SPEXTRALION

Recent developments in spectral filter array based systems

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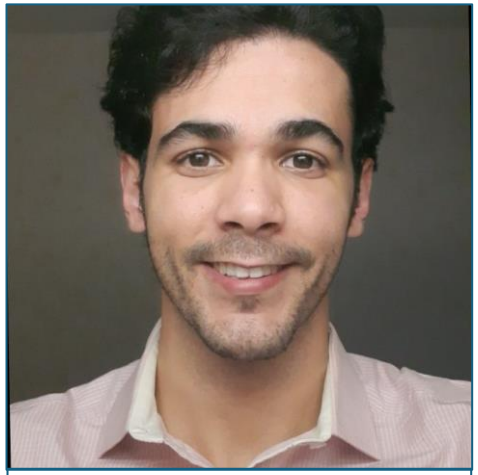
UNIVERSITÉ DE BOURGOGNE

ICC Spectral Imaging Experts' Day

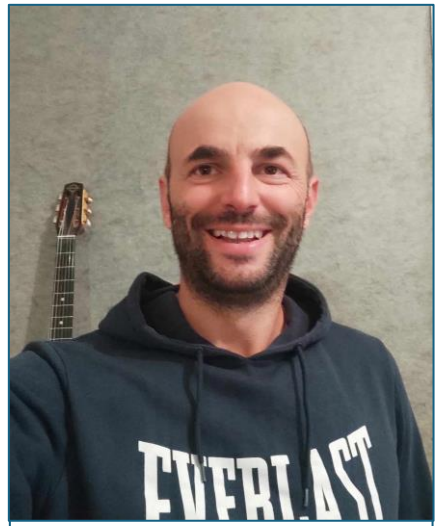
9th September 2024

SPEXTRALION



Abdelhamid Fsian

Jon Yngve Hardeberg



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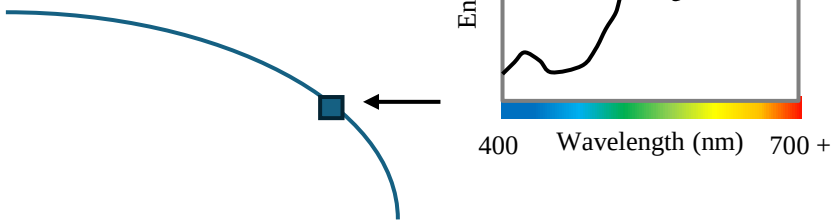
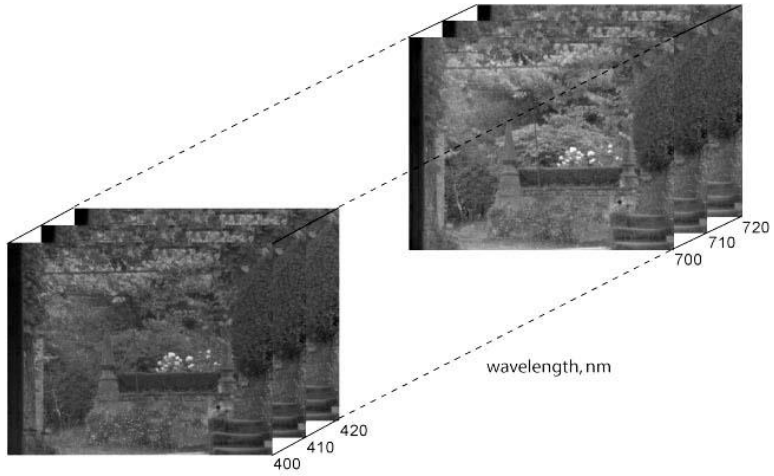
Agenda

- Spectral imaging
- Snapshot Spectral imaging and computational imaging
- SFA
- SFA pipeline
- Advances in Filters and Guides
- Image processing blocks and joint processing
- Current challenges
  - Standardization
  - Killer apps
  - Colour vs spectral in the visible?
  - Recent advances, how long does it need to tranfer to industry, that’s why we are here

Spectral imaging

- Measure the spectral irradiance of the scene $S(\lambda, x)$
- The sampling of **spatial**, **spectral**, **temporal** and **intensity** results in an image $I(x)$, which contains N bands
- In many cases, time is sacrificed

