Demosaicking Multispectral Images by Sphere Packing Filter Design

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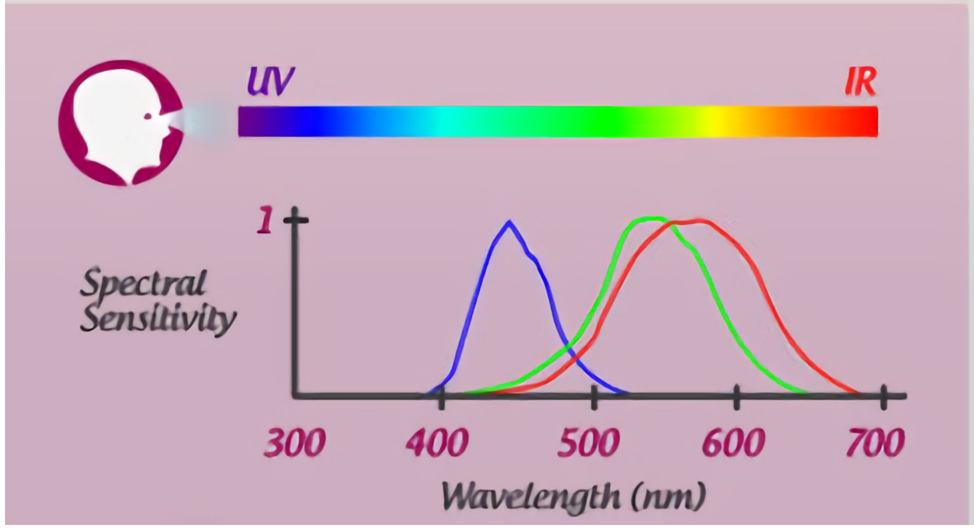
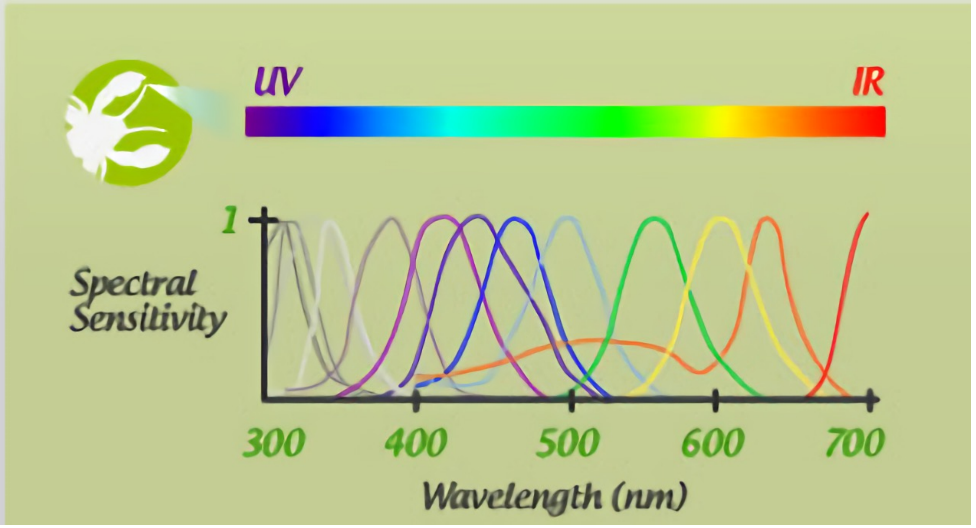
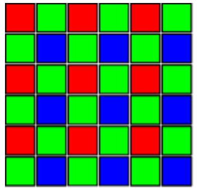
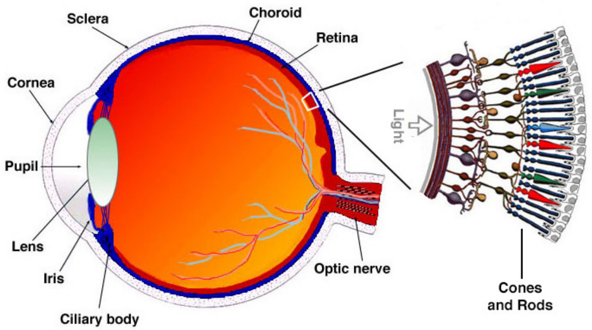
Motivation



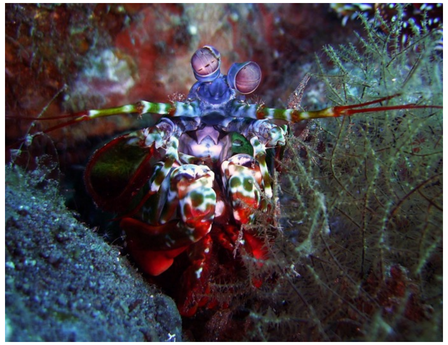


RGB



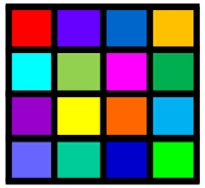


Human
3 Different types of Cones



Mantis Shrimp
12 Different types of Cones

MSI



Mathematical Model

Continuous acquisition of the grayscale mosaic

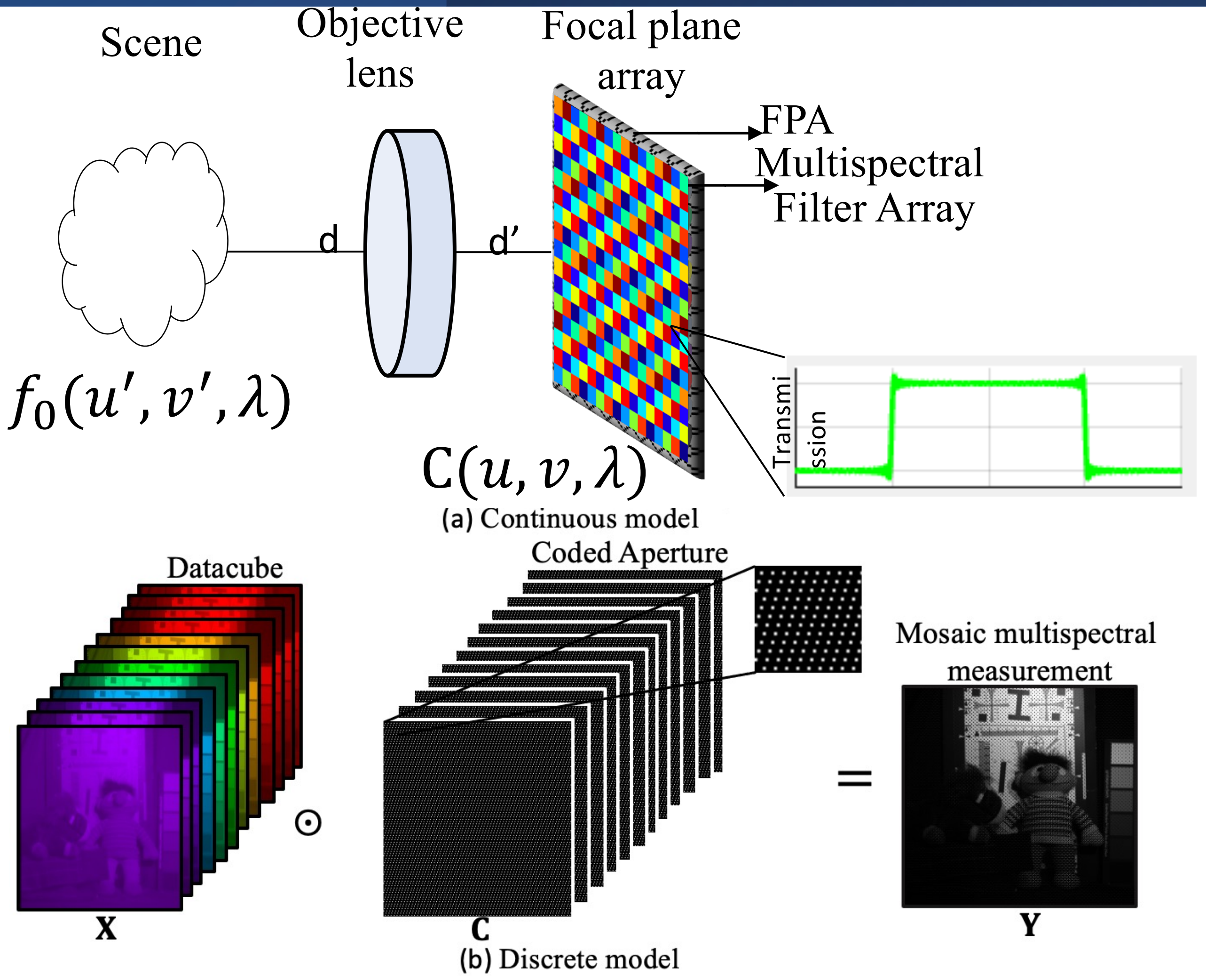
$$y(u,v) = \int_{\Lambda} C(u,v,\lambda) f_0(u',v',\lambda) d\lambda \quad (1)$$

Where C is coded aperture in focal plane and f_0 is the scene.

