Adaptive uniform grayscale coded aperture design for high dynamic range compressive spectral imaging

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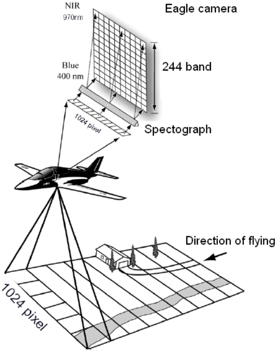
SPIE, Defense+Commercial

Outline

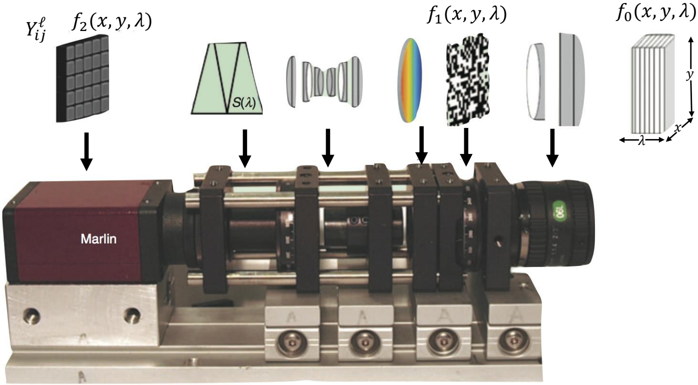
1. Compressive spectral imaging concepts
2. Sensor saturation problem
3. High-dynamic range method
4. Simulation results
5. Conclusions

Conventional spectral imaging architectures



- Push broom spectral imaging: Expensive, time consuming, senses $N \times N \times L$ voxels.
- Tuneable Spectral Filter: Sequential sensing of $N \times N \times L$ voxels, limited by the number of colors.

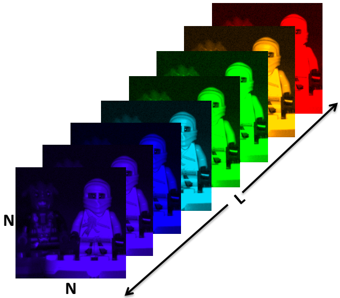
Compressive spectral imaging system

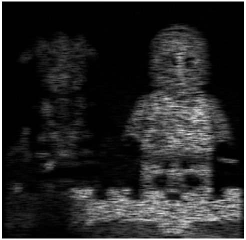


New compressive sensing method captures the datacube with a few snapshots[1].

[1] Compressive Coded Aperture Spectral Imaging: An Introduction, Gonzalo R. Arce, David J. Brady, Lawrence Carin, Henry Arguello, David S. Kittle

