COMPRESSIVE SPECTRAL IMAGING IN VIEW OF EARTH OBSERVATION APPLICATIONS

CLÉMENT THOMAS

LAURENT JACQUES, MARC GEORGES

INTERNATIONAL SYMPOSIUM ON COMPUTATIONAL SENSING 2025
03/06/25

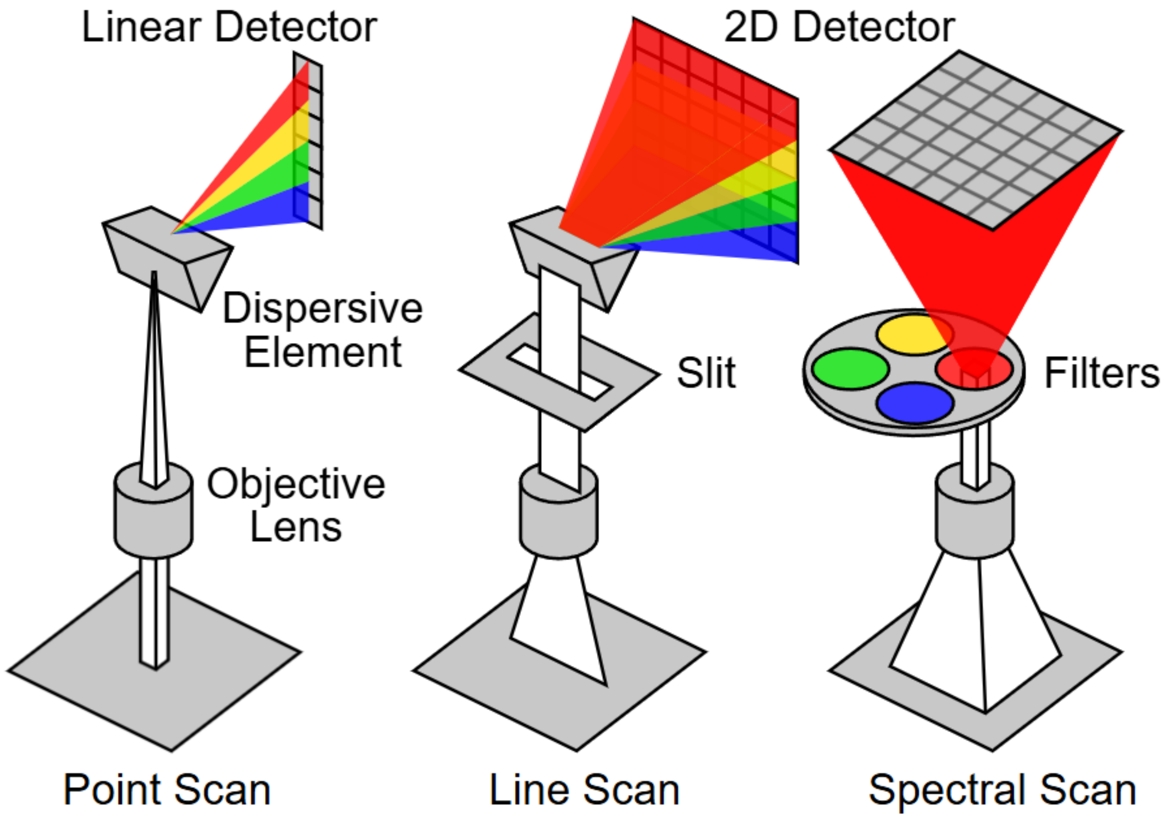
CSL LIÈGE université UCLouvain Wallonie

INTRODUCTION: EARTH OBSERVATION FROM SPACE

- Many applications: Meteorology, climatology, navigation, agriculture,…
- Large number of missions
- Need for high spatial and spectral resolutions (hyperspectral imagers)

→ Big Data: challenges for acquisition, storage, and transfer

TRADITIONAL SPECTRAL IMAGE ACQUISITION



Source: Lucas Bosh

- Large data quantity:

$$N = n_x \times n_y \times n_\lambda$$

- Complex optics
- Spatially extended detectors
- Idea: use CS principles to build compact and fast spectral imagers

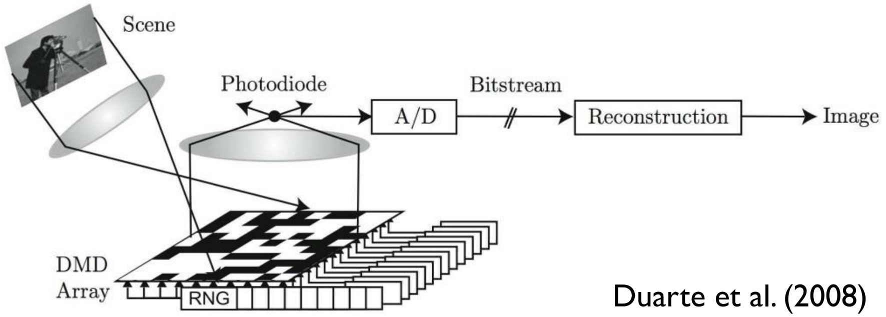
CHOICE OF ARCHITECTURE

Single-pixel camera : needs lots of time to acquire enough measurements

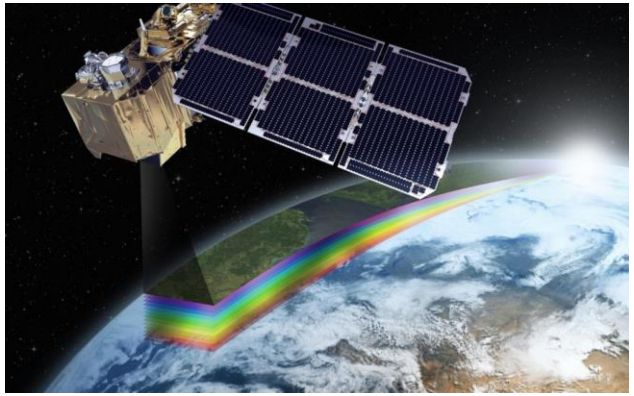
In Low Earth Orbit (LEO): time limited by the satellite's fast motion