The acquisition of the grayscale mosaic compressive multispectral (discrete) projection of L spectral bands is

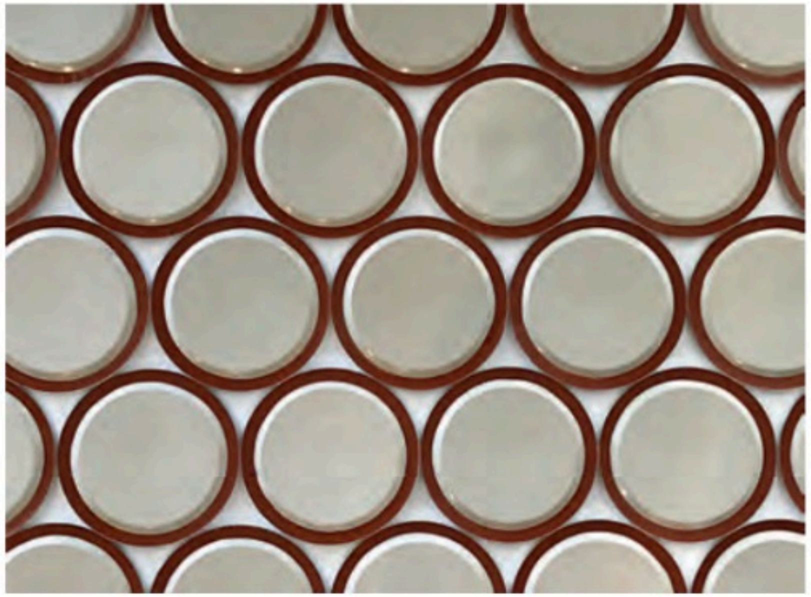
$$\mathbf{Y} = \sum_{l=1}^{L} \mathbf{X}_l \odot \mathbf{C}_l + \mathbf{\Omega} \quad (2)$$

Where $\mathbf{X}_l$ the individual grayscale image in the l^{th} wavelength



What is Sphere Packing?

2D



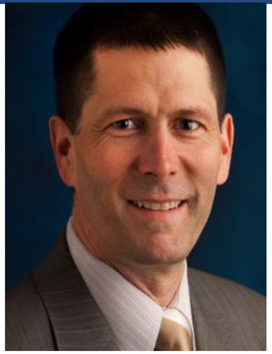
Density=$\frac{\pi}{\sqrt{12}} \approx 0.9068$

3D

Density=$\frac{\pi}{\sqrt{18}} \approx 0.7404$

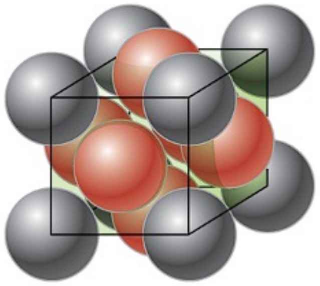
History of Sphere Packing Problem

- 1611
- Johannes **Kepler conjectured** about the closest packing of equal spheres.
- He did not have a prove to the conjecture.



- 1998
- Thomas Hales provides the formal proof of Kepler's conjecture.
- But **eliminating all posible irregular arregements** is very difficult, and this is what made the Kepler conjecture so hard to prove.

- 1831
- Carl Friedrich Gauss proved that the highest packing fraction that can be achieved by any packing of equal sphere.
- He proved that the Kepler conjecture is true if the spheres have to be arranged in a **regular lattice**.



Face-centered cubic structure

- 2017
- Maryna Viazovska solved sphere packing problem in **8-dimensions** [1] (E_8 lattice). And in collaboration with others **24-dimensions** [2] (Leech lattice).
- **Winner of the Fields Medal 2022.**

Theorem 1: No packing of congruent balls in Euclidean three space has density greater than that of the **face-centered cubic packing**, which corresponds to:

$$\rho = \frac{\pi}{3\sqrt{2}} \approx 0.7405$$

[1] M. S. Viazovska, “The sphere packing problem in dimension 8,”Annals of Mathematics, vol. 185, no. 3, pp. 991-1015, 2017.
[2] H. Cohn, A. Kumar, S. D. Miller, D. Radchenko, and M. Viazovska, “The sphere packing problem in dimension 24,” Annals of Mathematics, vol. 185, no. 3, pp. 1017-1033, 2017.

Proposed Multispectral Filter Array (MSFA)

The problem associated to the MSFA-sensing is

$$\mathbf{B} = (a \odot \mathbf{I} + b \odot \mathbf{J}) \mod L + 1 \tag{3}$$

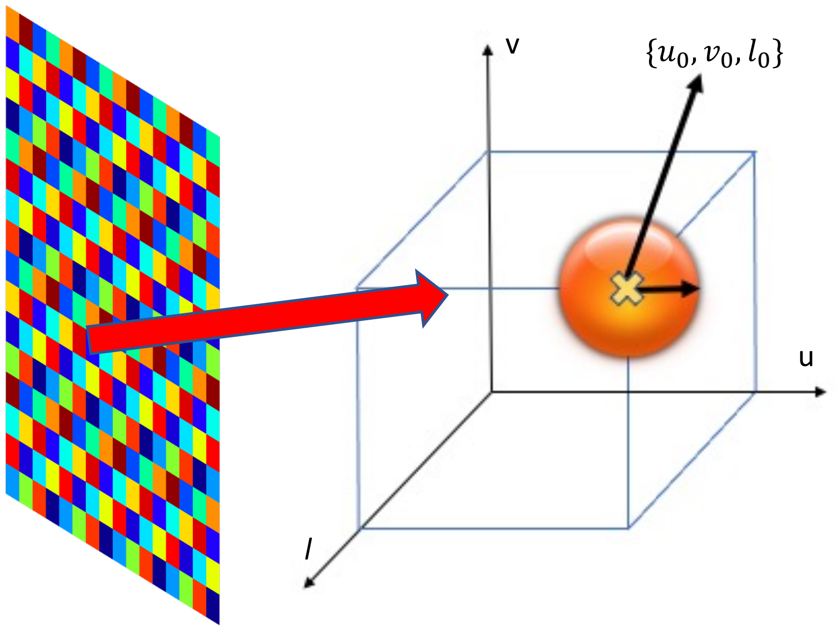
$\mathbf{I} = \mathbf{g}^{\mathbf{T}} \otimes \mathbf{q}$, g is a ones 1D-vector with length L, $\mathbf{q}$ is equal to [1,...,L] and $\mathbf{J} = \mathbf{I}^{\mathbf{T}}$. a and b were calculated with the proposed algorithm in [3]

The positions of the MSFA-OSP are given by:

$$\mathbf{E} = \mathbf{A} \otimes \mathbf{B} \tag{4}$$

Where $\mathbf{A}$ is a matrix of all ones such that $\mathbf{A} \in 1^{\alpha \times \beta}$, where $\alpha = \lfloor \frac{M}{L} \rfloor$ and $\beta = \lfloor \frac{N}{L} \rfloor$, M and N are number of pixels.

$\odot$ denotes the Hadamard product and $\otimes$ represents the Kronecker product.



