Reconstruction d'images hyperspectrales à faible coût pour un imageur pilotable à double dispersion

Ibrahim Ardi
Hervé Carfantan
Simon Lacroix
Antoine Monmayrant

Who’s who

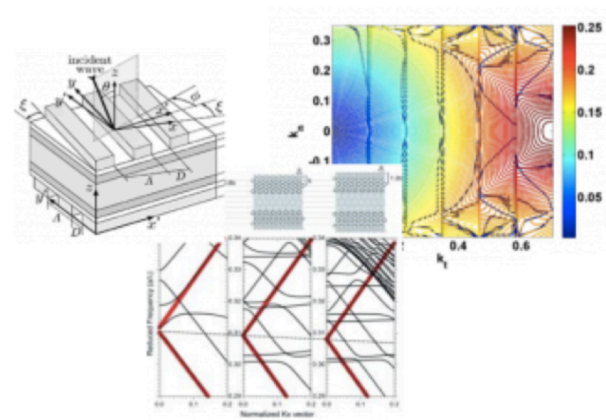
Ibrahim Ardi: PhD student I RAP/LAAS (2016-2019)

Hervé Carfantan: IRAP, team SISU

Inverse problems, estimation / optimization, deconvolution…

Antoine Monmayrant: LAAS, team PHOTO

Integrated photonic systems, modeling and conception



Simon Lacroix: LAAS, team RIS

Autonomy of mobile robots, environment perception & modeling

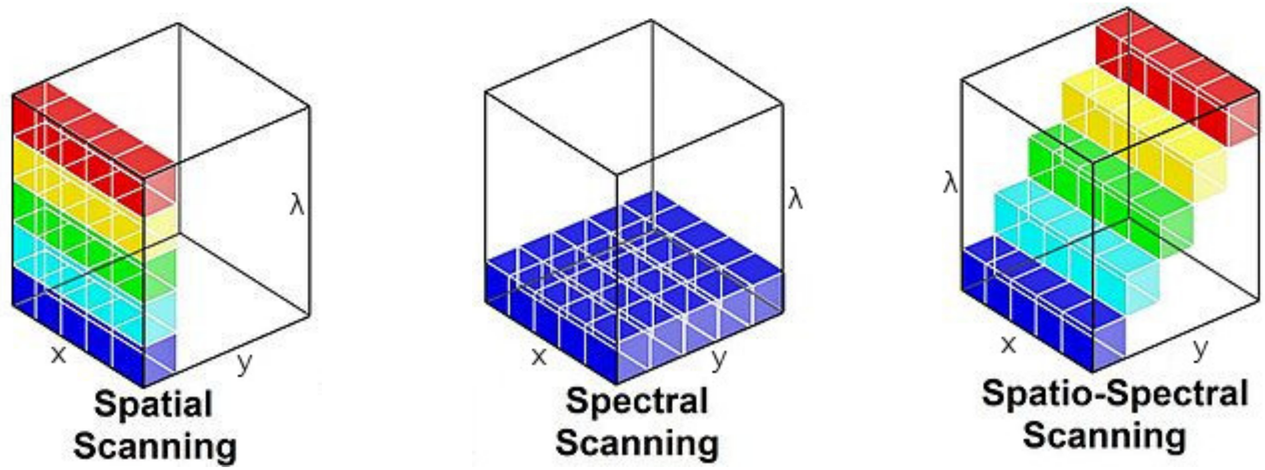
UAVs

UGVs

Field and aerial robotics

Motivations

Classic hyperspectral imagers fill the HS-cube slice by slice



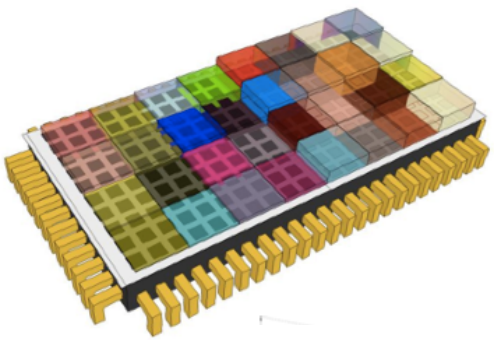
(moving slit) (rotating filter wheel) (gradient filter)

Characteristics of the systems RIS and PHOTO address:

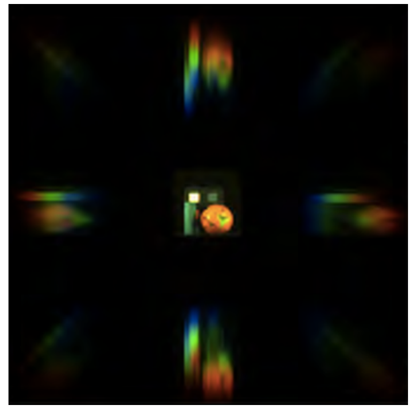
- Moving cameras
- Dynamic phenomena
- Real-time decision

Need for real-time (“snapshot”) acquisition and real-time data analysis

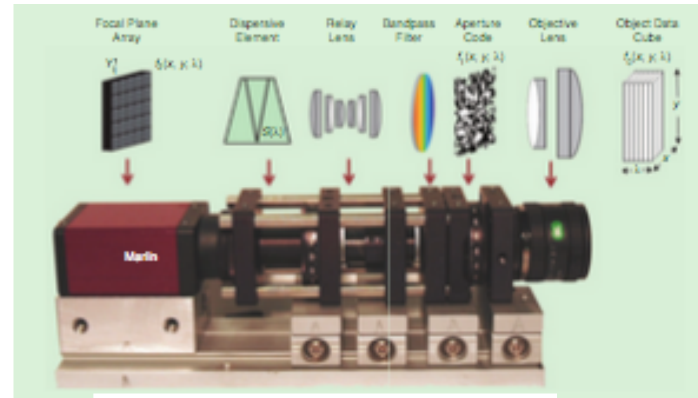
Snapshot hyperspectral imagery



IMEC / Ximea



Hable 2012



CASSI

- *Review of Snapshot Hyperspectral Imaging Technologies*. N. Hagen and M. Kudenov, Optical Engineering 52(9), Sept. 2013

Characteristics of these systems:

- Spatial / spectral compromise
- Often resort to heavy computations
- Tough calibration issues

Outline

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- (Aperçu des possibilités de l'imageur)

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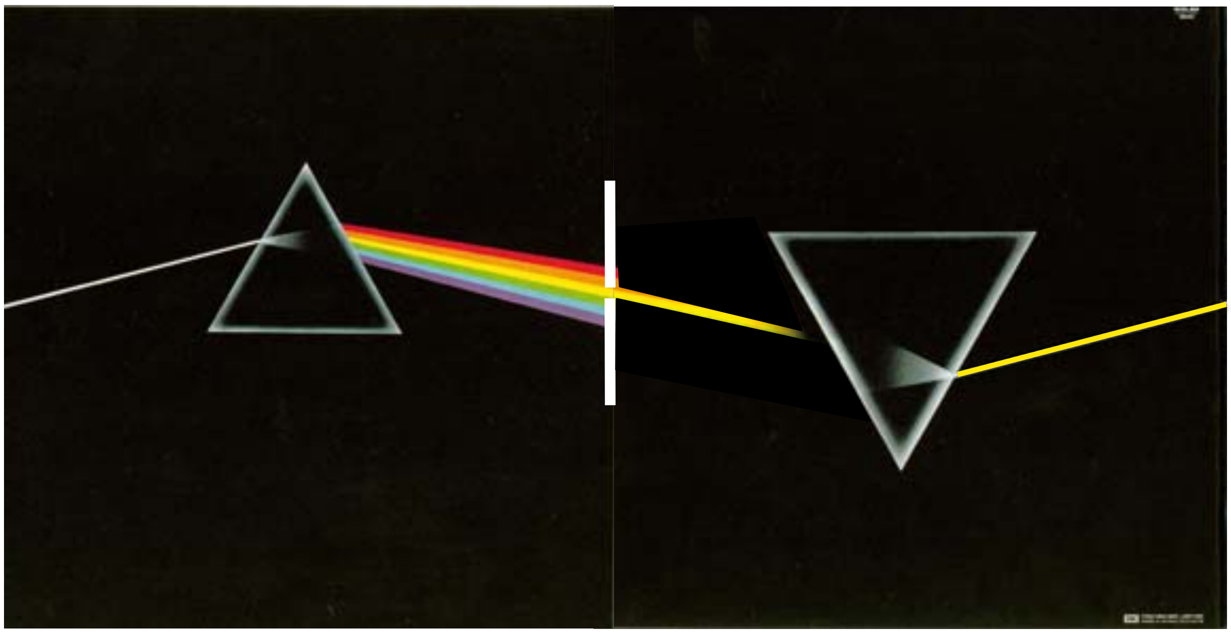
- Conclusion et perspectives

Controllable dual-disperser imager

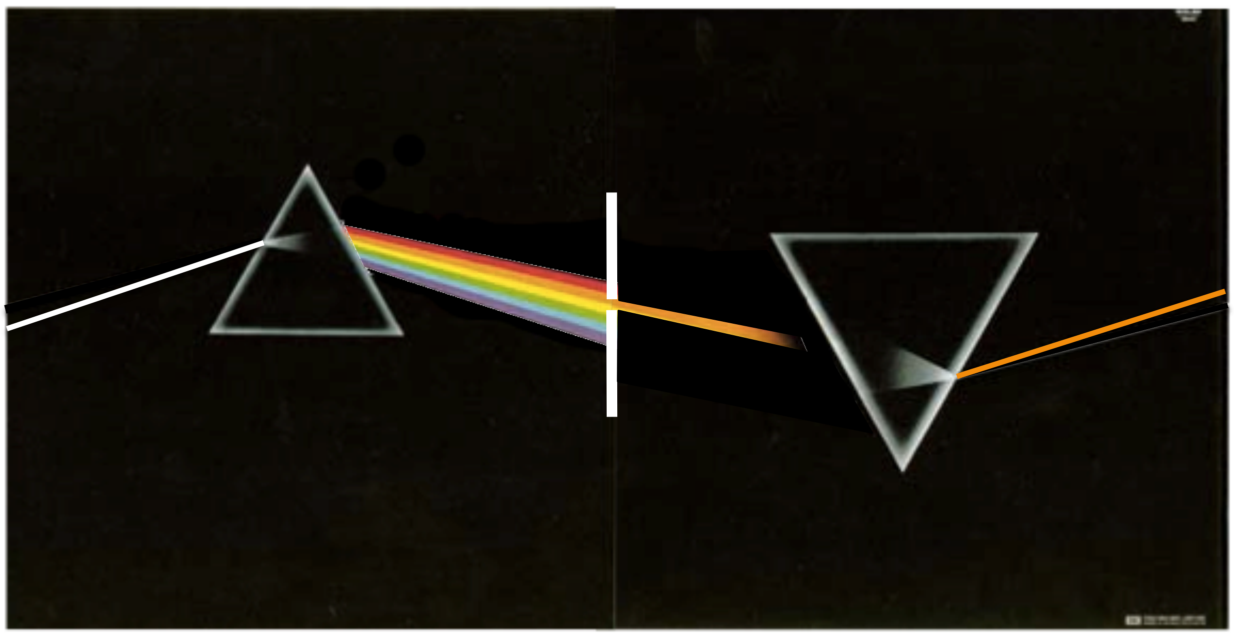
Dual-disperser architecture (inspired from [Coded Aperture Spectral Snapshot Imager, 2007])