Need a compressive architecture with fast data acquisition

➔ snapshot architectures

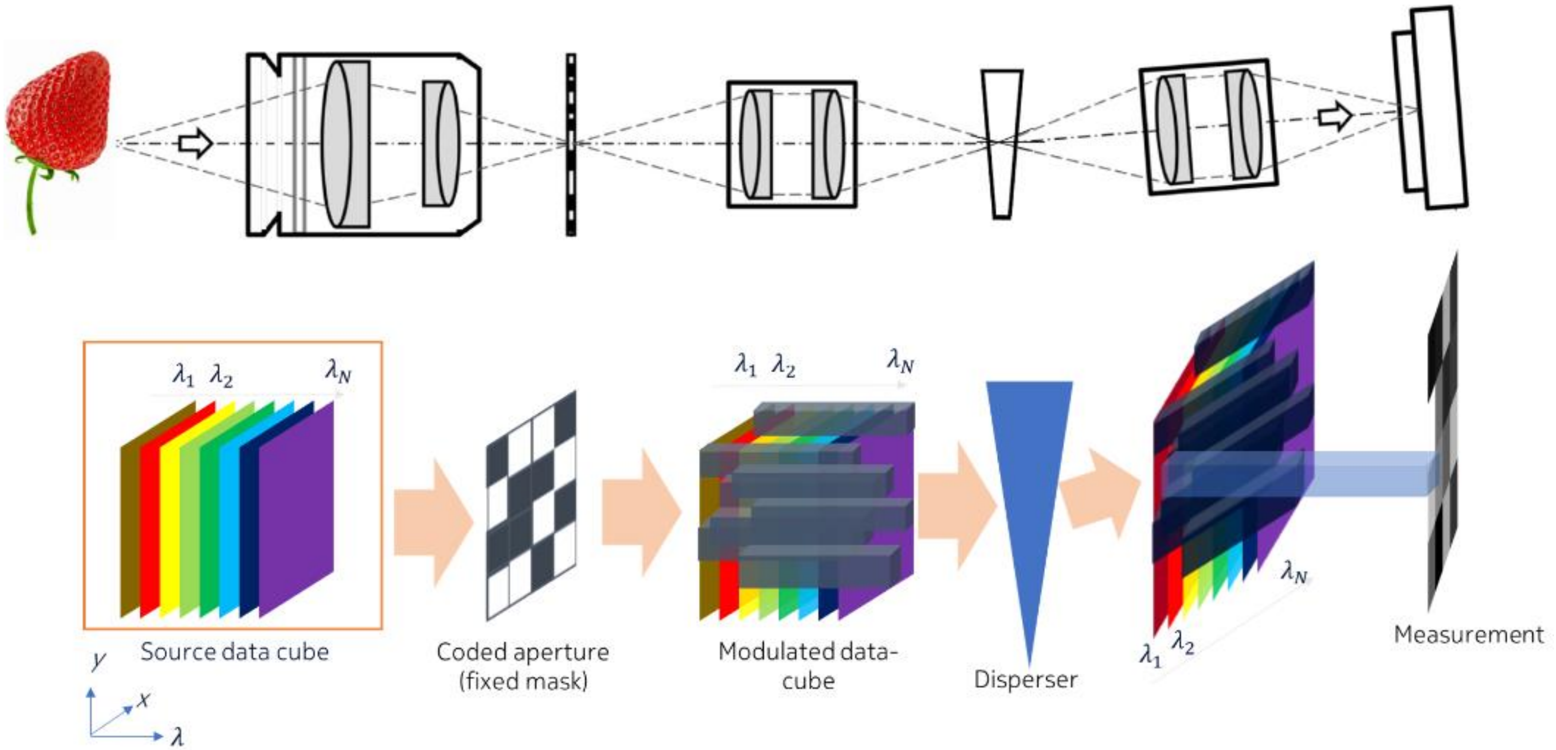


Duarte et al. (2008)



Source: ESA

CODED APERTURE SNAPSHOT SPECTRAL IMAGING (CASSI)



Measurement

$$y = S\ D\ C\ x$$

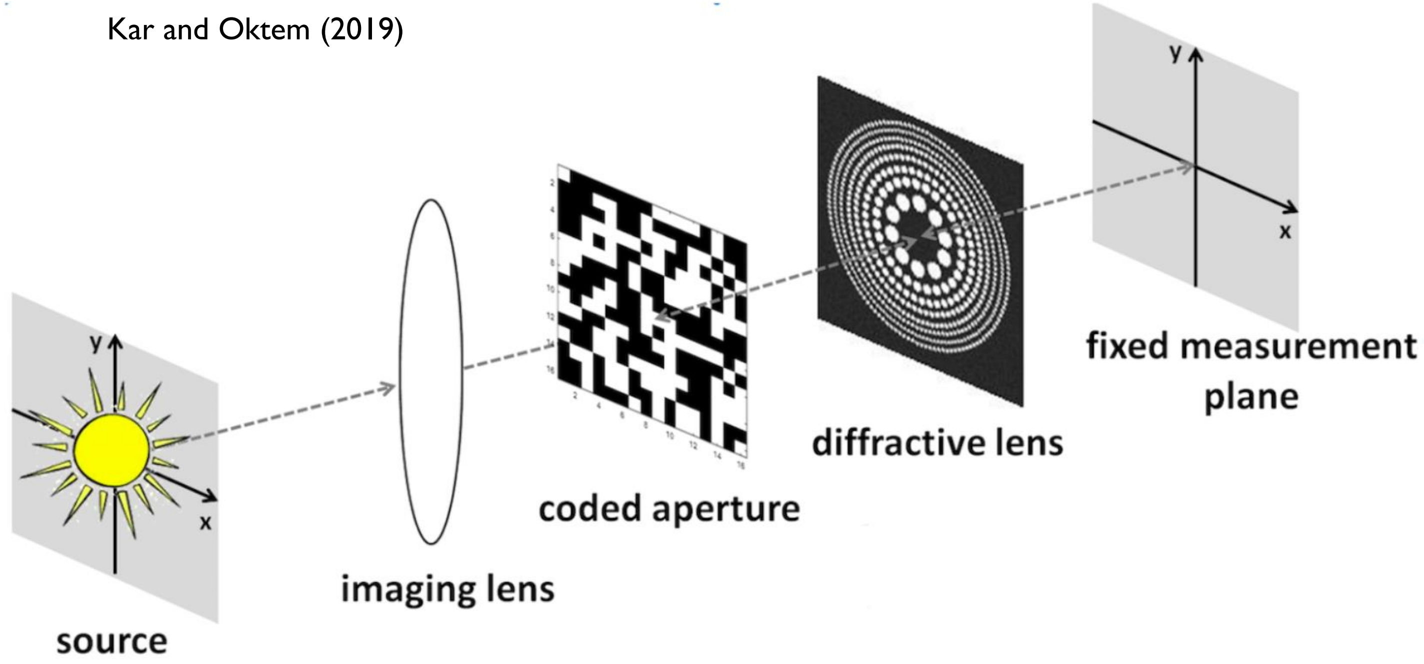
- S: Summation of the spectral bands
- D: Translation due to dispersion
- C: Coding matrix
- x: Spectral volume