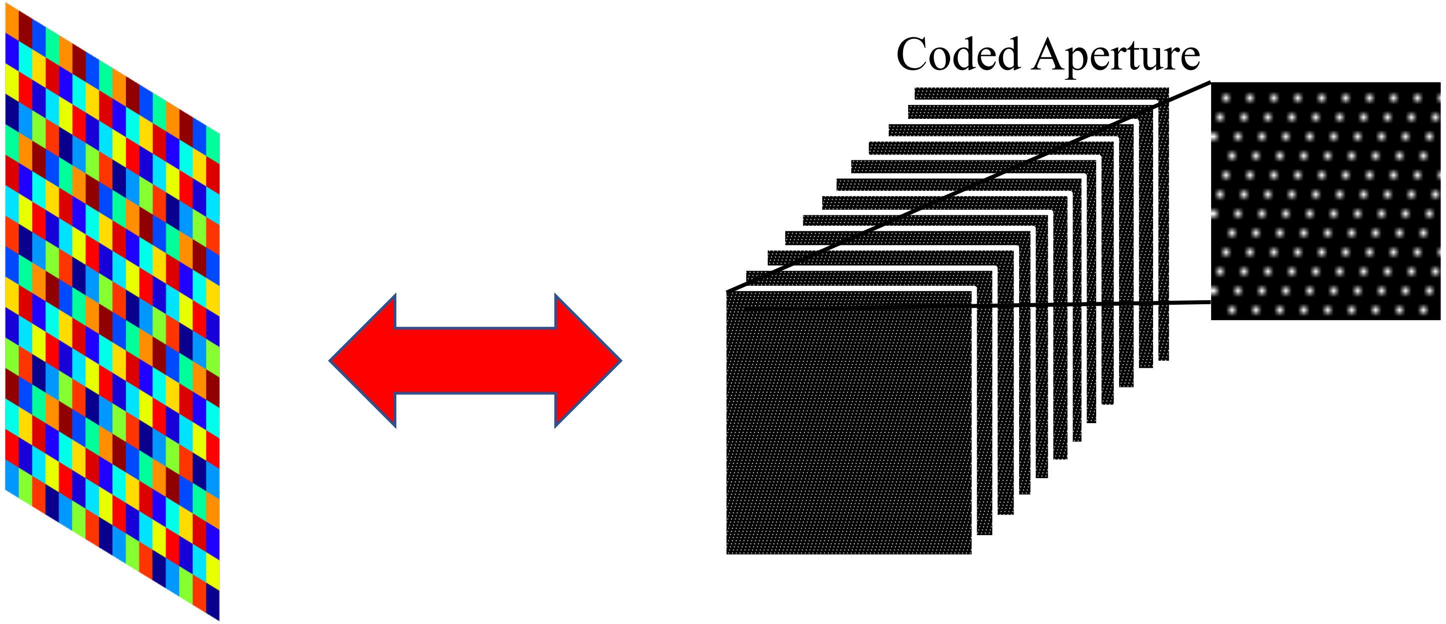
[3] **E. Vera**, F. Guzmán, and N. Díaz, **"Shuffled rolling shutter for snapshot temporal imaging"**, Optics Express, Jan 2022.

Proposed MSFA

The resulting positions of the MSFA can be expressed in binary coded aperture form:

$$C_{m,n,l} = \begin{cases} 1 & \text{if } l = E_{m,n} \\ 0 & \text{if } l \neq E_{m,n} \end{cases} \tag{5}$$

Where $m \in \{0, \ldots, M-1\}$, n $\in \{0, \ldots, N-1\}$, $l \in \{1, \ldots, L\}$.



Sphere Packing Upper Bound

Optimal Sphere Packing

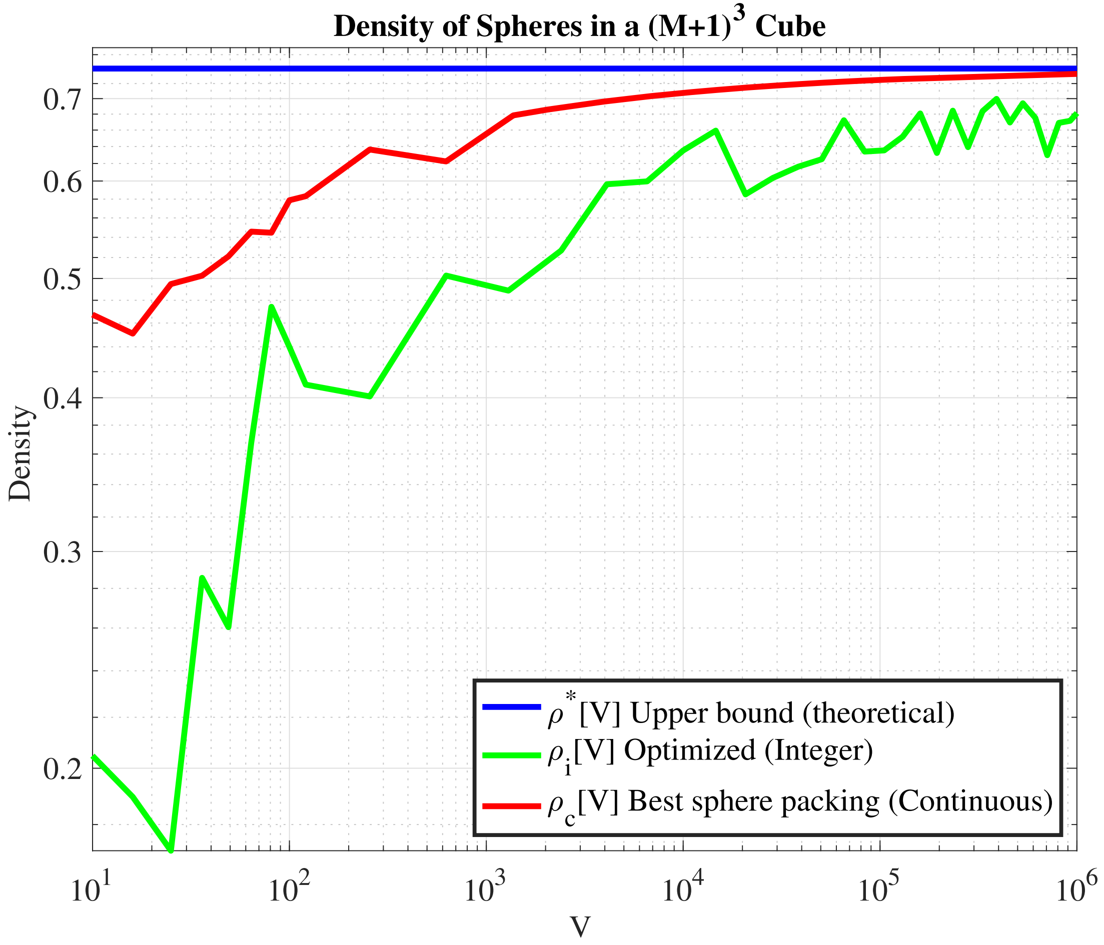
$$d^*(V) = \max(\min_{1 \leq k_1 < k_2 \leq V} D_{k_1,k_2}) \qquad (6)$$

V is the number of the spheres.

D_{k_1,k_2} is the all pairwise distance matrix

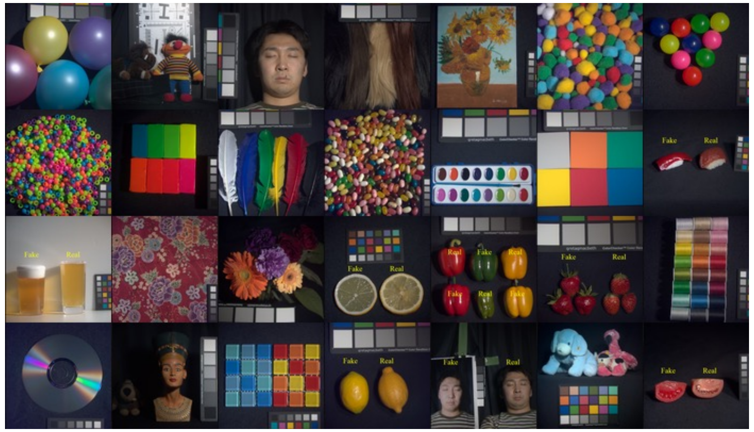
Theoretical upper bound sphere packing density

$$\rho^*(V) = 2\sqrt[3]{\frac{(\sqrt{V}+1)^3}{4V\sqrt{2}}} \qquad (7)$$



Continuous model: O. Packomania, "Packings of equal spheres in fixed-sized containers with maximum packing density," URL http://www. packomania.com, 2013.