A partial masking of the signal defines a spectral filter

Controllable dual-disperser imager

Dual-disperser architecture (inspired from [Coded Aperture Spectral Snapshot Imager, 2007])

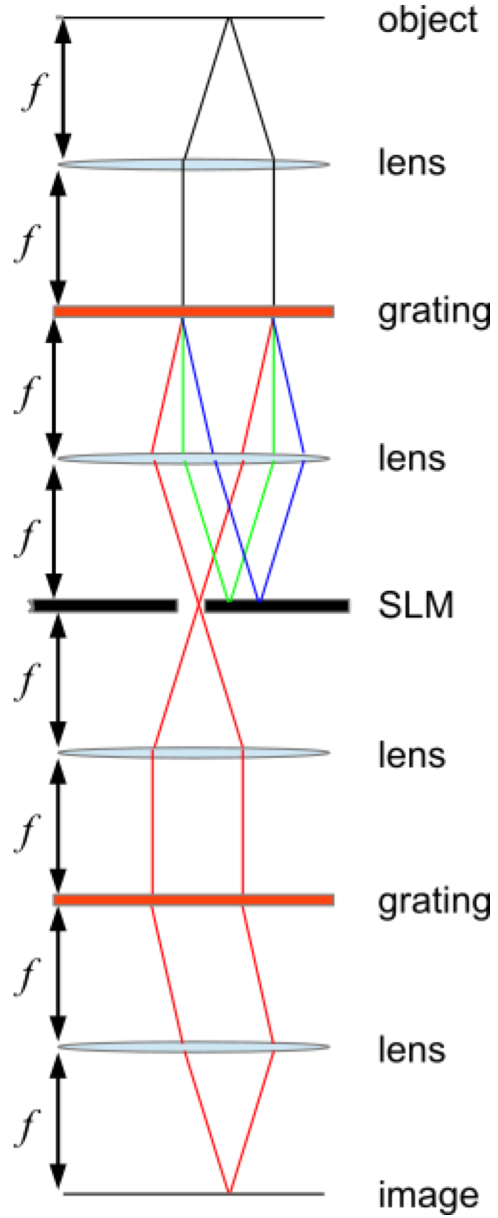


For the same mask, different spatial rays are differently spectrally filtered

Controllable dual-disperser imager

Dual-disperser architecture

- For a given mask, the spectral filtering depends on the objet position



Controllable dual-disperser imager

Dual-disperser architecture

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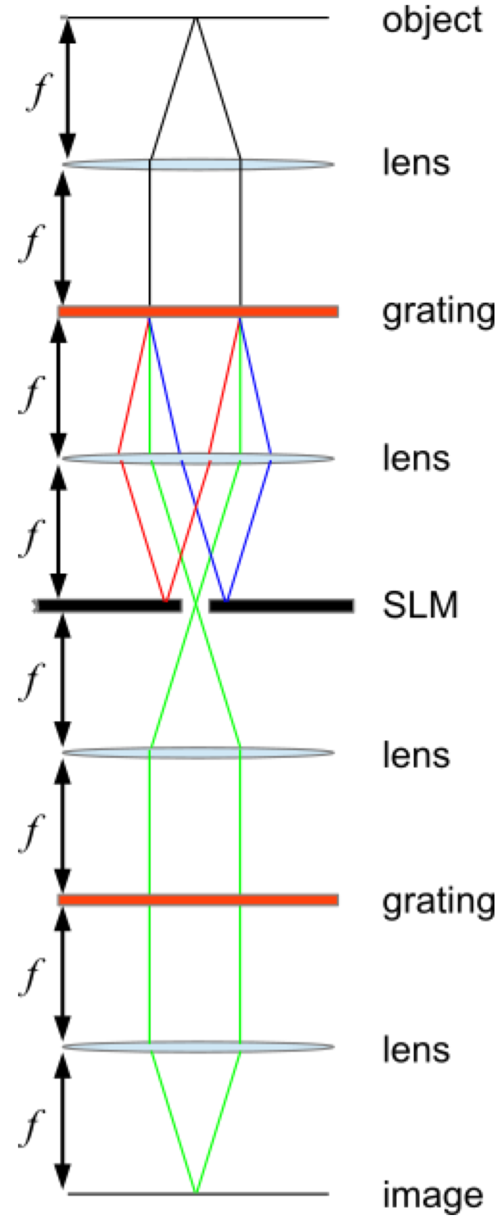
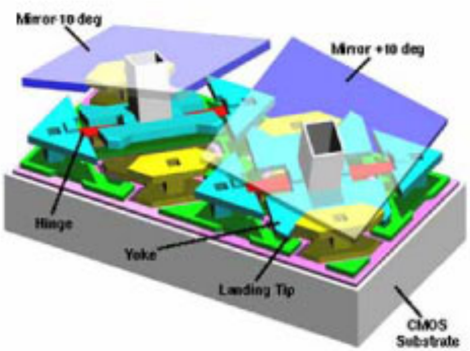