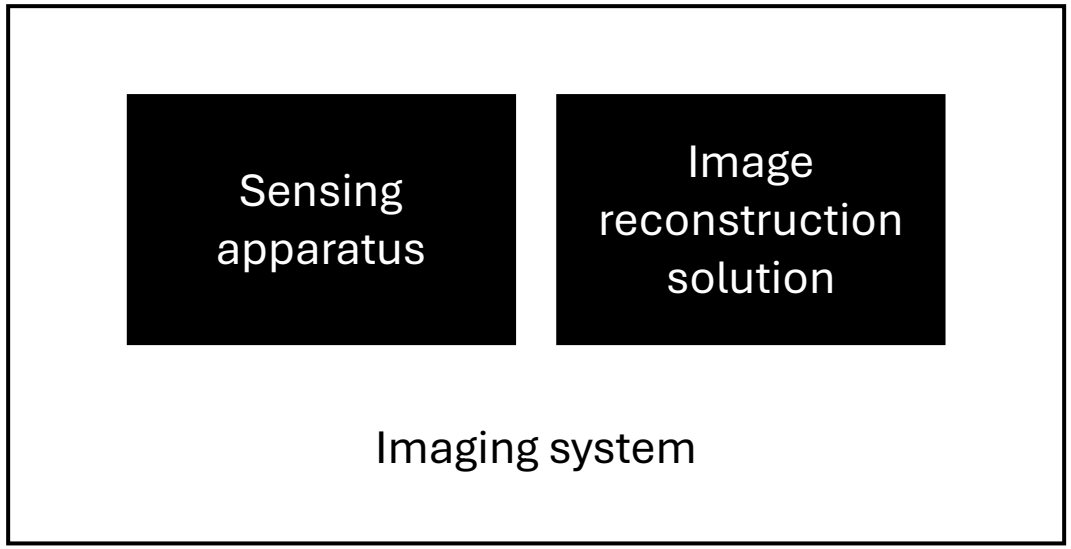




Spectral image

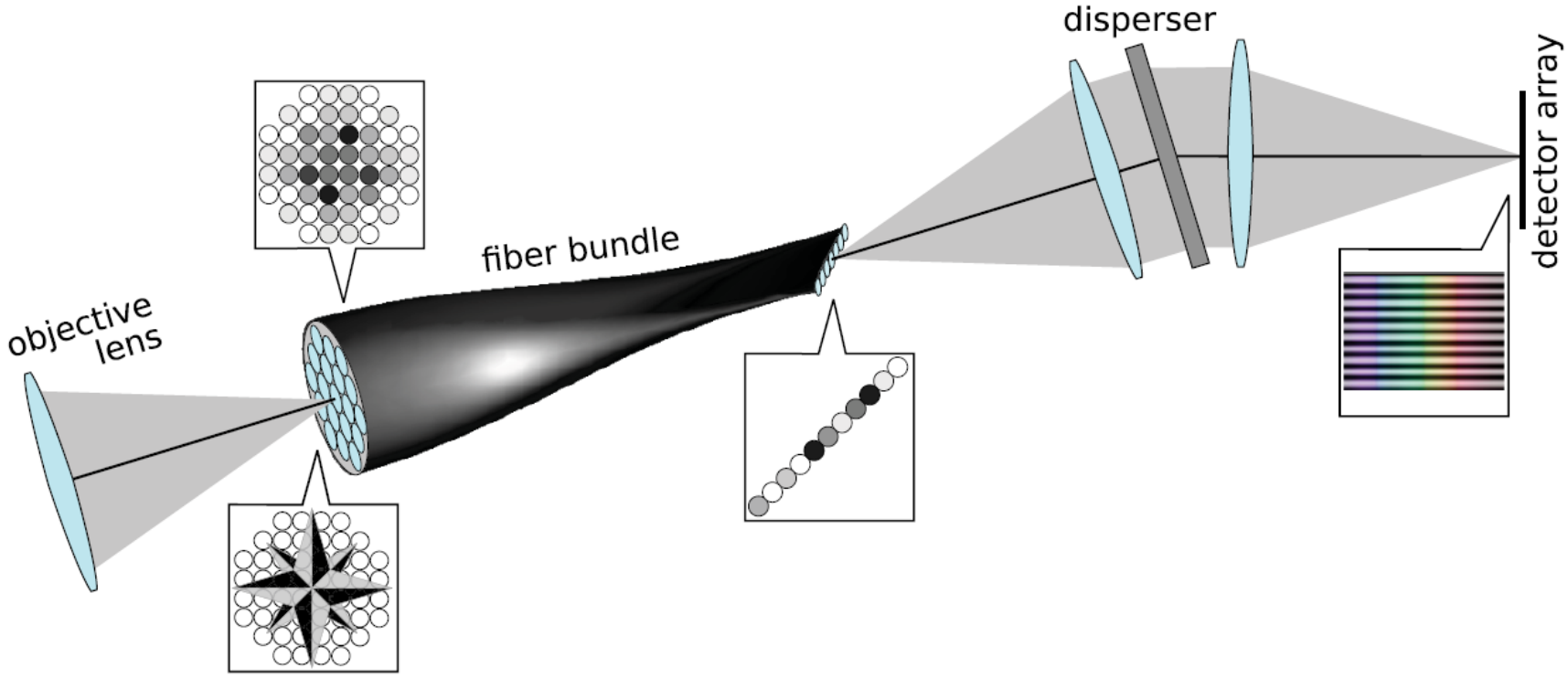
Snapshot spectral imaging - SSI

- Saving time to allow for the observation of dynamic phenomena
- Need to compensate spatio-spectral sacrifices by computational methods => Computational imaging



Examples of SSIs

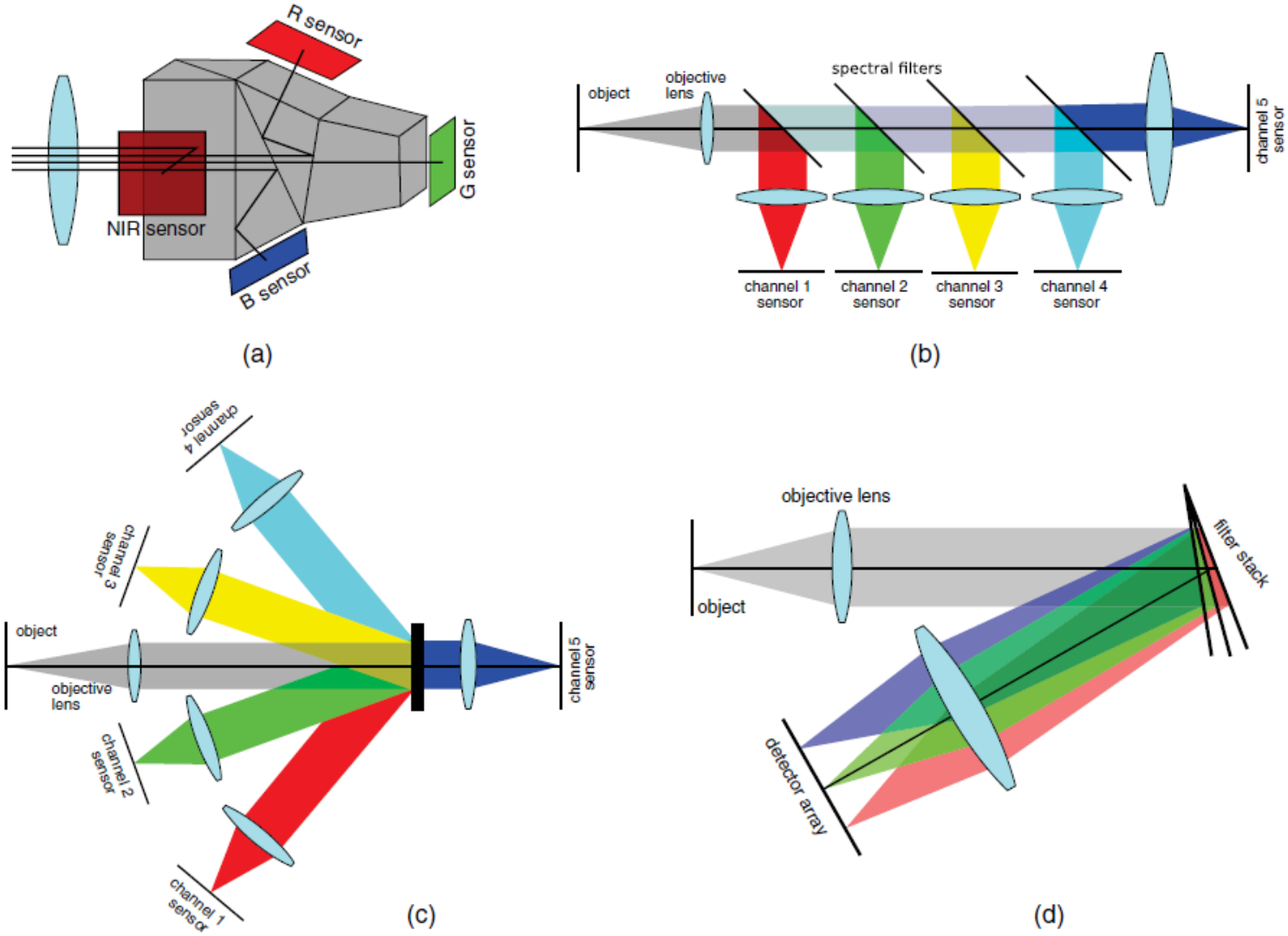
- Integral field spectrometry
  - E.g. Coherent fiber bundles



Nathan A. Hagen, Michael W. Kudenov, "Review of snapshot spectral imaging technologies," Opt. Eng. 52(9) 090901 (23 September 2013) https://doi.org/10.1117/1.OE.52.9.090901

