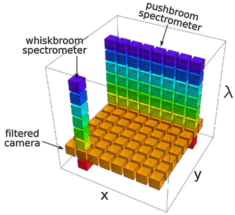
Compressive Spectral Imaging Using Multiple Snapshot Colored-mosaic Detector Measurements

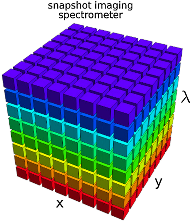
Carlos A. Hinojosa[1], Claudia V. Correa[2]
Henry Arguello[1], Gonzalo R. Arce[2].

April 17, 2016
SPIE DCS Computational Imaging Conference

Universidad Industrial de Santander [1]
University of Delaware [2]

- **Traditional Spectral Imaging Techniques**[1]



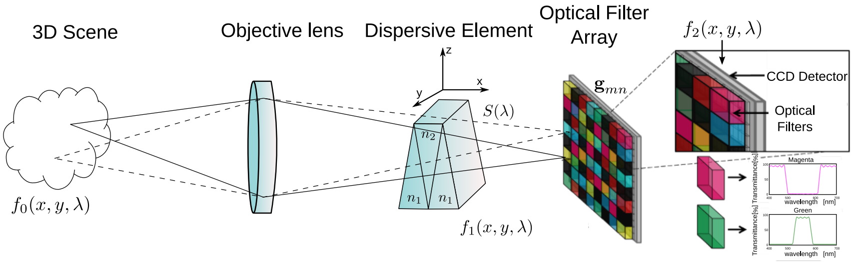


- **Compressive Spectral Imaging**
  - Senses and compresses a spectral image at the same time.
  - Captures less samples than traditional methods.
  - Assumes $\mathbf{f}$ is sparse.
  - $\mathbf{g}=\mathbf{H}\mathbf{f}=\mathbf{H}\boldsymbol{\Psi}\boldsymbol{\theta}$.
  - A sparse approximation $\hat{\boldsymbol{\theta}}$ obtained as

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \|\mathbf{g} - \mathbf{A}\boldsymbol{\theta}\|_2^2 + \tau\|\boldsymbol{\theta}\|_1.$$

[1] Hagen, Kester, Gao, and Tkaczyk. Snapshot advantage: a review of the light collection improvement for parallel high-dimensional measurement systems.

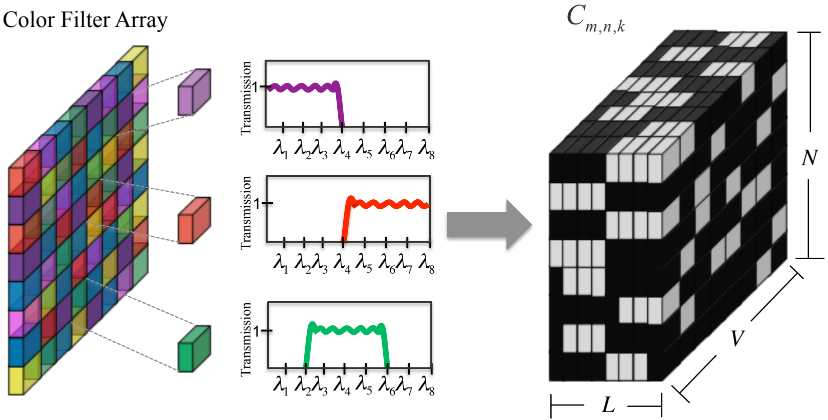
Snapshot Colored Compressive Spectral Imager (SCCSI)



- SCCSI measurements are optically realized by:
  - Objective lens.
  - Dispersive element.
  - FPA detector: Intensity sensor + Array of optical filters.

$$G_{m,n} = \sum_{k=0}^{L-1} F_{m,(n-k),k} C_{m,n,k}$$

- Example of a discrete color filter array **C**.