Compressive spectral imaging





Data cube

$$\mathbf{f} = \mathbf{\Psi}\mathbf{\Theta}$$

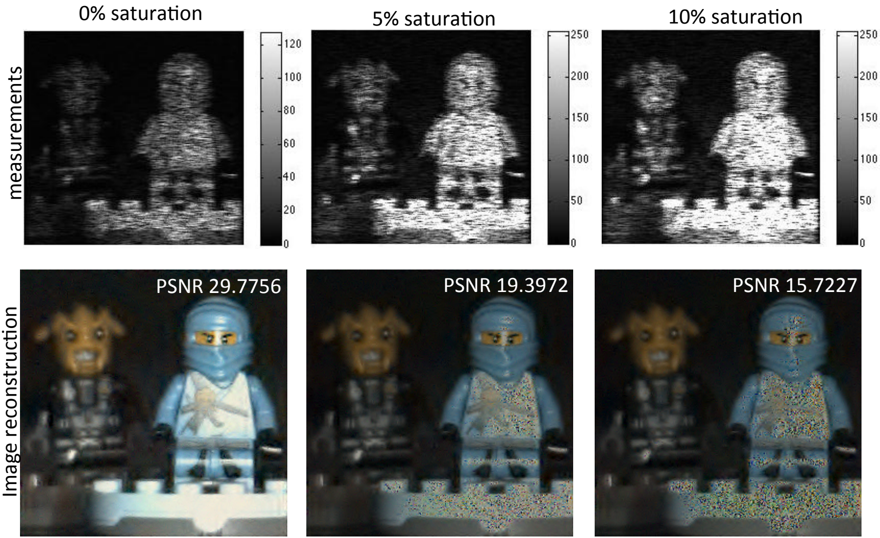
Compressive Measurements

$$\mathbf{y} = \mathbf{H}\mathbf{\Psi}\mathbf{\Theta} + \mathbf{w}$$

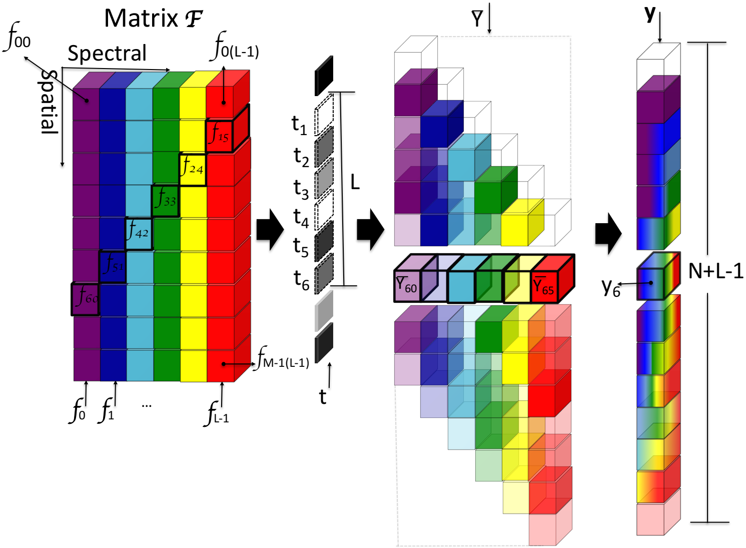
Undertermined system of equations

$$\hat{\mathbf{f}} = \mathbf{\Psi}(\underset{\mathbf{\Theta}}{\text{argmin}} \|\mathbf{y} - \mathbf{H}\mathbf{\Psi}\mathbf{\Theta}\|_2 + \boldsymbol{\tau}\|\mathbf{\Theta}\|_1)$$

