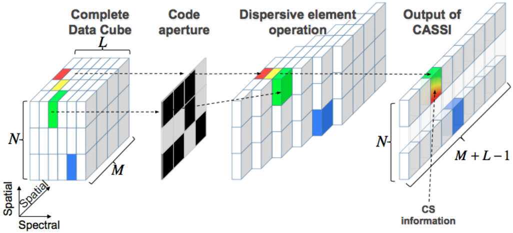
Coded Aperture Design in Compressive Spectral Imaging based on Side Information

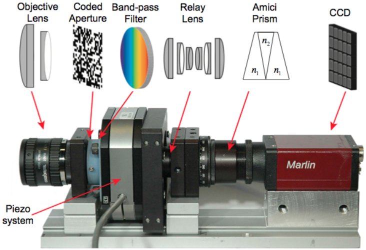
Laura Galvis, Henry Arguello, Gonzalo R. Arce

Electrical and Computer Engineering
University of Delaware
Newark

October 10, 2016

Coded Aperture Snapshot Spectral Imager (CASSI)



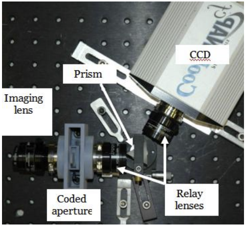


*

*A. Wagadarikar, R. John, R. Willett, and D. Brady, "Single disperser design for coded aperture snapshot spectral imaging," Applied Optics, Vol. 47, No. 10, pp. B44–B51, 2008.

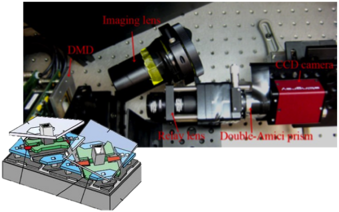
Implementation of Coded apertures patterns

Photomask



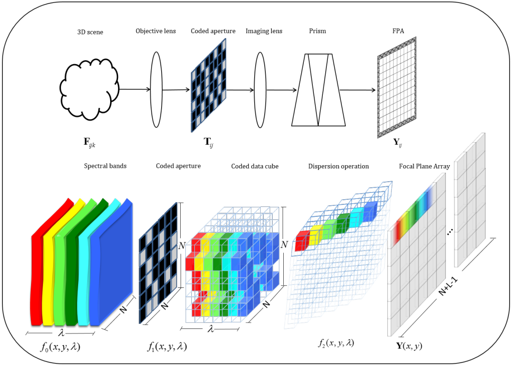
- A new photomask needs to be lithographically fabricated
- The entire system needs to be re-aligned after the installation of the new photomask and it is a very time-consuming process.

Digital Micromirror Device (DMD)



- New patterns can be implemented without optical and/or mechanical modification of the system
- Allows multi-shot coding

Coded Aperture Snapshot Spectral Imager (CASSI)