Examples of SSIs

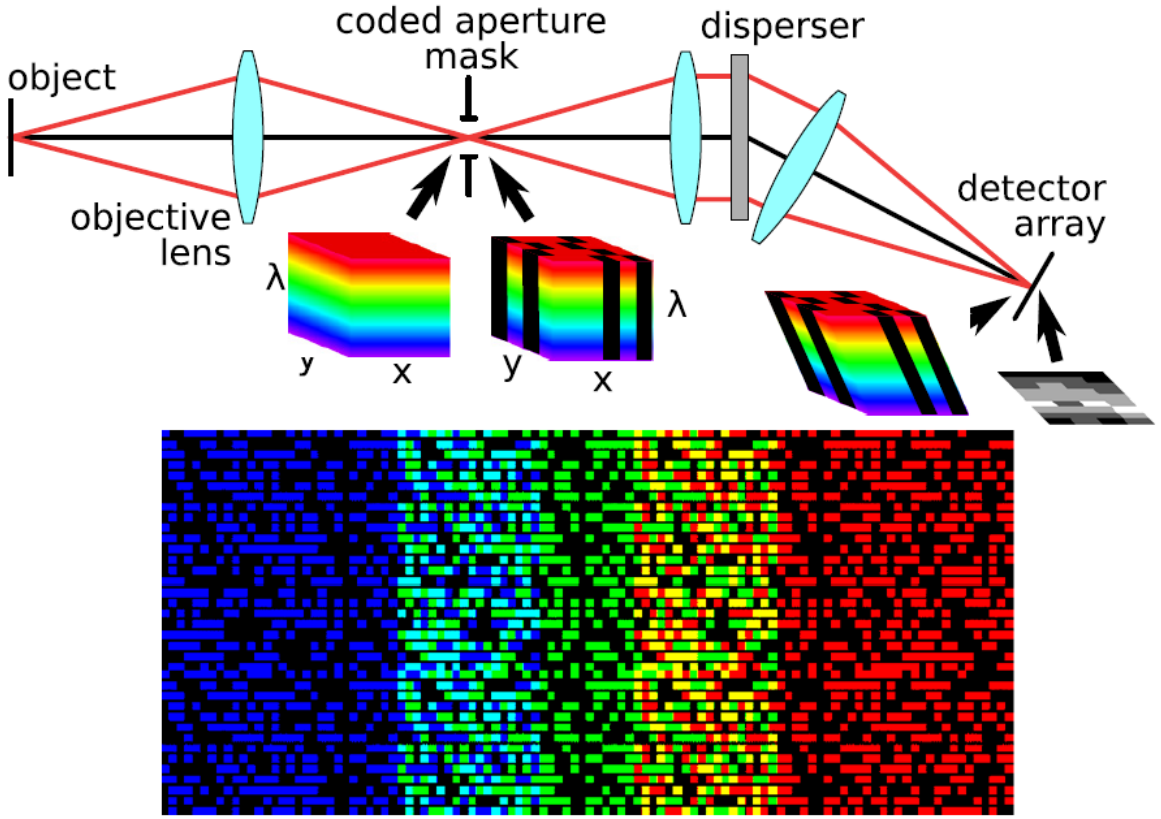
- Beamsplitting systems

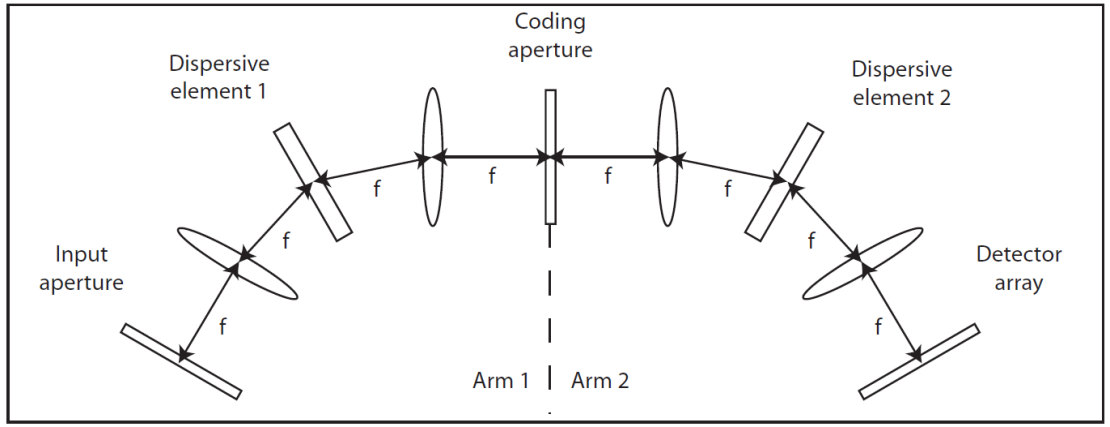


Nathan A. Hagen, Michael W. Kudenov, "Review of snapshot spectral imaging technologies," Opt. Eng. 52(9) 090901 (23 September 2013) https://doi.org/10.1117/1.OE.52.9.090901

Examples of SSIs

- Coded aperture snaphsot spectral imager



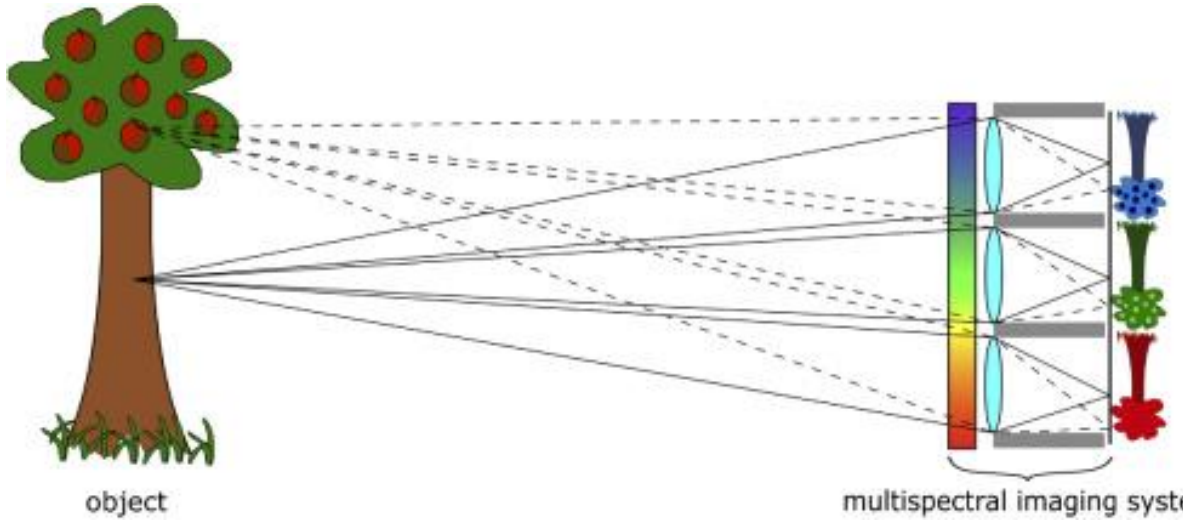


M. E. Gehm, R. John, D. J. Brady, R. M. Willett, and T. J. Schulz, "Single-shot compressive spectral imaging with a dual-disperser architecture," Opt. Express 15, 14013-14027 (2007)

