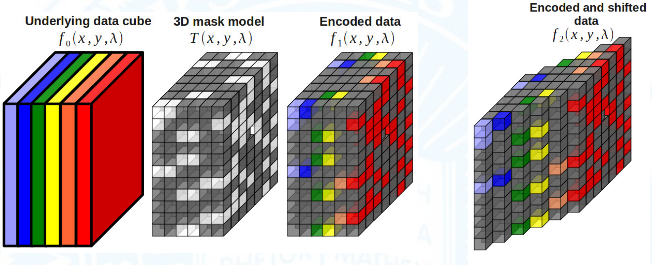


- Colored coded aperture is a color filter array
- Each entry is a wavelength selective color filter
- 3D Mask model has the same dimensions than the objective discrete data cube

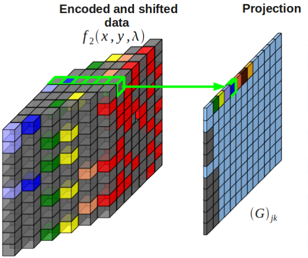


Linear dispersion and focal plane array integration

Linear shifting operation

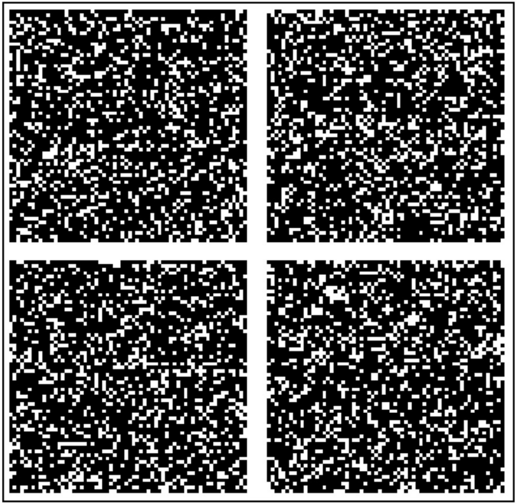


Focal plane array (FPA) projections



The number of pixels of the FPA detector is $N(N+L-1) \ll N^2L$ (size of the spectral data cube)

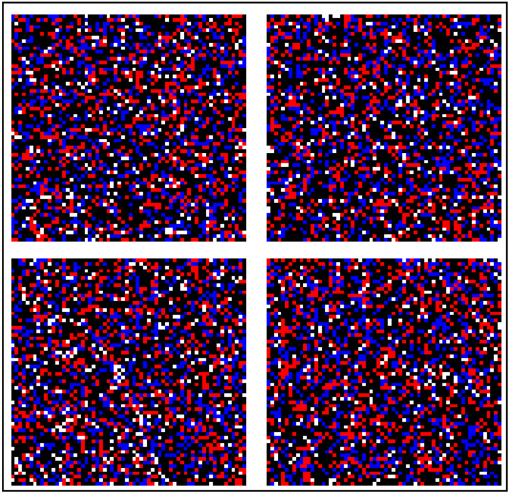
Random Boolean Code



Original Slice

Recovered Slice, PSNR = 38.89 dB

4 Colors Random Code



Original Slice

Recovered Slice, PSNR = 49.61 dB

Restricted Isometry Property of Colored CASSI

$\mathbf{A} = \mathbf{H}\boldsymbol{\Psi}, \quad \boldsymbol{f} = \boldsymbol{\Psi}\boldsymbol{\theta}, \quad \boldsymbol{\Psi} = \mathbf{W} \otimes \boldsymbol{\Psi}^{2D}$

Definition

$$(1-\delta_s)\,||\boldsymbol{\theta}||_2^2 \leq ||\mathbf{A}\boldsymbol{\theta}||_2^2 \leq (1+\delta_s)\,||\boldsymbol{\theta}||_2^2,$$

$$\delta_s = \max_{\mathcal{T}\subset[N^2L],|\mathcal{T}|\leq S} ||\mathbf{A}_{|\mathcal{T}|}^T\mathbf{A}_{|\mathcal{T}|} - \mathbf{I}||_2^2,$$

$\mathbf{A}_{|\mathcal{T}|}$, $|\mathcal{T}|$ columns of $\mathbf{A}$ indexed by the set $\mathcal{T}$

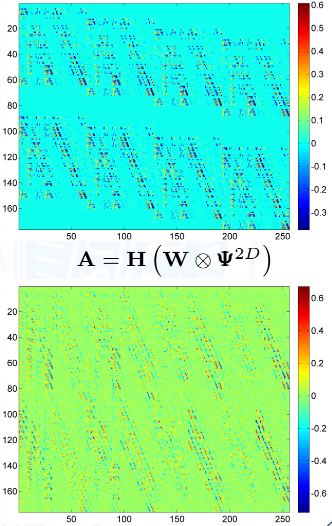
$$\delta_s = \max_{\mathcal{T}\subset[N^2L],|\mathcal{T}|\leq S} \lambda_{max}\left(\mathbf{A}_{|\mathcal{T}||\mathcal{T}|} - \mathbf{I}\right)$$

$$\left(\mathbf{A}_{|\mathcal{T}|}\right)_{ir} = \mathbf{h}_i\boldsymbol{\psi}_{\Omega_r} = \sum_{k=0}^{L-1}\left(\mathbf{t}_k^{\ell_i}\right)_{m_i-kN}\Psi_{m_i+k(N'),\Omega_r}$$

$$(\mathbf{h}_i)_j = \begin{cases}\left(\mathbf{t}_{k_j}^{\ell_i}\right)_{i-\ell_iV-k_jN}, & \text{if } i-\ell_iV = j-k_jN' \\ 0, & \text{otherwise,}\end{cases}$$

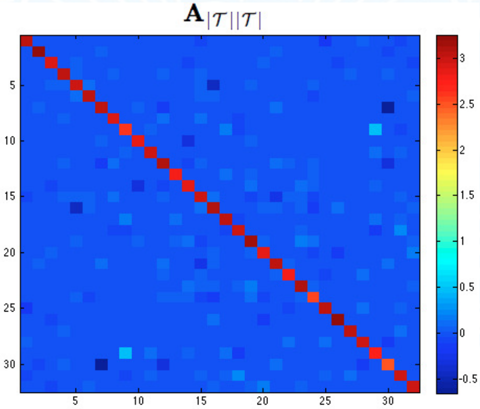
$\mathbf{A} = \mathbf{H}\boldsymbol{\Psi}^{2D}$

$\mathbf{A} = \mathbf{H}\left(\mathbf{W}\otimes\boldsymbol{\Psi}^{2D}\right)$

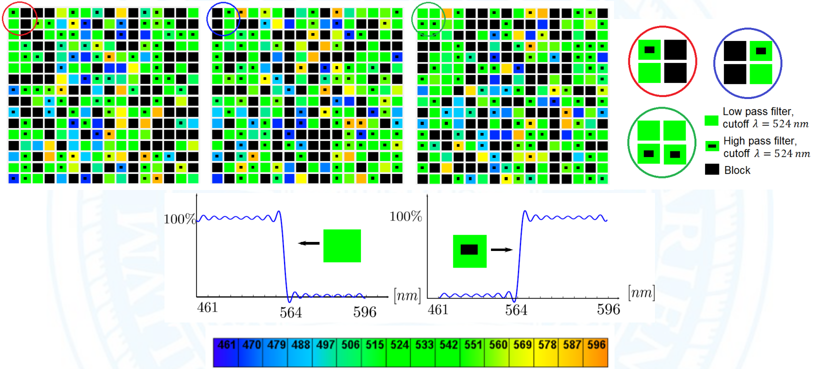


$$\mathbf{A}_{|\mathcal{T}||\mathcal{T}|} = \mathbf{A}^{T}_{|\mathcal{T}|}\mathbf{A}_{|\mathcal{T}|}$$

$$\left(\mathbf{A}_{|\mathcal{T}||\mathcal{T}|}\right)_{r,u} = \sum_{\ell=0}^{K-1}\sum_{i=0}^{V-1}\sum_{k_1=0}^{L-1}\sum_{k_2=0}^{L-1}\left(\mathbf{t}^{\ell}_{k_1}\right)_{i-k_1 N}\left(\mathbf{t}^{\ell}_{k_2}\right)_{i-k_2 N}\Psi_{i+k_1 N',\Omega_r}\Psi_{i+k_2 N',\Omega_u}$$

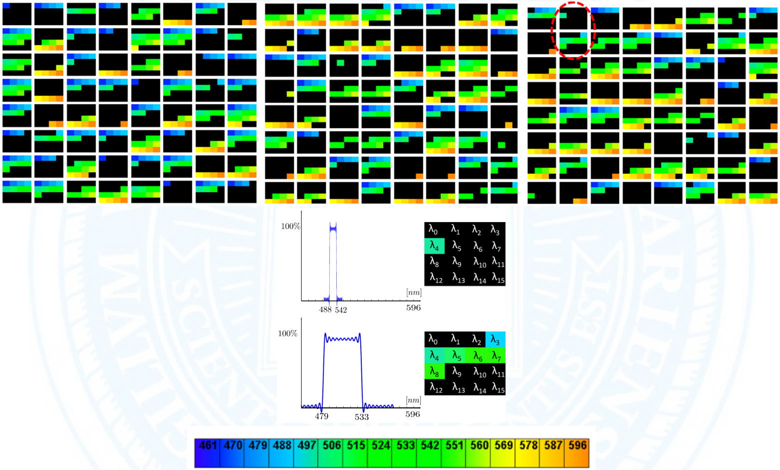


Results: LH-Colored Coded Aperture

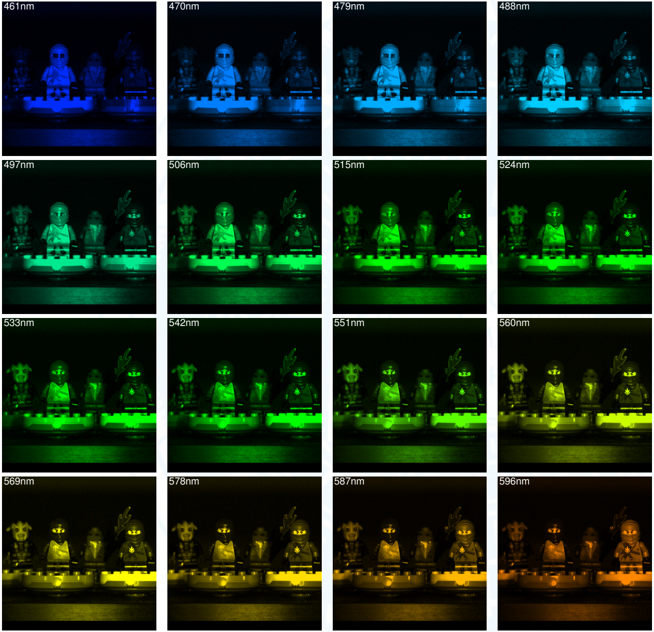


A geometric interpretation of the colored coded apertures for LH-Colored filters (3 shots).