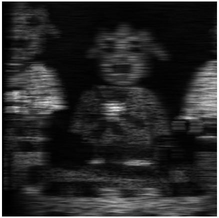


Forward Matrix Model

$$Y = \mathbf{Hf}$$

Coding + Dispersion

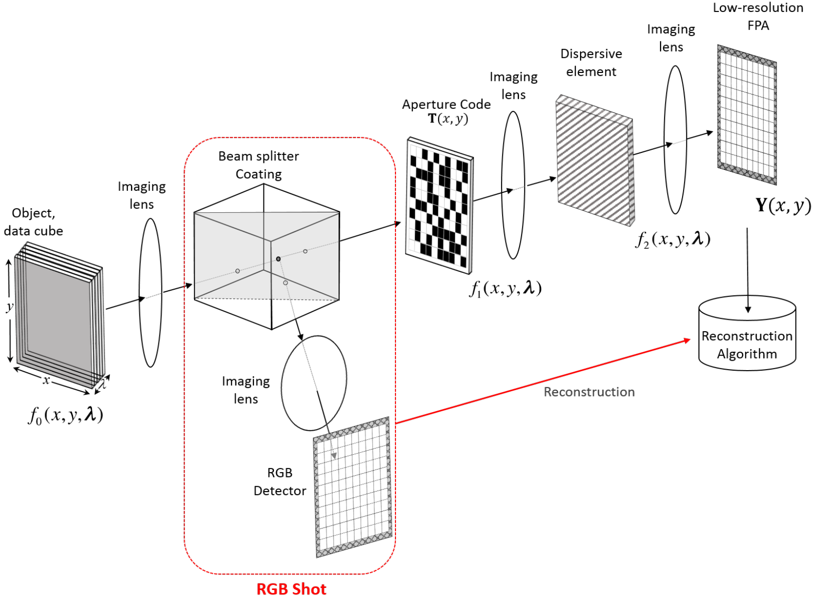
Spectral Data cube



Discrete Model

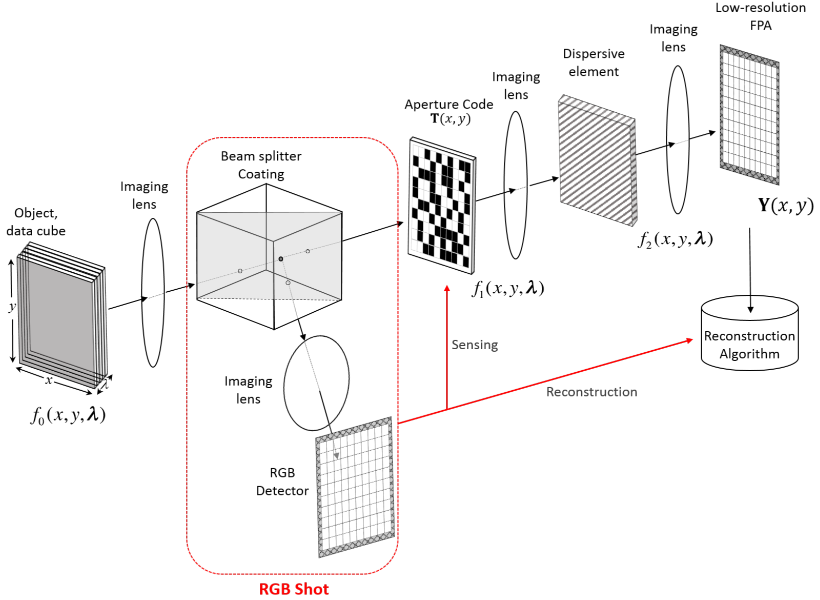
$$Y_{mn} = \sum_{k=0}^{L-1} \mathcal{F}_{m(n-k)k} T_{m(n-k)} + \omega_{mn}$$

Approach: CASSI with Side Information

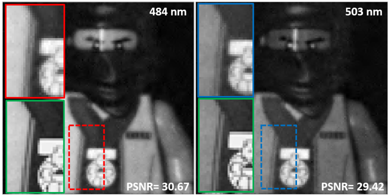


CASSI shot + RGB Side Information

Approach: CASSI with Side Information



Sensing process: Design of coded apertures based on side information



Correlation between the reconstruction error and the estimated edges. 19.84% and 14.97% (Yellow pixels) corresponds to errors on the edges.

Approach: CASSI with Side Information

The k^{th} spectral band of the spatiospectral image:

$$(\mathbf{F}_k)_{mn} \Rightarrow \mathbf{F}_k = (\mathbf{F}_k)_{mn} \text{ for } m, n = 0, \ldots, N-1 \text{ and } k = 0, 1, \ldots, L-1.$$

Side Information image:

$$\mathbf{F}_G = \sum_{k=0}^{L-1} w_k \mathbf{F}_k \quad w_k > 0,$$

where $\mathbf{w}$ gives the spectral response of the CCD sensor.

$$Canny(\mathbf{F}_G) = Canny\left(\sum_{k=0}^{L-1} w_k \mathbf{F}_k\right).$$

The edges of the side information image $\mathbf{F}_G$ are the linear combination of the edges of each band $\mathbf{F}_k$

$$\widehat{\mathbf{F}}_G = \sum_{k=0}^{L-1} w_k Canny(\mathbf{F}_k) = \sum_{k=0}^{L-1} w_k \widehat{\mathbf{F}}_k,$$

Then can be assumed that $\widehat{\mathbf{F}}_G$ contains information of all the spectral bands edges, and it is a good estimation of the edges for the spectral bands $\widehat{\mathbf{F}}_k$.