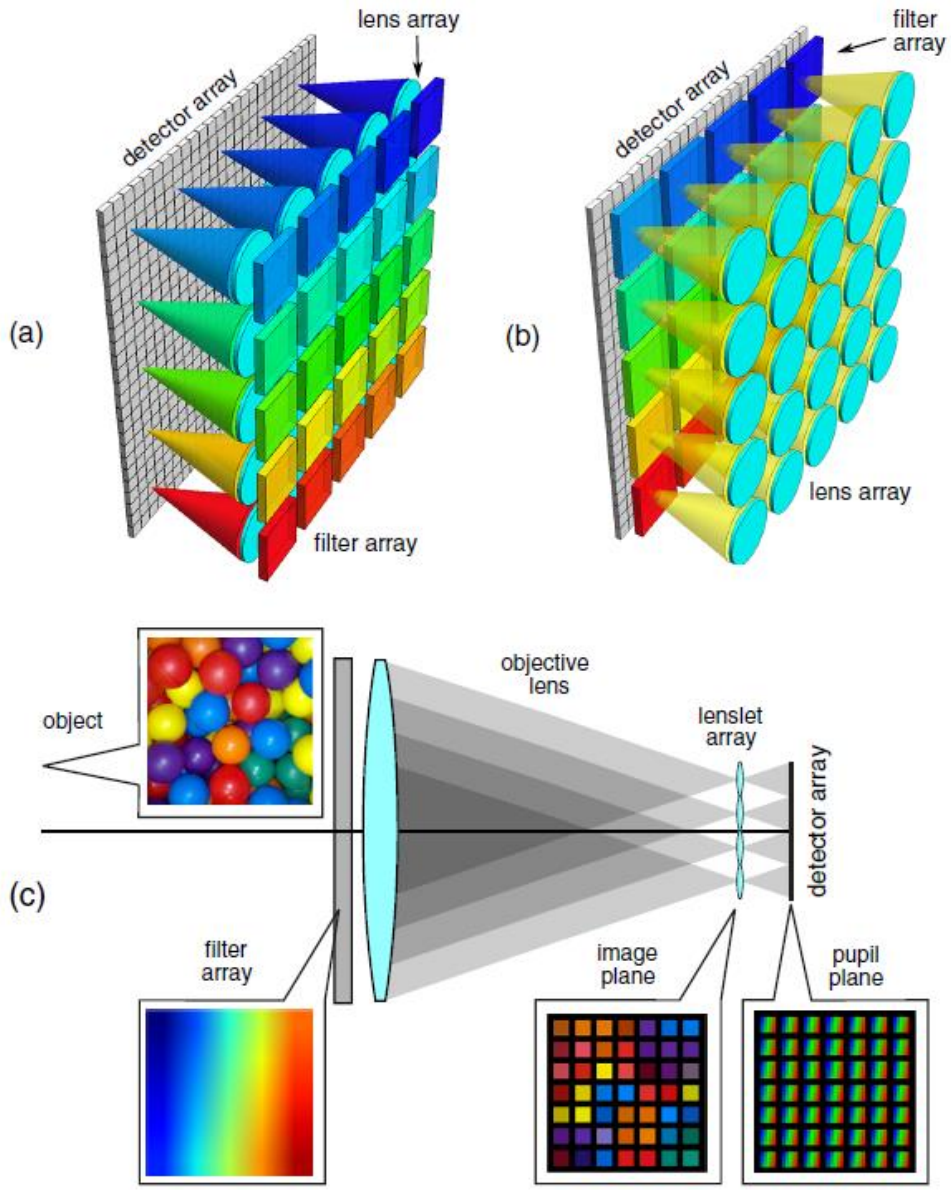
Nathan A. Hagen, Michael W. Kudenov, "Review of snapshot spectral imaging technologies," Opt. Eng. 52(9) 090901 (23 September 2013) https://doi.org/10.1117/1.OE.52.9.090901

Examples of SSIs

- Multi-aperture filtered camera



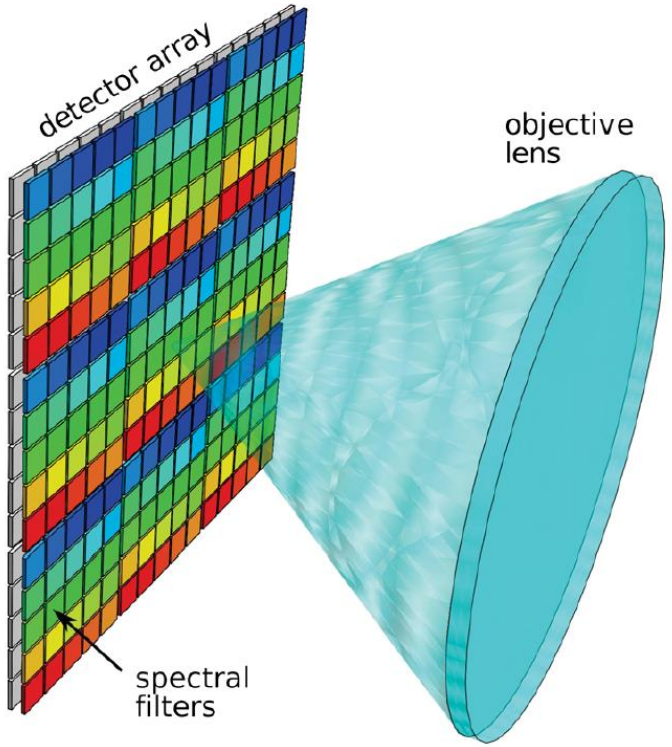
M Hubold, E Montag, R Berlich, R Brunner, and R Brüning, "Multi-aperture system approach for snapshot multispectral imaging applications," Opt. Express 29, 7361-7378 (2021)



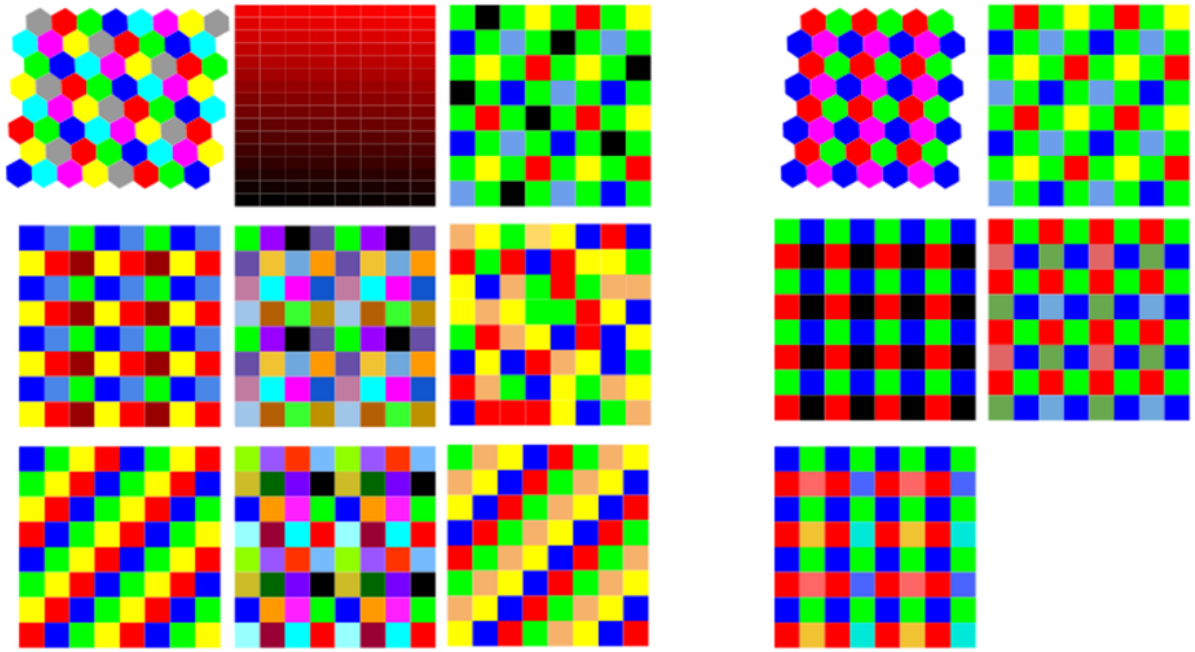
Nathan A. Hagen, Michael W. Kudenov, "Review of snapshot spectral imaging technologies," Opt. Eng. 52(9) 090901 (23 September 2013) https://doi.org/10.1117/1.OE.52.9.090901