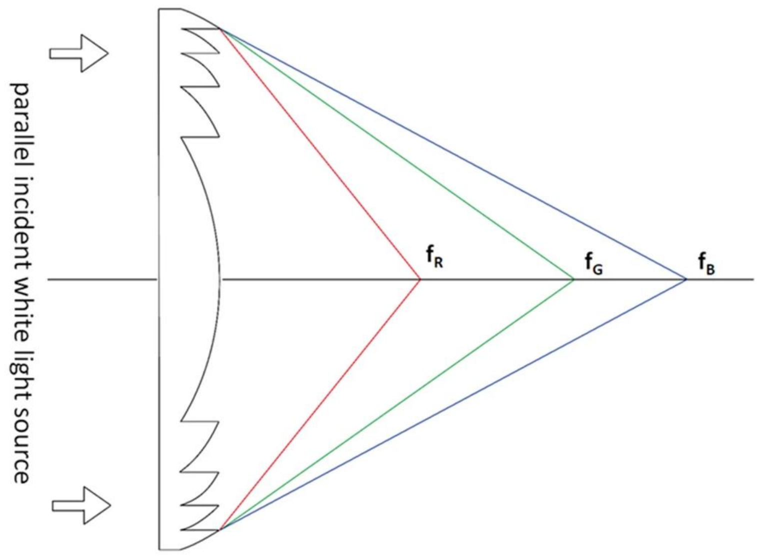
$$\text{Compression ratio} \sim \frac{\#snapshots}{\#\ spectral\ bands}$$

Yuan et al. (2021)

COMPRESSIVE SPECTRAL IMAGING USING A DIFFRACTIVE LENS (CSID)

Kar and Oktem (2019)