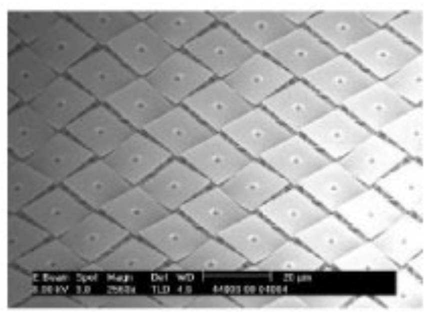
Controllable dual-disperser imager

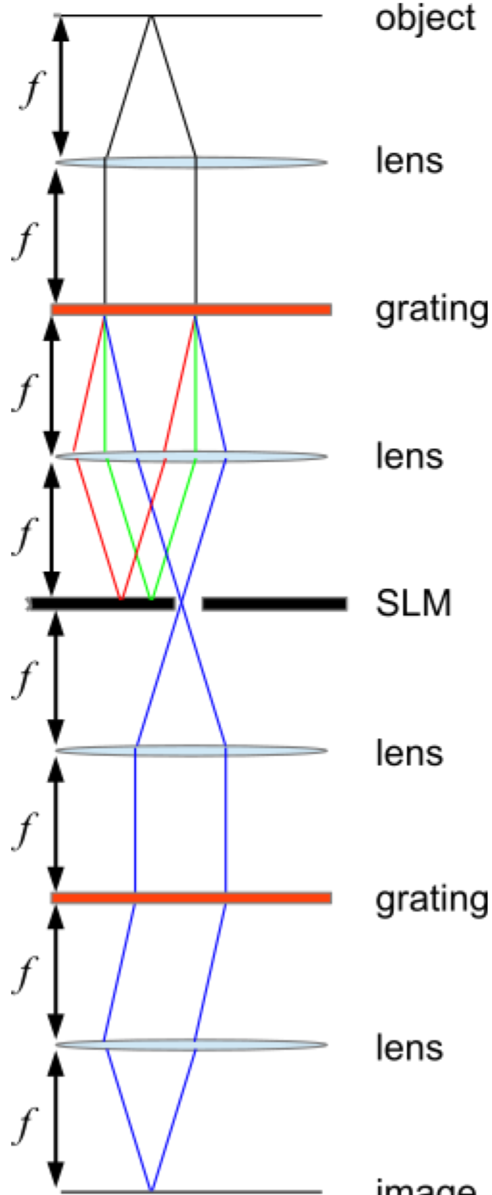
Dual-disperser architecture

- For a given mask, the spectral filtering depends on the objet position

SLM : “Spatial Light Modulator”
e.g. Digital Micro-mirror Device

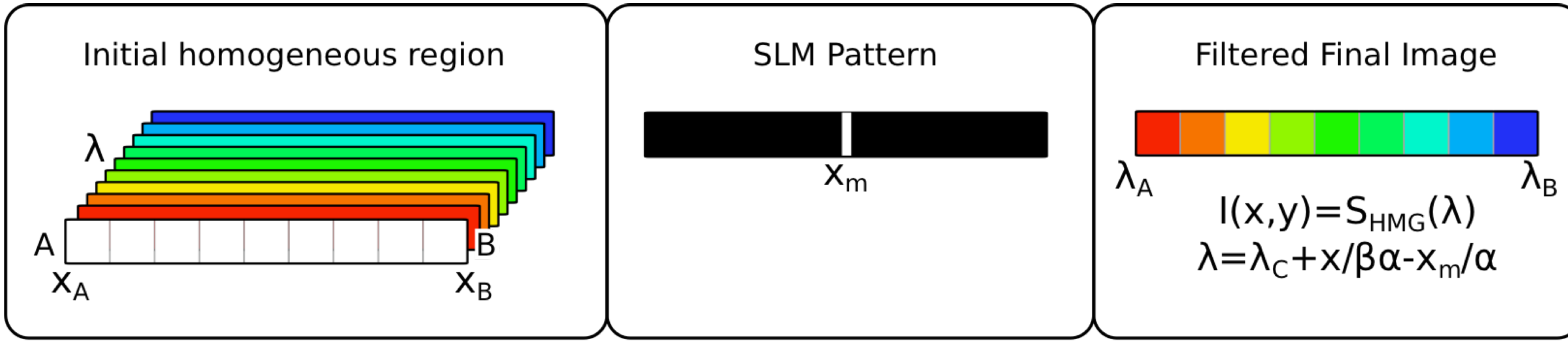




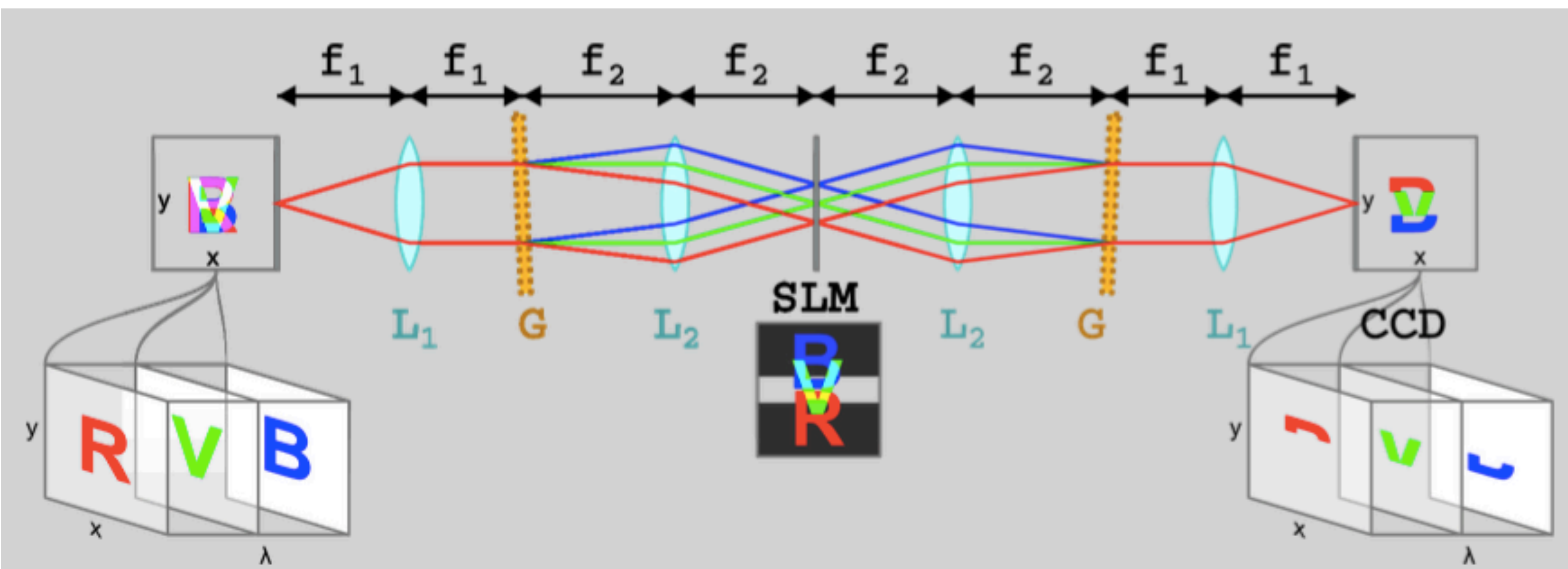


Controllable dual-disperser imager

Slit pattern on the DMD for a white line of pixels:

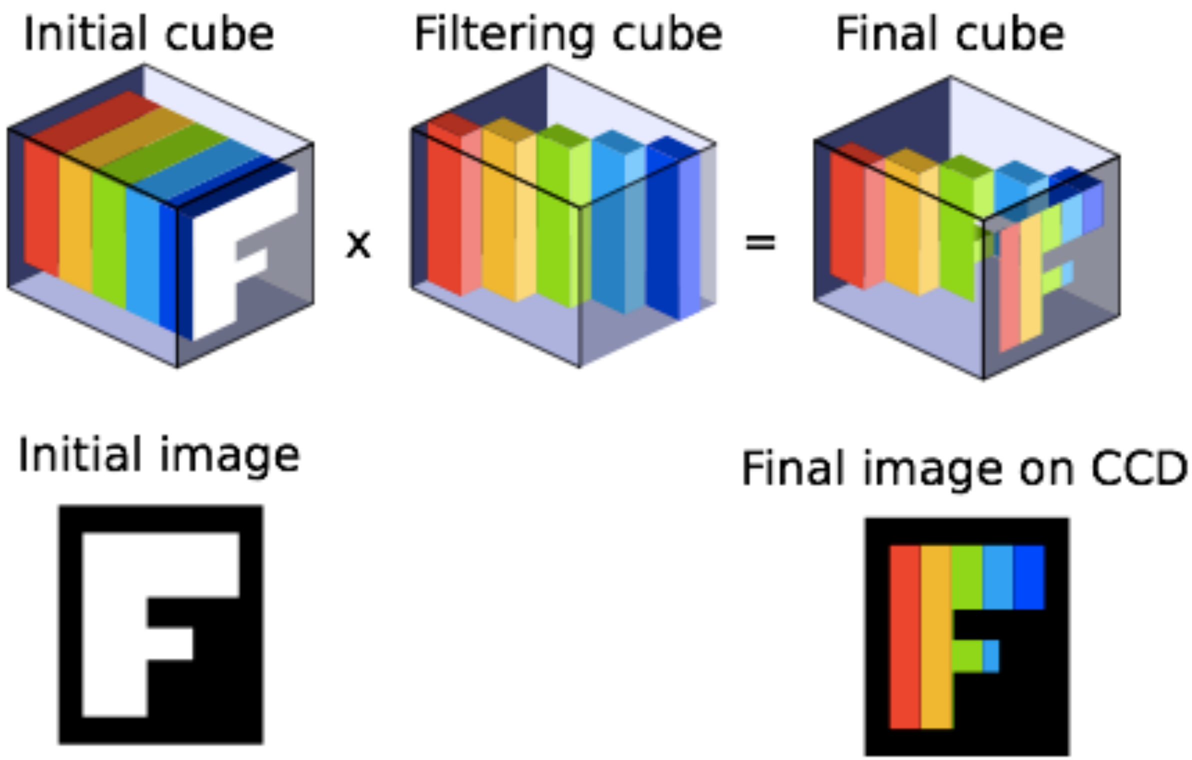


Slit pattern on the DMD for a whole image



Controllable dual-disperser imager

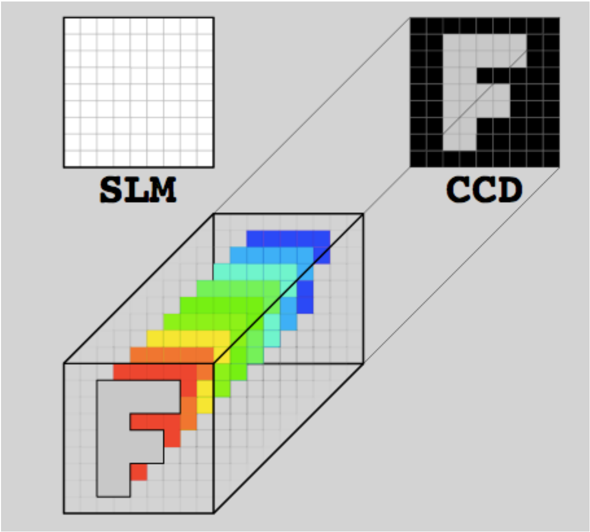
Slit pattern on the DMD for a whole image: the slit acts as a "filtering cube"



→ Basis of the simple linear matrix model

System characteristics

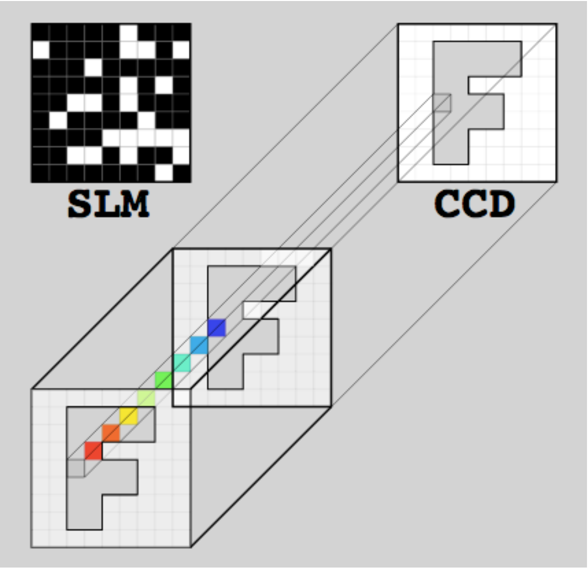
- Possibility to acquire an intensity image