Spectral Filter Arrays

- Generalization of color filter arrays (e.g. Bayer)



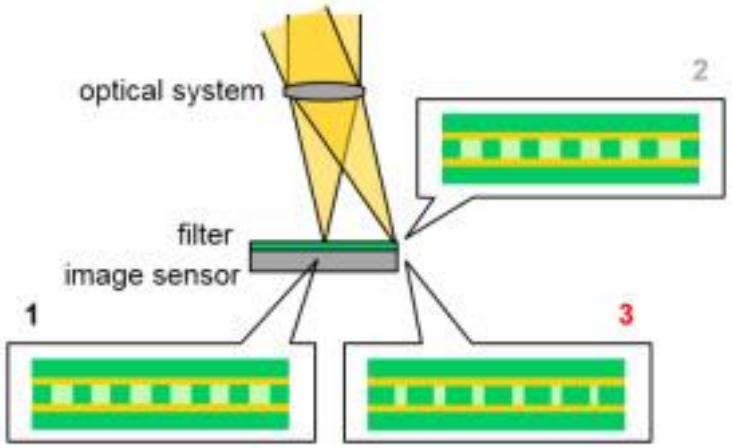
Nathan A. Hagen, Michael W. Kudenov, "Review of snapshot spectral imaging technologies," Opt. Eng. 52(9) 090901 (23 September 2013) https://doi.org/10.1117/1.OE.52.9.090901

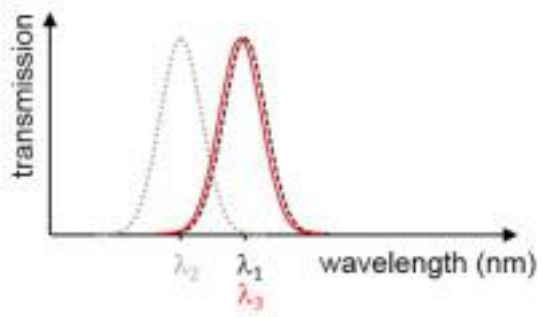


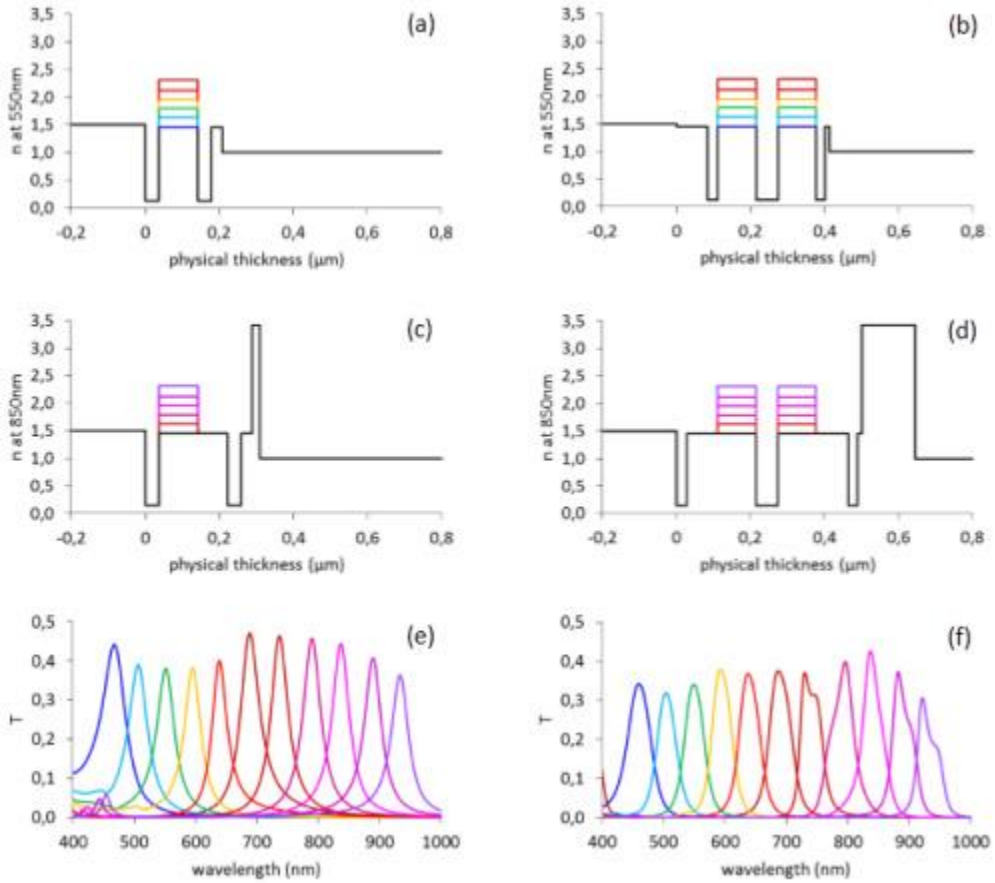
Lapray, P.-J.; Wang, X.; Thomas, J.-B.; Gouton, P. Multispectral Filter Arrays: Recent Advances and Practical Implementation. *Sensors* **2014**, *14*, 21626-21659. https://doi.org/10.3390/s141121626