Results: B-Colored Coded Aperture



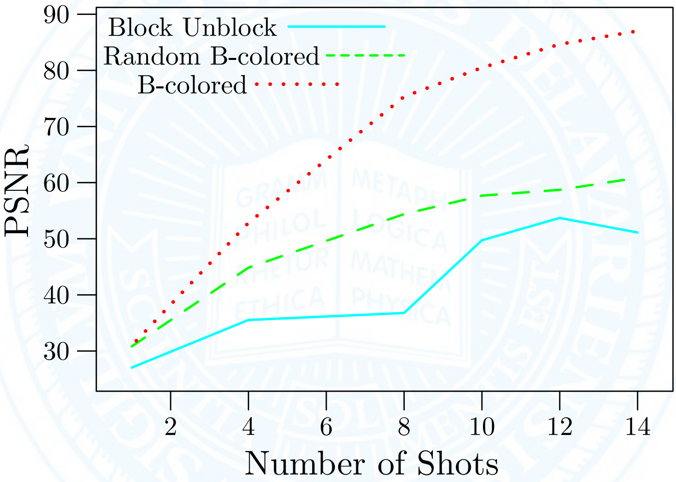
Geometric interpretation of colored coded apertures for B-filters (3 shots)



Data Base:

- 16 channels
- 461-596nm
- 256×256 pixels

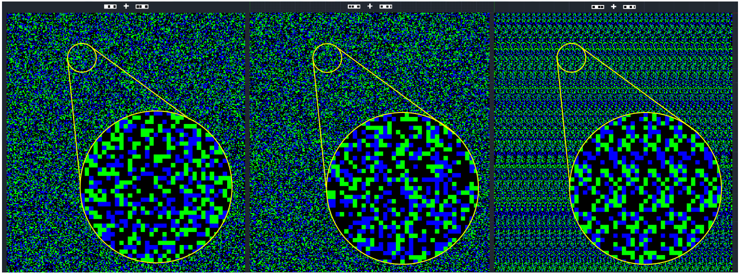
Reconstruction From B-Colored Coded Apertures



Mean PSNR of the reconstructed data cubes.

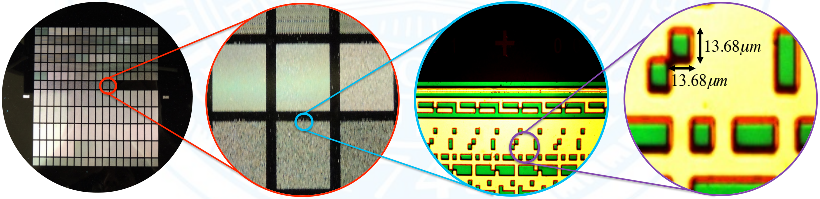
Real Design and Fabrication

- Design



Random distribution | Boolean distribution | Optimal distribution

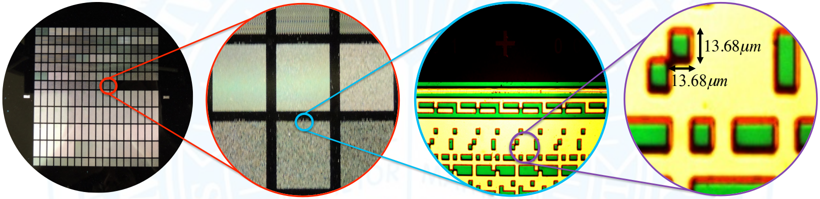
- Fabrication



Wafer with 210 patterns | Each pattern has a different entries distribution | Each distribution has realizations of LP, HP, or block filters | Pixel pitch of 13.68 um

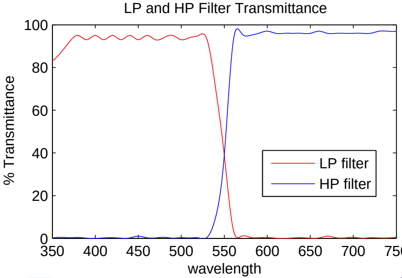
CCA Fabrication (Pixelteq Corp.)

- Eagle XG substrate with 1.1 mm thickness
- Each pattern has 256×256 pixels with $20um$ pitch
- Sharp-transition low pass and high pass filters

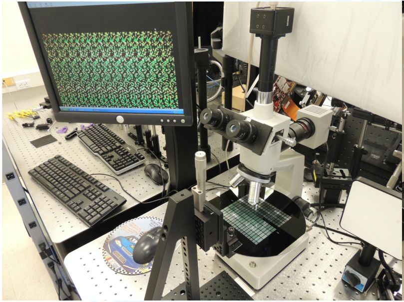


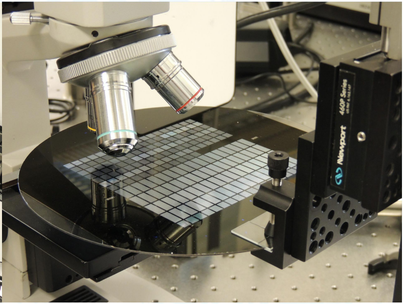
Wafer with 210 patterns | Each pattern has a different entries distribution | Each distribution has realizations of LP, HP, or block filters | Pixel pitch of 13.68 um

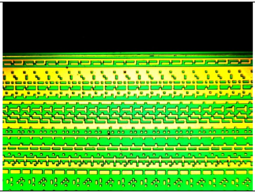
- LP transmittance: 93% in 350-450 nm, and 0.25% in 560-750 nm.
- HP transmittance: 0.04% in 350-450 nm, and 96% in 560-750 nm.



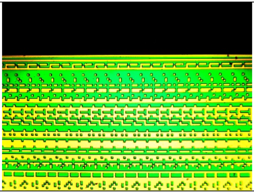
Analysis of the CCA



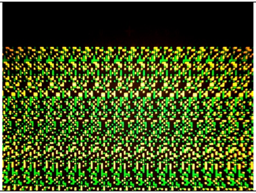




(a) 1st pattern FRONT side

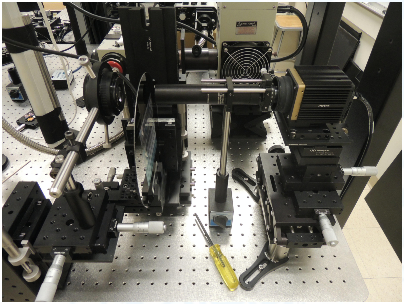


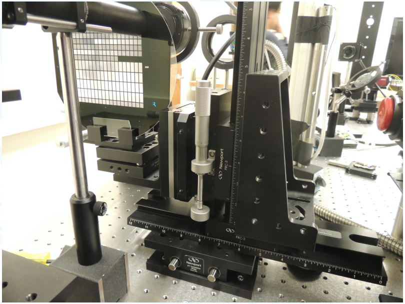
(b) 2nd pattern FRONT side



(c) 3rd pattern FRONT side

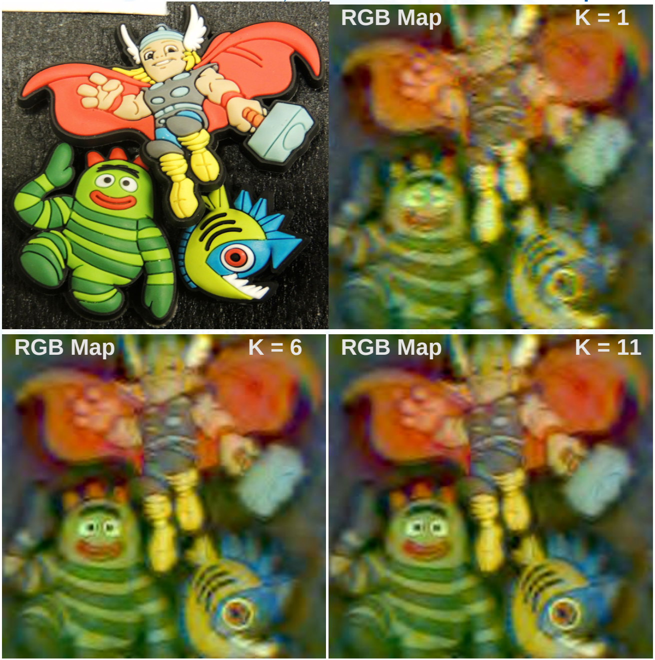
CCA-based CASSI System Testbed



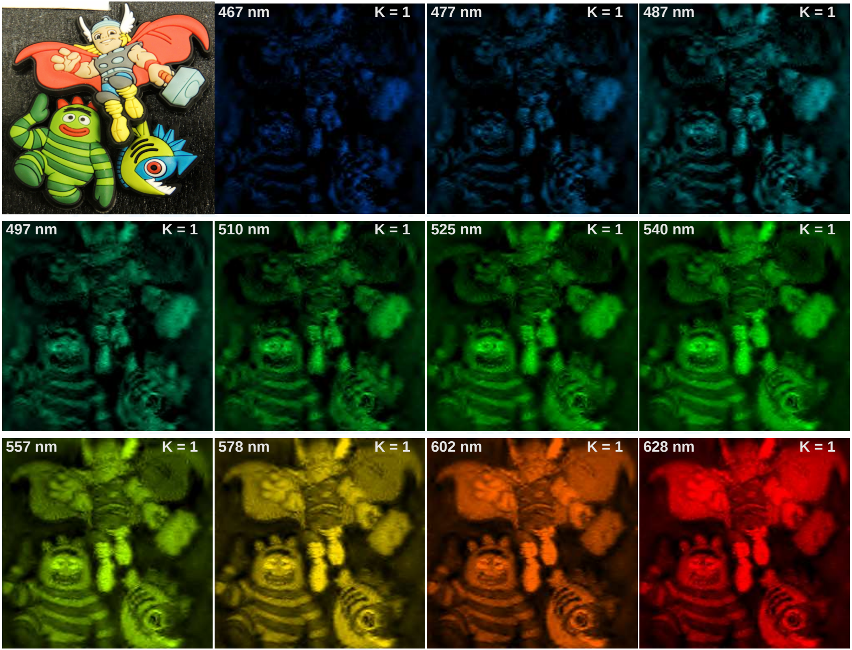


Objective Lens	Leica COLORPLAN-P2
CCA	256×256 pix., 20 um
Prism	Double Amici prism
Sensor	Bobcat B2021 (2048×2048 pix., 7.4 um)
Attainable resolution	$256 \times 256 \times 11$

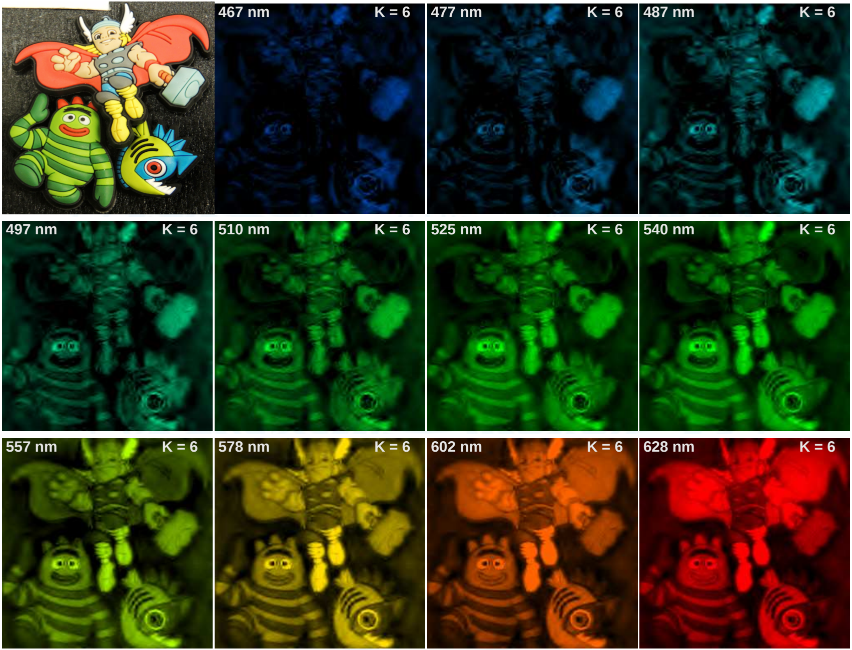
Preliminar Results: $K = 1, 6, 11$ Random Snapshots