The most representative edges are defined as

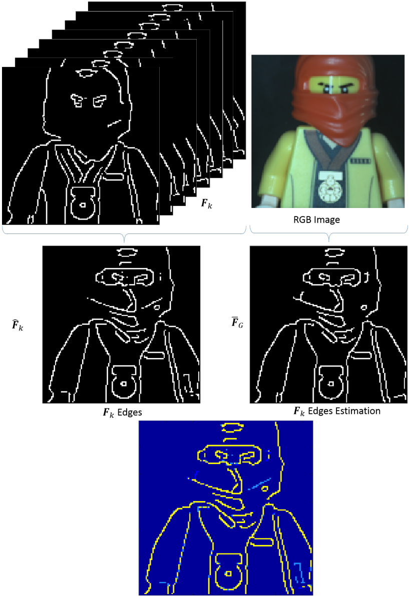
$$\left(\overline{\mathbf{F}}_{\mathbf{G}}\right)_{mn} = \begin{cases} \left(\widehat{\mathbf{F}}_G\right)_{mn}, & \text{if } \left(\widehat{\mathbf{F}}_G\right)_{mn} > \rho \\ 0, & \text{otherwise,} \end{cases}$$

Design of the codes

$$\mathbf{T} = \mathbf{T}_{b1} \cdot \mathbf{T}_e + \mathbf{T}_{b2} \cdot (1 - \mathbf{T}_e),$$

$$\mathbf{T} = \mathbf{T}_{b1} \cdot \overline{\mathbf{F}}_G + \mathbf{T}_{b2} \cdot (1 - \overline{\mathbf{F}}_G).$$

- First component: Blue noise pattern (in order to achieve a more uniform sensing)
- Second component: Edge component
- $\mathbf{T}_{b1} \neq \mathbf{T}_{b2}$



Approach: CASSI with Side Information

$$Y_{mn}=\sum_{k=0}^{L-1}\left[(\mathbf{T}_{b1})_{m(n-k)}\left(\overline{\mathbf{F}}_G\right)_{m(n-k)}+(\mathbf{T}_{b2})_{m(n-k)}\left(1-\overline{\mathbf{F}}_G\right)_{m(n-k)}\right](\mathbf{F}_k)_{m(n-k)}$$

$$Y_{mn}=\underbrace{\sum_{k=0}^{L-1}(\mathbf{T}_{b1})_{m(n-k)}\left(\overline{\mathbf{F}}_k\right)_{m(n-k)}(\mathbf{F}_k)_{m(n-k)}}_{\text{a. Sensing of edge sections}}+\underbrace{\sum_{k=0}^{L-1}(\mathbf{T}_{b2})_{m(n-k)}\left(1-\overline{\mathbf{F}}_G\right)_{m(n-k)}(\mathbf{F}_k)_{m(n-k)}}_{\text{b. Sensing of background}},$$

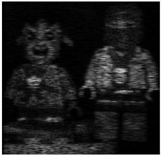
- Several coded apertures patterns can be calculated
- Transmittance of the final coded aperture is in the range of $16\% - 26\%$
- The width of the edges give us many more options of coded apertures to test
- $\mathbf{T}_{b1} \neq \mathbf{T}_{b2}$
- It is possible to use low or high transmittances in the borders

Reconstruction Process

Optimization Problem

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

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

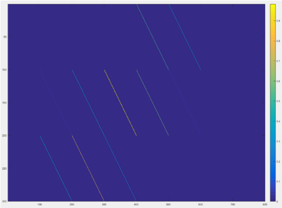


CASSI System:

$$\begin{bmatrix} \mathbf{y} \end{bmatrix} = \begin{bmatrix} \mathbf{H} \end{bmatrix} \begin{bmatrix} \mathbf{f} \end{bmatrix}$$

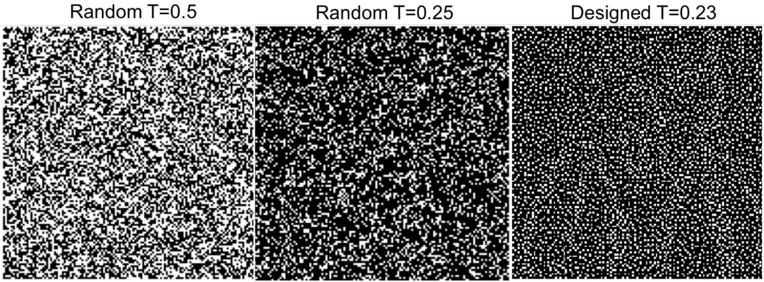
CASSI System + RGB Side Information:

$$\begin{bmatrix} \mathbf{y} \\ \mathbf{y}_R \\ \mathbf{y}_G \\ \mathbf{y}_B \end{bmatrix} = \begin{bmatrix} \mathbf{H} \\ \mathbf{R} \\ \mathbf{G} \\ \mathbf{B} \end{bmatrix} \begin{bmatrix} \mathbf{f} \end{bmatrix}$$