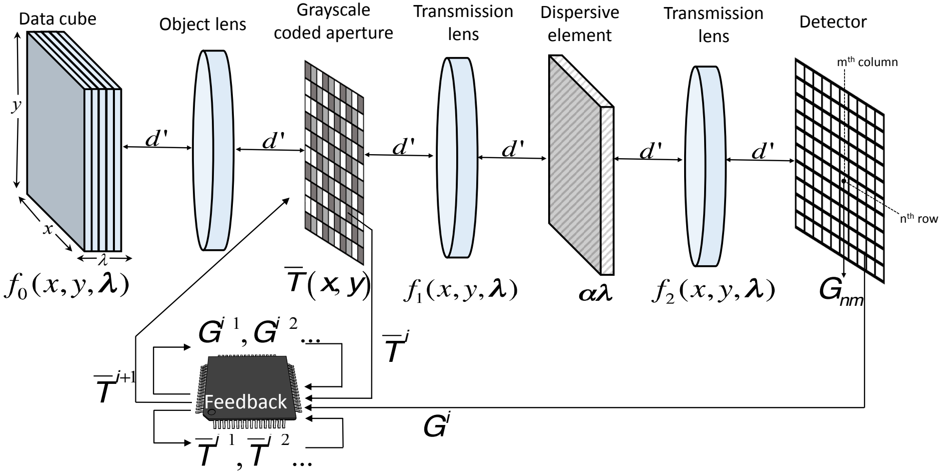
Saturation problem



Sensor saturation

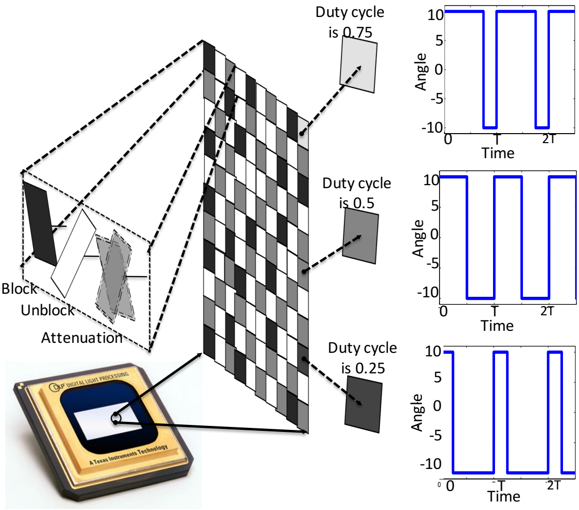


Proposed System



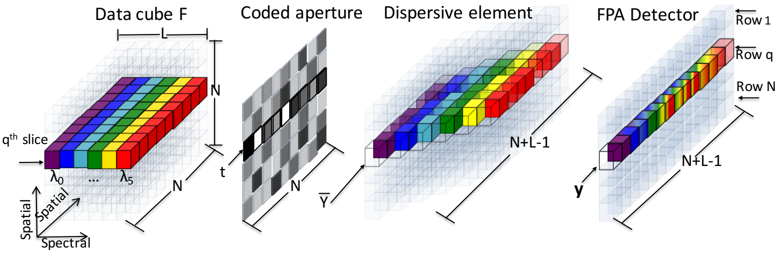
CASSI Sketch with Adaptive Uniform Grayscale Coded Aperture

Grayscale Coded Apertures via a DMD



Grayscale Coded Aperture and different values of Duty cycle

Data cube analysis by rows



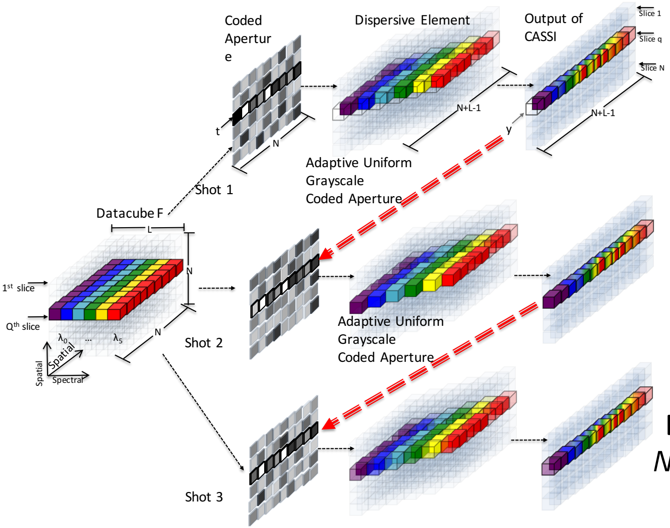
CASSI Sketch with Grayscale Coded Aperture

A single shot compressive measurement across the FPA

$$\mathbf{y} = \sum_{j=0}^{V-1} \mathbf{P}_{V;j} \sum_{k=0}^{L-1} (\boldsymbol{\Theta}_V)^{\mathbf{k}} \bar{\mathbf{I}}\mathbf{RFP}_{L;k} \mathbf{C} (\boldsymbol{\Theta}_L^T)^{j+1} \mathbf{w},$$

1. $\mathbf{y} \in \mathbb{R}^V$
2. $\mathbf{P}_{V;j}$ is a $V \times V$ unique column/row matrix,
3. $(\boldsymbol{\Theta}_V)^{\mathbf{k}}$ $V \times V$ is cyclic permutation matrix

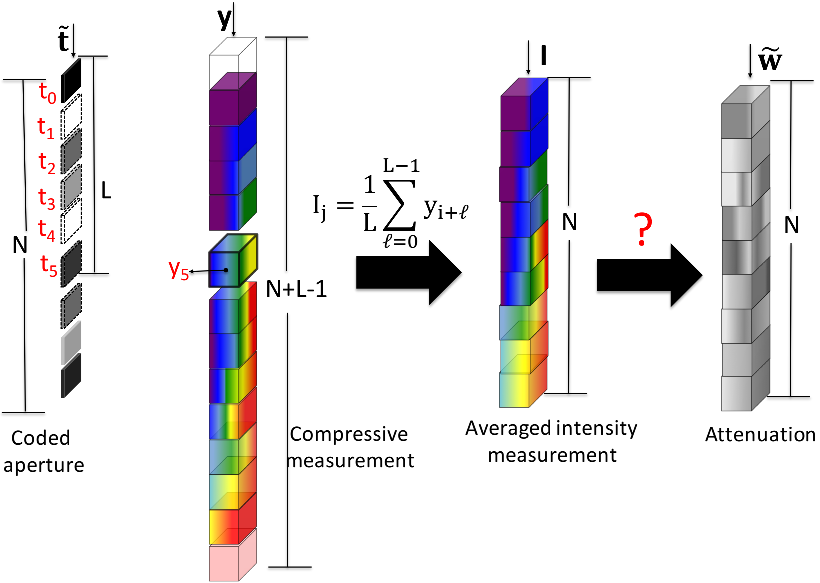
CASSI Multishot Matrix Model



$$\begin{bmatrix} \mathbf{y}^0 \\ \mathbf{y}^1 \\ \vdots \\ \mathbf{y}^2 \end{bmatrix} = \begin{bmatrix} \mathbf{H}^0 \\ \mathbf{H}^1 \\ \vdots \\ \mathbf{H}^2 \end{bmatrix} [\mathbf{f}]$$