System characteristics

- Possibility to acquire an intensity image

- “Colocation” property

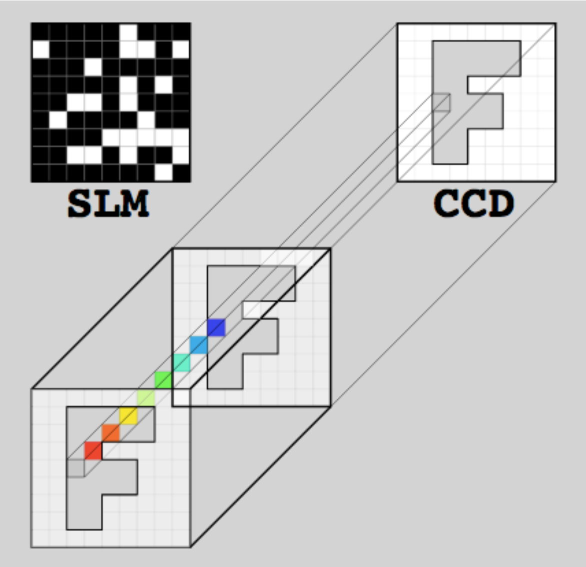


System characteristics

- Possibility to acquire an intensity image

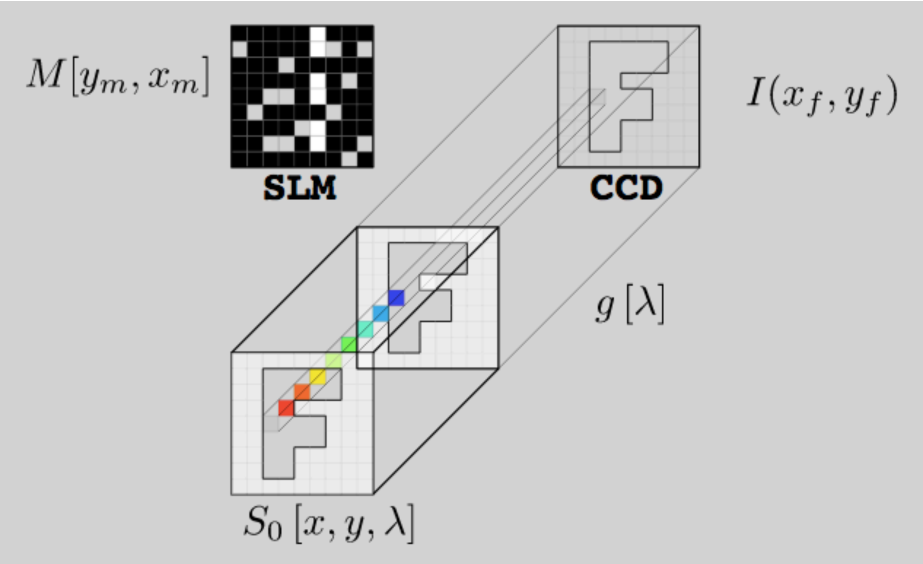
- “Colocation” property

(independence between lines)



System characteristics

- Possibility to acquire an intensity image
- “Colocation” property
- Simplicity of the model

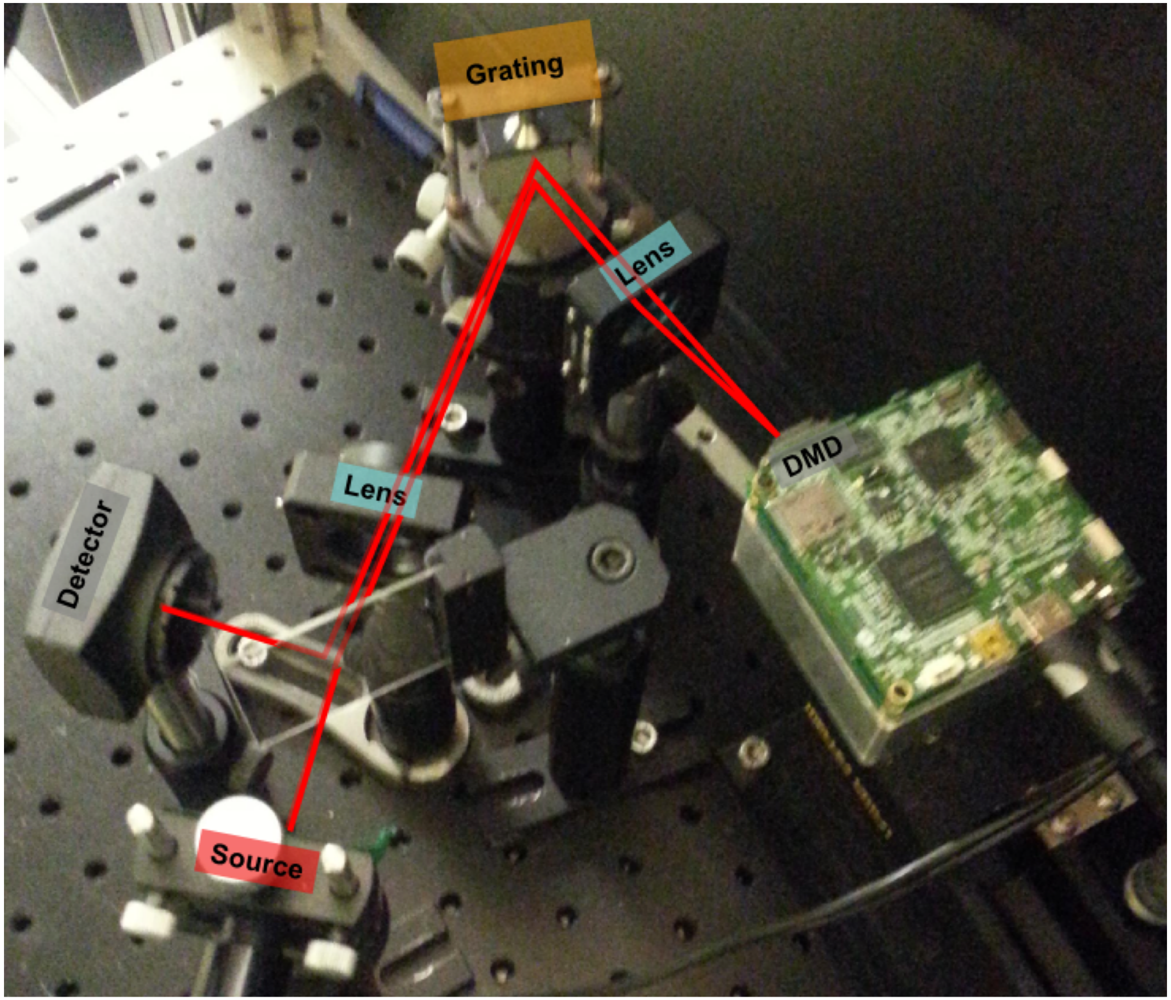


$$\lambda(x_f, x_m) = \lambda_c + x_f/(\beta\alpha) - x_m/\alpha$$

System characteristics

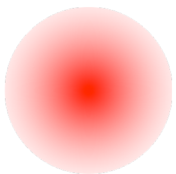
- Possibility to acquire an intensity image
- “Colocation” property
- Simplicity of the model
- Programmable acquisition

First prototype (end 2014)

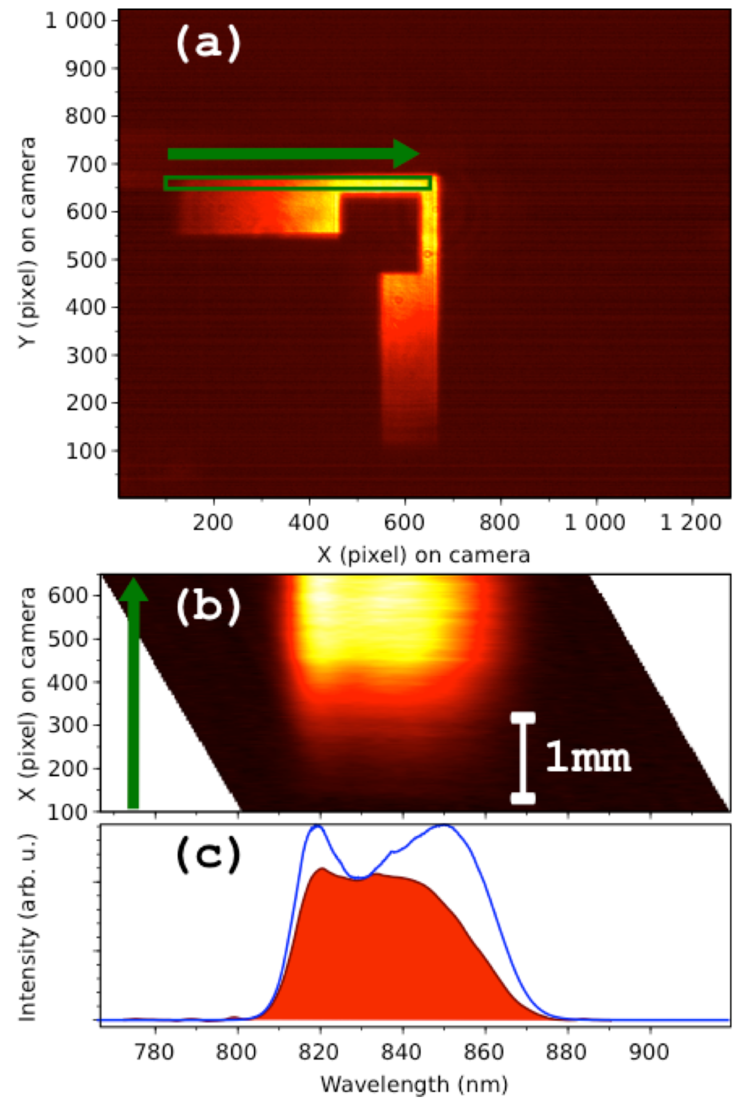


First prototype validation

- Scanning slit



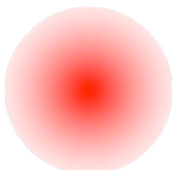
Imaged object: known light source through a mask

