Processing ImSPOC data: current status and next steps

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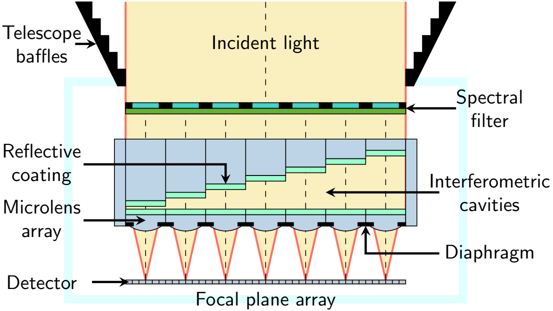
Outline

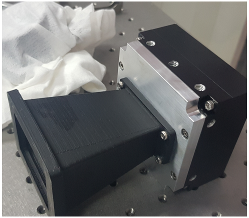
Topic

1. Image Spectrometer on Chip (ImSPOC)
2. The processing problem
3. Interferometer response characterization algorithm (IRCA)
4. Pixel-based spectral reconstruction
5. Conclusion

General principle [1]



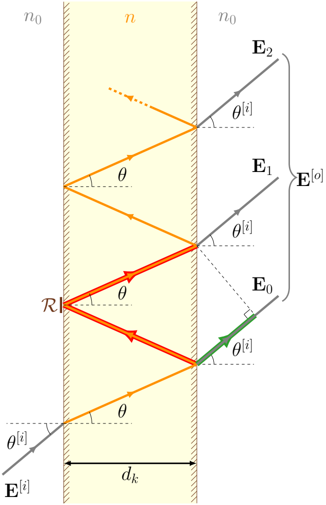
Operating principle



Prototype

[1] https:\imspoc.osug.fr

Fourier transform spectrometry



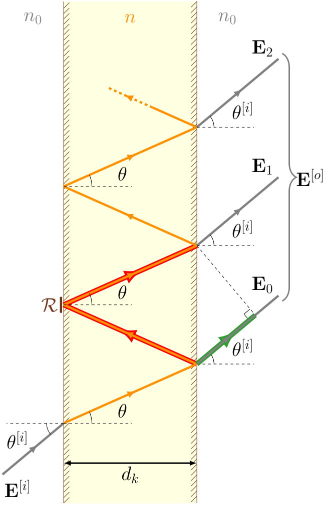
Interferometry

- Measuring through interfering rays
- Light rays travel different optical paths

Domain transform

- Input domain: spectrum
  - λ: wavelengths
  - $\sigma = 1/\lambda$: wavenumbers
- Output domain: interferogram
  - δ: Optical path difference (OPD)

Fabry-Perot interferometry



Transmittance function

$$\left|\frac{\mathbf{E}^{[o]}}{\mathbf{E}^{[i]}}\right|^2 = \frac{(1-\mathcal{R})^2}{(1-\mathcal{R})^2+4\mathcal{R}\sin^2(\pi\sigma\delta)}$$

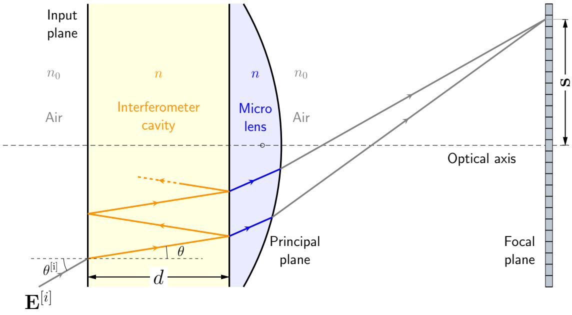
- $\mathcal{R}$: Reflectivity
- σ: Wavenumbers
- δ: OPD

Optical path difference (OPD)

$$\delta = 2nd\cos\theta$$

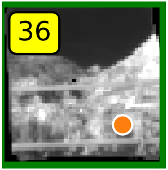
- n: Refractive index
- d: Interferometer thickness
- θ: Internal reflectance angle