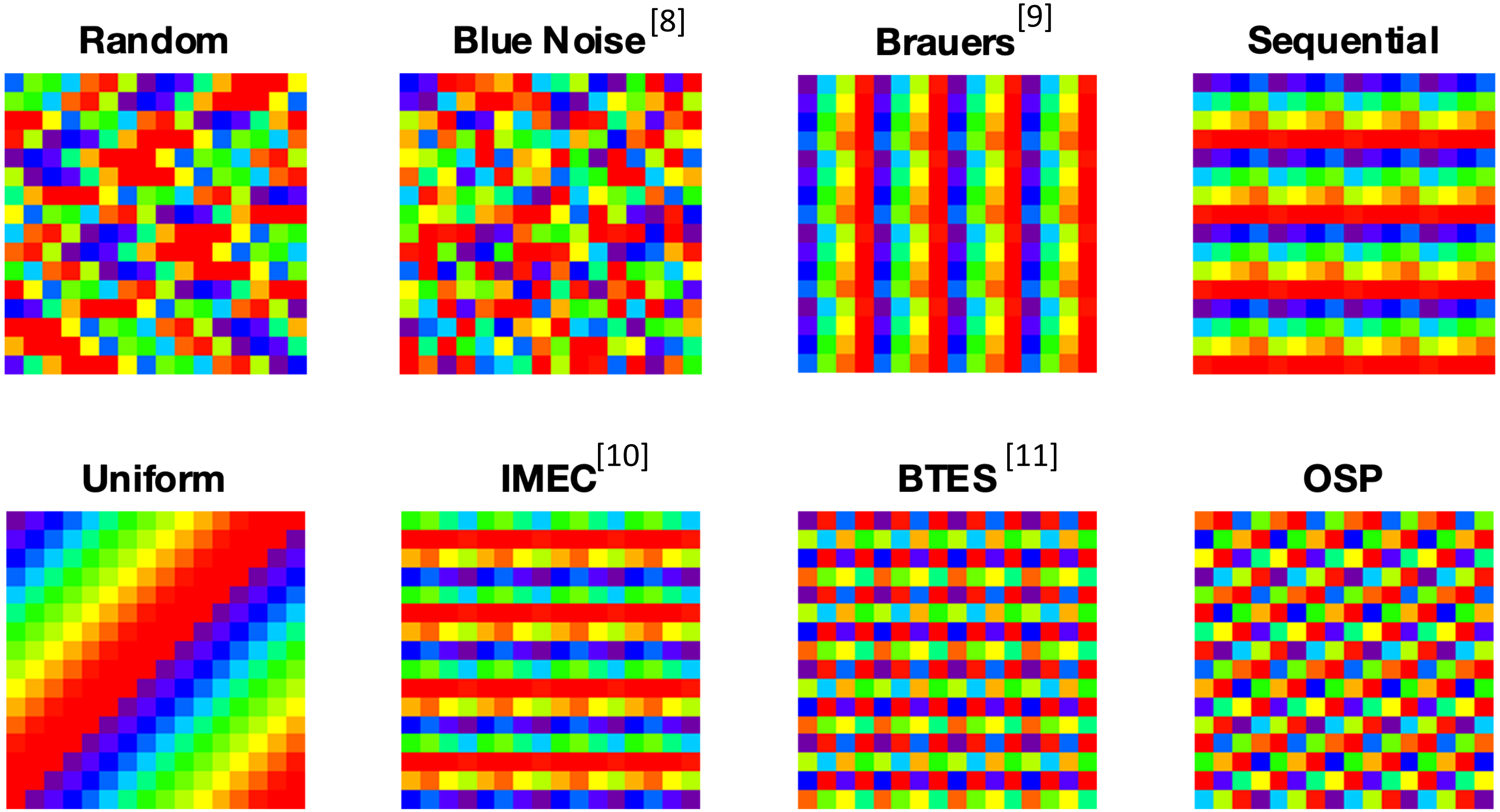
Dataset and Network



- Use Cave Dataset [4]
  - 32 Scenes with 31 spectral bands and 512x512 pixels.
  - Scenes resized to 256x256 pixels and 16 spectral bands.
- State-Of-The-Art in Demosaicking Algorithms:
  - **WB**: Weighted bilinear [5]
  - **itID**: Iterative intensity difference [6]
  - **itNCD**: Iterative nearby channel difference [6]
- TRevSCI-net [7] (3D-CNN for tensor completion) was training with 10560 cubes.
  - Name: Tensor reversible snapshot compressive imaging.
  - 80% train and 20% validation.
  - L1 cost function

[4] **F. Yasuma**, T. Mitsunaga, D. Iso, and S. K. Nayar, **"Generalized assorted pixel camera: Postcapture control of resolution, dynamic range, and spectrum"**, IEEE Transactions on Image Processing, 2010.
[5] **J. Brauers** and T. Aach, **"A color filter array based multispectral camera"**, Workshop Farbbildverarbeitung, Oct 2006.
[6] **S. Mihoubi**, O. Losson, B. Mathon, and L. Macaire, **"Multispectral demosaicing using intensity in edge-sensing and iterative difference-based methods"** , in 2016 12th International Conference on Signal-Image Technology Internet-Based Systems (SITIS), 2016.
[8] **Z. Cheng**, B. Chen, G. Liu, H. Zhang, R. Lu, Z. Wang, and X. Yuan,**"Memory-Efficient Network for Large-scale Video Compressive Sensing",** Proceedings of the IEEE Computer Society Conference on CVPR, 2021.

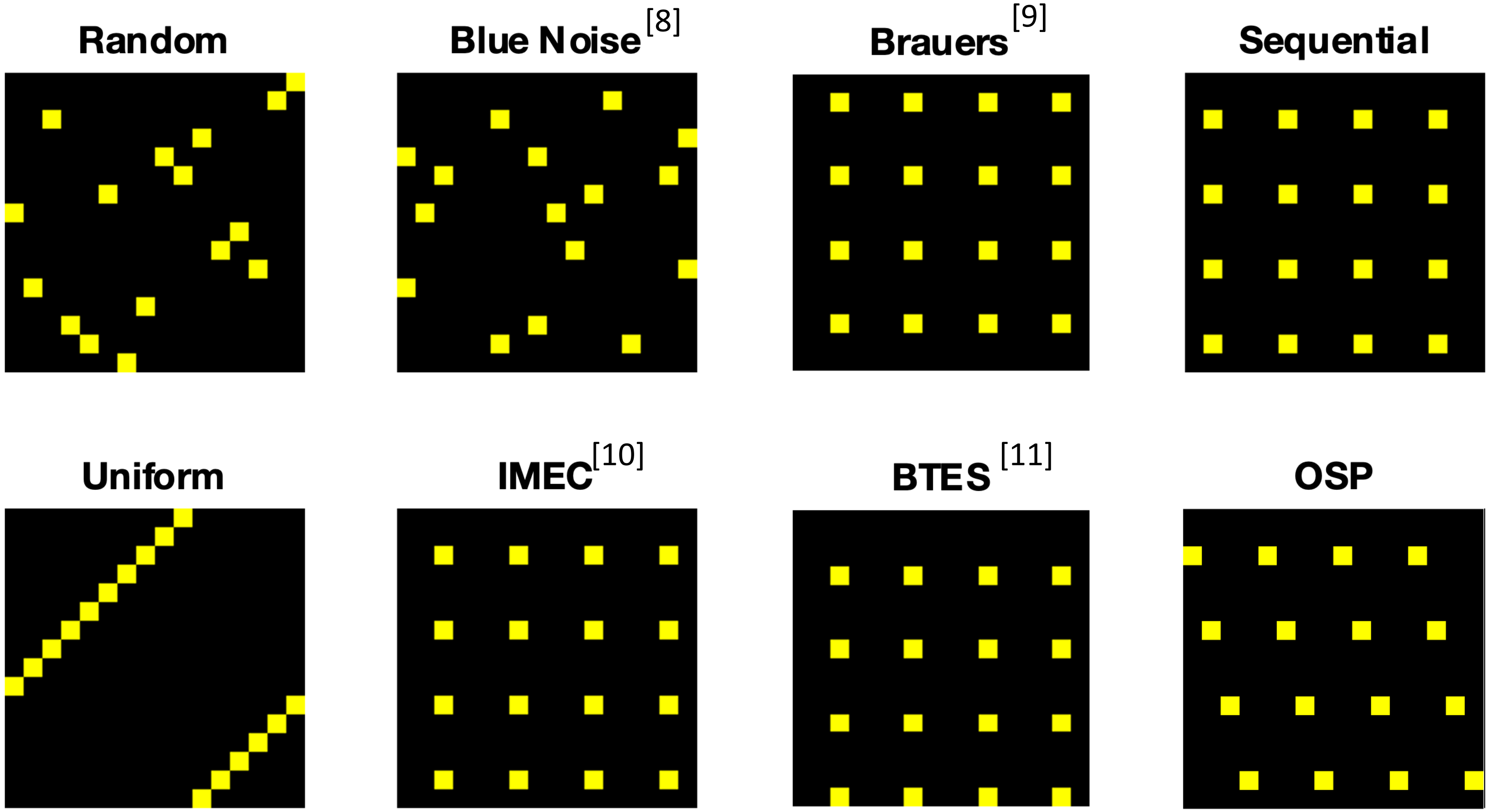
MSFA patterns



*Blue Noise is the only irregular lattice included in the comparison but satisfies the restricted isometry property (RIP).