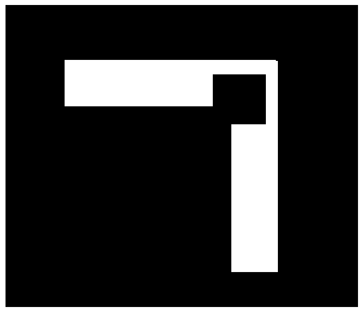


“white” illumination

First prototype validation

- Scanning slit





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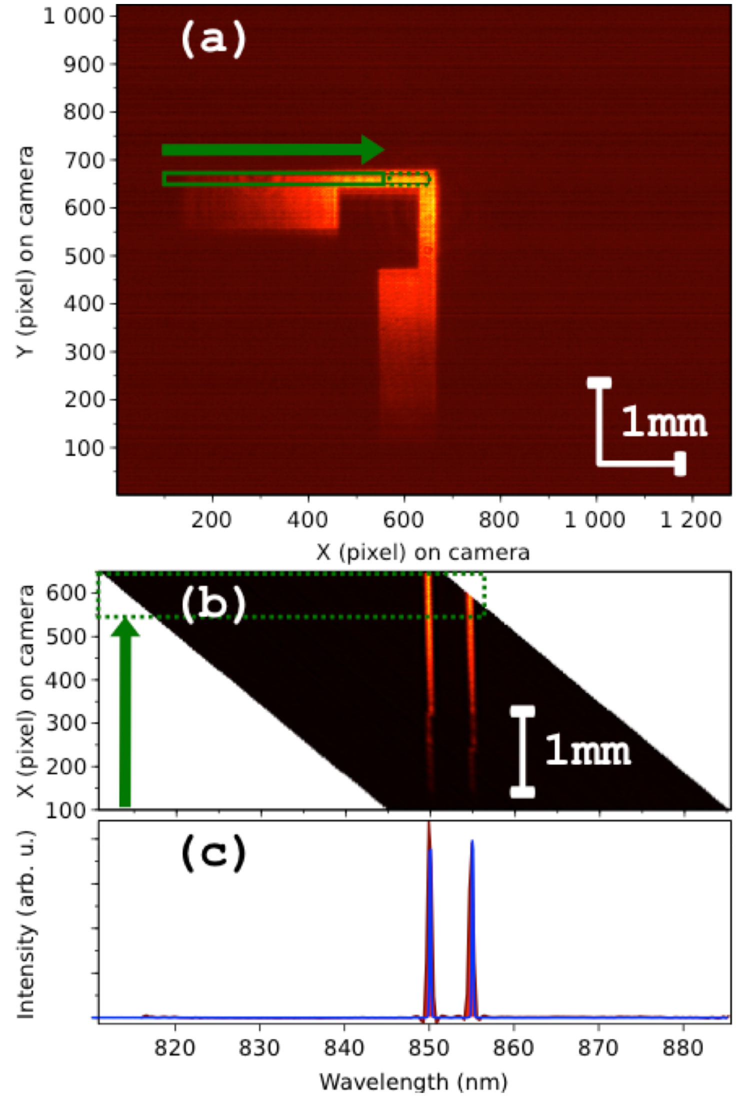


“bi-λ” illumination

Outline

- Reconstruction d’images hyperspectrales à faible coût pour un imageur pilotable à double dispersion

- (Aperçu des possibilités de l’imageur)

A typology of use-cases

1. Two usual HS "products" *(i.e.* type of recovered information):
   - Full HS cube
   - Specific spectra
2. Two ways to control the system *(i.e.* type of DMD settings):
   - Pre-defined patterns (structured or random)
   - On-line controlled / adapted patterns

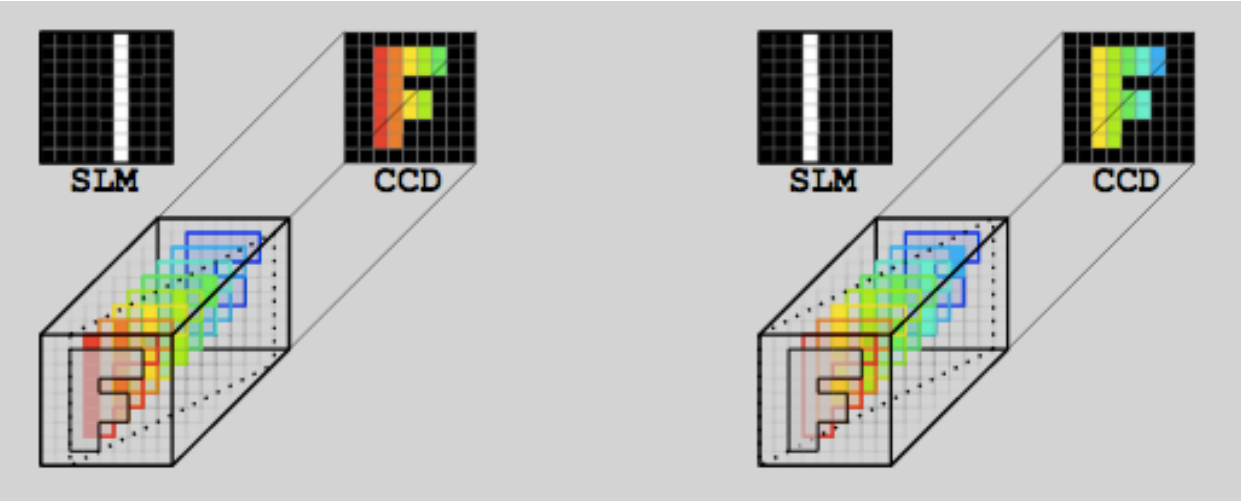
→ Four "families" of processes

Various "evaluation" criteria:

1. Number of acquisitions (→ transmission volume)
2. Computational load
3. Robustness wrt. noise and approximated model of the system

Full HS cube / Predefined DMD sequence

Scanning SLIT

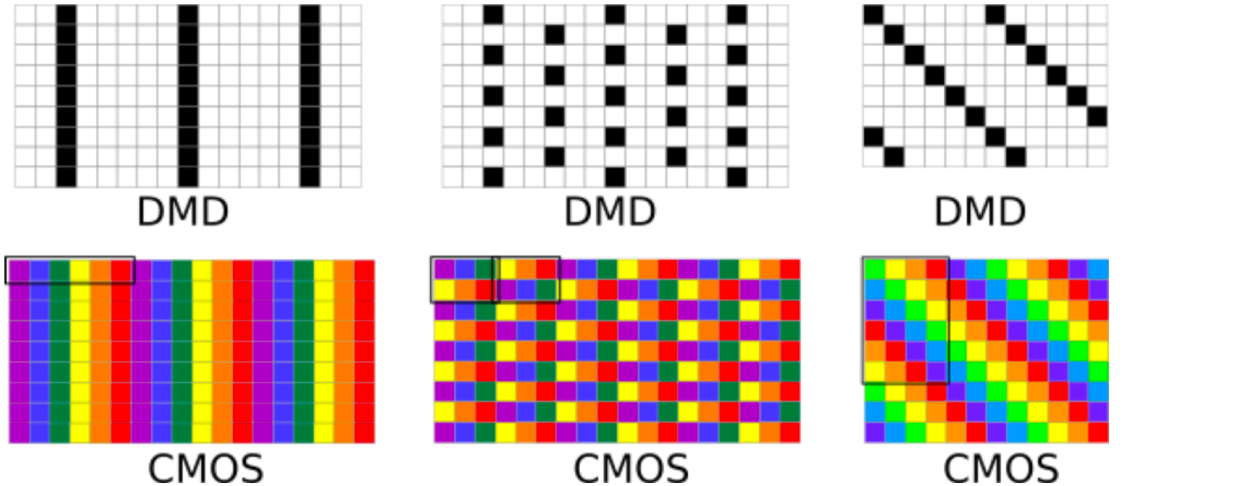


1. Number of acquisitions: as much as the DMD width
2. Computational load: Null

- Interest / relevance: best achievable spatial/spectral resolution (to benchmark other approaches)
- No mechanical system involved

“Full” HS cube / Predefined DMD sequence

Generalised Bayer mosaic



Variants: more than one acquisitions, randomized mosaic

1. Number of acquisitions: one or a few
2. Computational load: low

Note: depending on \alpha some patterns may yield some spectral mixing

Relevance:

- pan-X processing readily applicable, no intrinsic registration issue
- Unmixing? (because the mixing is somehow controllable, to be further discussed)

Full HS-Cube / Random DMD sequence

Current work of Ibrahim Ardi (see 3rd part of the talk later)

1. Number of acquisitions: ~ < 1/5th of spectral depth
2. Computational load: medium (but can be parallelized and adapted to GPUs)

Full HS-Cube / 2 DMD controlled acquisitions

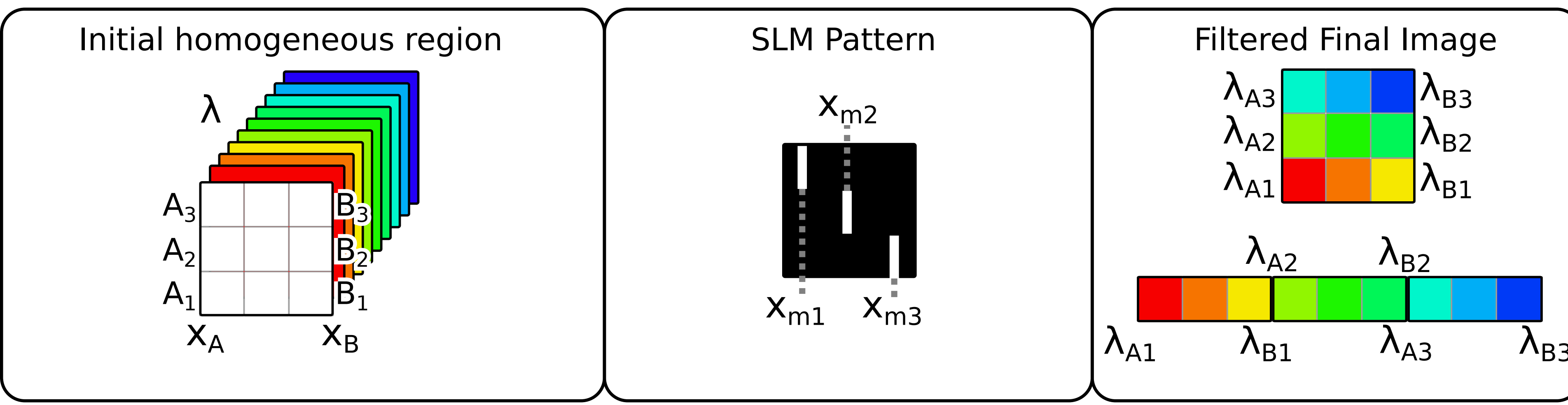
”Near snapshot partitioning”

→ An *adaptive* scheme

Regularity hypothesis: presence of spectrally homogeneous regions

Steps of the approach:

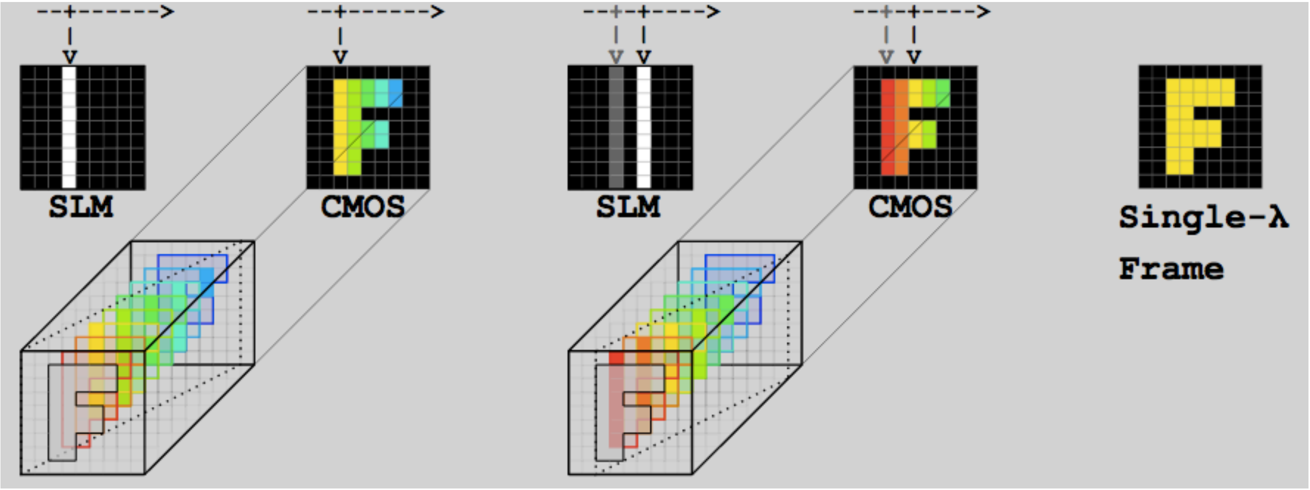
1. Acquire and segment the intensity image
2. Define mask pattern to recover the whole spectrum
3. “filtered” image acquisition and analysis



(possibility to validate the homogeneity assumption – actual algorithms yet to develop)

Specific spectrum / Fixed DMD

Mono-chromatic



Variants: multi-spectral images, spectra correlation

1. Number of acquisitions: “one” (rolling shutter)
2. Computational load: nearly null

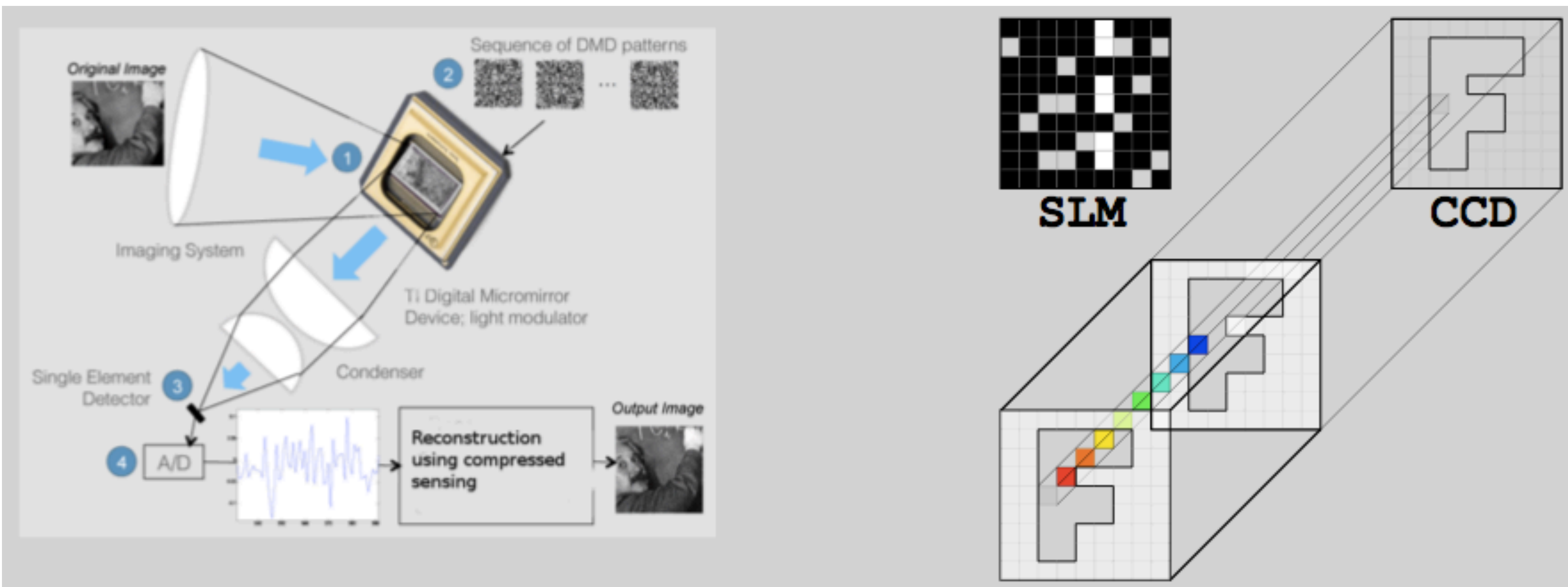
Notes: the camera lines should be oriented normally to the dispersing direction

Relevance: random-access of mono-chromatic images (\delta \lambda controllable), possibility to define adaptive schemes (with a sequence of acquisitions)

Specific spectra / Random DMD sequence

Compressed sensing

→ Analogy with the 1-pixel camera



Numerous 1-pixel spectrometers in parallel
A quick unmixing approach with known end-members

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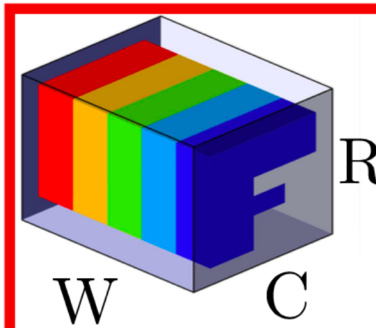
Direct matrix model

$$\mathrm{d} = H \times o$$

$I(r,c)$

filtrage DMD+8f

$T(r,c,w)$



$S_0(r,c,w)$

- $I \Rightarrow \mathbf{d}$: vecteur de taille $RC \times 1$
- $S_0 \Rightarrow \mathbf{o}$: vecteur de taille $RCW \times 1$
- $T \Rightarrow \mathbf{H}$: matrice de taille $RC \times RCW$

♦ H est non-inversible "$W >> 1$ (hyperspectral)"
♦ H est bloc-diagonale et parcimonieuse "grâce à la co-localisation"

Inverse problem statement

♣ Objectif : Reconstruire l'objet d'intérêt, le plus rapidement possible avec quelques acquisitions aléatoires.

$$\mathbf{i} = \begin{pmatrix} d^{(1)} \\ \vdots \\ d^{(S)} \end{pmatrix} = \begin{pmatrix} H^{(1)} \\ \vdots \\ H^{(S)} \end{pmatrix} \mathbf{o} = \mathbf{A}\mathbf{o}$$

- $\mathbf{i}$: vecteur de taille $RCS \times 1$
- $\mathbf{A}$: matrice de taille $RCS \times RCW$

Critère quadratique pénalisé (Type Tikhnov) :

$$\hat{\mathbf{o}} = \arg\min_{\mathbf{o}} (||\mathbf{i} - \mathbf{A}\mathbf{o}||^2 + \mu_x ||\nabla_x \mathbf{o}||^2 + \mu_y ||\nabla_y \mathbf{o}||^2 + \mu_\lambda ||\nabla_\lambda \mathbf{o}||^2)$$

Inverse problem solving

♣ Objectif : Reconstruire l'objet d'intérêt, le plus <u>rapidement</u> possible avec <u>quelques acquisitions aléatoires</u>.

$$\mathbf{i} = \begin{pmatrix} d^{(1)} \\ \cdot \\ \cdot \\ d^{(S)} \end{pmatrix} = \begin{pmatrix} H^{(1)} \\ \cdot \\ \cdot \\ H^{(S)} \end{pmatrix} \mathbf{o} = \mathbf{A}\mathbf{o}$$

- $\mathbf{i}$: vecteur de taille $RCS \times 1$
- $\mathbf{A}$: matrice de taille $RCS \times RCW$

Résolution direct (inversion) impossible

Résolution itérative (CGNE) : $\mathbf{A}$ & $\mathbf{A}^t$

★ Implémentation efficace grâce à la co-localisation

Inverse problem solving

♣ Objectif : Reconstruire l'objet d'intérêt, le plus <u>rapidement</u> possible avec <u>quelques acquisitions aléatoires</u>.

$$\mathbf{i} = \begin{pmatrix} d^{(1)} \\ \cdot \\ \cdot \\ d^{(S)} \end{pmatrix} = \begin{pmatrix} H^{(1)} \\ \cdot \\ \cdot \\ H^{(S)} \end{pmatrix} \mathbf{o} = \mathbf{A}\mathbf{o}$$