Many ways to realize filters

- Fabry-Perot interferometers



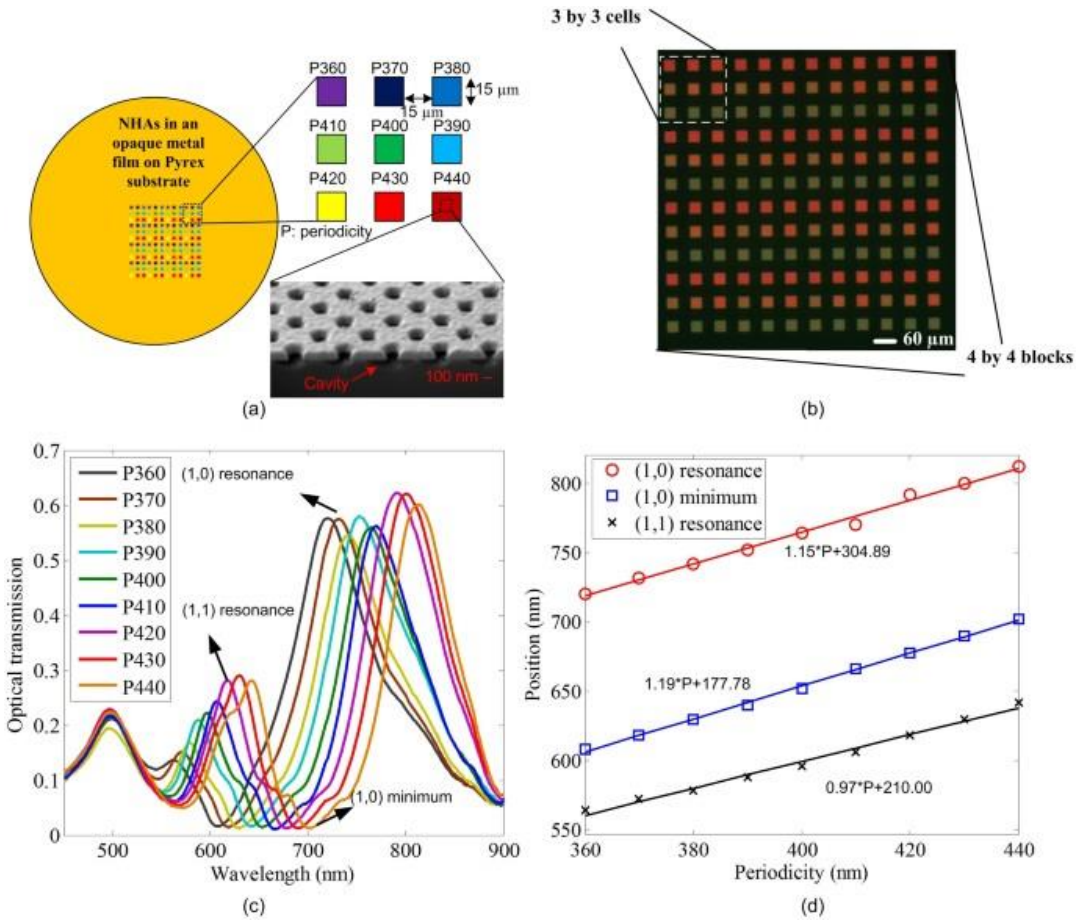




Laurent Frey, Lilian Masarotto, Marilyn Armand, Marie-Lyne Charles, and Olivier Lartigue, "Multispectral interference filter arrays with compensation of angular dependence or extended spectral range," Opt. Express 23, 11799-11812 (2015)

Many ways to realize filters

- Nano-holes/bits

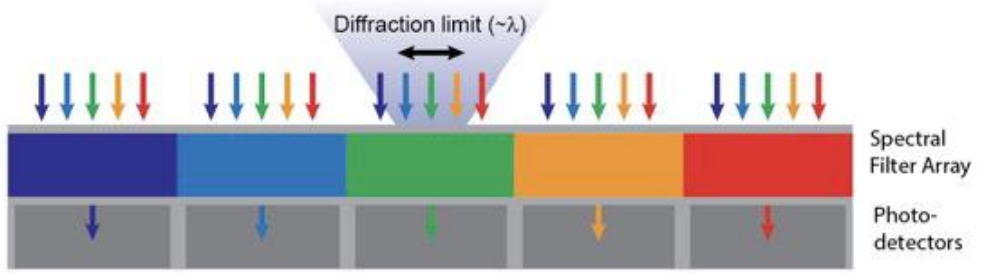


Najiminaini, M., Vasefi, F., Kaminska, B. *et al.* Nanohole-array-based device for 2D snapshot multispectral imaging. *Sci Rep* **3**, 2589 (2013). https://doi.org/10.1038/srep02589

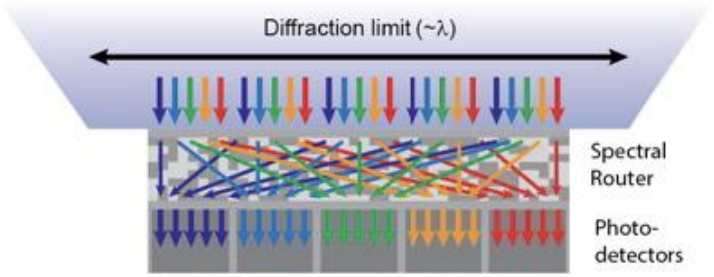
Many ways to realize filters

- Spectral routers

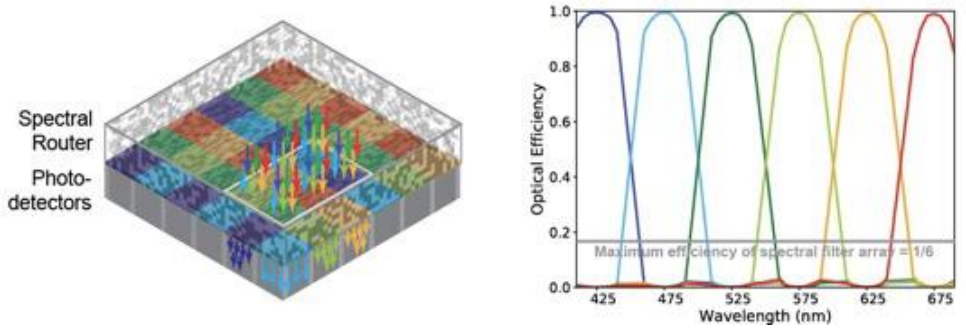
(a) Conventional on-chip solution: Spectral filter array with large, photon-inefficient filters



(b) **Spectral router**: **Highly efficient** routing of spectral components in **(sub)wavelength footprint**