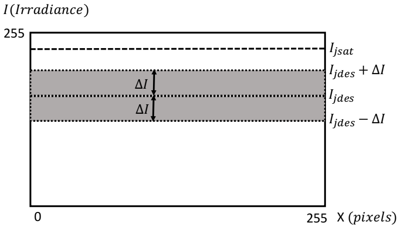
$\bar{\mathbf{y}} = \mathbf{Hf} + \mathbf{w}$ Where
$\mathbf{H} \in \{0, 1\}$ with size
$N(N+L-1)\times(N \cdot N \cdot L)$

Feedback (Computational model to reduce saturation)



Feedback (Computational model to reduce saturation) [2]

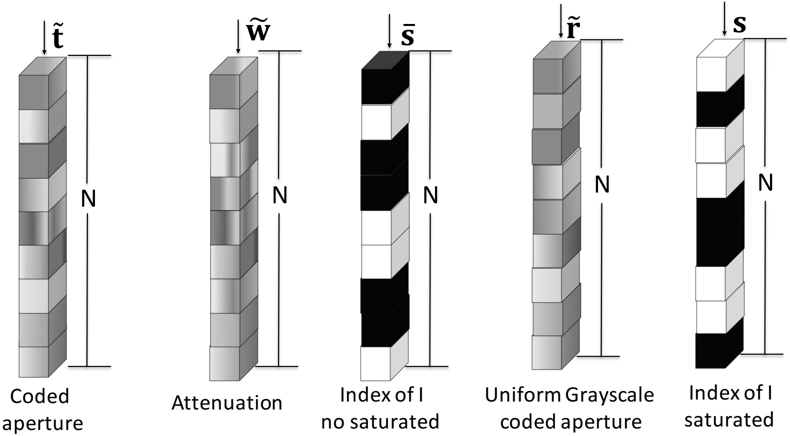
$$\tilde{w}_j^{t+1} = \begin{cases} \alpha \frac{\tilde{w}_j^t}{2} + (1-\alpha)\tilde{w}_j^t & I_j \geq I_{jsat} \\ \alpha \tilde{w}_j^t \frac{I_{jdes}}{I_j} + (1-\alpha)\tilde{w}_j^t & I_{jsat} > I_j \geq I_{jdes} + \Delta I_j \\ \tilde{w}_j^t & I_{jdes} + \Delta I_j > I_j \geq I_{jdes} - \Delta I_j \\ \beta \tilde{w}_j^t \frac{I_{jdes}}{I_j} + (1-\beta)\tilde{w}_j^t & I_{jdes} - \Delta I_j > I_j \end{cases}$$



[2] Adaptive Dynamic Range Imaging: Optical Control of Pixel Exposures Over Space and Time, Shree K. Nayar and Vlad Branzoi, Computer Vision, 2003. Proceedings. Ninth

Feedback (Computational model to reduce saturation)

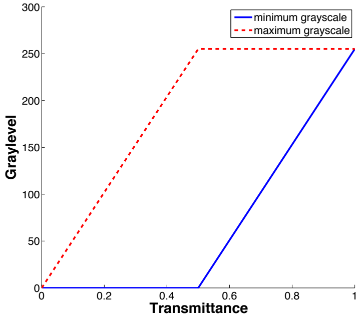
$$\tilde{\mathbf{t}} = \tilde{\mathbf{w}} \circ \bar{\mathbf{s}} + \tilde{\mathbf{r}} \circ \mathbf{s}$$



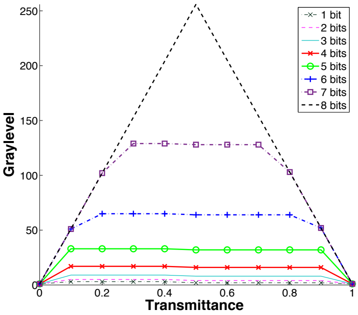
Uniform Grayscale Coded Apertures (UGCA)

$$I_L = \begin{cases} [I_{min}, I_{max} * 2 * T_r] & 0 \leq T_r \leq 0.5 \\ [I_{max} * (2 * T_r - 1), I_{max}] & 0.5 < T_r \leq 1 \end{cases}$$