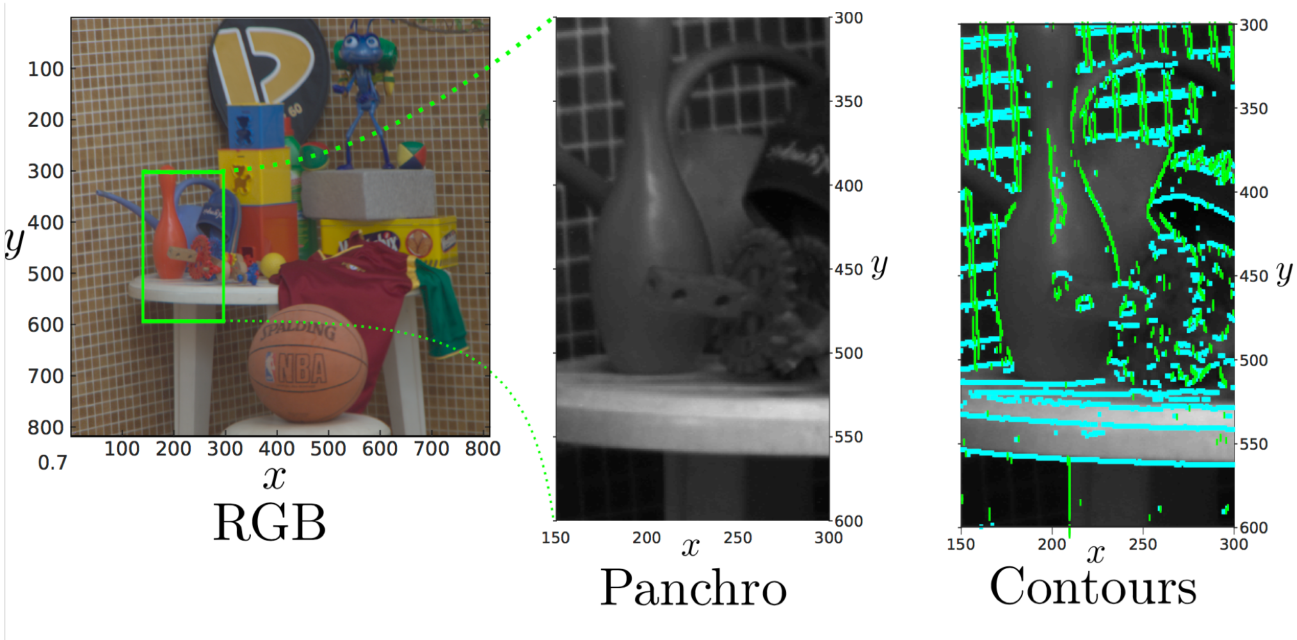
- $\mathbf{i}$: vecteur de taille $RCS \times 1$
- $\mathbf{A}$: matrice de taille $RCS \times RCW$

Effet de lissage

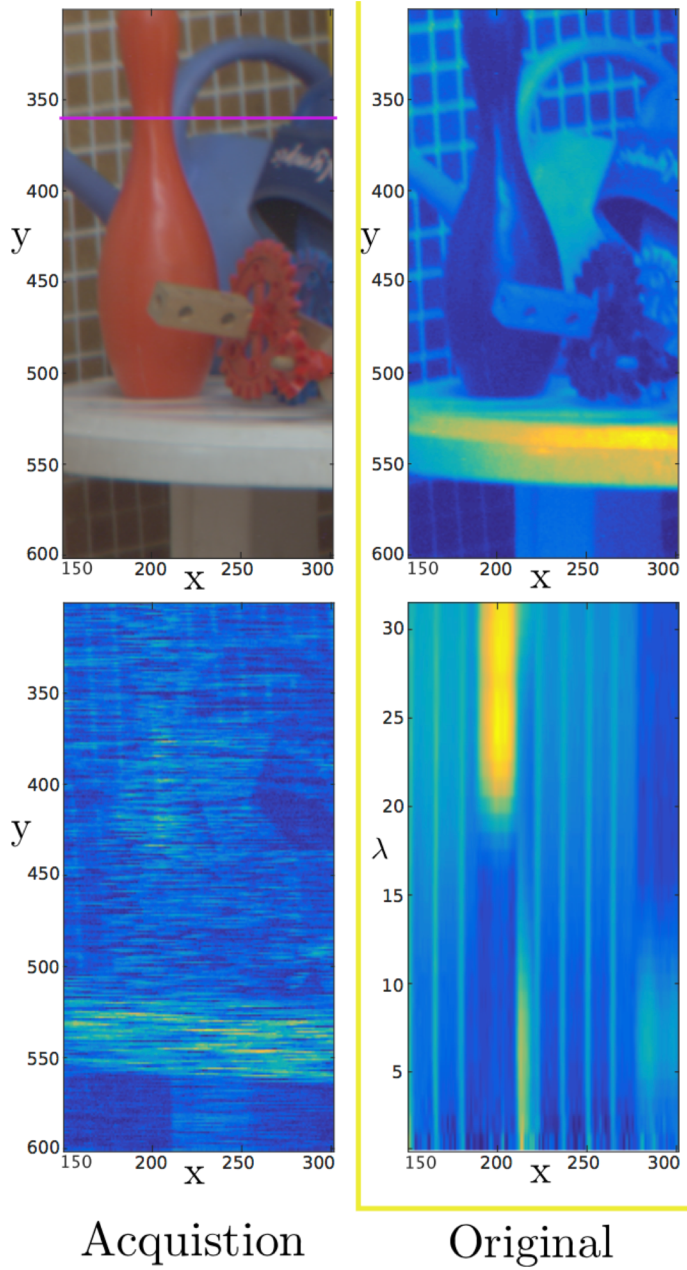
★ Extraction de contours sur l'image panchromatique