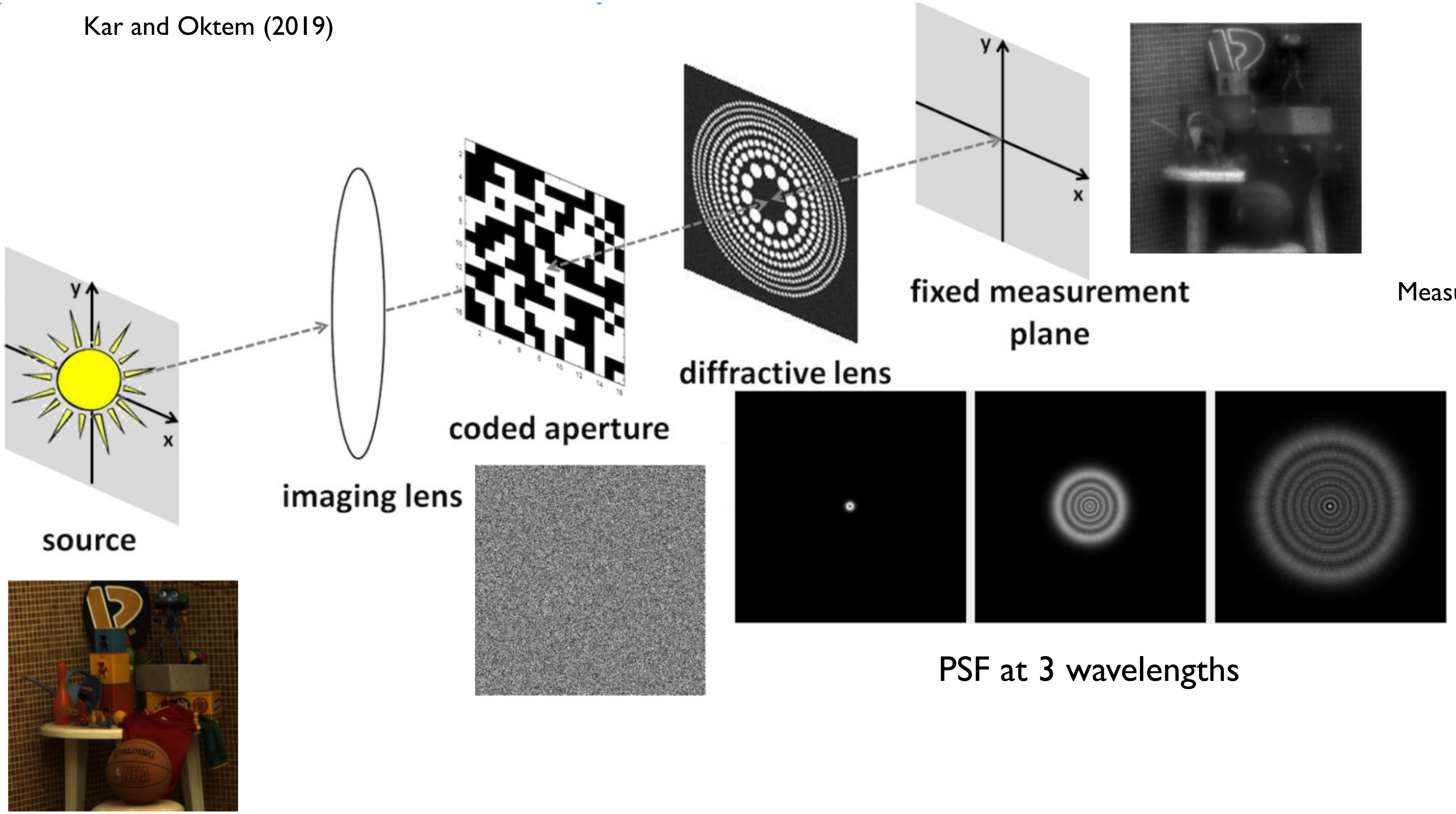




- Idea: using a diffractive lens to simultaneously disperse and focus light
- Knowledge of the Point Spread Functions (PSFs) at the different wavelengths enables reconstruction

COMPRESSIVE SPECTRAL IMAGING USING A DIFFRACTIVE LENS (CSID)

Kar and Oktem (2019)



PSF at 3 wavelengths

$$y = \mathrm{H} \;\; \mathrm{C} \;\; \mathrm{x}$$

- y → Measurement
- H → Convolution with the PSFs (and summation of the blurred spectral bands)
- C → Coding matrix
- x → Spectral volume

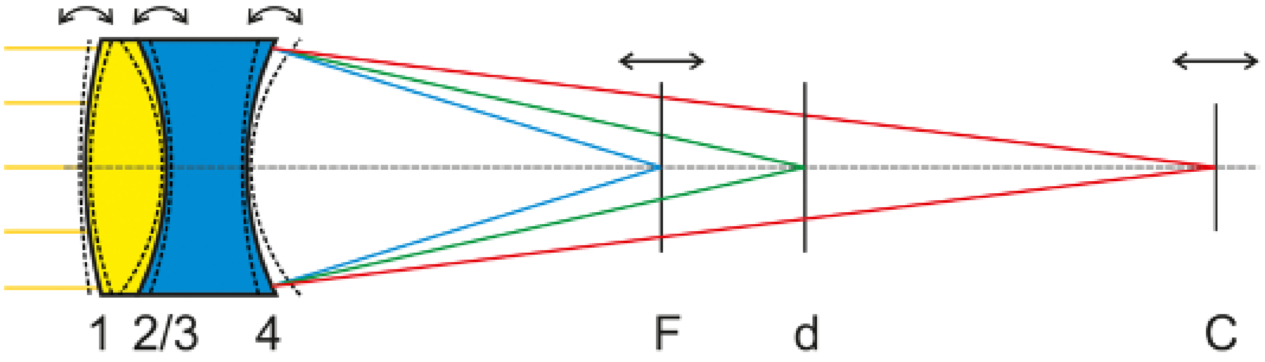
ALTERNATIVE TO THE DIFFRACTIVE LENS

- Diffractive lenses can be complex to manufacture and sometimes expensive: is there an alternative?
- Idea: use chromatic aberration of refractive lenses

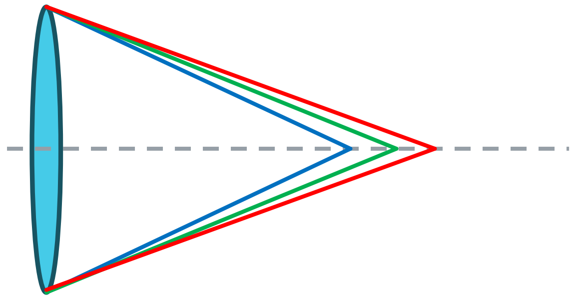
Refractive index:

$$n(\lambda) = A + \frac{B}{\lambda^2}$$

Hyperchromatic doublet

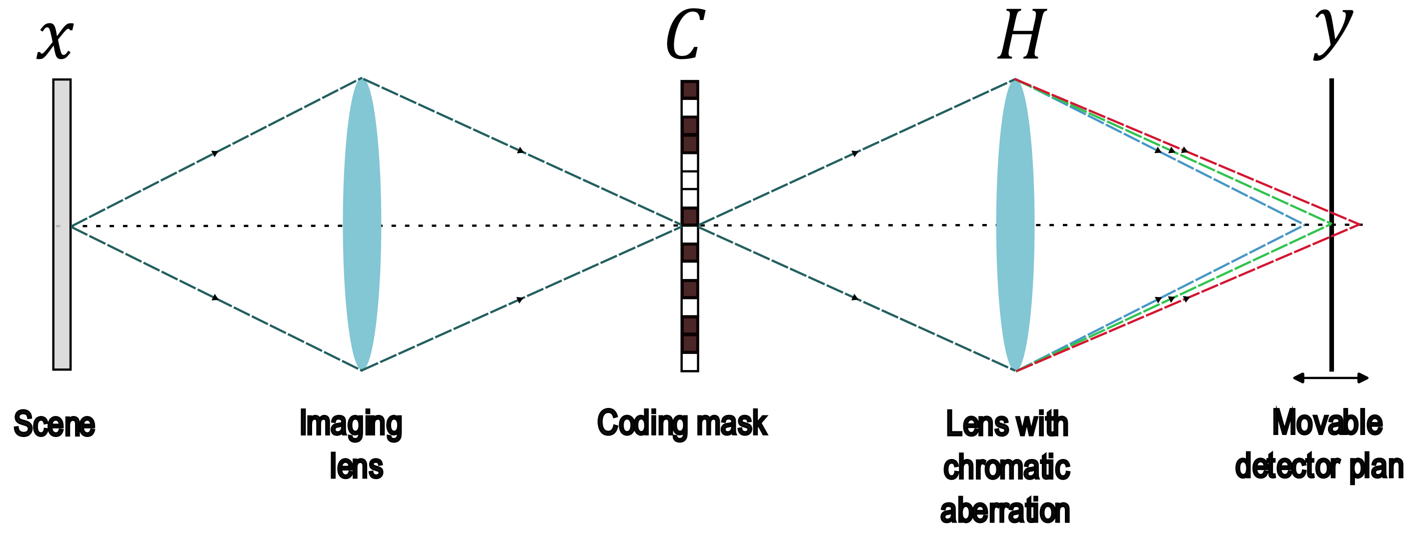


Single lens



Förster et al. (2022)