[8] **C. V. Correa**, H. Arguello, and G. R. Arce, **"Spatiotemporal blue noise coded aperture design for multi-shot compressive spectral imaging"**, Journal of the Optical Society of America A, Dec 2016.
[9] **J. Brauers** and T. Aach, **"A color filter array based multispectral camera"**, Workshop Farbbildverarbeitung, Oct 2006.
[10] **B. Geelen**, N. Tack, and A. Lambrechts, **"A compact snapshot multispectral imager with a monolithically integrated per-pixel filter mosaic"**, Advanced Fabrication Technologies for Micro/Nano Optics and Photonics VII, 2014.
[11] **L. Miao**, H. Qi, R. Ramanath, and W. Snyder, **"Binary tree-based generic demosaicking algorithm for multispectral filter arrays"**, IEEE Transactions on Image Processing, 2006.

MSFA patterns



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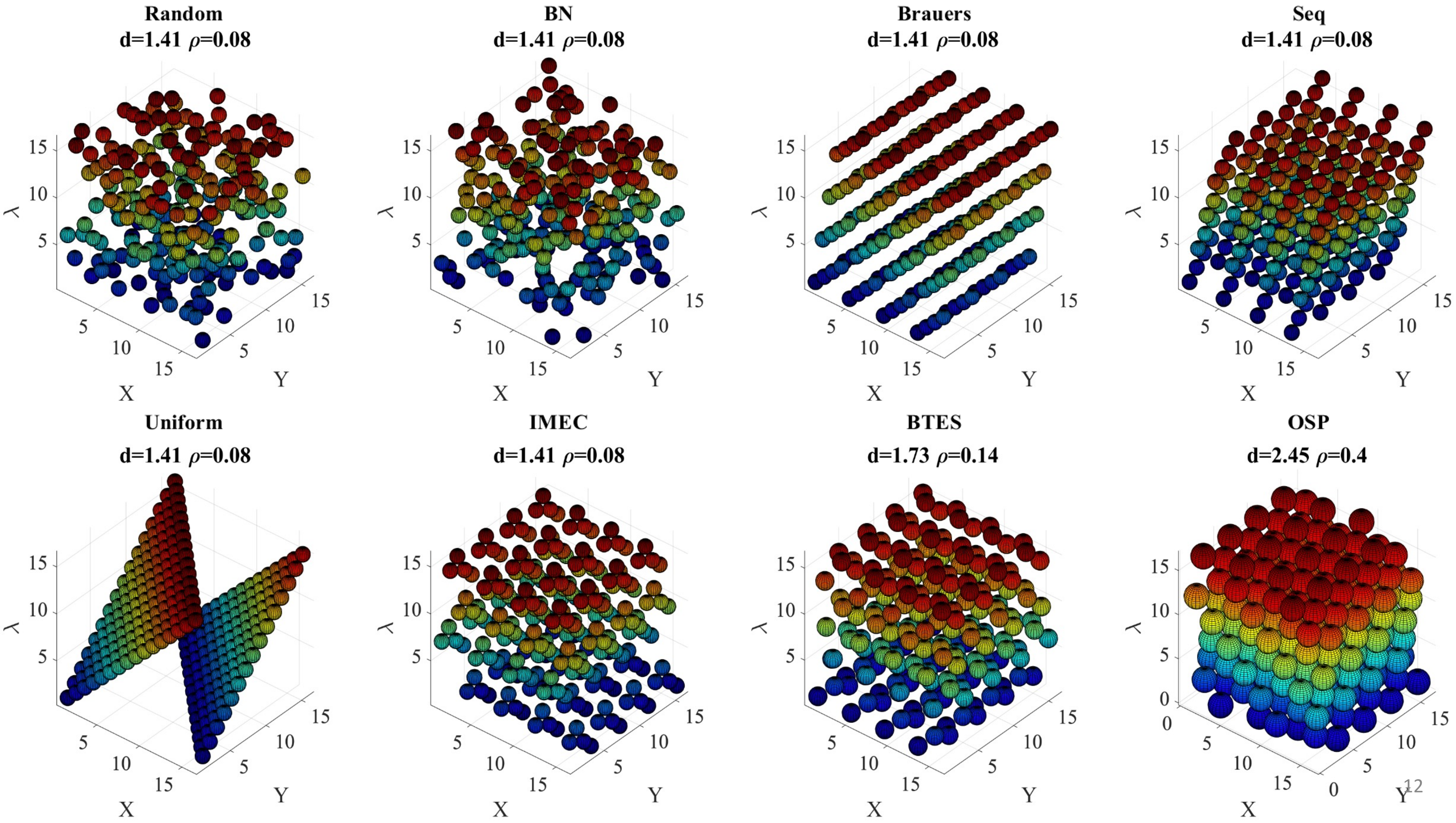
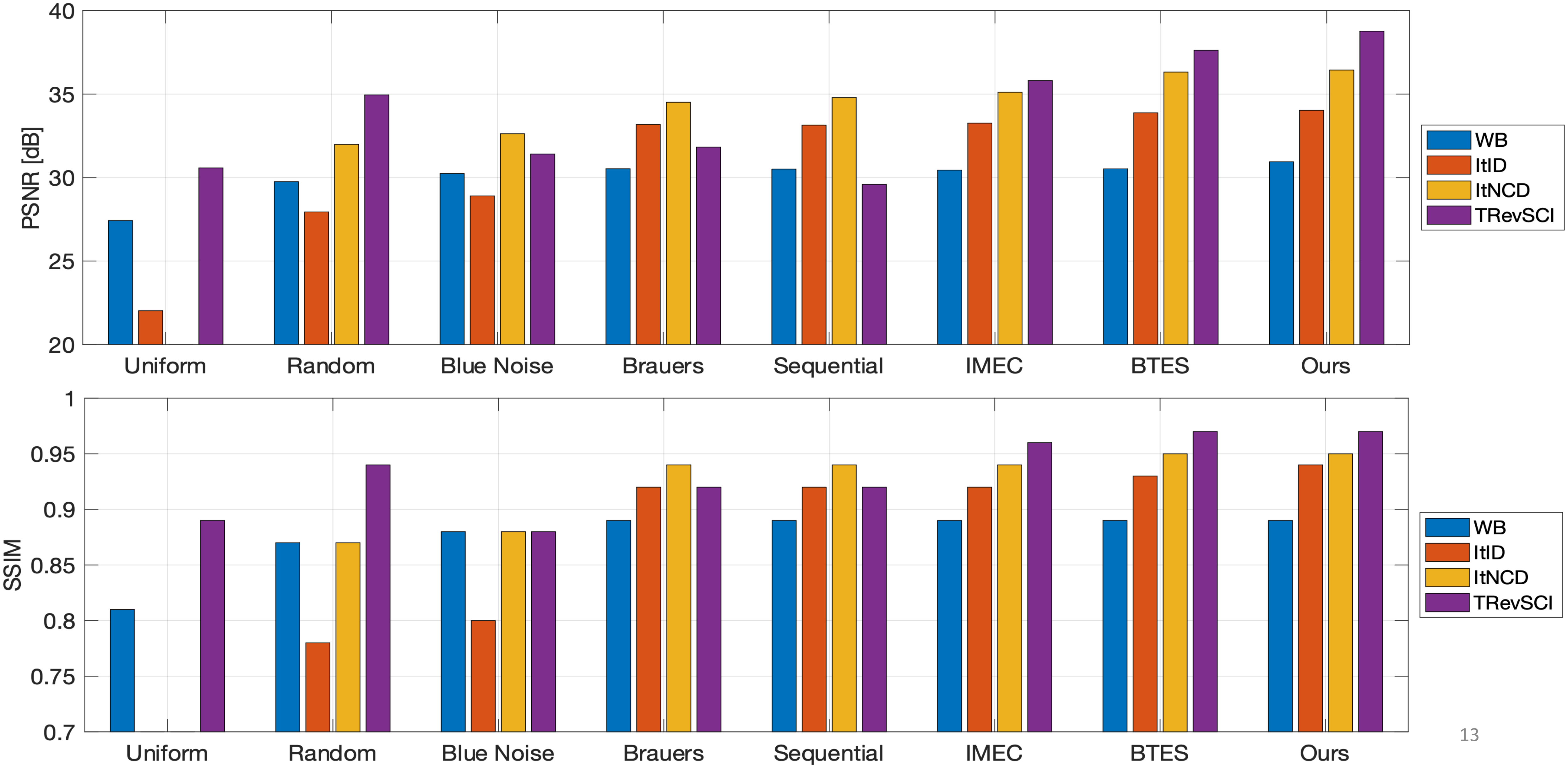
[11] **L. Miao**, H. Qi, R. Ramanath, and W. Snyder, **"Binary tree-based generic demosaicking algorithm for multispectral filter arrays"**, IEEE Transactions on Image Processing, 2006.