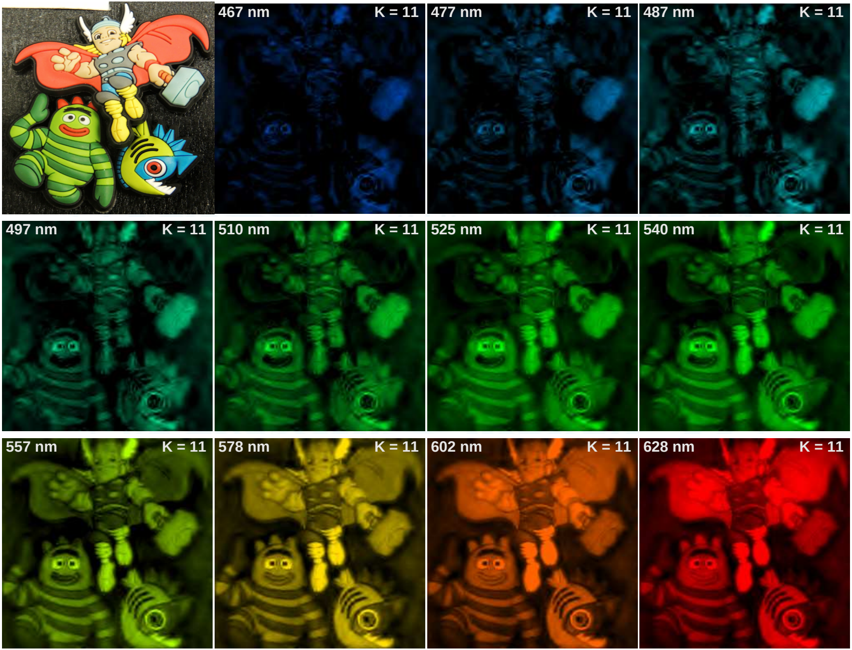
Preliminar Results: $K = 1$ Random Snapshots



Preliminar Results: $K = 6$ Random Snapshots



Preliminar Results: $K = 11$ Random Snapshots



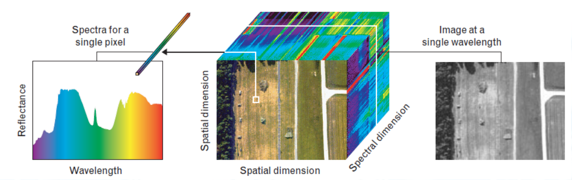
CSI Extensions

- Compressive Spectral + Polarization Imaging
- Compressive Imaging with Rotating Polar Coded Apertures
- Compressive Spectral Imaging + Side Information
- Compressive Spectral + Integral Imaging
- Compressive Spectral + 3D ranging (Time-of-Flight Imaging)

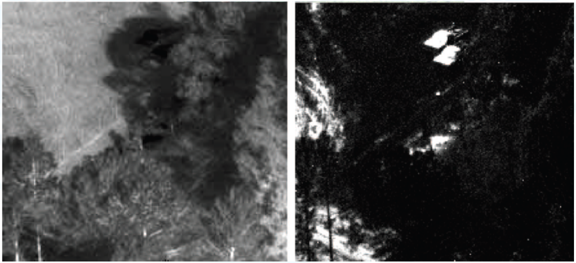
Compressive Spectral + Polarization Imaging

Compressive Spectral+Polarization Imaging

- Spectral imaging provides a spectral profile of targets.



- Polarization imaging provides surface information of targets, such as smoothness and orientation.



Stokes Parameters and Polarization Intensity

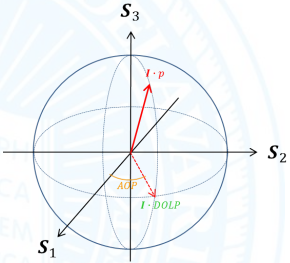
I_θ is the intensity of θ^o linear polarization. I_{left} and I_{right} represent the intensity of left and right handed polarization.

$$S_0 = I_0 + I_{90} = I_{45} + I_{135}$$

$$S_1 = I_0 - I_{90}$$

$$S_2 = I_{45} - I_{135}$$

$$S_3 = I_{right} - I_{left}$$



From the Stokes parameters, we calculate the degree of linear polarization and angle of polarization:[1]

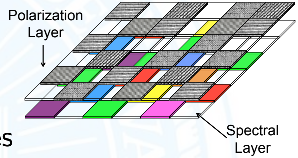
$$DoLP = \sqrt{\frac{S_1^2 + S_2^2}{S_0^2}}$$

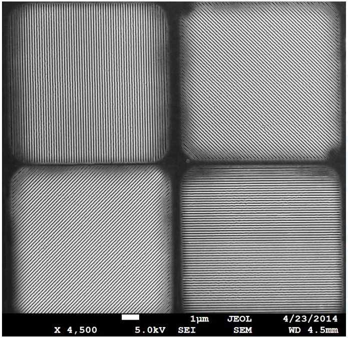
$$AoP = \frac{1}{2}\arg\tan(\frac{S_2}{S_1})$$

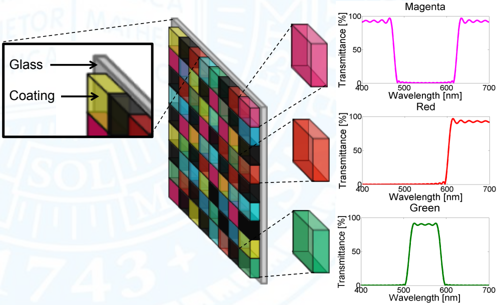
Spectro-Polarimetric Pixelated Technology

Patterned coating combines micro-lithography with optical coating technology.

- Precision patterned coating and patterns
- Sub-pixel alignment accuracy
- Ultraviolet, visible, NIR, SWIR
- Multi-filter arrays on monolithic substrates

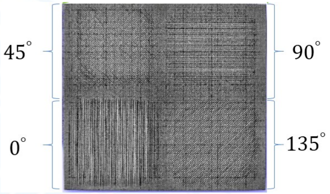




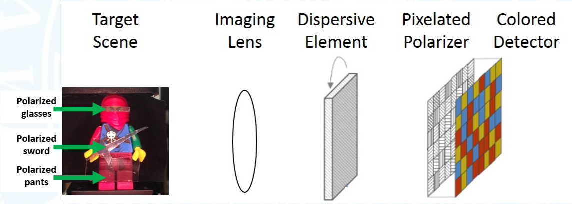


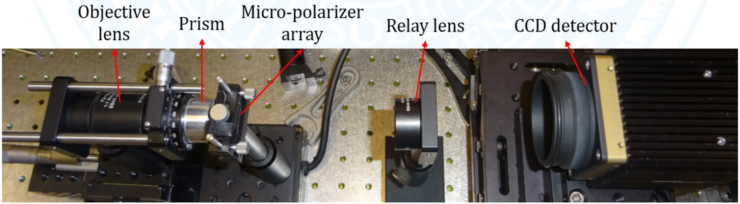
Proposed Imaging System

- Detector with spectral and polarization filtering.
- Rotation of the dispersive element enables multiple snapshots.



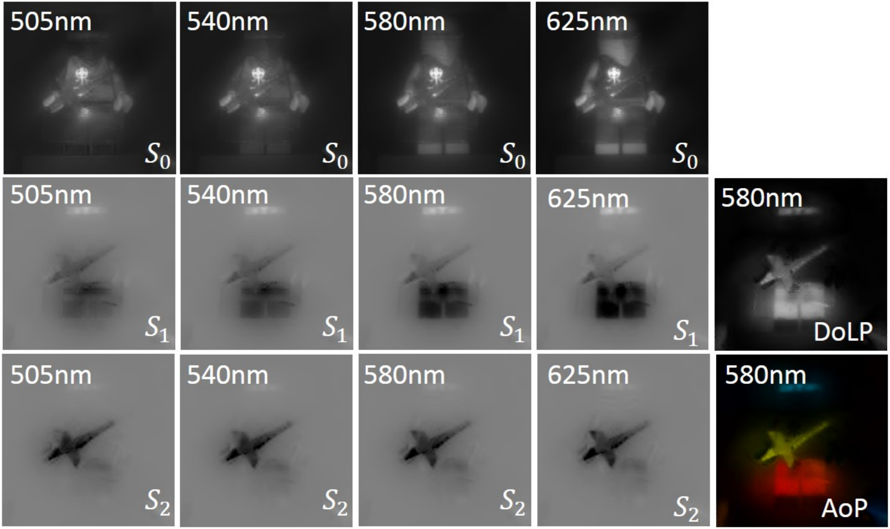
Zoomed pixelated polarizer



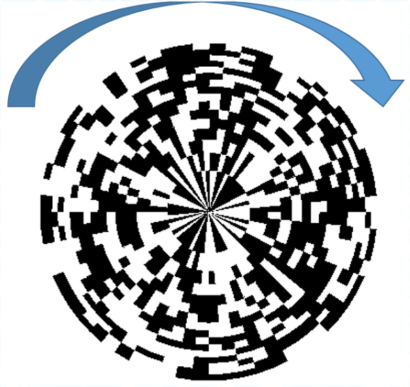


Reconstruction Results with 4 snapshots

- 3 Stokes image planes (S_0, S_1, S_2) are reconstructed
- 8 spectral bands are reconstructed. (Shown: 505, 540, 580, 625 nm).
- Degree of linear polarization (DoLP) and angle of polarization (AoP).



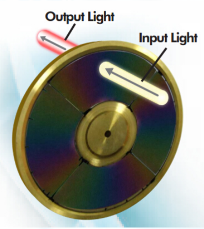
Compressive Spectral Imaging with Polar Coded Apertures

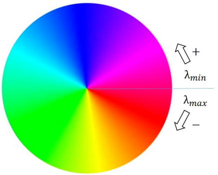


Polar Coded Aperture on Spinning Munitions

- Given the natural spin of munitions, spatial coding via a rotating polar coded aperture.

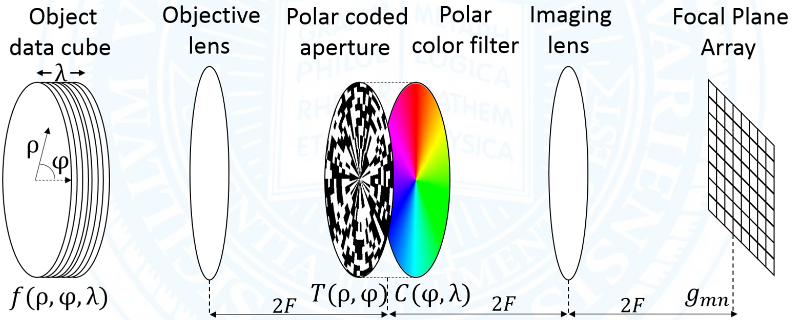
- Spectral modulation via a circular variable filter (CVF) [2].