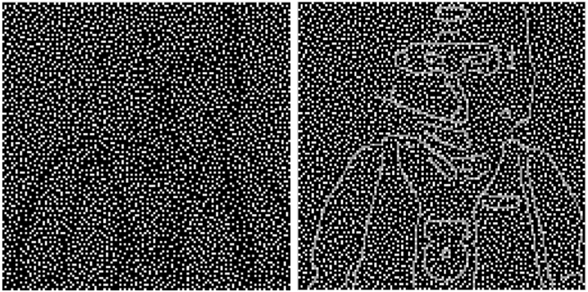


Simulations results

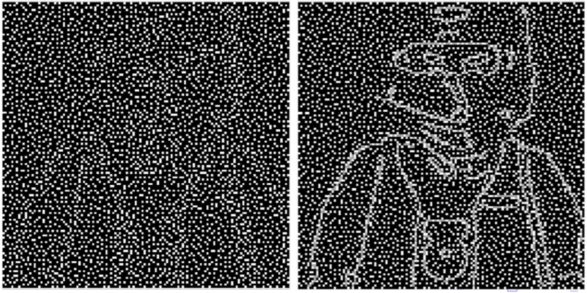
- Test data cube $\mathcal{F}$: $128 \times 128 \times 8$
- Reconstruction algorithm: GPSR
- Designed coded aperture $T = 0.23$
- Random coded aperture $T = 0.25 - 0.5$