PROPOSED ARCHITECTURE



Measurement

$$y = \mathrm{H}\ \ \mathrm{C}\ \ \mathrm{x}$$

Convolution with the PSFs (and summation of the blurred spectral bands)

Coding matrix

Spectral volume

Simple NBK7 catalog lens:

- Cheap
- Easily procurable

RECONSTRUCTION

Saprsifying basis:

$$x = \Psi\alpha \quad \text{and} \quad \Psi = \Psi_2 \otimes \Psi_1^T$$

- x: Spectral volume
- Ψ: Sparse basis
- α: Sparse coefficients
- Ψ_2: DCT (spectral dimension)
- Ψ_1^T: 2D DWT (spatial dimension)

Forward model:

$$y = H\,C\,\Psi\,\alpha \rightarrow y = A\,\alpha$$

- H: Convolution with the PSFs
- C: Coding mask
- A: Sensing operator

RECONSTRUCTION

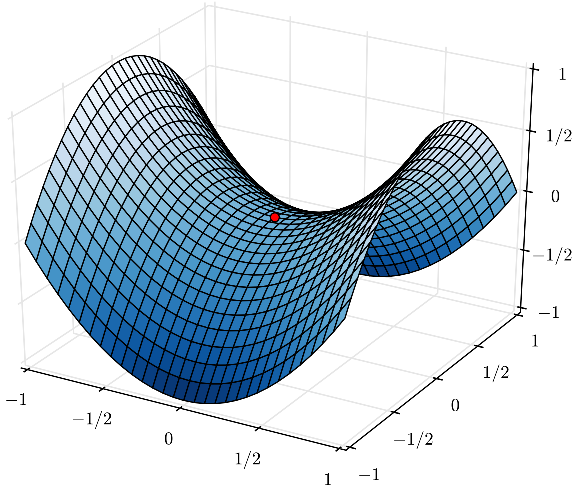
Basis Pursuit:

$$\min_{\alpha} ||\alpha||_1 \; s.t. \; ||y - A\alpha||_2^2 \leq \epsilon$$

Primal-dual formulation:

$$\max_{p} \min_{\alpha} \langle A\alpha, p\rangle + g(\alpha) - f^*(p)$$

Where p is the dual variable



$$g(\alpha) = ||\alpha||_1$$

↓

$$prox_{\lambda g}(s) = soft_\lambda(s)$$

$$f(p) = \begin{cases} 0 \; if \; ||p||_2 \leq \epsilon \\ +\infty \; otherwise \end{cases}$$

↓

$prox_f$ = projection on the Euclidean ball $B_\epsilon(y)$

RECONSTRUCTION

Accelerated Chambolle-Pock algorithm

Iterations:

$$p^{k+1} = p^k + \sigma^k A\overline{\alpha}^k - prox_{\sigma^k f}\left(p^k + \sigma^k A\,\overline{\alpha}^k\right)$$

$$\alpha^{k+1} = prox_{\tau^k g}(\alpha^k - \tau^k A^T p^{k+1})$$

$$\theta^k = \frac{1}{\sqrt{1 + 2\gamma\tau^k}}$$

$$\tau^{k+1} = \theta^k \tau^k$$

$$\sigma^{k+1} = \frac{\sigma^k}{\theta^k}$$

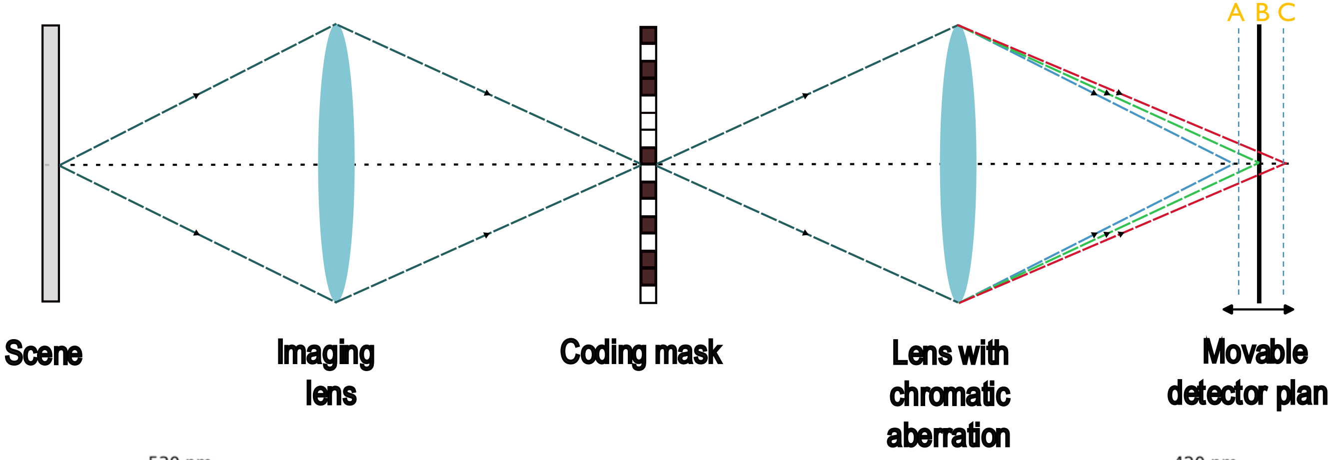
$$\overline{\alpha}^{k+1} = \alpha^{k+1} + \theta^k(\alpha^{k+1} - \alpha^k)$$