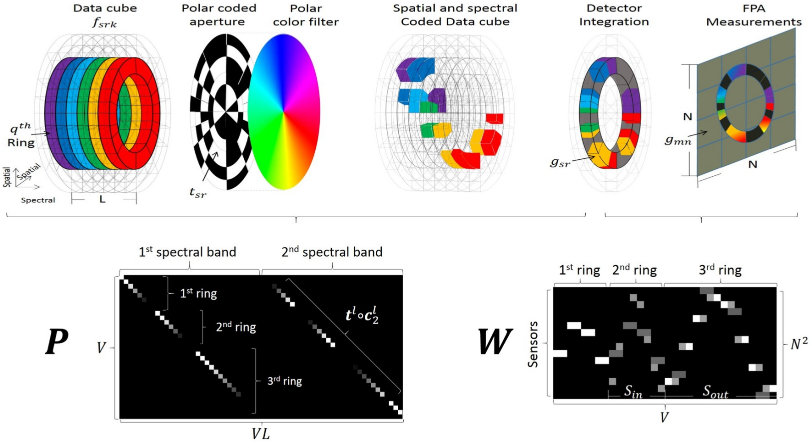
Polar Coded Aperture Compressive Spectral Imager

- Polar coded aperture combined with a CVF.
- Low resolution focal plane array (FPA).
- Imager rotating with the munition spin.



Rotating compressive polar coded aperture spectral imaging system.

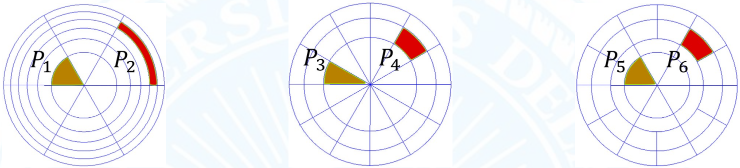
System Forward Model



- $\mathbf{P}$: Spatial and spectral modulation.
- $\mathbf{W}$: Rectangular to polar pixel transformation.
- System forward matrix: $\mathbf{H} = \mathbf{WP}$.

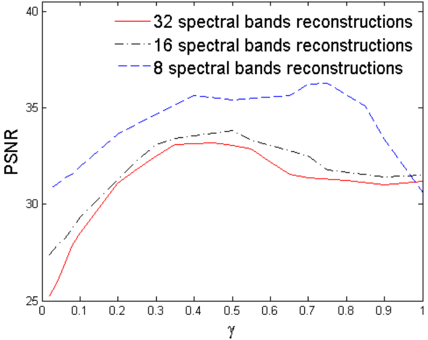
Imaging System Optimization

- Coded aperture geometry design.

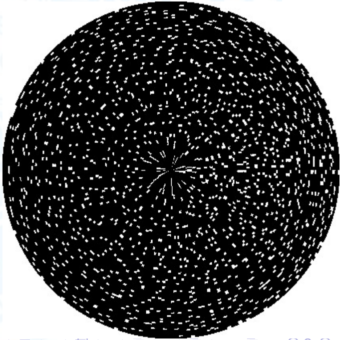


Spokes/Rings=1 Spokes/Rings=4 2-sections

- CVF bandwidth analysis.

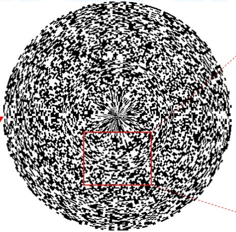


- Aperture optimization.

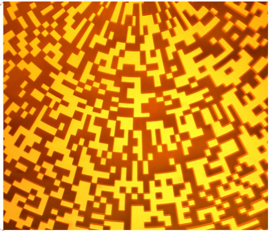


Polar Coded Aperture Fabrication

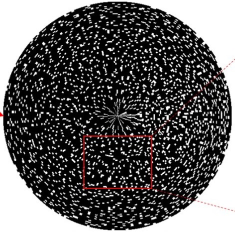
144 Aperture Code Patterns
Each contains 128^2 pixels



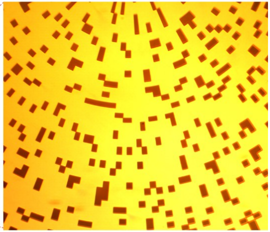
Random



Microscope zoomed



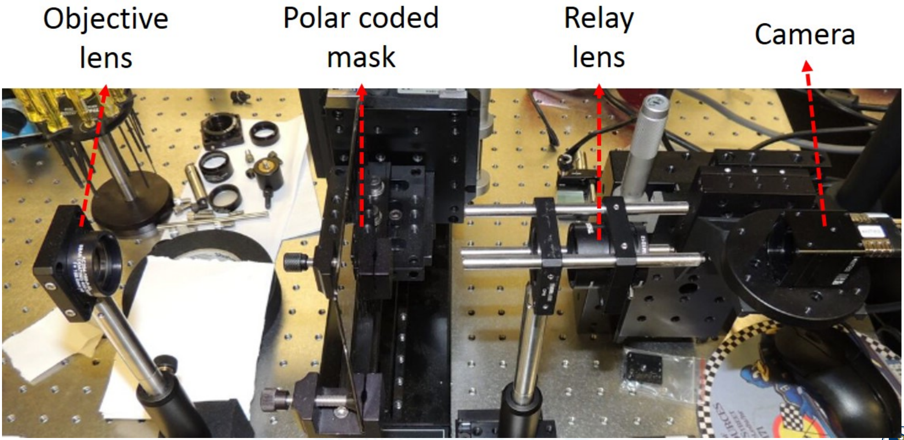
Optimized



Microscope zoomed

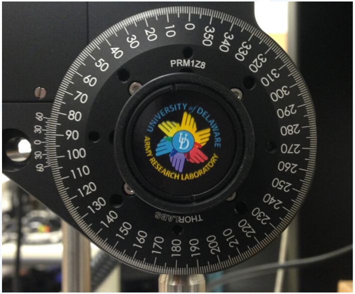
Laboratory Implementation

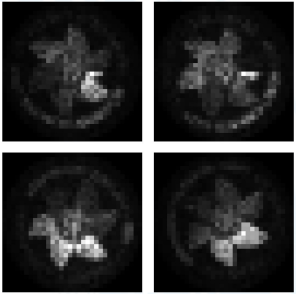
- Target Rotation instead of imager rotation.
- CVF emulated through a set of bandpass filters.
- Sensor measurements are grouped into 32×32.



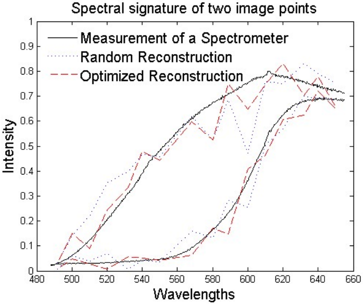
Laboratory Measurements and Spectral Reconstructions

- 64 shots are captured in a 2π rotation (75% compression).





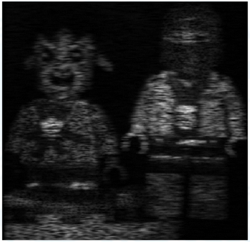
- Spectral Reconstructions.



Laboratory Reconstruction

- 16 spectral bands are reconstructed (9 are shown).

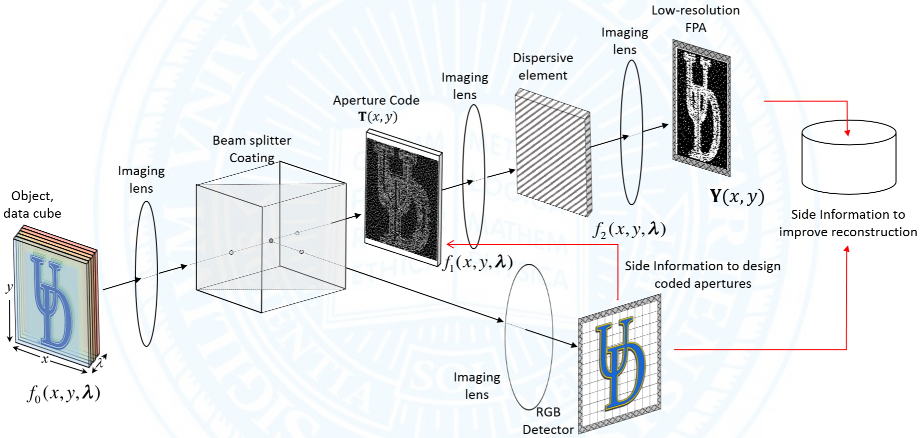
Compressive Spectral Imaging with Side Information



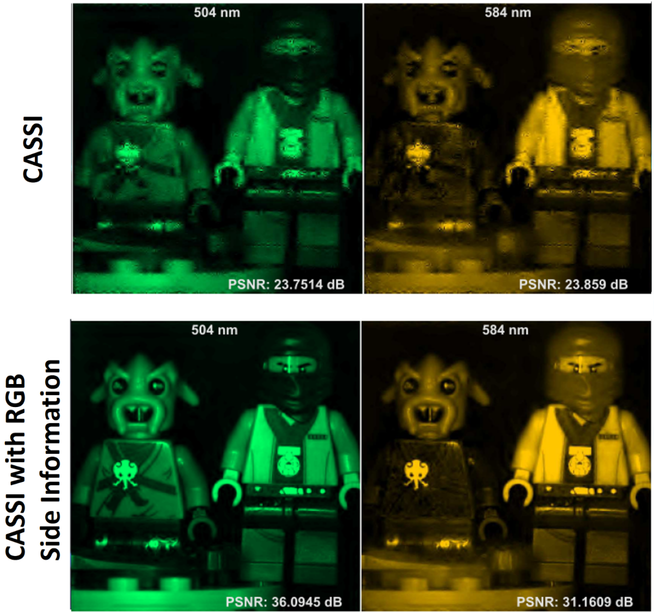
Compressive Measurement

Side- Info

CSI + Side Information System Design



CSI vs CSI+Side Information



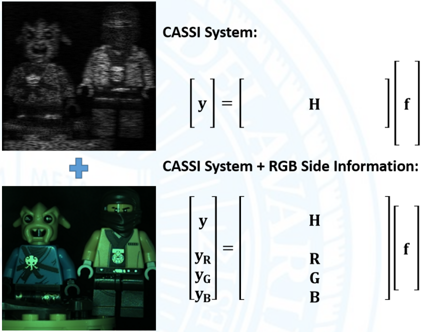
- Improvement of around 10 dBs.