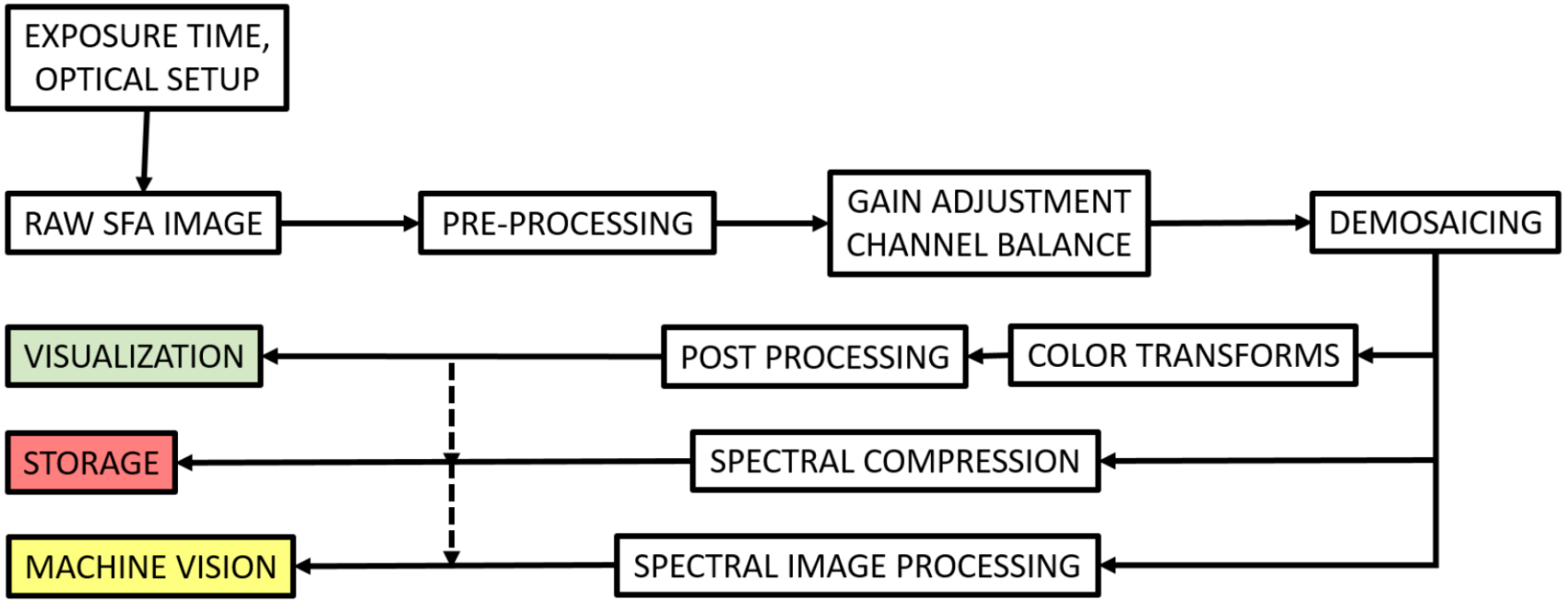
(c) **Example** spectral router with **6 spectral channels** in the **visible wavelength range**



P. B. Catrysse and S. Fan, "Multispectral Routers for Snapshot Spectral Imaging," in *CLEO 2023*, Technical Digest Series (Optica Publishing Group, 2023), paper ATu3K.5.

Imaging pipeline

- From data to image



Lapray, P.-J.; Thomas, J.-B.; Gouton, P. High Dynamic Range Spectral Imaging Pipeline For Multispectral Filter Array Cameras. *Sensors* **2017**, *17*, 1281. https://doi.org/10.3390/s17061281

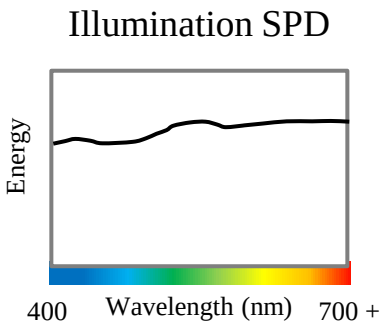
From data to image

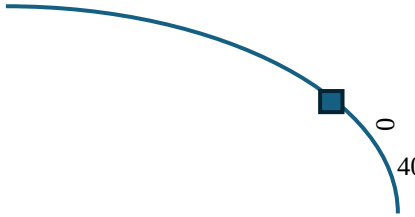
- **Demosaicing** & **Spectral reconstruction**
- From $I(x)$ to $\mathrm{S}(\lambda, x)$
- Used to be sequential items
- Todays, joint/fusion approaches (e.g. *denoisacing, PPI*)
- Heavy use of machine learning
  - Several databases, cost functions, sensor designs
- Tons of publications from different communities
  - From imaging science to computer vision, through remote sensing and computer graphics
  - E.g. Demosaicing challenge at CVPR

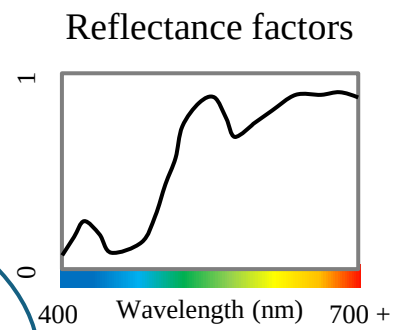
B. Arad *et al*., "NTIRE 2022 Spectral Demosaicing Challenge and Data Set," *2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, New Orleans, LA, USA, 2022, pp. 881-895, doi: 10.1109/CVPRW56347.2022.00103.