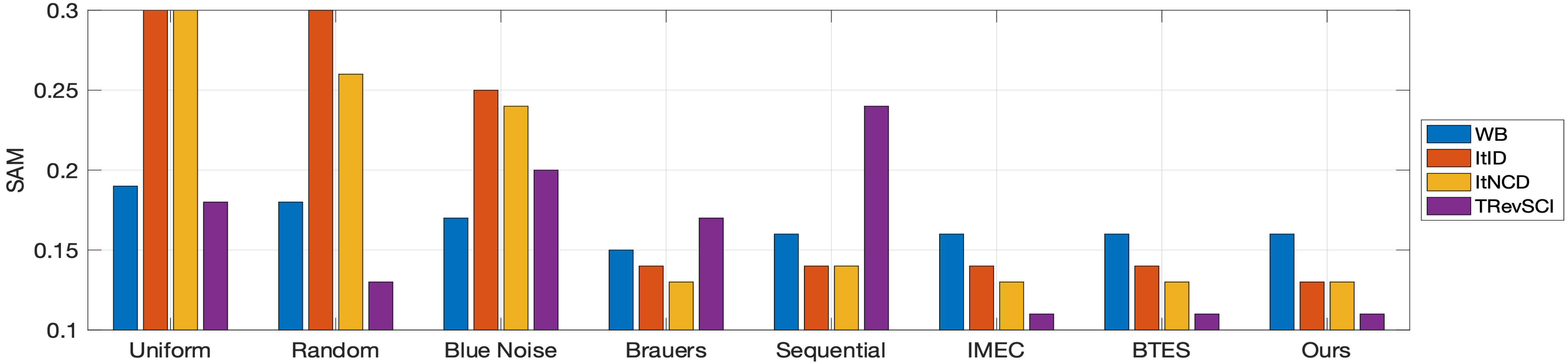
Density Comparison

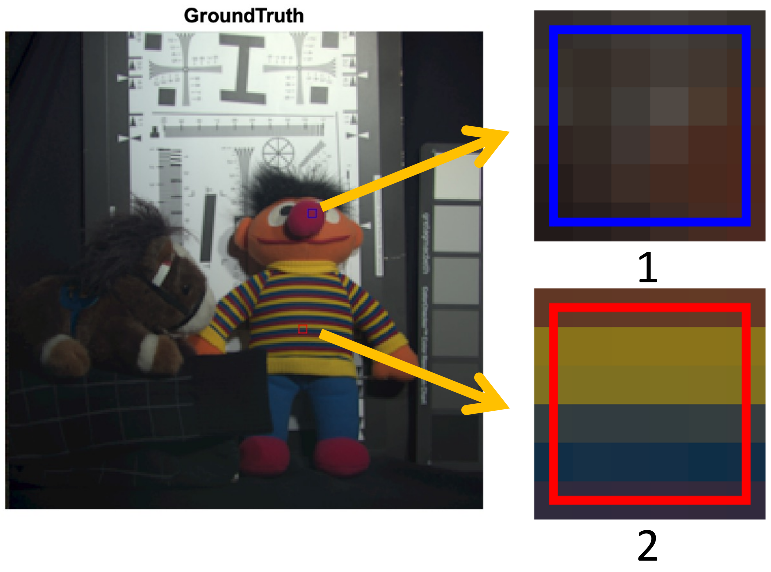


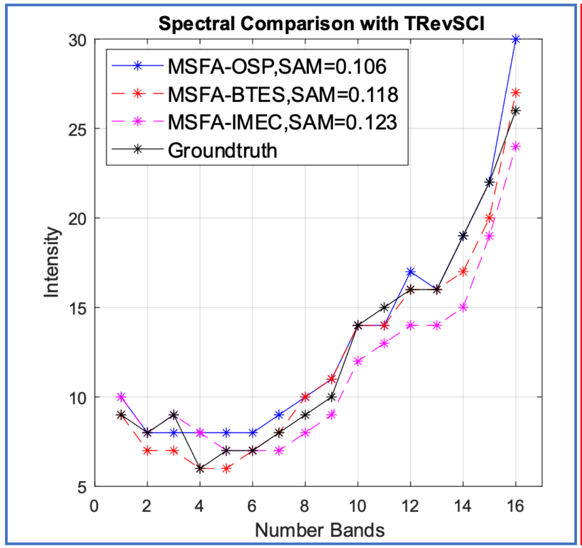
Results: Cave Dataset



Results: Cave Dataset







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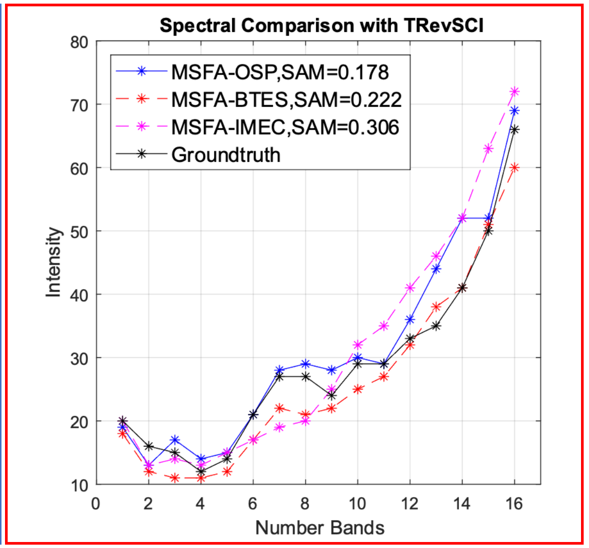
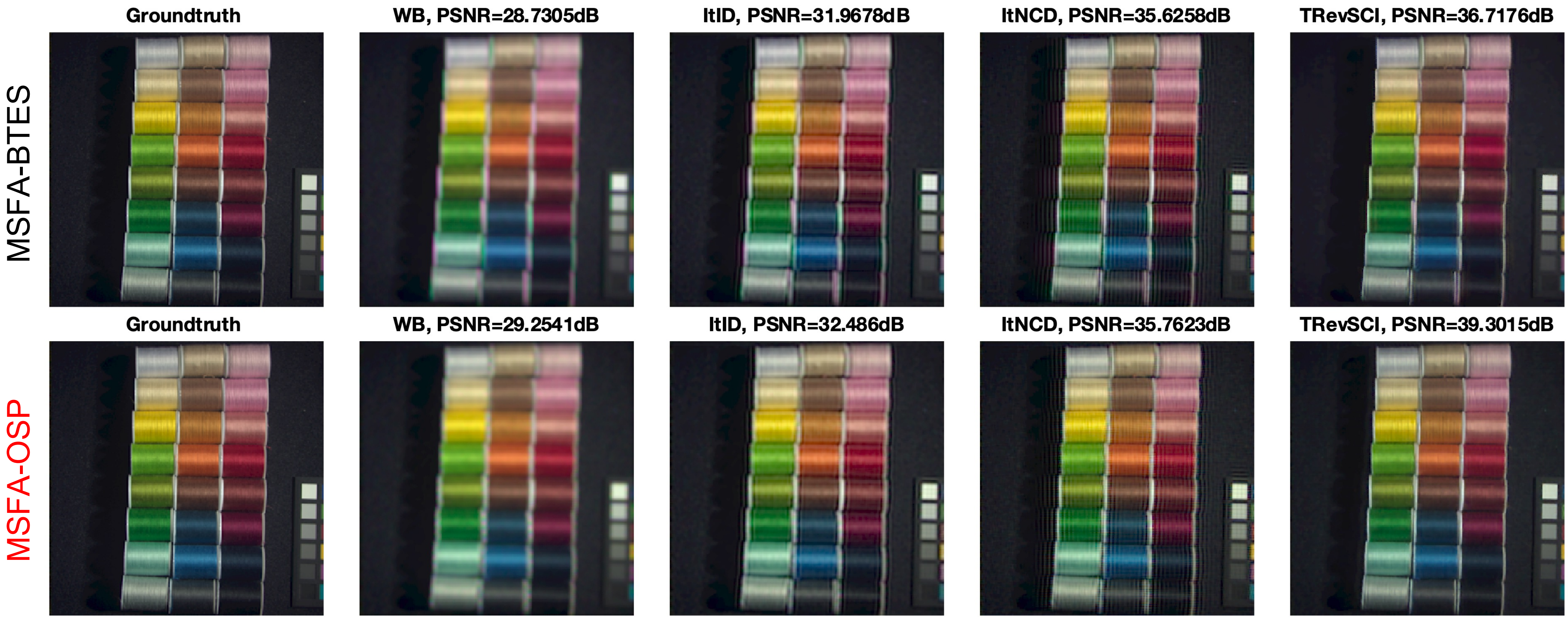
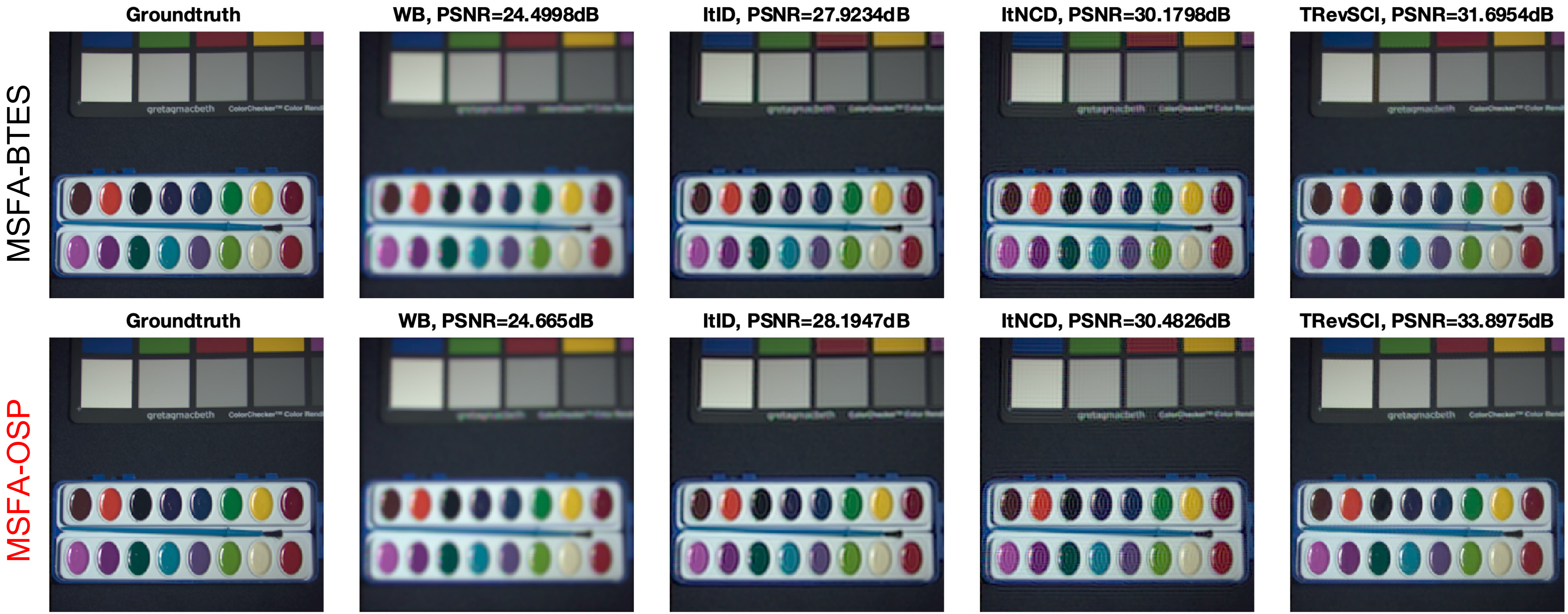