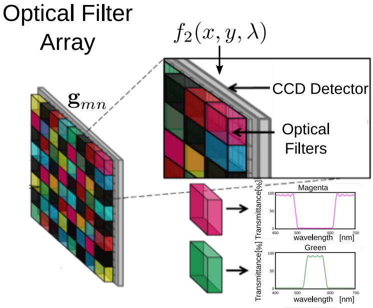


Snapshot Colored Compressive Spectral Imager (SCCSI)

- Compressive sensing dictates that the number of measurements must be in excess of $S\log(N \cdot M \cdot L)$.
- Multiple CSI shot measurements

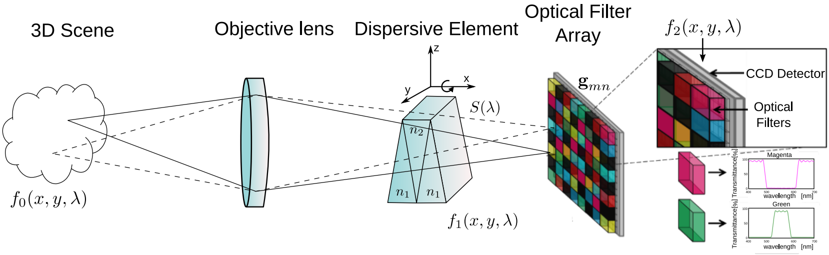
$$\mathbf{g}^i = \mathbf{H}^i\mathbf{f} = \mathbf{H}^i\boldsymbol{\Psi}\boldsymbol{\theta}.$$

- **Limitation:** SCCSI only admits a single shot



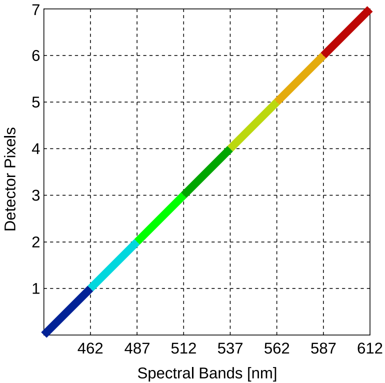
- The pixelated tiling of optical filters is directly attached to the detector.
- Modifying the optical filter array leads to change all the FPA detector.

- Proposed Solution: prism rotation in the yz-plane, such that the dispersed spectral image is directed to different areas of the detector.



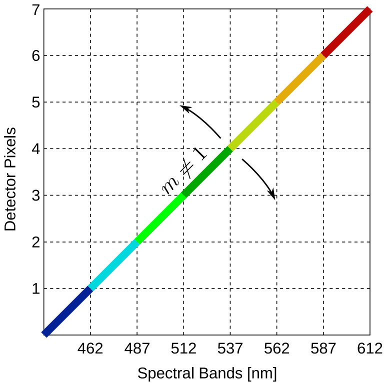
- Any angle?

- Selected angles: $0°, 90°, 180°, 270°$
- Why?



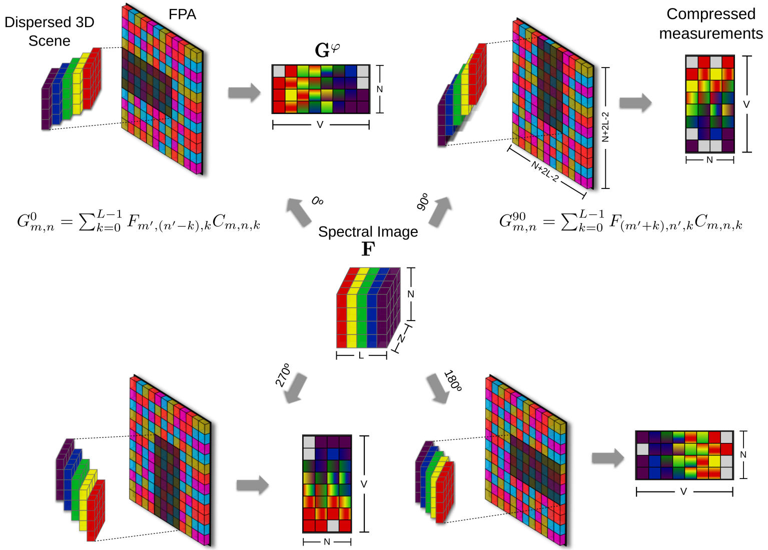
- Using a different angle ⇒ the slope changes hence there is not a one-to-one matching between the voxels and the FPA elements.