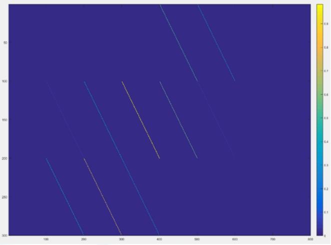
Reconstruction Process

Optimization Problem

$$\hat{\mathbf{f}} = \mathbf{\Psi}\{\text{argmin}_{\boldsymbol{\theta}}||\mathbf{y}-\mathbf{H}\mathbf{\Psi}\boldsymbol{\theta}||_2+\tau||\boldsymbol{\theta}||_1\}$$

- $\boldsymbol{\theta}$ is an S-sparse representation of $\mathbf{f}$
- τ is a regularization constant
- $\mathbf{\Psi} = \mathbf{\Psi}_1 \bigotimes \mathbf{\Psi}_2$,
  - $\mathbf{\Psi}_1$ is a 2D-Wavelet Symmlet 8 basis
  - $\mathbf{\Psi}_2$ is the 1D-Discrete Cosine Transform
- GPSR algorithm is used to obtain the reconstructions

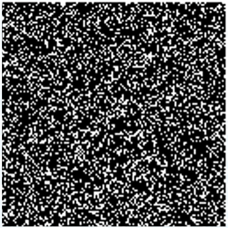




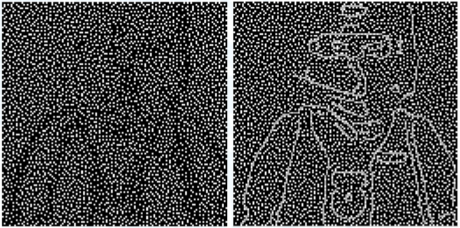
Simulations results

- Test data cube $\mathcal{F}$: $128 \times 128 \times 8$
- Reconstruction algorithm: GPSR
- Coded apertures $T = 0.25$

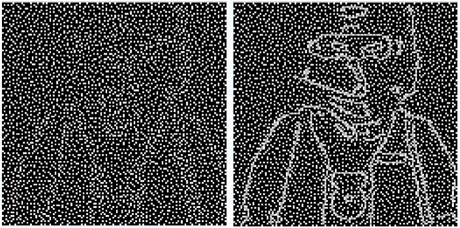
RGB image



Random Coded Aperture

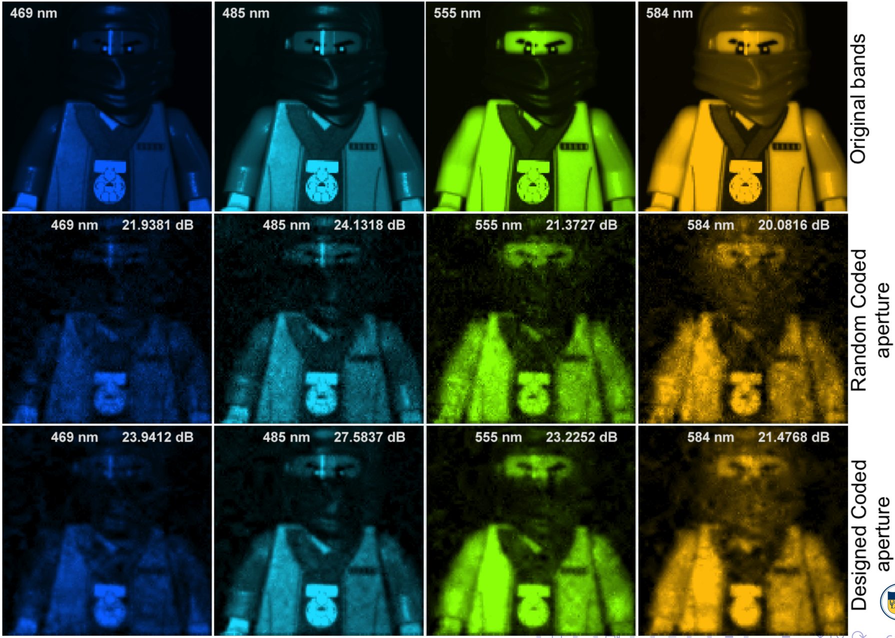


Low transmittance in borders

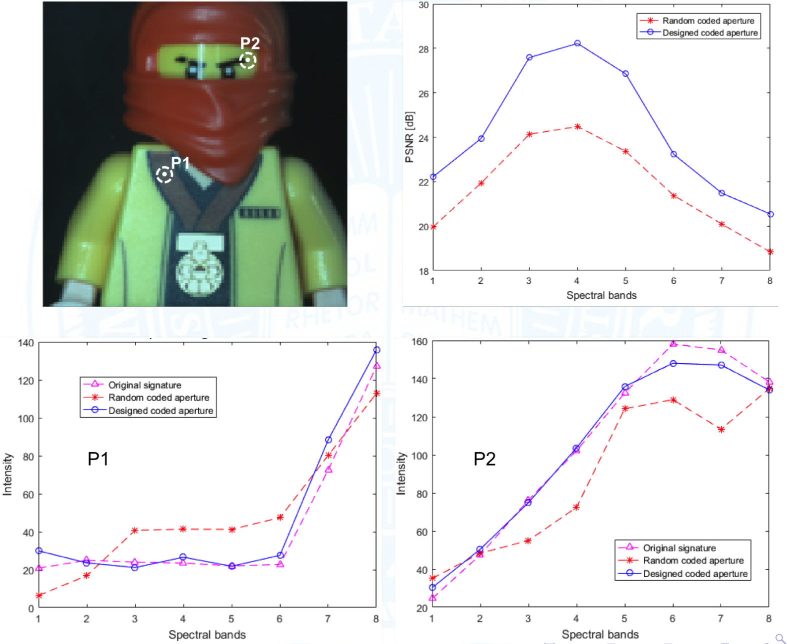


High transmittance in borders

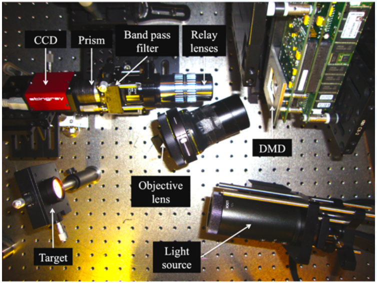
Spatial Reconstruction



Spectral Reconstruction



Experimental results



CASSI

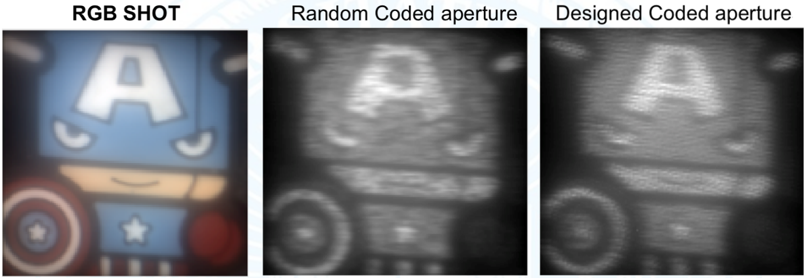
- Test data cube $\mathcal{F}$: $128 \times 128 \times 10$
- DMD $\Delta_c = 13.68\mu m$.
- CCD camera $\Delta_d = 6.45\mu m$.
- Coded Aperture T: 128×128 pixels.

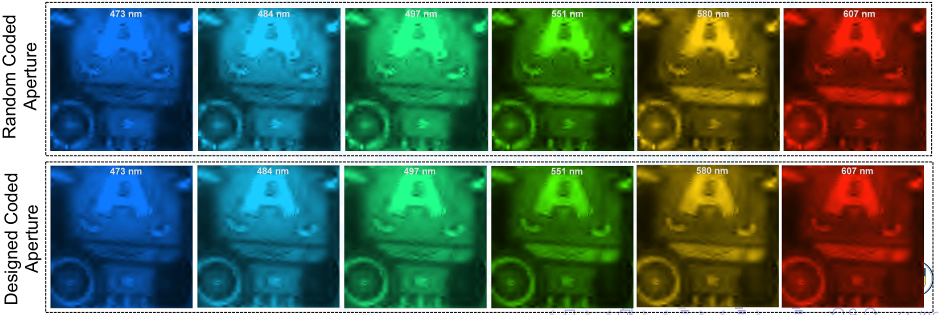
Target 1

Target 2

Target 3

Real Measurements and Reconstructions

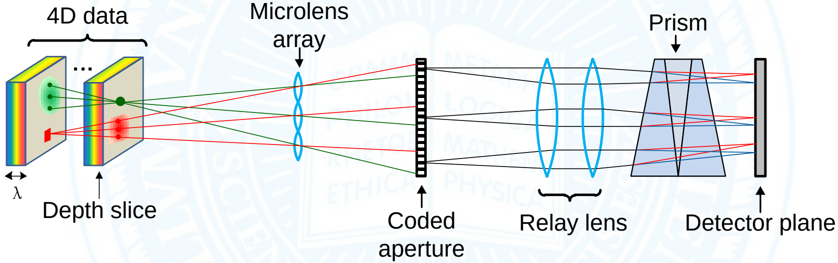




Compressive Spectral + Integral Imaging

Proposed System with Integral Imaging

- A micro-lens array captures **different perspectives** of the scene.
- Coded aperture **spatially encodes** 4D data cube.
- Relay lens transmits the array of coded light **through the prism**.
- Sensor captures **2D grayscale** compressive measurements.

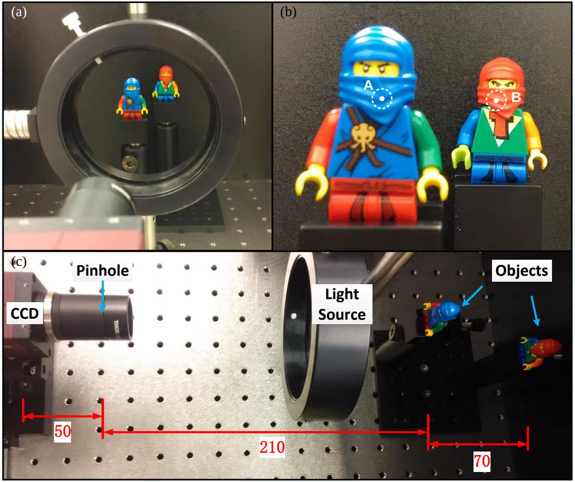


Ill-posed reconstruction problem

- 4D image captured by 2D compressive random projections
- FPA pixels $(\sim KN^2) \ll$ 4D Datacube voxels (N^2DL)
- Compression ratio: $DL : 1$
- The system can be seen as a 2D array of CASSI systems

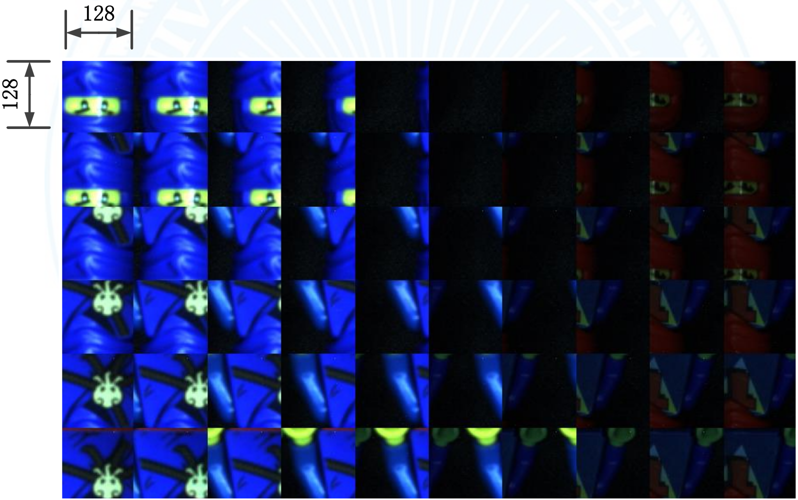
Simulations: 4D Datacube (1/2)

- 4D datacube captured in the lab to perform simulations.
- A pinhole CCD camera was built to scan the scene along X-Y.
- Two objects were used as the target, at distances of 210mm and 280mm.
- Light at 11 wavelengths between 450-650 nm was used to illuminate the target.