Final output: $\overline{\alpha}$

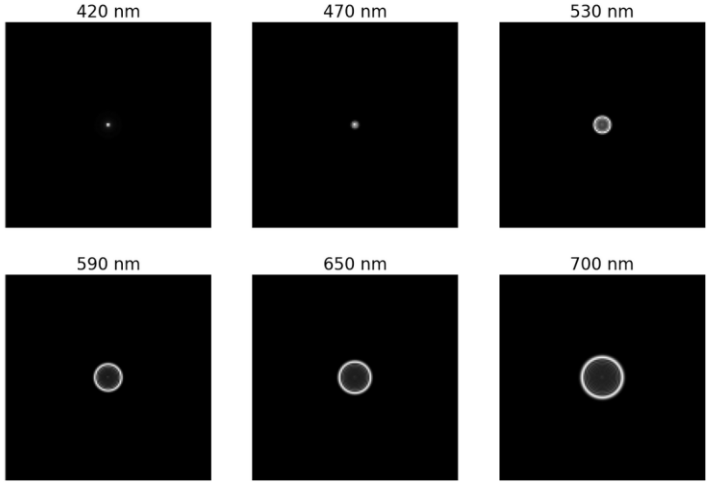
Final reconstructed datacube:

$$\tilde{x} = \Psi\,\overline{\alpha}$$

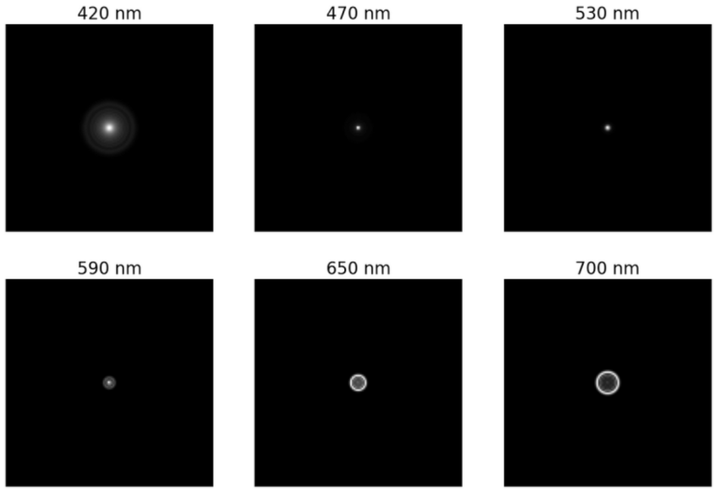
SIMULATION - PSF



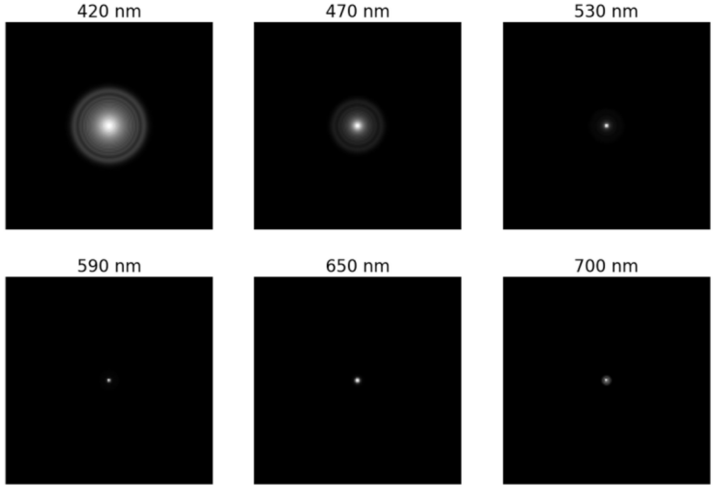
A



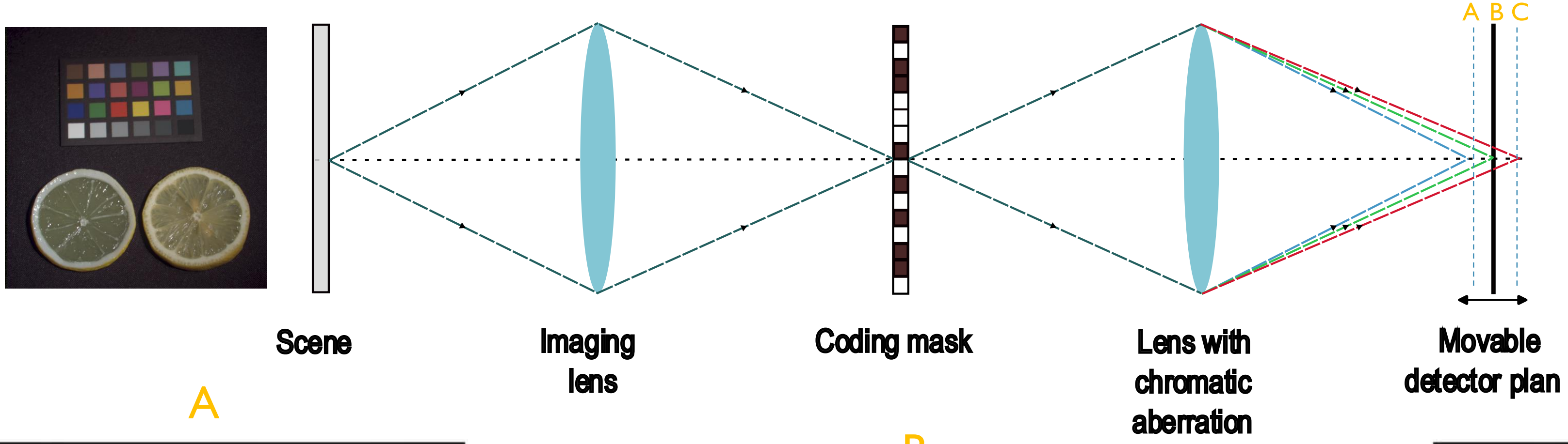
B