- Selected angles: $0°, 90°, 180°, 270°$
- Why?



- Using a different angle ⇒ the slope changes hence there is not a one-to-one matching between the voxels and the FPA elements.

Discrete SCCSI Multishot Model



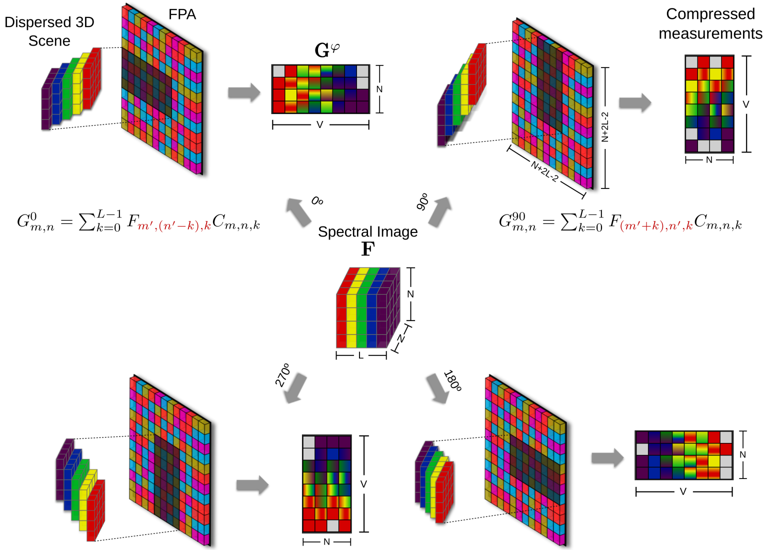
$$G^{0}_{m,n} = \sum_{k=0}^{L-1} F_{m',(n'-k),k} C_{m,n,k}$$

$$G^{90}_{m,n} = \sum_{k=0}^{L-1} F_{(m'+k),n',k} C_{m,n,k}$$

$$G^{270}_{m,n} = \sum_{k=0}^{L-1} F_{(m'-k),n',k} C_{m,n,k}$$

$$G^{180}_{m,n} = \sum_{k=0}^{L-1} F_{m',(n'+k),k} C_{m,n,k}$$

Discrete SCCSI Multishot Model



$G^{0}_{m,n} = \sum_{k=0}^{L-1} F_{m',(n'-k),k} C_{m,n,k}$

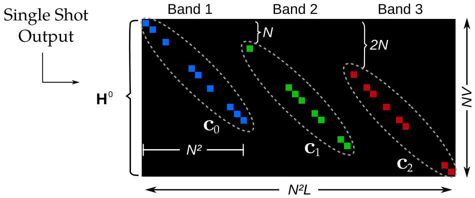
$G^{90}_{m,n} = \sum_{k=0}^{L-1} F_{(m'+k),n',k} C_{m,n,k}$

$G^{270}_{m,n} = \sum_{k=0}^{L-1} F_{(m'-k),n',k} C_{m,n,k}$

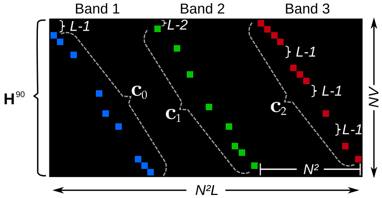
$G^{180}_{m,n} = \sum_{k=0}^{L-1} F_{m',(n'+k),k} C_{m,n,k}$

Matrix Model

$$\mathbf{g}^{\varphi} = \mathbf{H}^{\varphi}\mathbf{f}, \quad \text{where } \varphi \in \{0, 90, 180, 270\}$$

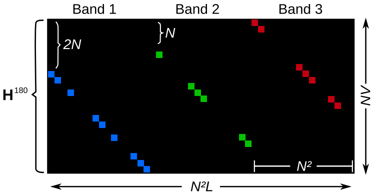


$$(\mathbf{h}_j)^0_\ell = \begin{cases} (\boldsymbol{c}_k)_{(L-1)(w+2\lfloor \ell'/N \rfloor+1)+j+k(2L-2)}, & \text{If } \ell - k\check{N} = j \\ 0, & \text{Otherwise} \end{cases}$$