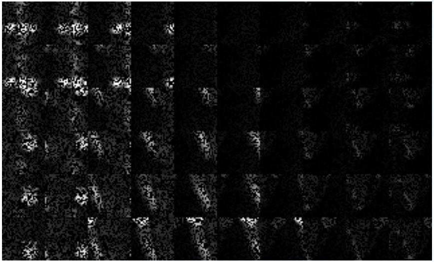
Simulations: 4D Datacube (2/2)

- Elemental Images: 6×10 equally spaced by 2.5 mm vertically and horizontally
- Elemental Images size: 128×128 pixels (Final reconstruction size: 768×1280)
- The 11 spectral bands are mapped to RGB for illustration.

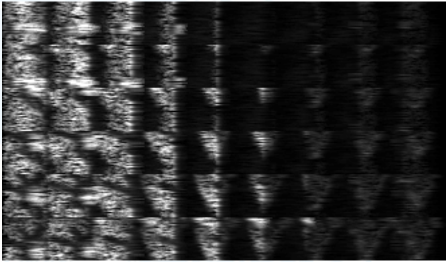


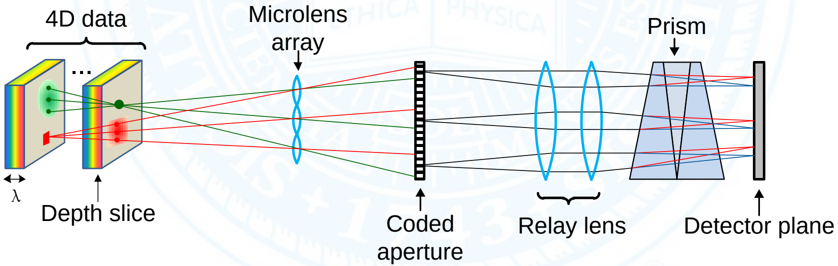
Simulations: Coded data and Measurements

Elemental Images in the coded aperture



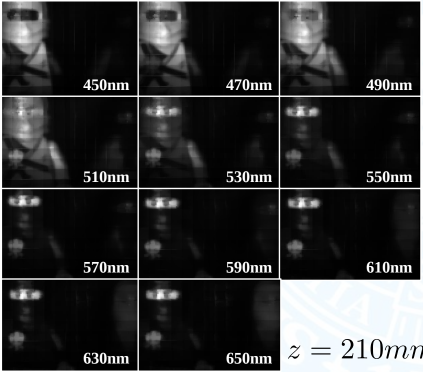
Compressive measurements



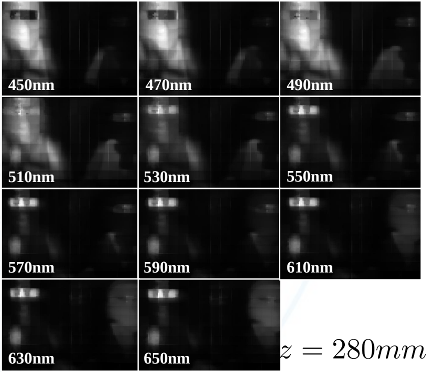


Simulation Results: Spectral Reconstruction (1/2)

- The TwIST algorithm was used with total-variation penalty.
- Results attained with 6 snapshots ($\sim 25\%$ data).
- 11 spectral bands are shown for comparison.
- Left object located at 210 mm, and right object at 280 mm.



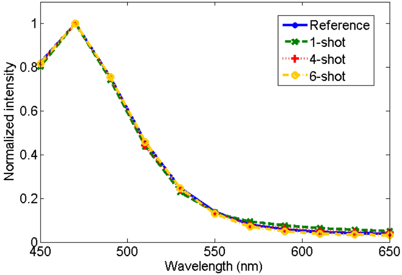
$z = 210mm$



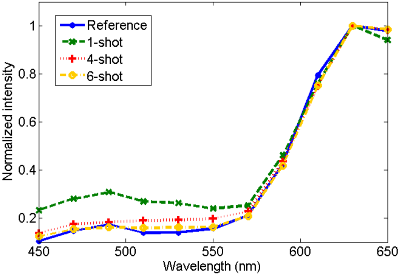
$z = 280mm$

J. Bioucas-Dias, M. Figueiredo, "A new TwIST: two-step iterative shrinkage/thresholding algorithms for image restoration", IEEE Transactions on Image Processing, (2007).

Simulation Results: Spectral Reconstruction (2/2)

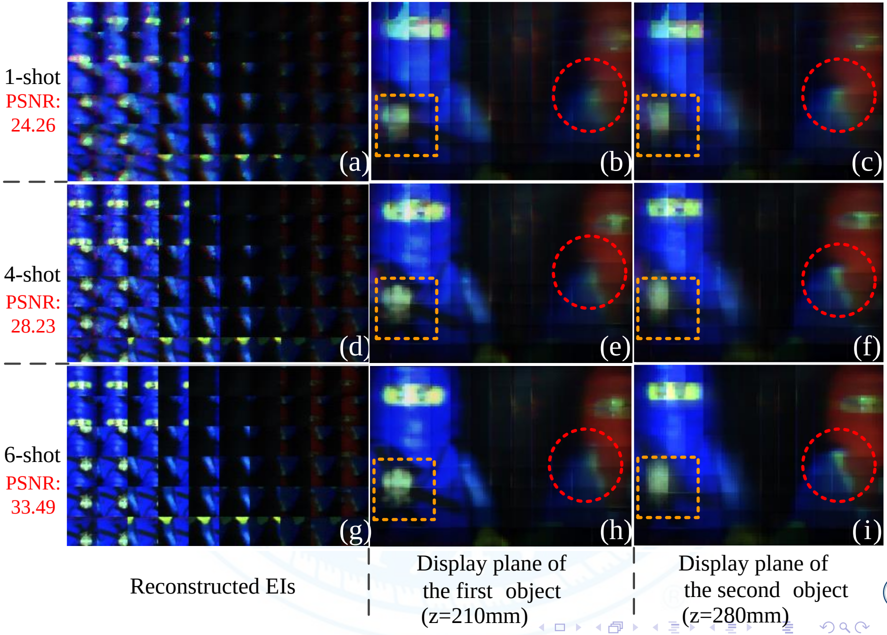


(a) Point A



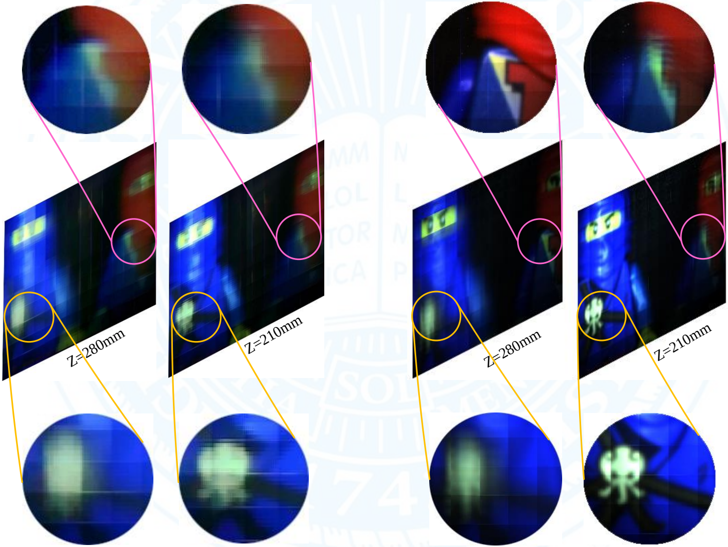
(b) Point B

Simulation Results: Depth Reconstruction (1/2)

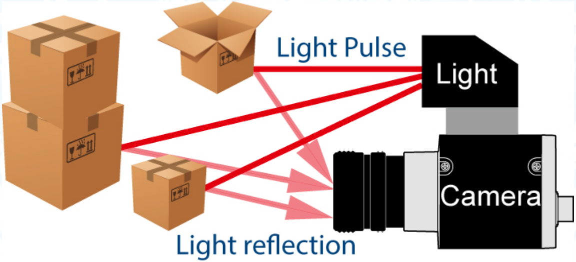


Simulation Results: Depth Reconstruction (2/2)

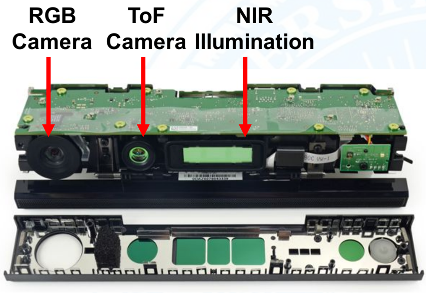
- Comparison for (left) 6-shot estimation (right) original data

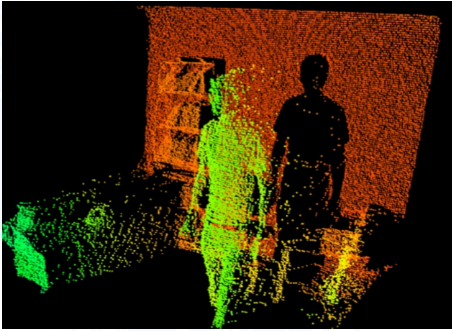


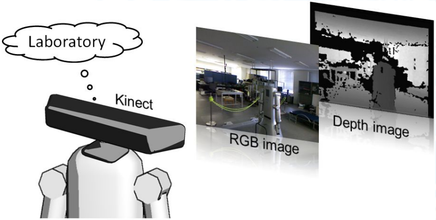
Compressive Spectral+Time-of-Flight Imaging

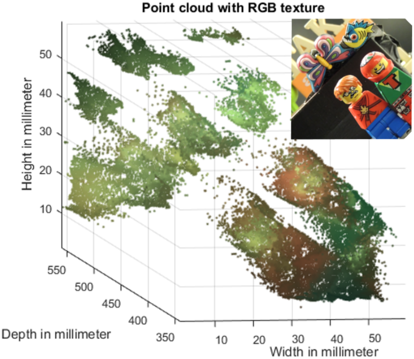


Project Overview

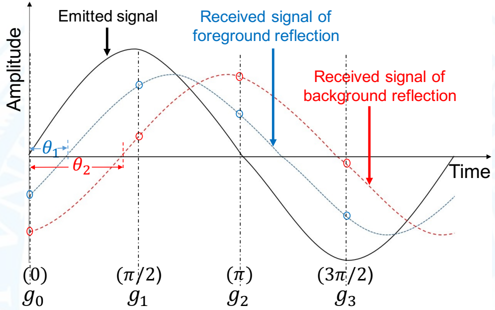








ToF-Sensor Operation



$$
\begin{aligned}
g_{m,n} &= \frac{1}{\tau}\int_{t=0}^{\tau} A f_{m,n} dt = A f_{m,n}, (\tau = \text{exposure}, A = \text{ambient light}, f = \text{reflectance}) \\
&= \frac{1}{\tau}\int_{t=0}^{\tau} \left(A + B\cos(2\pi f t + \theta)\right) f_{m,n} dt, (\text{Add modulated light with phase } \theta) \\
&= \frac{1}{\tau}\int_{t=0}^{\tau} \left(A + B\cos(2\pi f t + \theta)\right) r(t) f_{m,n} dt. (\text{Gating function } r(t) \text{ with duty cycle } D) \\
&= \frac{K}{\tau}\int_{t=0}^{\frac{D\tau}{K}} \left(A + B\cos(2\pi f t + \theta)\right) f_{m,n} dt. (\text{Integrating over one period}) \\
&\approx D f_{m,n} \left(A + B\cos(\theta)\right) (\text{Assuming a small } D). \qquad (1)
\end{aligned}
$$