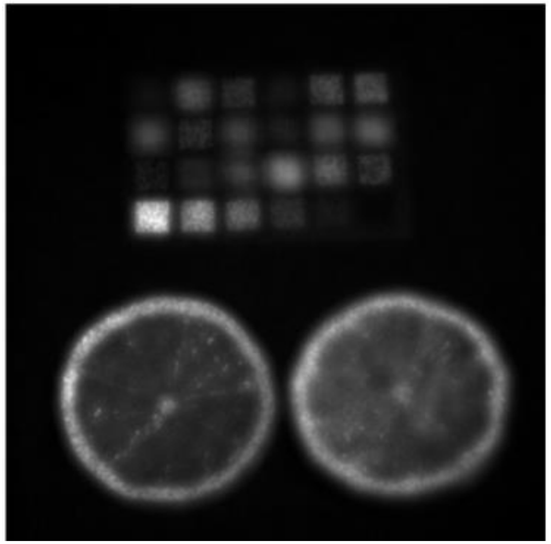
C



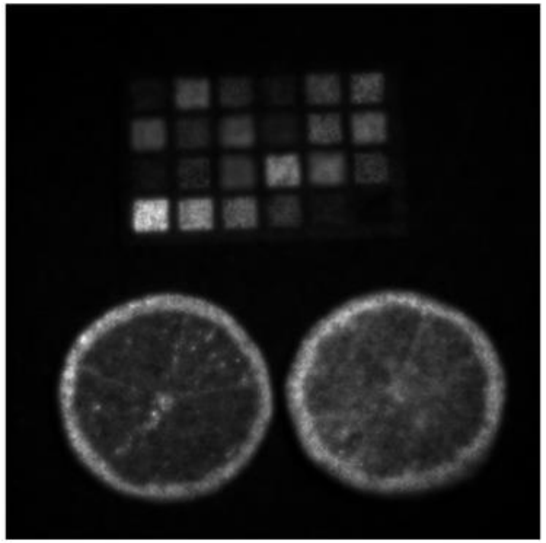
SIMULATION - MEASUREMENTS



A



B



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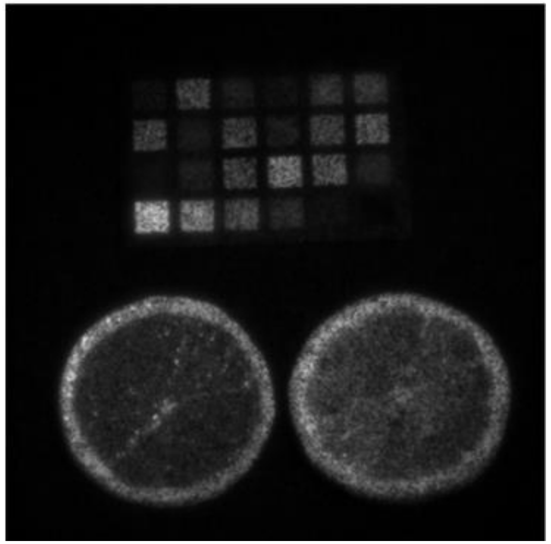
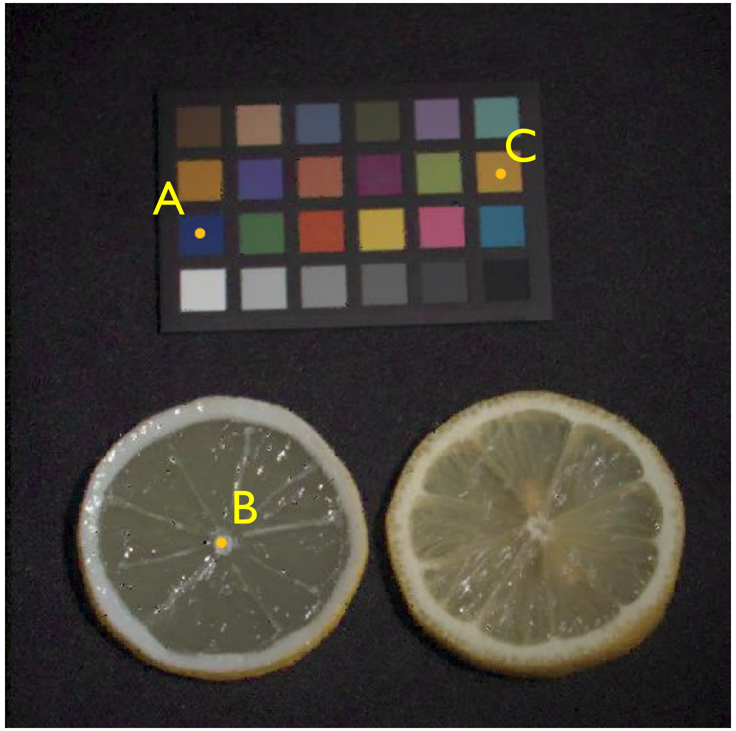
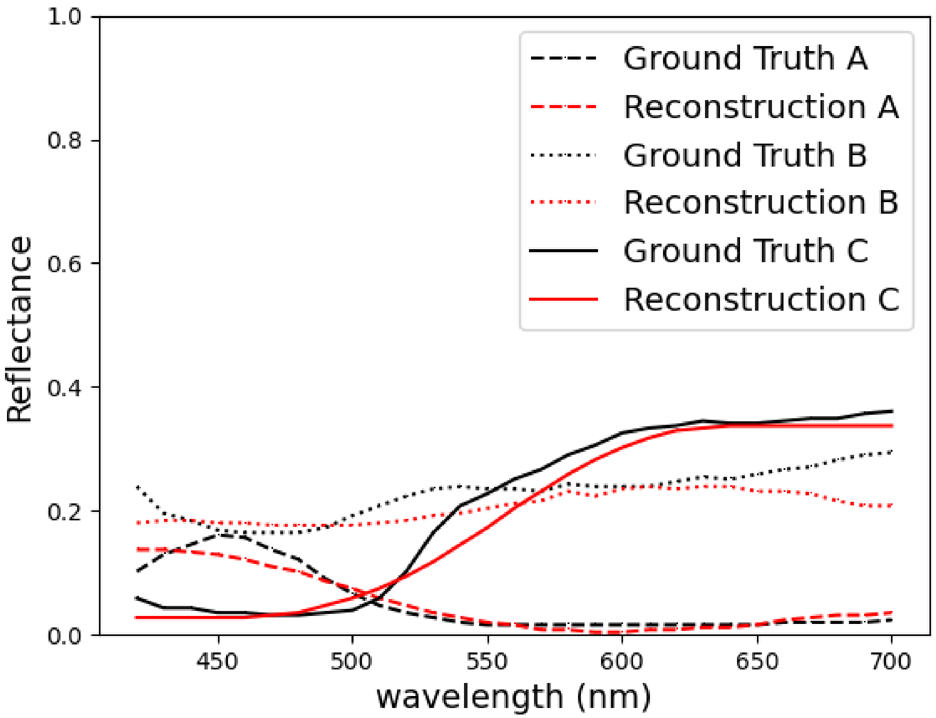