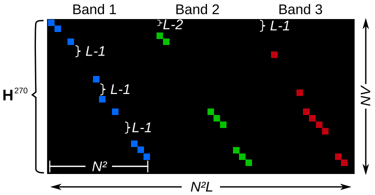


$$(\mathbf{h}_j)^{90}_\ell = \begin{cases} (\boldsymbol{c}_k)_{(L-1)(w+\lfloor \ell'/N \rfloor)+j}, & \text{If } (L-1)(\lfloor \ell'/N \rfloor + 1) + \ell - k(N^2+1) = j \\ 0, & \text{Otherwise} \end{cases}$$

Matrix Model



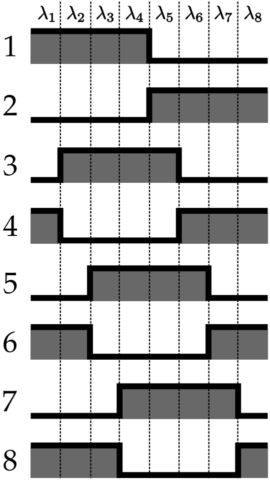
$$(\mathbf{h}_j)^{180}_{\ell} = \begin{cases} (\boldsymbol{c}_k)_{(L-1)(w+2\lfloor \ell'/N \rfloor-(N-1))+j-k(2L-2)}, & \text{If } \ell - k\hat{N} + N(L-1) = j \\ 0, & \text{Otherwise} \end{cases}$$



$$(\mathbf{h}_j)^{270}_{\ell} = \begin{cases} (\boldsymbol{c}_k)_{(L-1)(w+\lfloor \ell'/N \rfloor+1)+j}, & \text{If } (L-1)(\lfloor \ell'/N \rfloor) + \ell - k(N^2-1) = j \\ 0, & \text{Otherwise} \end{cases}$$

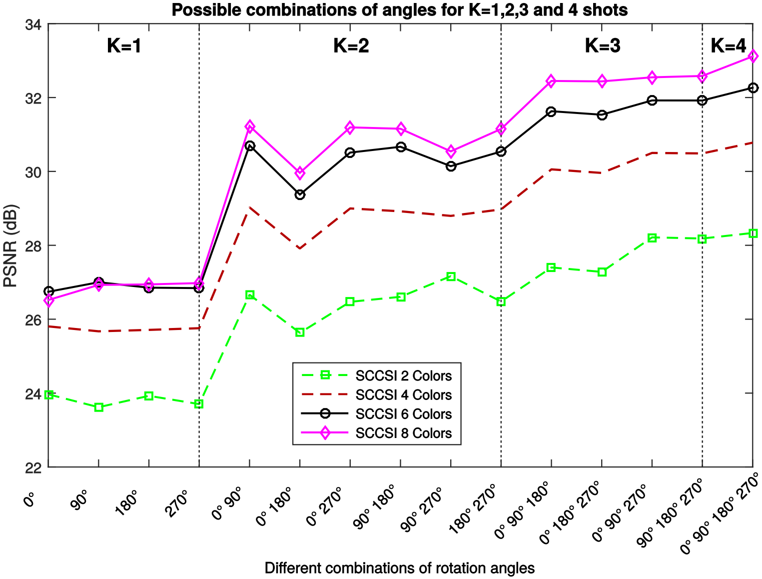
- Database: $N = 256, L = 8$.
- The transmittance of the color filter array was set to 50 %.
- The 3D sparse basis: $\mathbf{\Psi} = \mathbf{\Psi}_C \otimes \mathbf{\Psi}_{2D}$.
- The results are compared with reconstructions obtained from the original SCCSI single-shot system.
- The number of Colors in the detector varies between 2 and 8.

(a) Test Data Cubes.