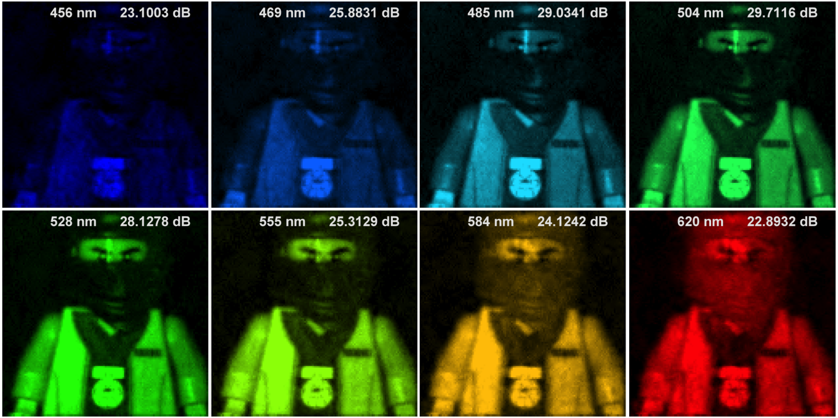
Low transmittance in borders



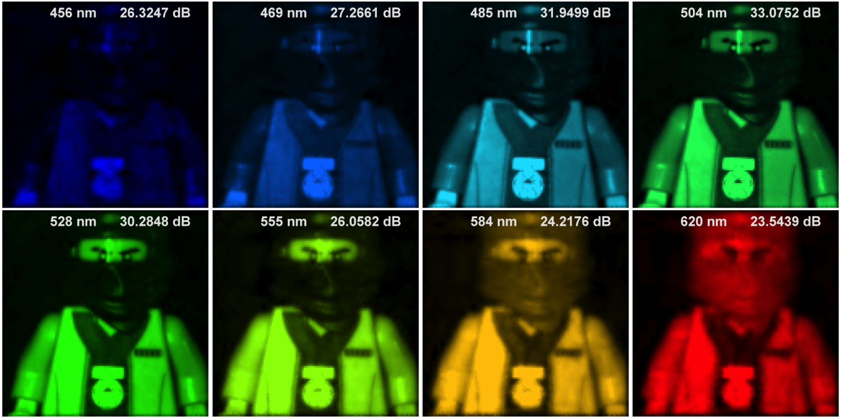
High transmittance in borders



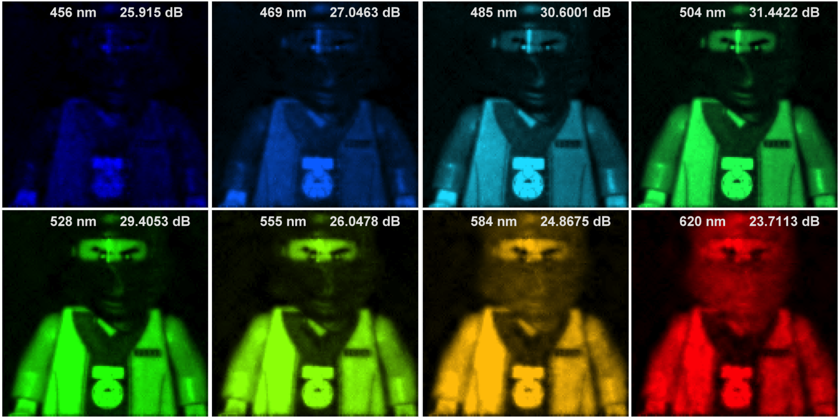
Random coded apertures $T = 0.25$

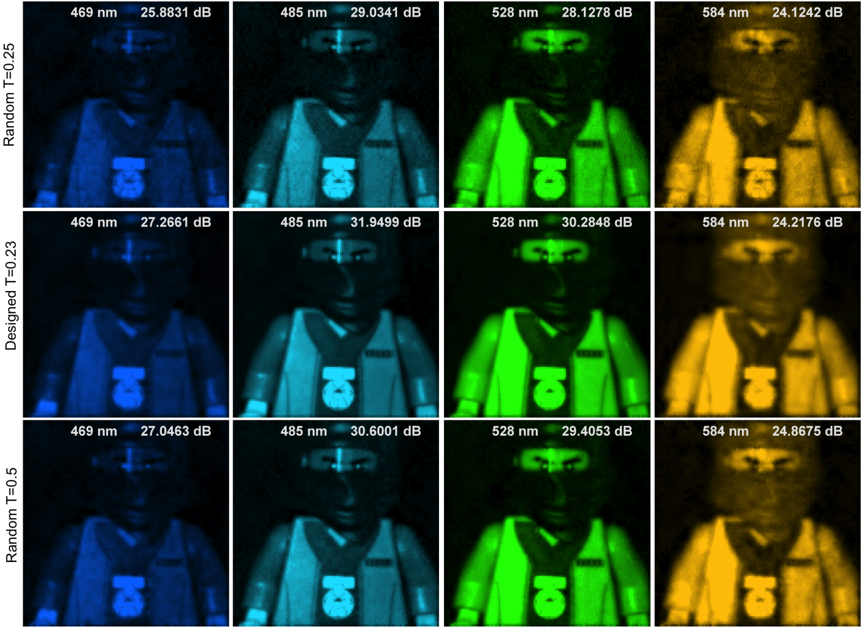


Designed coded apertures $T = 0.23$

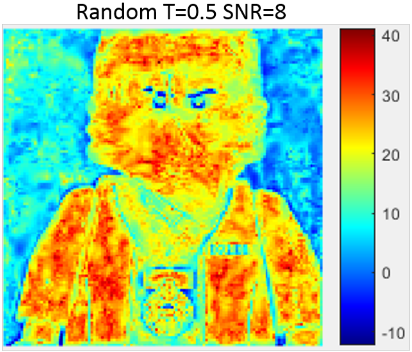


Random coded apertures $T = 0.5$

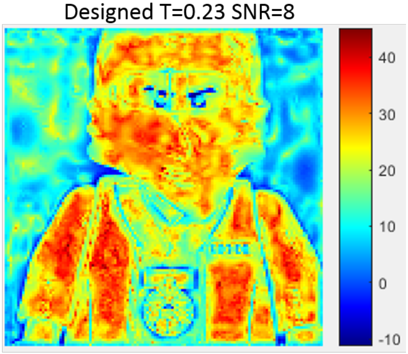



Random T=0.25
Designed T=0.23
Random T=0.5
469 nm 25.8831 dB
485 nm 29.0341 dB
528 nm 28.1278 dB
584 nm 24.1242 dB
469 nm 27.2661 dB
485 nm 31.9499 dB
528 nm 30.2848 dB
584 nm 24.2176 dB
469 nm 27.0463 dB
485 nm 30.6001 dB
528 nm 29.4053 dB
584 nm 24.8675 dB