RECONSTRUCTION FROM 10% SUBSAMPLING

Original

Reconstruction (noiseless measurement)
PSNR = 35.46 dB

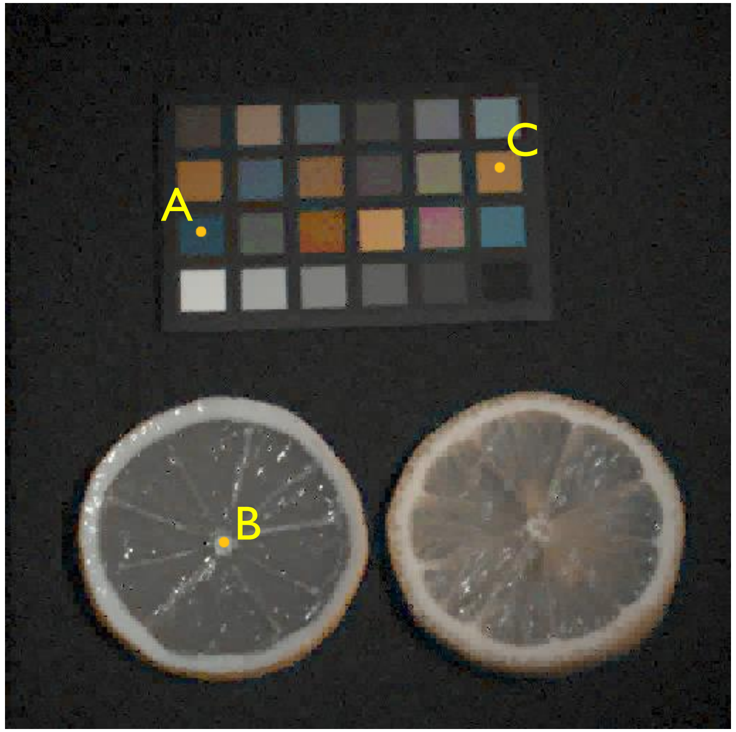


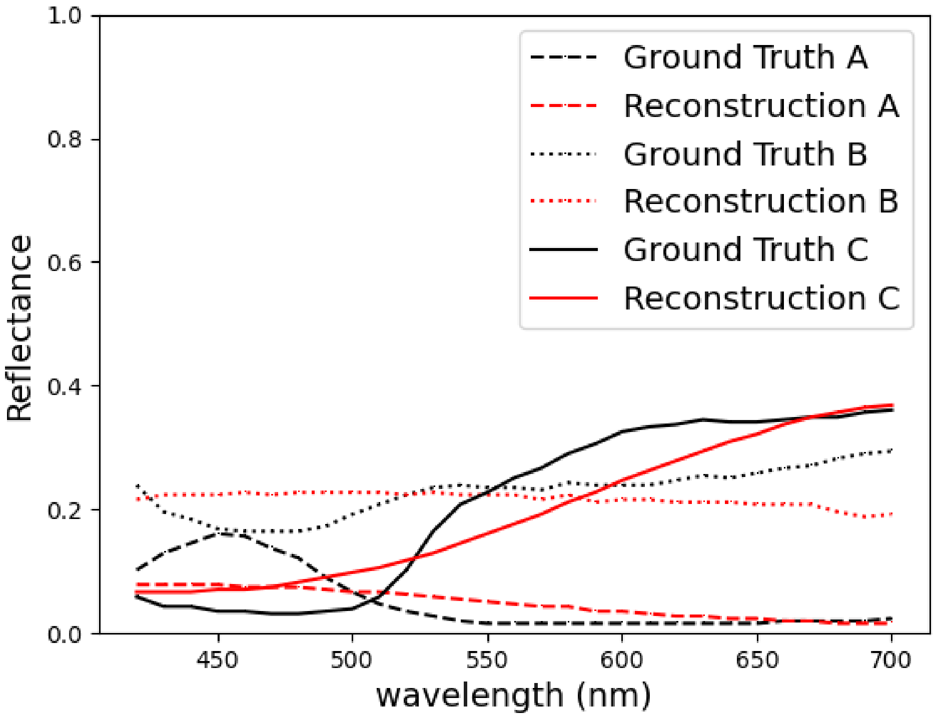


RECONSTRUCTION FROM 10% SUBSAMPLING

Original

Reconstruction (measurement SNR = 28 dB)
PSNR = 31.76 dB





Measurement SNR	22 dB	28 dB	34 dB
Reconstruction PSNR	30.58 dB	31.76 dB	32.82 dB

CONCLUSION AND FUTURE WORK

Simulations show the feasibility of the method

Compact compressive spectral imager using:

- Two lenses
- One SLM
- One panchromatic detector

Laboratory setup is under development

Areas of improvement:

Reconstruction method

Coding patterns