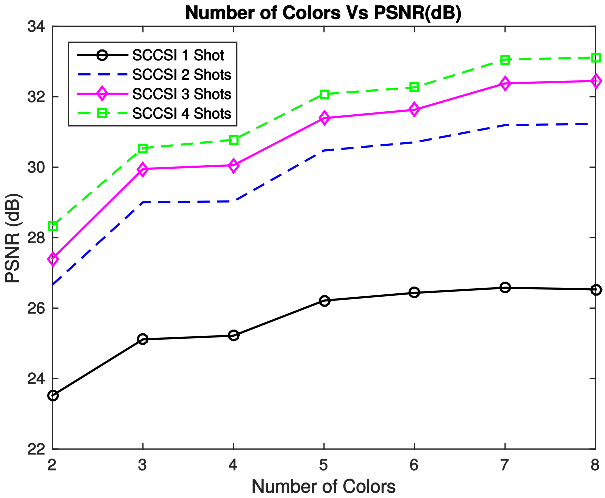
(b) Set of predefined band-pass optical filters

- Possible angle combinations for $K = 1, 2, 3, 4$.



Selected angles:

- $K = 1 \rightarrow \varphi = 0°$
- $K = 2 \rightarrow \varphi = 0°\ 90°$
- $K = 3 \rightarrow \varphi = 0°\ 90°\ 180°$
- $K = 4 \rightarrow \varphi = 0°\ 90°\ 180°\ 270°$



Simulations and Results: Reconstructions

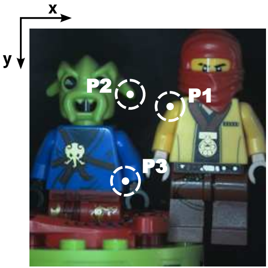
SCCSI
6 Colors

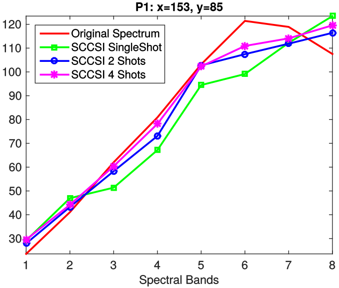
K=1

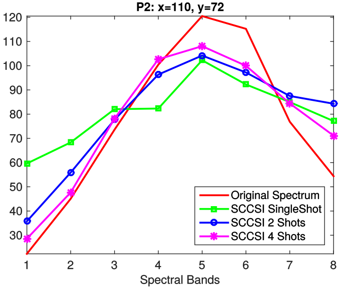
K=4

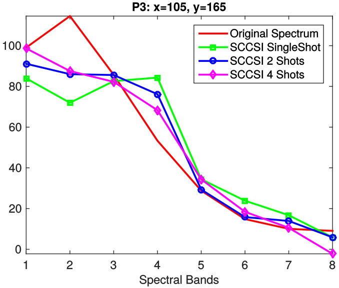
Original

- Used number of colors: 4.









Conclusions

- Multiple snapshots in SCCSI can be achieved by rotating the dispersive element of the original architecture at different angles.
- By taking multiple snapshots, the inverse problem becomes less ill-posed which results on improved reconstructions.
- More accurate spectral reconstructions are obtained with the SCCSI multi-shot system.
- A gain up to 7 dB is obtained when comparing the results from four measurement shots with a single SCCSI snapshot.

Thank You

Universidad Industrial de Santander

University of Delaware

High-Dimensional Signal Processing Research Group
www.hdspgroup.com

SPIE. DCS COMMERCIAL+SCIENTIFIC SENSING AND IMAGING

References I

Claudia V Correa, Henry Arguello, and Gonzalo R Arce.
Snapshot colored compressive spectral imager.
JOSA A, 32(10):1754–1763, 2015.

Henry Arguello and Gonzalo R Arce.
Colored coded aperture design by concentration of measure in compressive spectral imaging.
Image Processing, IEEE Transactions on, 23(4):1896–1908, 2014.

Emmanuel J Candè and Michael B Wakin.
An introduction to compressive sampling.
Signal Processing Magazine, IEEE, 25(2):21–30, 2008.