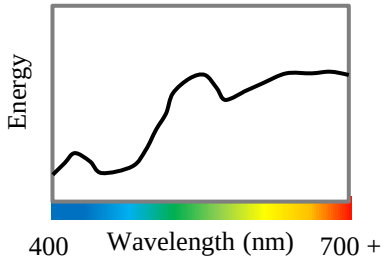
Illumination

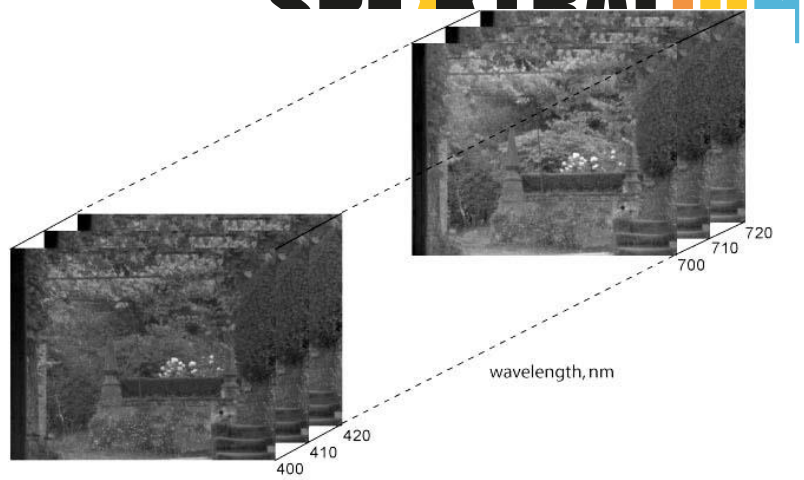
- From color to spectral constancy









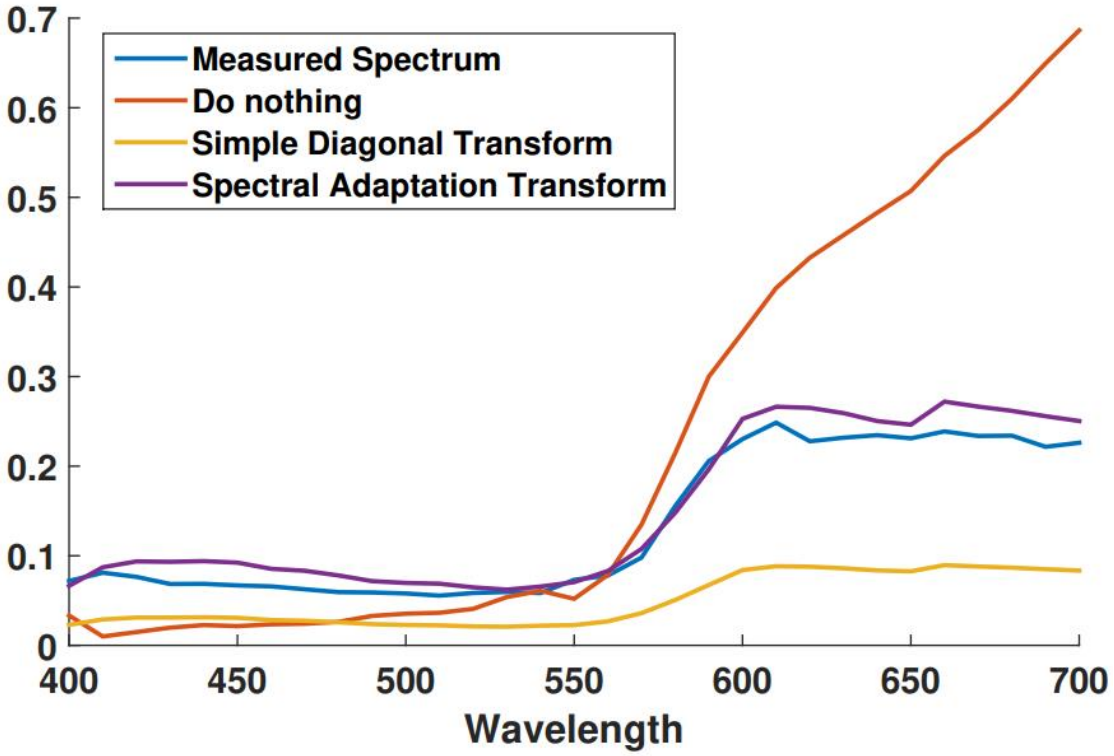


Spectral image

Haris Ahmad Khan, Jean-Baptiste Thomas, Jon Yngve Hardeberg, and Olivier Laligant, "Illuminant estimation in multispectral imaging," J. Opt. Soc. Am. A 34, 1085-1098 (2017)

Illumination

- From color to spectral constancy



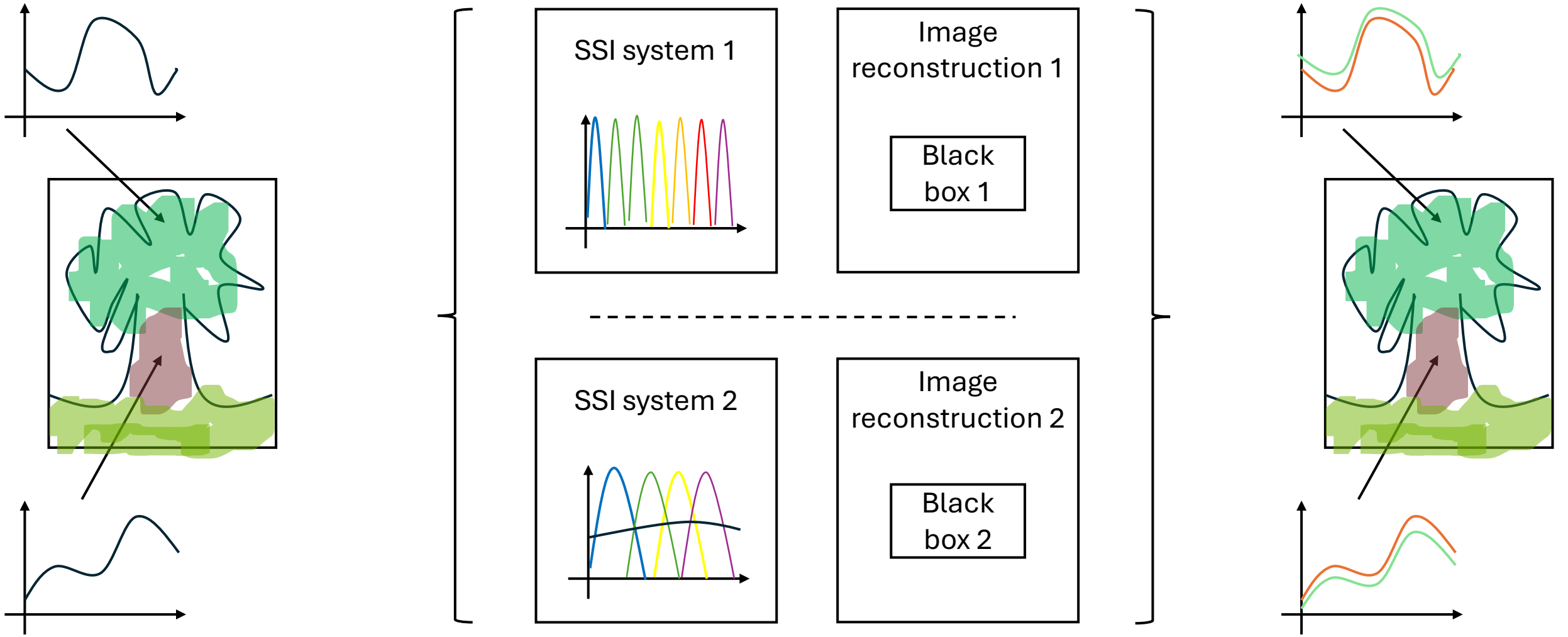
HA Khan, JB Thomas, JY Hardeberg, O Laligant Spectral adaptation transform for multispectral constancy Journal of Imaging Science and Technology, 2018

Open questions: What is the killer app?

- Despite many research demonstrating the performance of spectral imaging in solving classification problems, some industries struggle to find how to make money with it
- What is the exact maturity of the solution and of the market?
- Several commercial products with different positions, e.g.:
  - SILIOS: Space
  - Sony: polarization&color, HDR, spectral
- Several items to be discussed

Open questions: Standardization & quality

Estimate 1
Estimate 2



Open questions: RGB2spectral

- Does it compete?
- 3 challenges at CVPR

B. Arad *et al*., "NTIRE 2018 Challenge on Spectral Reconstruction from RGB Images," *2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW)*, Salt Lake City, UT, USA, 2018, pp. 1042-104209, doi: 10.1109/CVPRW.2018.00138.
B. Arad, et al., "NTIRE 2020 Challenge on Spectral Reconstruction from an RGB Image," in 2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), Seattle, WA, USA, 2020 pp. 1806-1822. doi: 10.1109/CVPRW50498.2020.00231
B. Arad, et al., "NTIRE 2022 Spectral Recovery Challenge and Data Set," in 2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), New Orleans, LA, USA, 2022.

- MST++

Y. Cai et al., "MST++: Multi-stage Spectral-wise Transformer for Efficient Spectral Reconstruction," 2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), New Orleans, LA, USA, 2022, pp. 744-754, doi: 10.1109/CVPRW56347.2022.00090.

- What information is there?

Fsian, A.N.; Thomas, J.-B.; Hardeberg, J.Y.; Gouton, P. Spectral Reconstruction from RGB Imagery: A Potential Option for Infinite Spectral Data? *Sensors* **2024**, *24*, 3666. https://doi.org/10.3390/s24113666

Conclusion

- Technology is *ready* both in hardware and software
  - Still lack of quality assessment
- Delay to transfer to industry
  - Requires some developments
  - Major players are contributing
- We are here!