Spectral Reconstruction

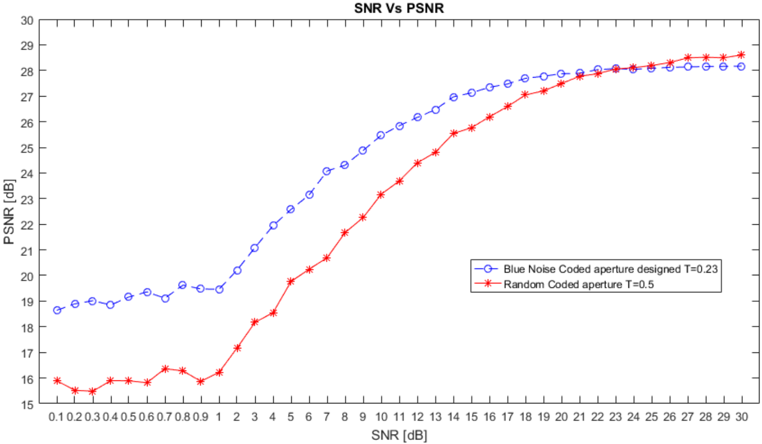


Average spectral reconstruction: 16.99

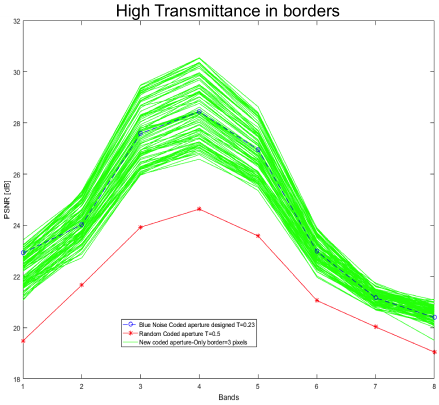


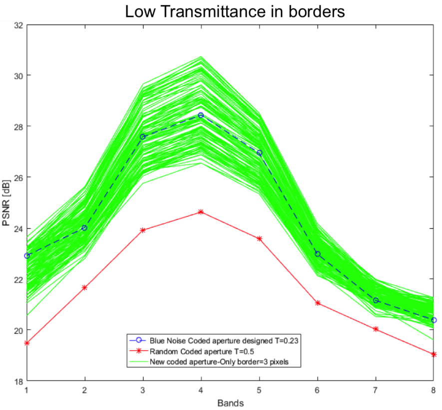
Average spectral reconstruction: 19.51

SNR analysis



Selection of coded apertures



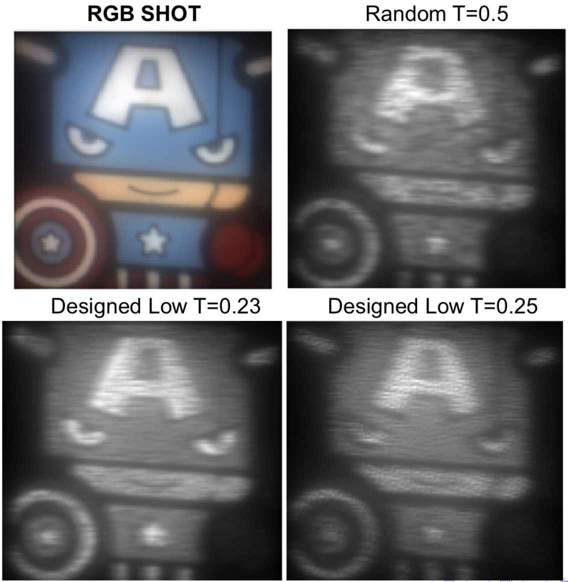


Experimental results

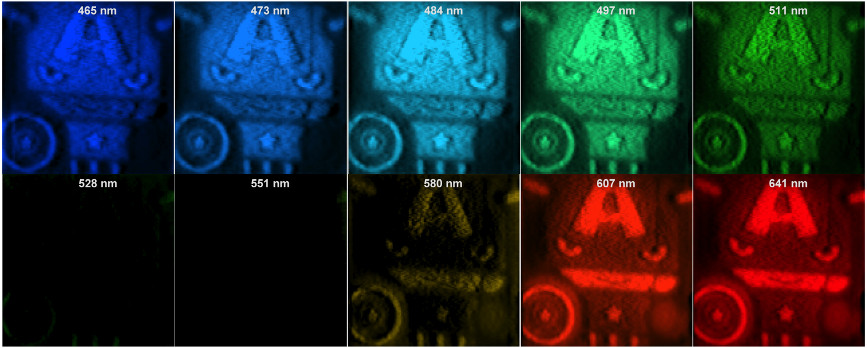
Scene

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

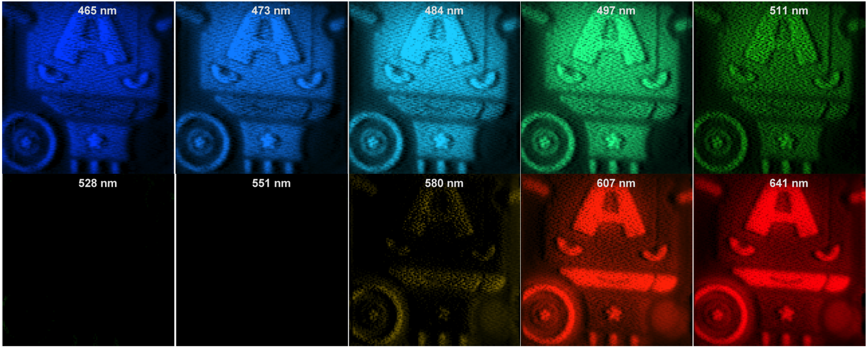
Measurements



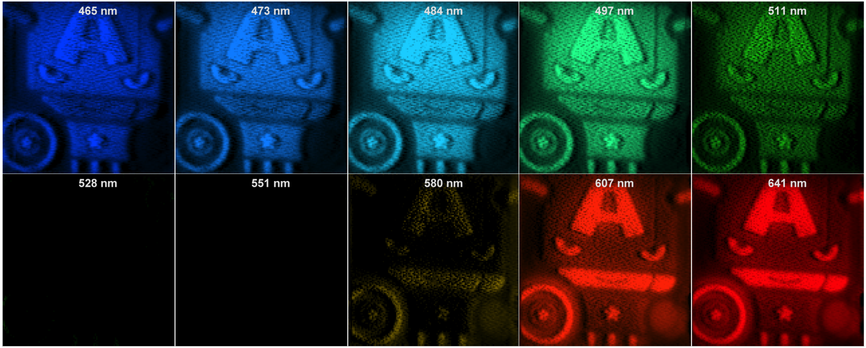
Random coded aperture $T = 0.5$

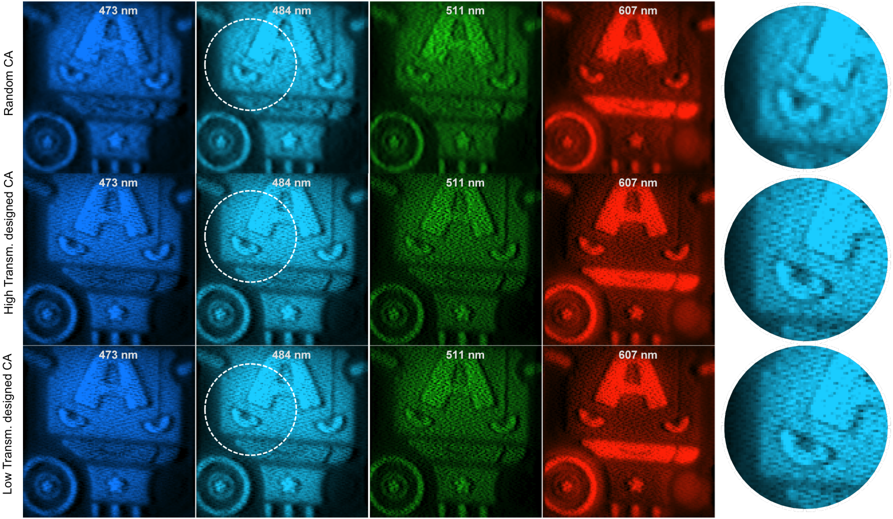


Designed coded aperture, Low T at borders, $T = 0.23$



Designed coded aperture, High T at borders, $T = 0.25$




Random CA
High Transm. designed CA
Low Transm. designed CA
473 nm
484 nm
511 nm
607 nm
473 nm
484 nm
511 nm
607 nm
473 nm
484 nm
511 nm
607 nm

Conclusions

- A forward model of CASSI with side information has been developed.
- The model uses the side information for the sensing and the reconstruction process.
- The coded aperture design exploits key features in the scene such as scene edges.
- this strategy improves significantly the reconstruction of spectral data cubes, particularly with low SNR measurements.

Questions?

Thanks!