David L Donoho.
Compressed sensing.
Information Theory, IEEE Transactions on, 52(4):1289–1306, 2006.

Gonzalo R Arce, David J Brady, Lawrence Carin, Henry Arguello, and David S Kittle.
Compressive coded aperture spectral imaging: An introduction.
Signal Processing Magazine, IEEE, 31(1):105–115, 2014.

PA Stupar, RL Borwick III, JF DeNatale, PH Kobrin, and WJ Gunning.
Mems tunable fabry-perot filters with thick, two sided optical coatings.
In *Solid-State Sensors, Actuators and Microsystems Conference, 2009. TRANSDUCERS 2009. International*, pages 1357–1360. IEEE, 2009.

Ashwin Wagadarikar, Renu John, Rebecca Willett, and David Brady.
Single disperser design for coded aperture snapshot spectral imaging.
Applied optics, 47(10):B44–B51, 2008.

David J Brady.
Optical imaging and spectroscopy.
John Wiley & Sons, 2009.

David Kittle, Kerkil Choi, Ashwin Wagadarikar, and David J Brady.
Multiframe image estimation for coded aperture snapshot spectral imagers.
Applied Optics, 49(36):6824–6833, 2010.

Mário AT Figueiredo, Robert D Nowak, and Stephen J Wright.
Gradient projection for sparse reconstruction: Application to compressed sensing and other inverse problems.
Selected Topics in Signal Processing, IEEE Journal of, 1(4):586–597, 2007.

References IV

Ashwin Ashok Wagadarikar.
Compressive spectral and coherence imaging.
PhD thesis, Duke University, 2010.

D Kittle.
Compressive spectral imaging.
PhD thesis, Duke University, Durham, North Carolina, USA, 2010.

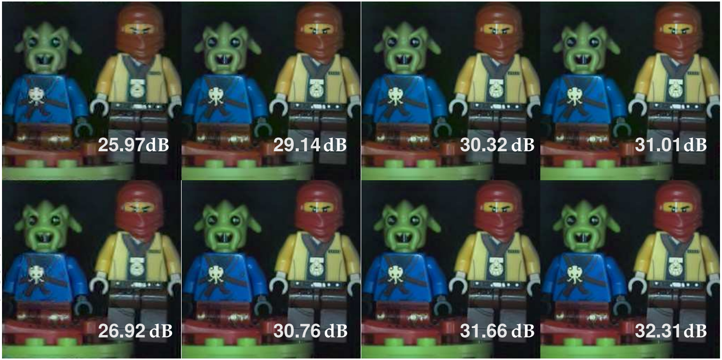
Simulations and Results: Reconstructions

Original

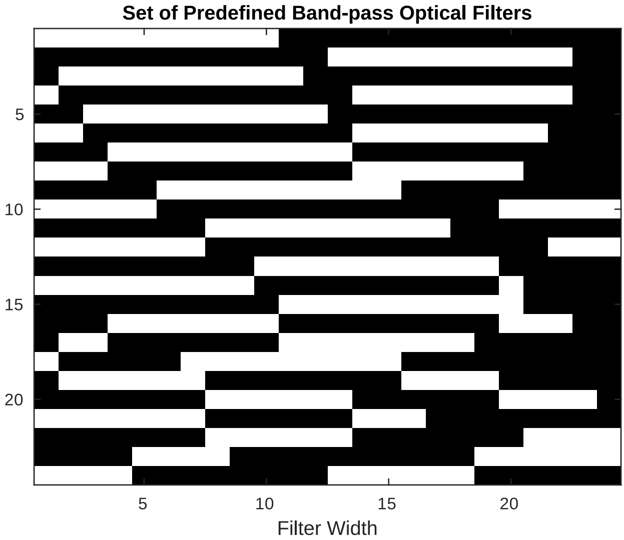
K=1 **K=2** **K=3** **K=4**

SCCSI 4 Colors

SCCSI 6 Colors



- Database $N = 512, L = 24$. The transmittance for both architectures was set to 0,4167.


Set of Predefined Band-pass Optical Filters
5
10
15
20
5
10
15
20
Filter Width

Second DataBase