- $I_{min} = 0$ minimum grayscale level $I_{max} = 2^m - 1$ maximum grayscale level, m is the number of bits, T_r the desired transmittance

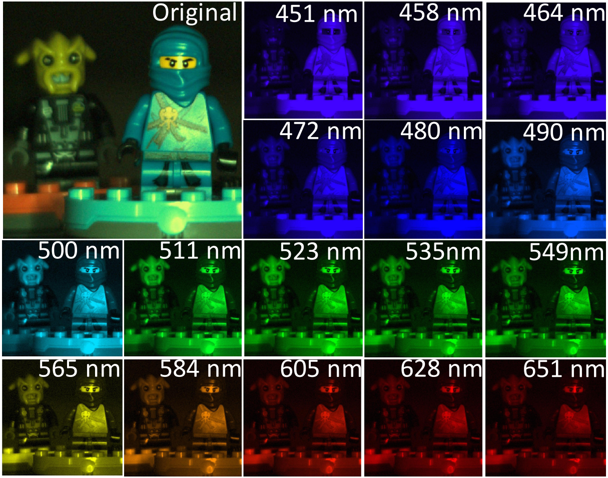


(a) Grayscale Boundary Function $\mathbf{I}_L$



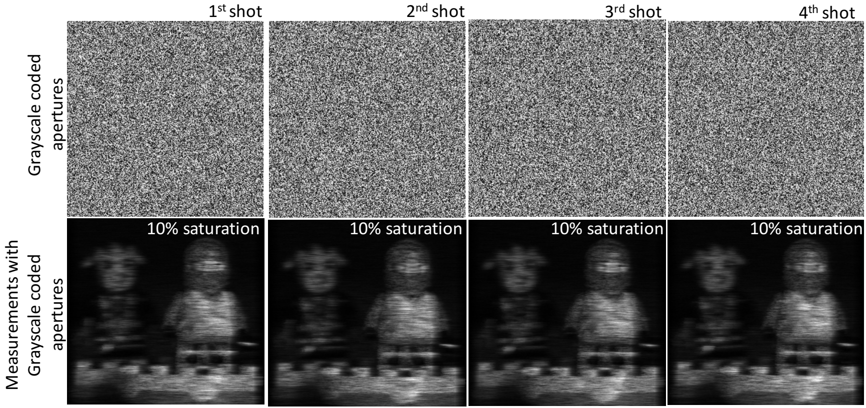
(b) Optimal Transmittance

Dataset



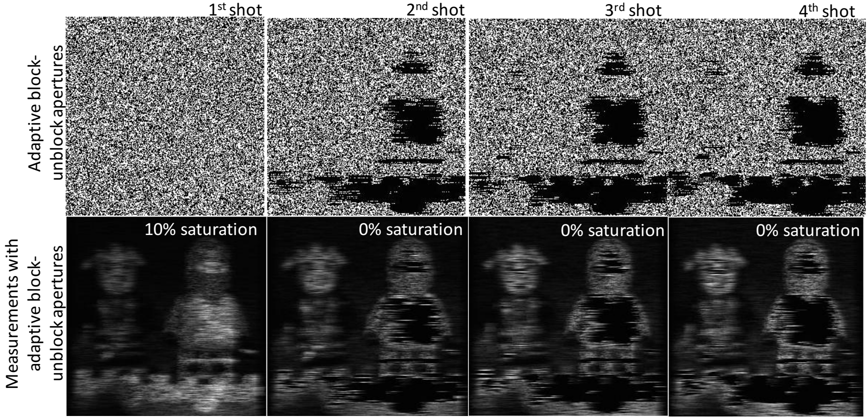
Database obtained using a wide-band Xenon lamp as the light source, a visible mochromator (450nm and 650nm). The image intensity was captured using a CCD camera exhibiting 256 × 256 pixels.