ToF Principles: Depth Estimation

- Solve for θ, collecting 4 images indexed by ℓ with a phase shift:

$$(g_\ell)_{m,n} \approx D f_{m,n} \left(A + B \cos \left(\frac{\pi \ell}{2} + \theta \right) \right) \quad (2)$$

- Define the difference of complements, $g_{0,2}$ and $g_{3,1}$, according to:

$$\begin{aligned} (g_{0,2})_{m,n} &= (g_0)_{m,n} - (g_2)_{m,n} \\ &= 2 D f_{m,n} B \cos \theta \end{aligned} \qquad \begin{aligned} (g_{3,1})_{m,n} &= (g_3)_{m,n} - (g_1)_{m,n} \\ &= 2 D f_{m,n} B \sin \theta \end{aligned}$$

- Extract θ by treating $(g_{0,2})_{m,n}$ and $(g_{3,1})_{m,n}$ as quadrature components:

$$\begin{aligned} \theta &= \tan^{-1} \left(\frac{(g_{3,1})_{m,n}}{(g_{0,2})_{m,n}} \right), \\ &= \tan^{-1} \left(\frac{2 D f_{m,n} B \sin \theta}{2 D f_{m,n} B \cos \theta} \right), \\ &= \tan^{-1} \left(\frac{\sin \theta}{\cos \theta} \right). \end{aligned} \quad (3)$$

- The depth value, at every $(m,n)^{th}$ sensor pixel is given by:

$$d_{m,n} = \frac{c}{2} \frac{\theta}{2 \pi f}, \quad (4)$$

ToF Principles: Amplitude Estimation

- Extract surface reflectance, $f_{m,n}$, by looking at the magnitude of the quadrature components

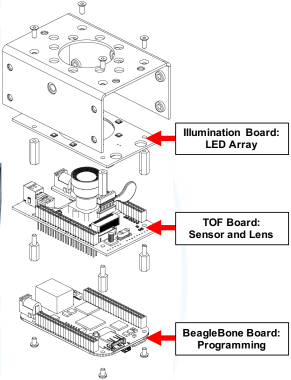
$$f_{m,n} = \frac{\sqrt{(g_{3,1})^2_{m,n} + (g_{0,2})^2_{m,n}}}{2DB}, \qquad (2DB \text{ is known}) \tag{5}$$

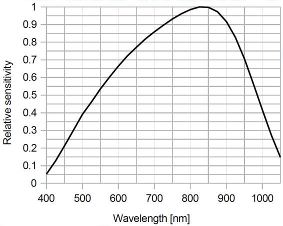
- Alternatively since $(g_0)_{m,n}$ and $(g_2)_{m,n}$ are 180^o out-of-phase, as are $(g_1)_{m,n}$ and $(g_3)_{m,n}$:

$$(g_0)_{m,n} + (g_2)_{m,n} = 2DAf_{m,n}, \Rightarrow Af_{m,n} = \frac{(g_0)_{m,n} + (g_2)_{m,n}}{2D}. \tag{6}$$

ToF ESPROS Sensor: QVGA Espros EPC660

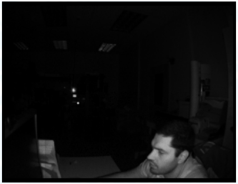
- $320\times$ 240 pixels
- 12 bit data output
- 8 NIR LEDs at 800nm
- Modulation frequencies: 0.625 to 20 MHz
- Resulting in Range: 240 to 7.5 meters
- Sub-centimeter accuracy
- Ambient light measurement!





ToF-Sensor Modes

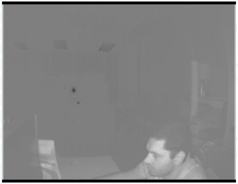
Ambient Light



LED Amplitude

Colored LED Amplitude

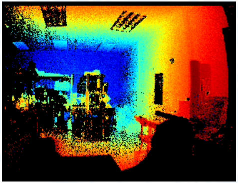
g_0



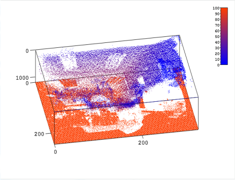
g_1

g_2

g_3

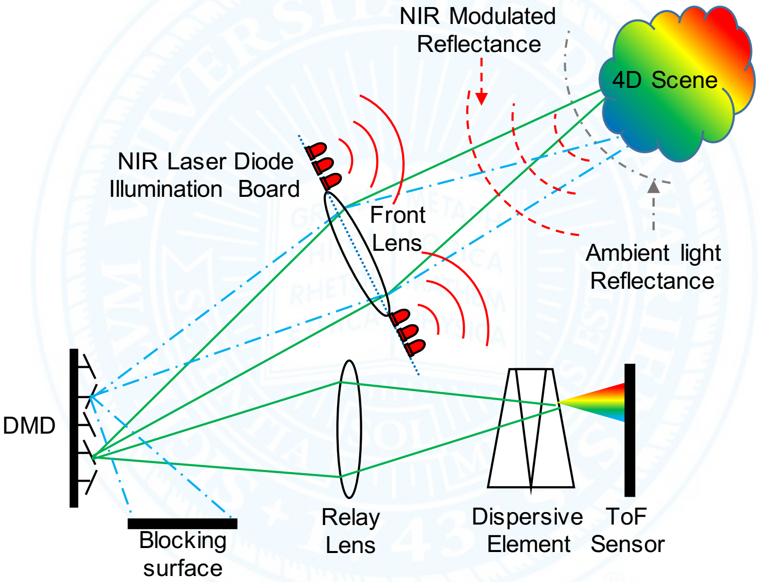


Depth Map



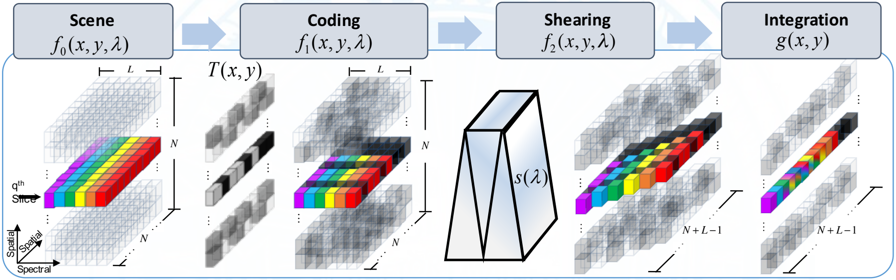
Point Cloud

Proposed ToF+Spectral Imager

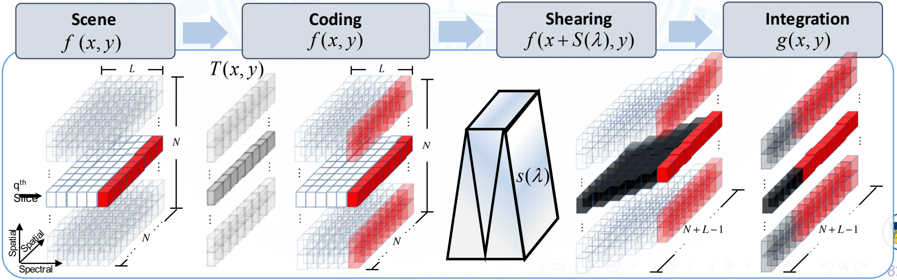


ToF+Spectral Imager: Dual-shot Operation

- Compressive spectral imaging under ambient light reading



- ToF under LED active illumination reading



ToF+Spectral Imager: Reconstruction

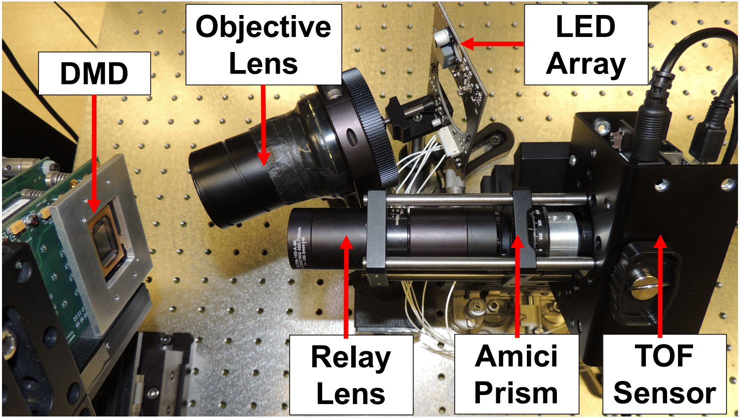
Ambient Light Mode

- Measurement: $g_{m,n} = \sum_l \chi_{m,n,l} T_{m,n-l} f_{m,n-l,l} + \omega_{m,n}$
- Matrix model: $\mathbf{g} = \mathbf{PXTf} = \mathbf{Hf} = \mathbf{H\Psi}\boldsymbol{\theta} = \mathbf{A}\boldsymbol{\theta}$
- Reconstruction: $\hat{\mathbf{f}} = \mathbf{\Psi}(\underset{\boldsymbol{\theta}'}{\text{argmin}} \|\mathbf{g} - \mathbf{A}\boldsymbol{\theta}'\|_2^2 + \tau \|\boldsymbol{\theta}'\|_1)$

Modulated Light Mode

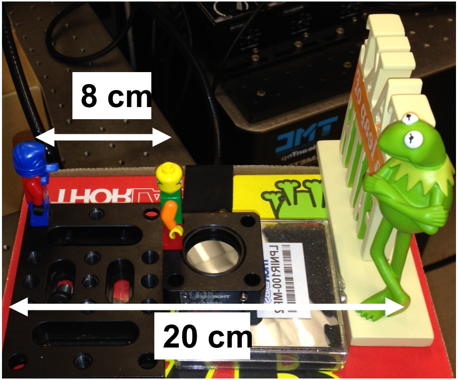
- Measurement: $(g_\ell)_{m,n} \approx D f_{m,n} \left(A + B \cos \left(\frac{\pi \ell}{2} + \theta \right) \right)$
- Phase delay: $\theta = \tan^{-1} \left(\frac{(g_{3,1})_{m,n}}{(g_{0,2})_{m,n}} \right)$
- Depth Calculation: $d_{m,n} = \frac{c}{2} \frac{\theta}{2\pi f}$
- Amplitude Calculation: $f_{m,n} = \frac{\sqrt{(g_{3,1})^2_{m,n} + (g_{0,2})^2_{m,n}}}{2DB}$

First Prototype



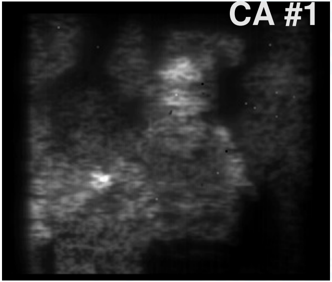
- DMD resolution: 1024×768. ToF resolution: 320×240
- DMD pixel: 13.68um. ToF pixel: 20um. (3:2 correspondence).
- Dispersion between 471 - 776 nm onto 14 sensor pixels.
- Final spectral cube resolution: $64 \times 64 \times 7$

First Prototype: Target Scene

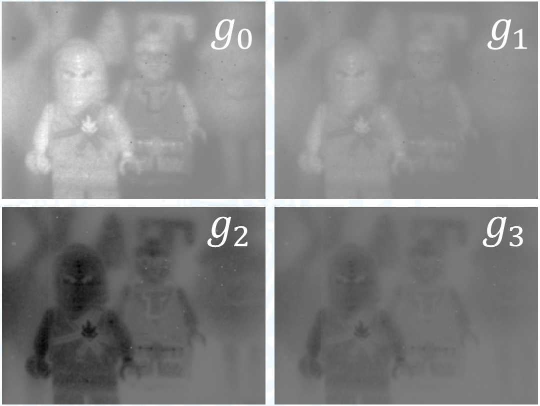


- Target scene used in the experiments.
- Larger or smaller FOV can be attained with different lens.