Spectral imaging system



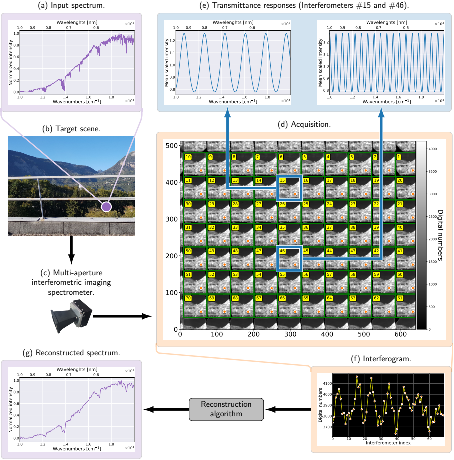
Imaging unit

Input scene



Acquisition

Acquisition system



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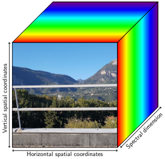
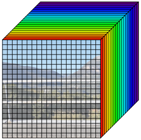
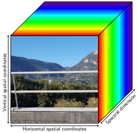
Computational imaging

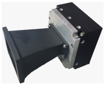
Scene → Conventional camera → Observation datacube

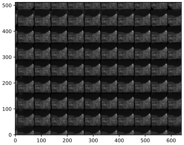


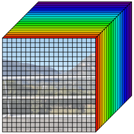


Scene → ImSPOC camera → Observation → Computational algorithm → Reconstructed product

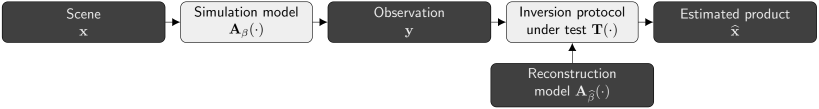




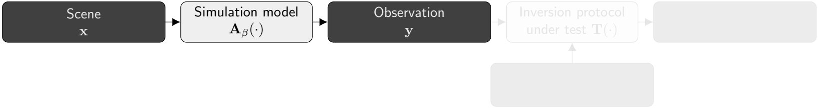




Problem statement



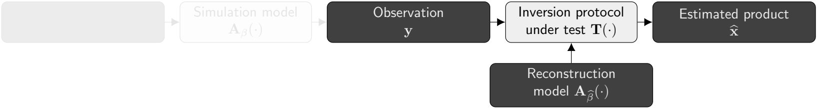
Problem statement



Characterization

- Find the parameters β the transmittance response
- Estimate the OPD to properly place the samples on the interferogram
- Verify that the system follows the design specifics

Problem statement



Characterization

- Find the parameters β the transmittance response
- Estimate the OPD to properly place the samples on the interferogram
- Verify that the system follows the design specifics

Inversion

- Reconstruct the image datacube
- Optimize the result for the application (e.g., concentration of gases)

Topic

Interferometer response character. algorithm [2]

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Abstract: In recent years, the demand for hyperspectral imaging devices has grown significantly, driven by their ability of capturing high-resolution spectral information. Among the several possible optical designs for acquiring hyperspectral images, there is a growing interest in

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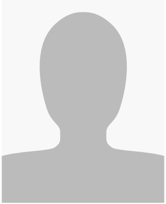


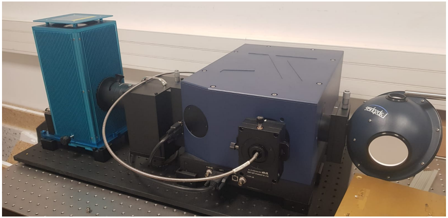
Yann Ferrec

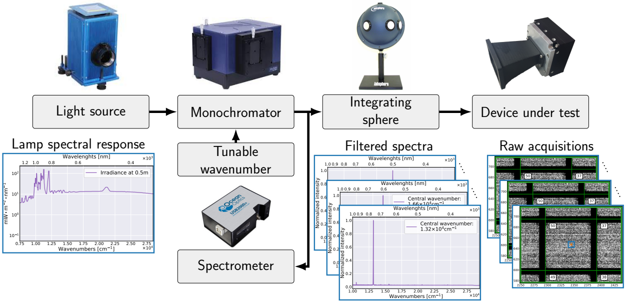
Mauro Dalla Mura

Etienne le Coarer

[2] **Pico23a**

Experimental setup





Algorithm description

The acquisition can be organized in a matrix $\mathbf{Y} = (y_{ik})$:

- i spans across the array of interferometers
- k spans across the central wavenumbers σ_k

Goal: Fit the matrix with a parametric interferometer response

$$t_{jk}(\boldsymbol{\beta}) = \frac{\mathcal{G}(1-\mathcal{R})^2}{1-\mathcal{R}^2+4\mathcal{R}\sin^2(\pi\delta_i\sigma_k-\phi_0)}$$

- δ_i: i-th OPD
- $\mathcal{R}$: Reflectivity
- $\mathcal{G}$: Overall gain
- ϕ_0: Phase shift

by minimizing a cost function such as:

$$\arg\min_{\boldsymbol{\beta}} \sum_{i,k} \left(t_{ik}(\boldsymbol{\beta}) - y_{ik}\right)^2$$

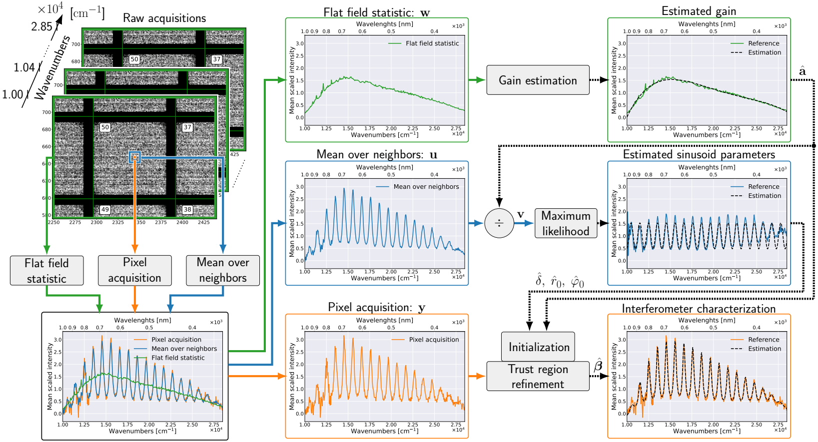
Challenges

- The gain and reflectivity depend on the wavenumbers
    - Assign a polynomial expression as function of σ:

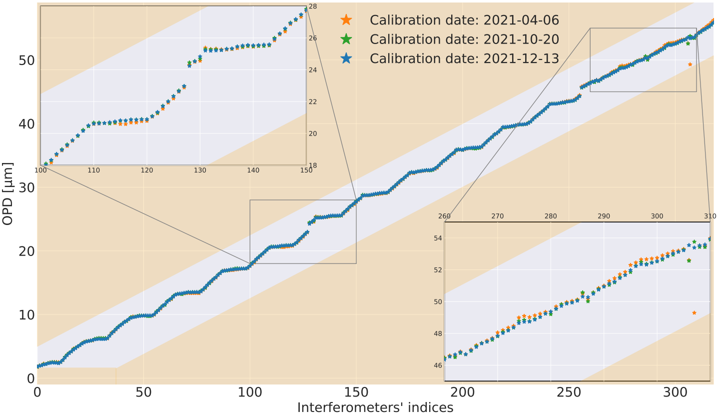
$$\mathcal{R} = \sum_m r_m \sigma^m$$

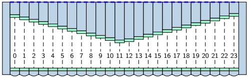
- The solution of the minimization problem is non-convex
    - Use an ad-hoc algorithm for non-linear regression
    - Levenberg-Marqardt algorithm: iterate alternatively linearization and regression
- The algorithm often falls into local minima
    - Properly initialize the algorithm
    - Assume that the gain scaled transmittance response is sinusoidal