2

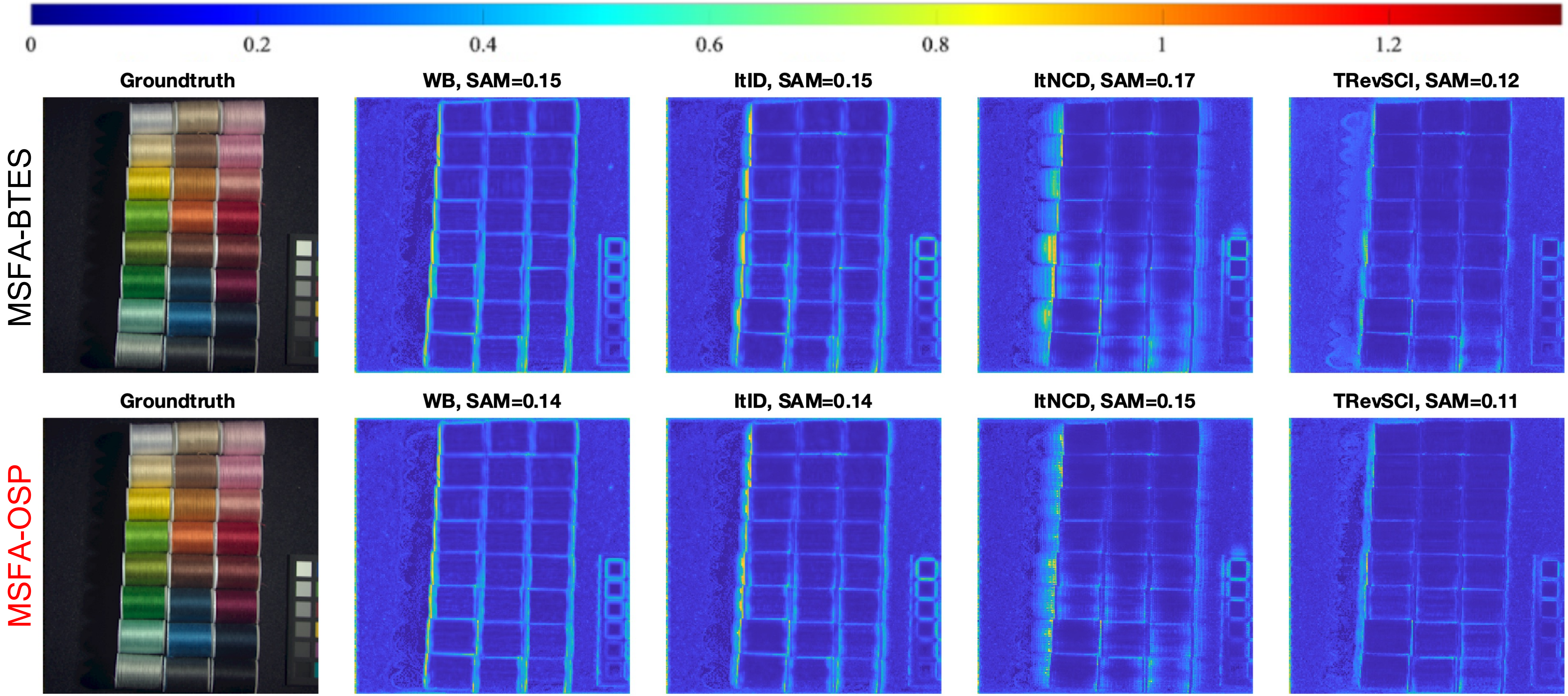
Comparison: RGB



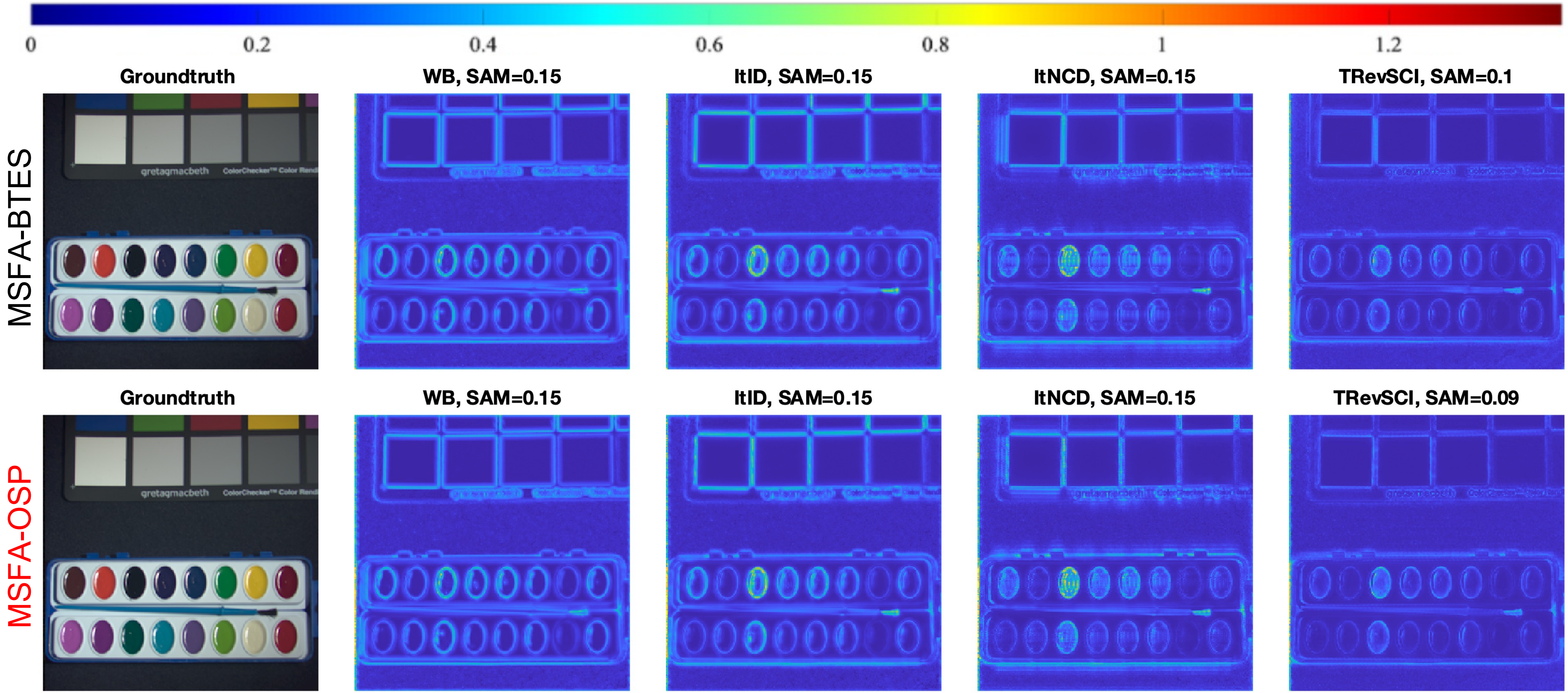
Comparison: RGB



Comparison: SAM

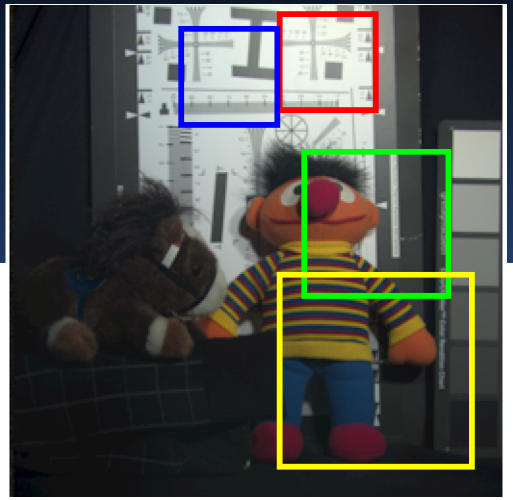


Comparison: SAM

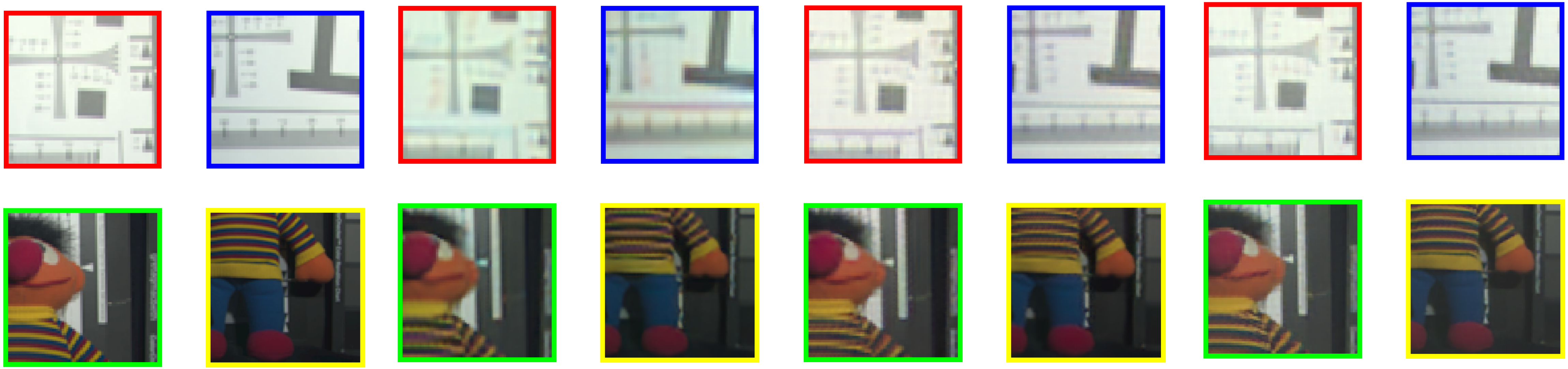


Comparative with TRevSCI

- Aliasing
- Zipper effect
- Color artifacts



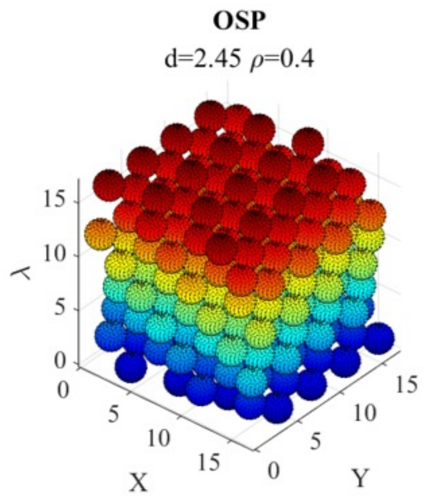
Groundtruth

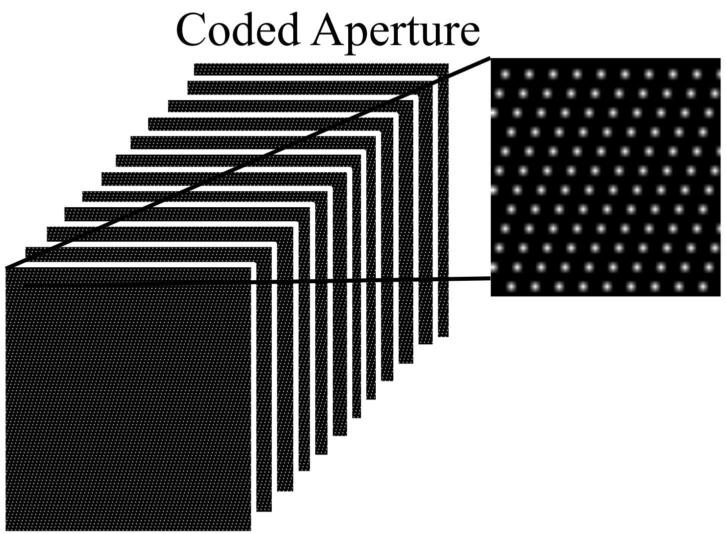


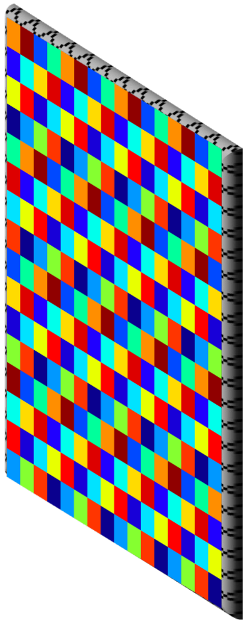
Groundtruth IMEC16 BTES16 OSP16

Conclusion

- We present a Multispectral Filter Array by Optimal Sphere Packing (MSFA-OSP). This approach extends the idea of CFA (RGB) to multispectral imaging.
- Our MSFA-OSP provides 2 [dB] extra of PSNR compared to the best of other SOTA MSFA.
- The advantages of the optimal filter distribution include reducing artifacts such as false colors and the zipper effect of demosaicking algorithms.
- Future works will extend the sphere packing framework to higher dimensions of the plenoptic function, such as compressive spectral-video.







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