First Prototype: Compressive Measurements



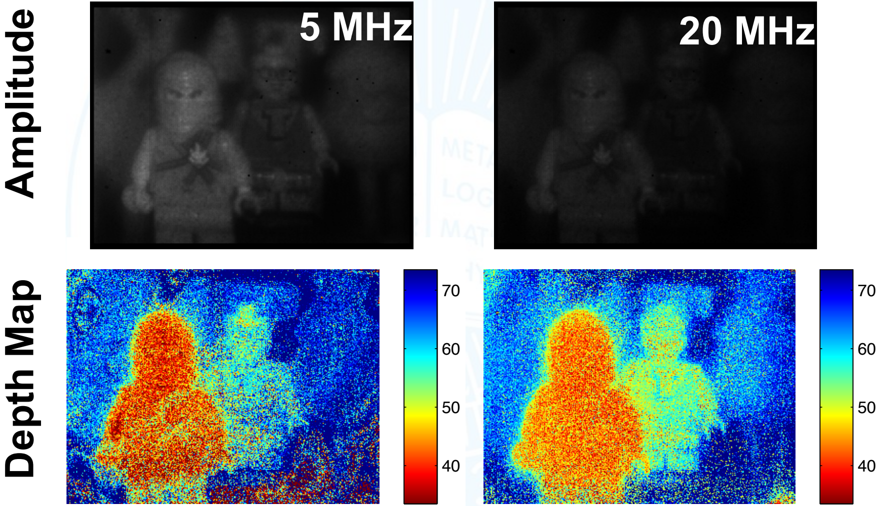
Compressed projection under grayscale mode.



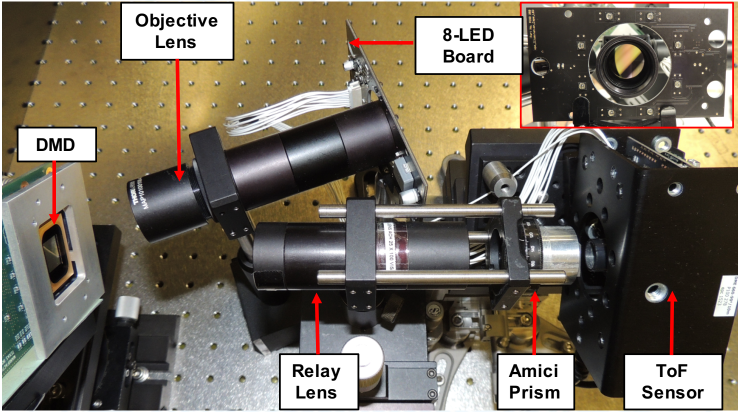
Quadrature components under ToF mode.

First Prototype: RGB-mapped Reconstructions

First Prototype: ToF Depth Estimation

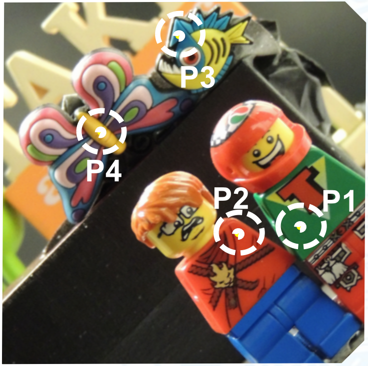


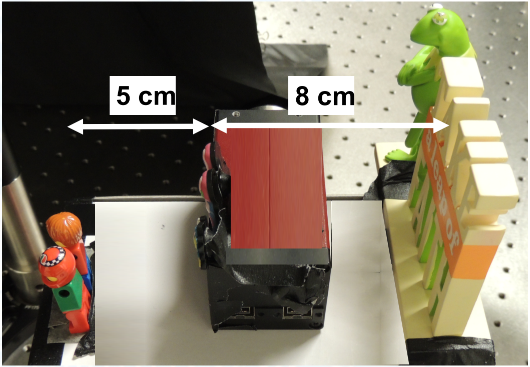
Updated Prototype



- DMD resolution: 1024×768. ToF resolution: 320×240
- DMD pixel: 13.68um. ToF pixel: 20um. (3:2 correspondence).
- Dispersion between 486 - 766 nm onto 16 sensor pixels.
- Final spectral cube resolution: $128 \times 128 \times 8$
- New objective lens with $f = 50mm$, FOV from 4^o to 8^o
- Extended depth of field from 10 to around 20 centimeters.

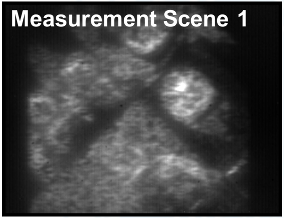
Updated: Target Scene



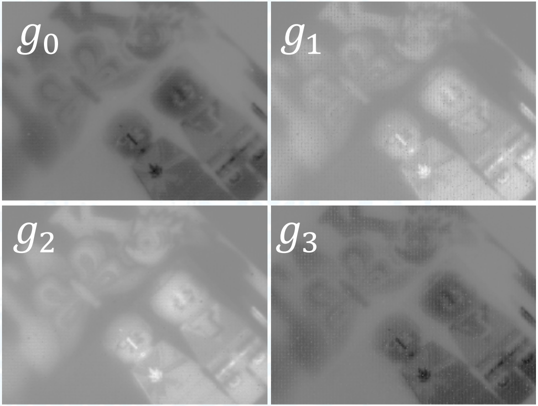


- Scene placed at around 50 cm of the camera
- Three depth planes
- FOV of around 8 deg

Updated: Ambient Compressive Measurement

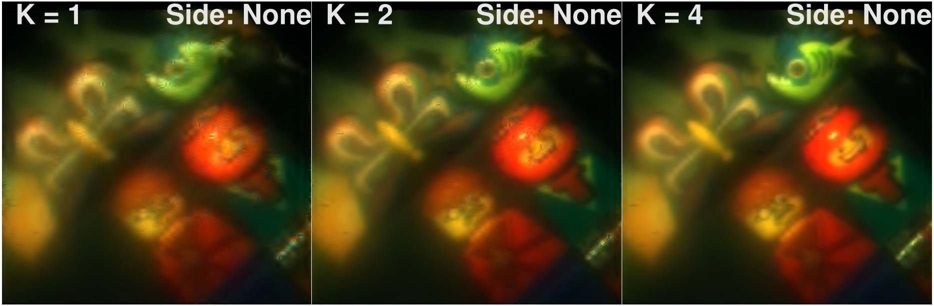


Compressed projection under grayscale mode.



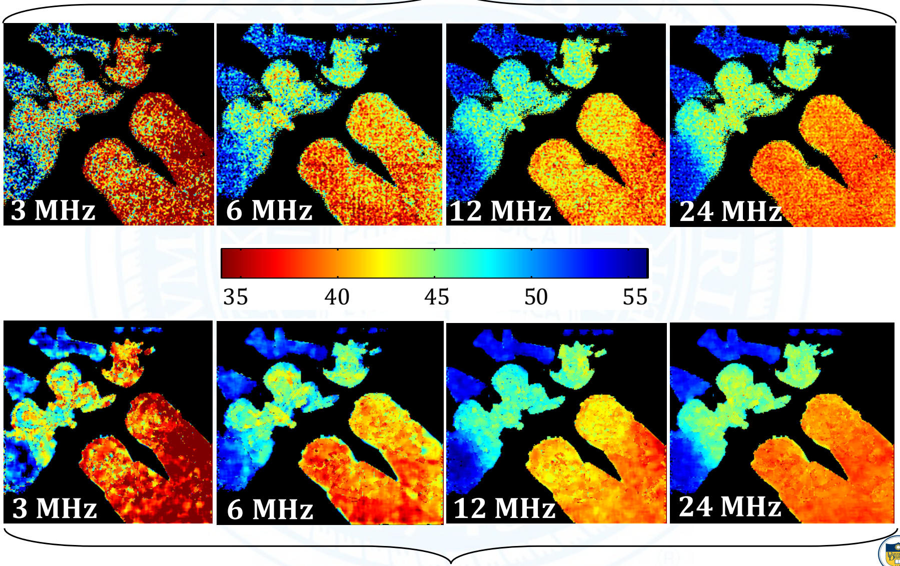
Quadrature components under ToF mode.

Updated: RGB-mapped Reconstructions of Scene



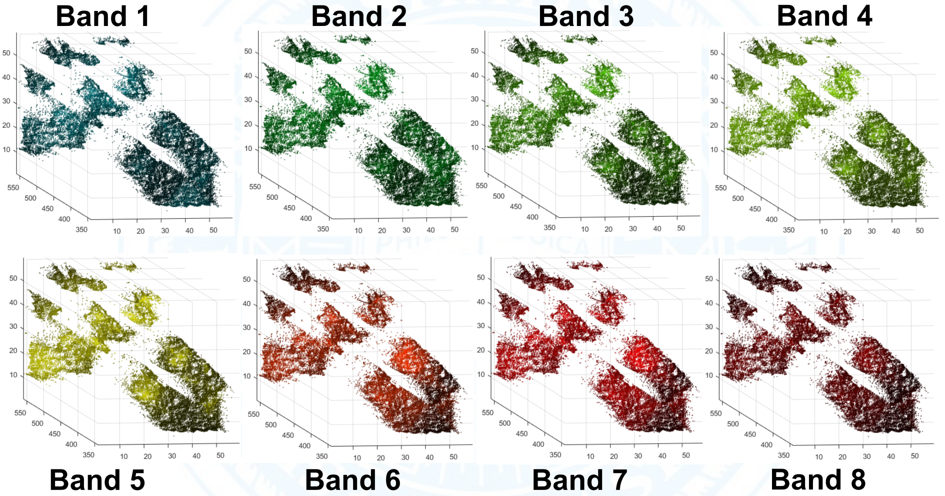
Updated: ToF Depth Estimation Scene

Without Processing



Using the CWMF

Spectral Point Clouds



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Thank you for your attention!