Characterization algorithm

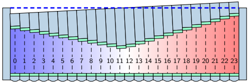


Results: OPD estimation



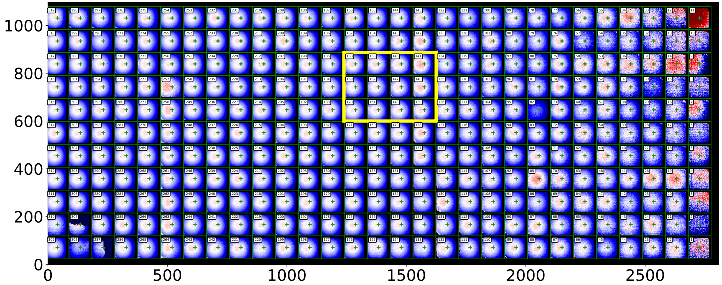


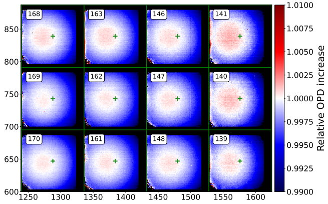
Aligned plates



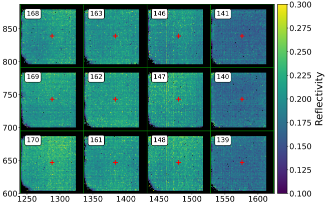
Misaligned plates

Results: Angle of incidence





OPD ($\delta = 2nd\cos\theta$)



Reflectivity

Topic

Pixel-based spectral reconstruction [3]

MODEL-BASED SPECTRAL RECONSTRUCTION OF INTERFEROMETRIC ACQUISITIONS

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ABSTRACT

Spectral information of the scene can be reconstructed from processing observations acquired by interferometric devices. In the case of devices that have multiple wave interference (e.g., Fabry-Pérot

The (ideally continuous) interferogram can be interpreted as a Fourier transformation of the original spectrum, and the reconstruction is customarily performed as an inverse transformation. However, two main issues arise: firstly, this model is just an approximation of the optical transformations that are performed by the instru-

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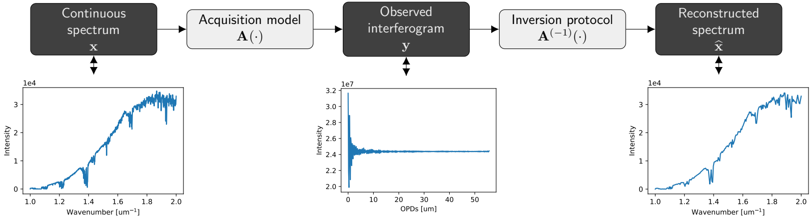
[3] **Joun23**

Model



Problem statement

- Goal: Find an estimation $\hat{\mathbf{x}}$ of the spectrum $\mathbf{x}$
- Naive solution (Pseudo-inversion)

$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \|\mathbf{A}\mathbf{x} - \mathbf{y}\|^2 = \mathbf{A}^{\dagger}\mathbf{y}$$

- Challenge: The problem is not well-posed

Regularization techniques

Penalized matrix decomposition

$$\hat{\mathbf{x}} = \tilde{\mathbf{A}}^{\dagger}\mathbf{y}$$

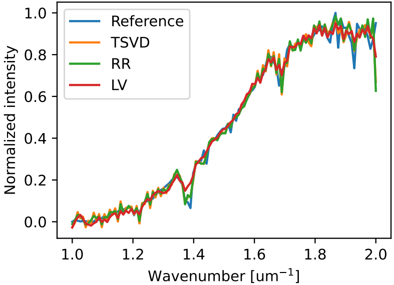
- Singular value decomposition (SVD) $\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^T$
- Inversion through SVD $\mathbf{A}^{\dagger} = \mathbf{V}\mathbf{S}^{-1}\mathbf{U}^T$
- Penalize the largest eigenvalues in $\mathbf{S}^{-1}$ generating $\tilde{\mathbf{A}}^{\dagger} = \mathbf{V}\hat{\mathbf{S}}^{-1}\mathbf{V}^T$