Uniform Grayscale coded apertures (UGCA)



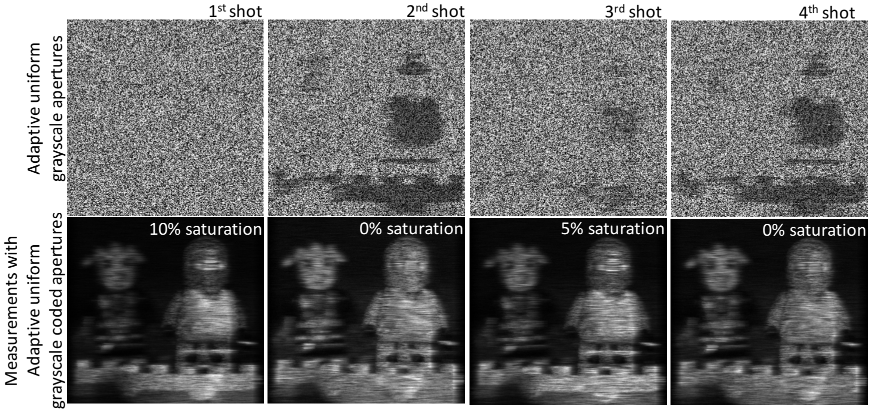
Uniform grayscale coded apertures and compressive measurements, **dynamic range** $20\log(255 \times 255) = \mathbf{96.32dB}$

Adaptive block-unblock coded apertures (ABCA)



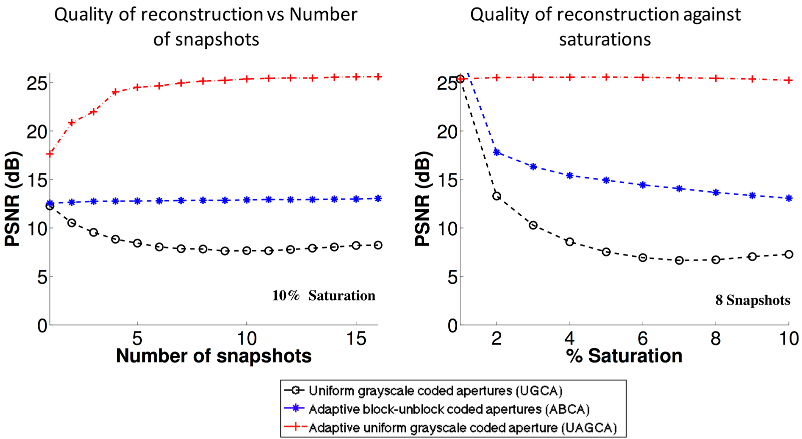
Adaptive block-unblock coded aperture (ABCA) and compressive measurements, **dynamic range** $20\log(255 \times 255) = \mathbf{96.32dB}$

Uniform adaptive grayscale coded apertures (UAGCA)



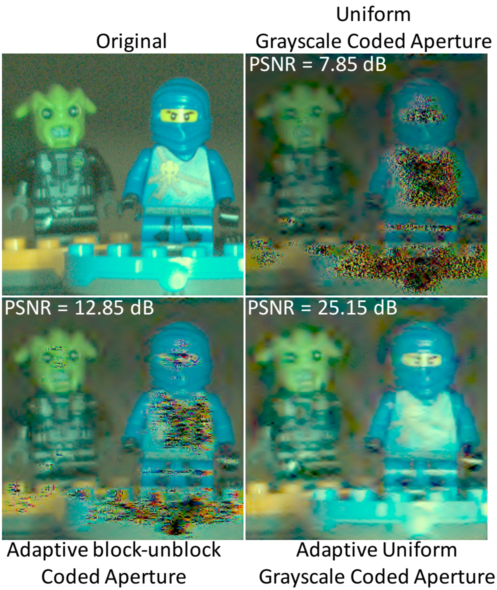
Uniform Adaptive Grayscale Coded Apertures and compressive measurements, **dynamic range** $20\log(255 \times 255) = \mathbf{96.32dB}$

Quality of reconstruction vs saturation percentage and snapshots



The proposed method (UAGCA) overcomes the two methods (UGCA and ABCA) in up to **10 dB**

Image reconstruction



Conclusions

1. **Adaptive Uniform Grayscale Coded Apertures** (AUGCA) have been introduced in CASSI system to **replace** the traditional **block-unblock coded apertures**.
2. The **proposed architecture increases** the dynamic range of the system from **48.16 dB to 96.32 dB**.
3. The designed **AUGCA** outperforms the block-unblock adaptive coded apertures and Uniform Grayscale Coded Aperture in up to **10 dB** in the quality of the reconstructed images.

Thank You!