Inverse problem solving: first results

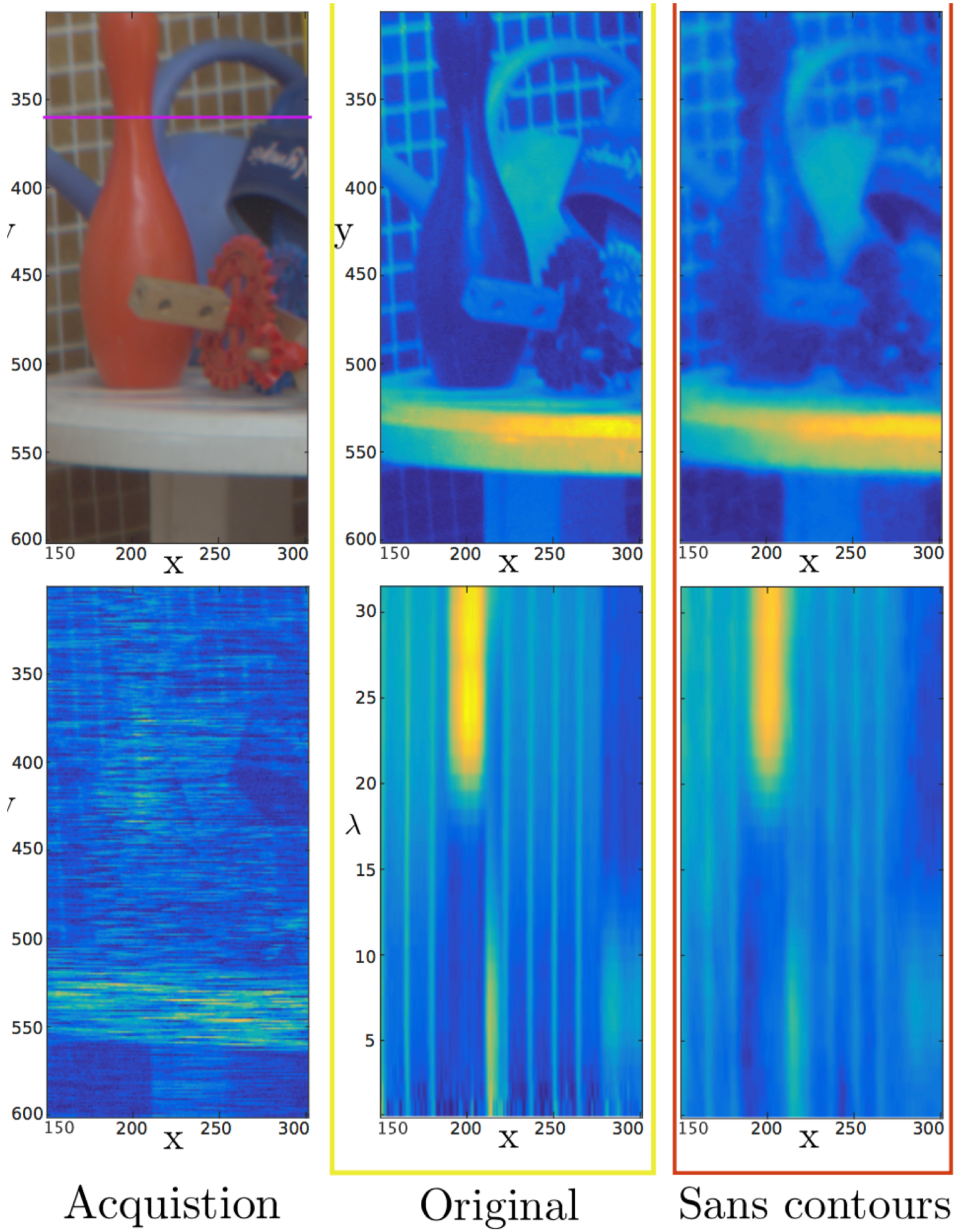
- Input data



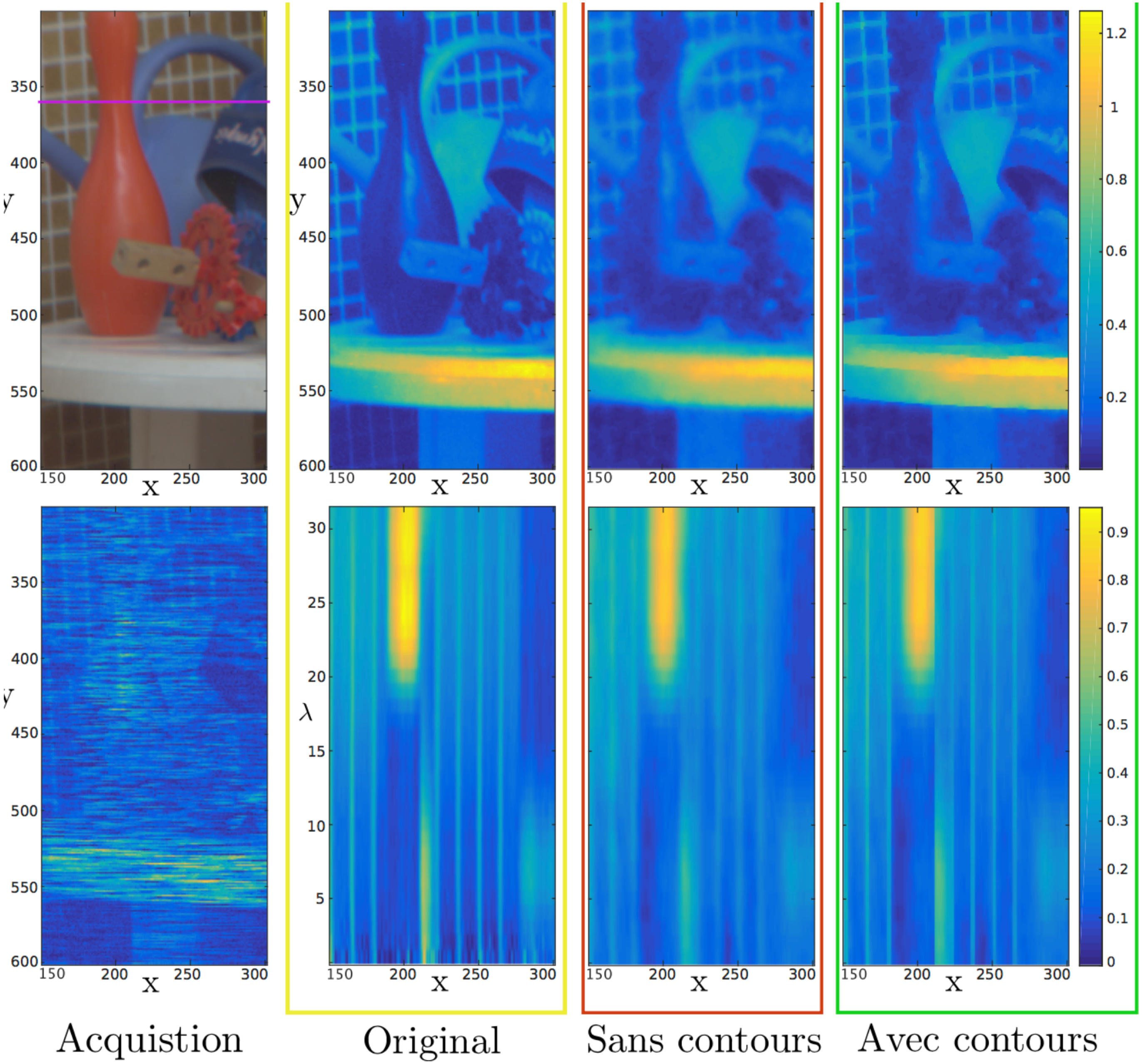
Inverse problem solving: first results



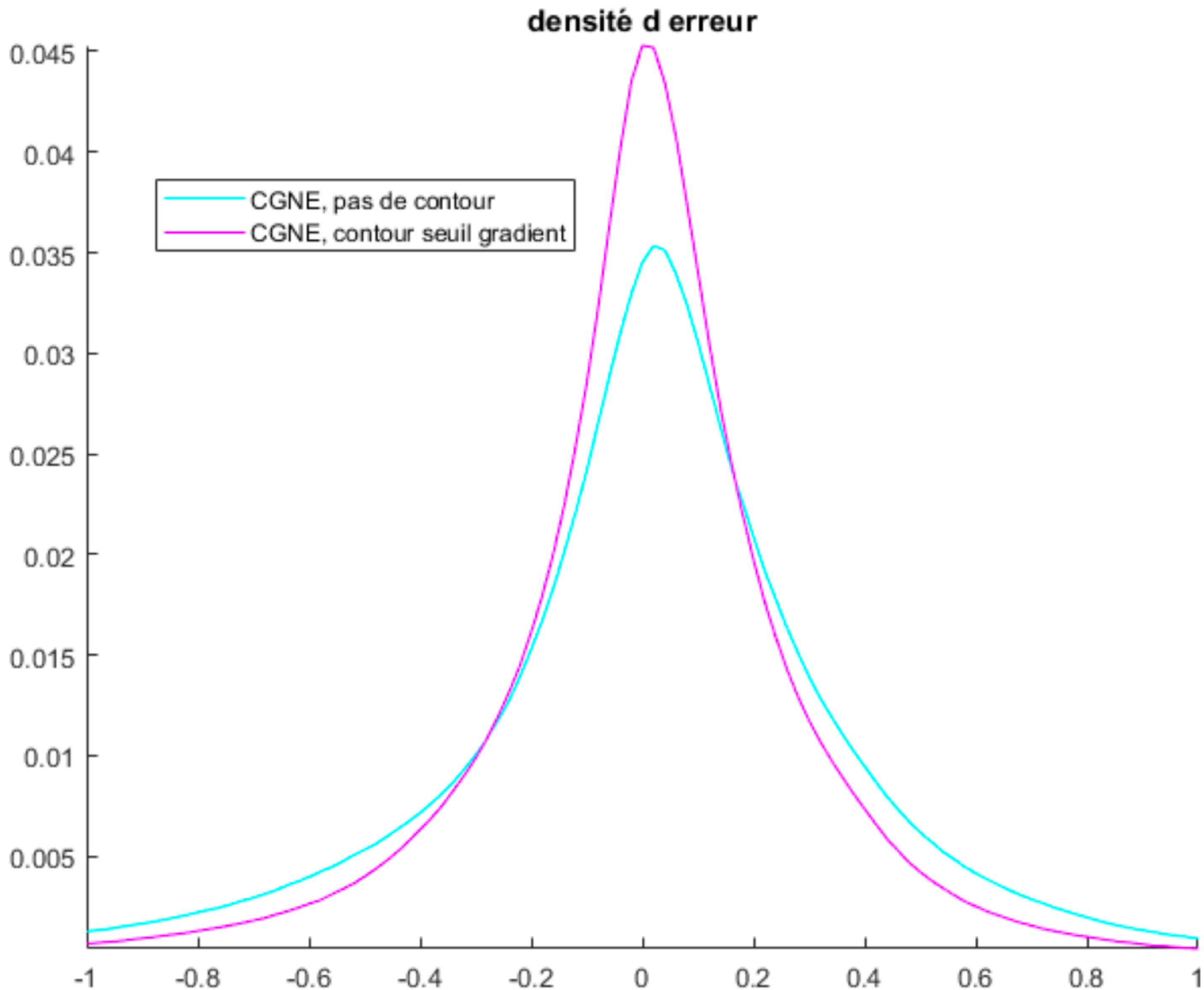
Inverse problem solving: first results



Inverse problem solving: first results

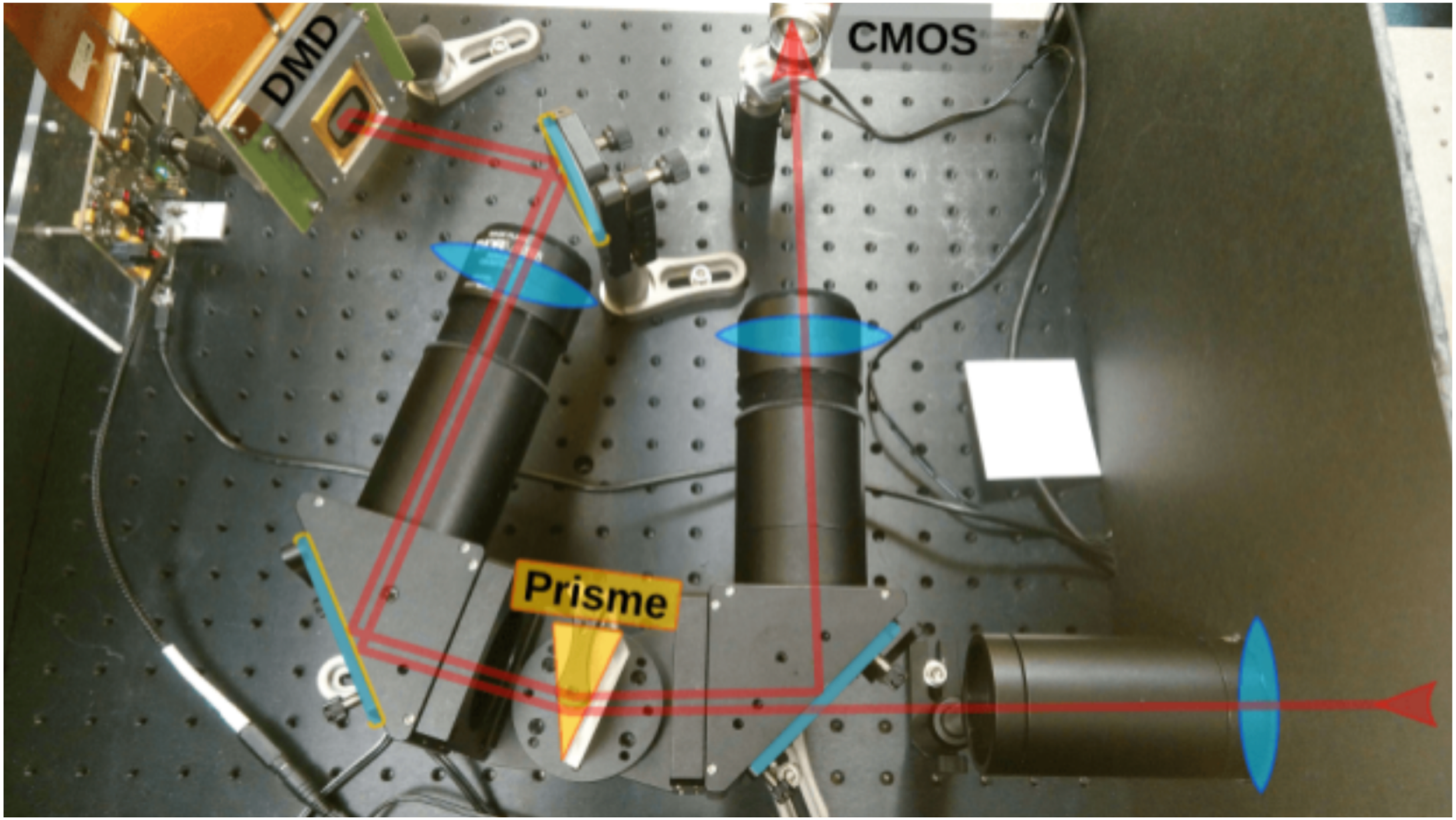


Inverse problem solving: first results



Perspectives

- On the device: V2 prototype



Perspectives

- On the device: V2 prototype
- Model the prototype (ray transfer matrix model)
- On the Full HS-Cube reconstruction algorithm:
    - Slight improvements to the proposed approach
    - Towards *adaptive* acquisition schemes
- On other acquisition schemes
    - Engineering developments on-going
    - Analysis of earth-observation use cases

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irap astrophysique & planétologie
LAAS CNRS