LASSO

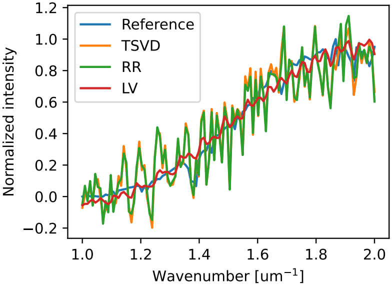
$$\hat{\mathbf{x}} = \arg\min_{\mathbf{x}} \|\mathbf{A}\mathbf{x} - \mathbf{y}\|^2 + \|\mathbf{W}\mathbf{x}\|_1$$

- $\mathbf{W}$: Sparce-inducing transformation matrix (e.g., DCT)
- Impose the ℓ_1 norm
- Iterate the estimation with an ad-hoc solver (e.g. Loris-Varhoeven)

Results: Pixel based reconstruction



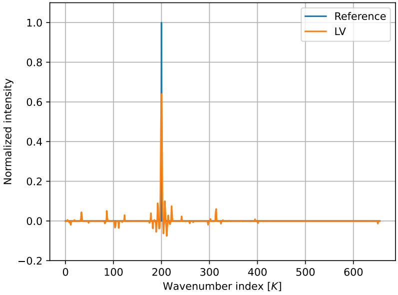
SNR = 60 dB



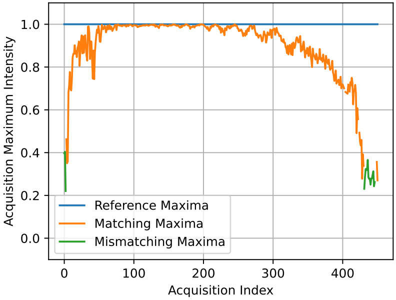
SNR = 40 dB

Results: Real data reconstruction

- Goal: Reconstruct the monochromatic spectra for an older characterization measurement with the model obtained with a more recent one



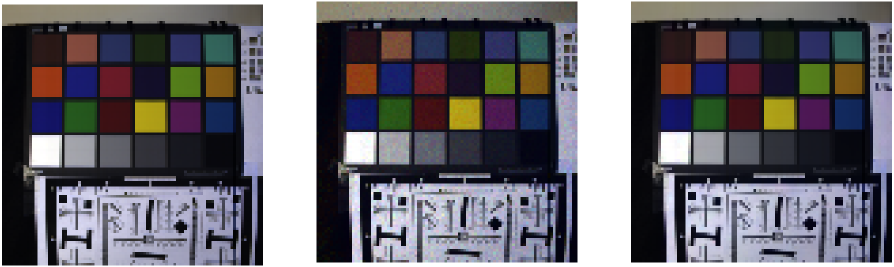
Reconstructed spectrum



Maxima comparison

Results: Image reconstruction

- Goal: Reconstruct the datacube from a simulated acquisition with SNR=10dB
- New strategy: Adding a spatial prior (Total variation)



Reference — Pixel-by-pixel — With spatial prior

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Conclusions

- ImSPOC: a multi-aperture Fabry-Perot image spectrometer
- Characterization algorithms:
  - Need to deal with non-linearities
  - Allow to find defects in manufacturing
- Inversion:
  - Assigning a well-adapted prior is fundamental
  - There is a benefit to consider both spectral and spatial information

Future works

- Explore the hybrid model/deep learning based algorithms (PnP, unrolling, etc.)
- Explores mismatches sources between the model and the measurement
- Multimodality: embed additional data into the acquisition from other devices

Thanks!