Fusion of hyperspectral and multispectral infrared astronomical images

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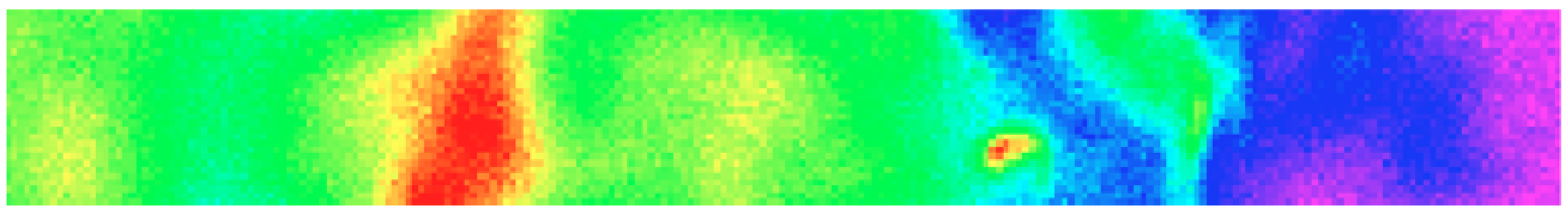
Problem

The James Webb Space Telescope (JWST) [1] will be launched in 2021 and will provide multispectral images on wide fields-of-view and hyperspectral images on small fields-of-view.
This contribution aims at developing a fusion method that will combine those images to reconstruct the astrophysical scene at high spatial *and* spectral resolutions.

Multispectral
high spatial resolution, low spectral resolution

+
Hyperspectral
low spatial resolution, high spectral resolution



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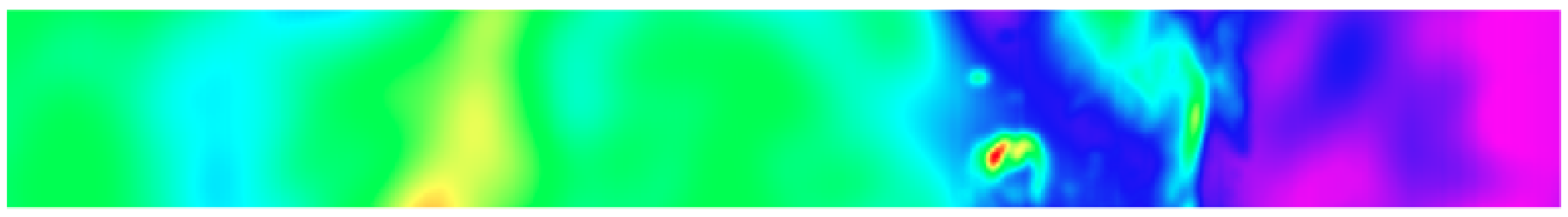
Reconstruction
high spatial resolution, high spectral resolution



- Main challenges :
  – **Very large scale** problem, considerably larger than problems encountered in Remote Sensing [2, 3].
  – **Complexity of instruments** embedded in JWST.

Forward models of instruments

- $\mathbf{X}$ the astrophysical scene to be reconstructed.
- Measurement equations :

$$\mathbf{Y}_{\mathrm{m}} \approx \mathbf{L}_{\mathrm{m}}\mathcal{M}(\mathbf{X}) \quad \text{and} \quad \mathbf{Y}_{\mathrm{h}} \approx \mathbf{L}_{\mathrm{h}}\mathcal{H}(\mathbf{X})\mathbf{S}$$

– $\mathcal{M}(\cdot)$: Spatial 2D convolution with spectrally dependant point spread functions (PSFs) [4].
– $\mathbf{L}_{\mathrm{m}}$: Spectral integration with spectral responses of filters of the instrument [5].
– $\mathcal{H}(\cdot)$: Spatial 2D convolution with spectrally dependant PSFs [4].
– $\mathbf{S}$: Spatial subsampling.
– $\mathbf{L}_{\mathrm{h}}$: Spectral transmission of the instrument.

Regularizations

- **Spectral regularization** : $\mathbf{X} = \mathbf{VZ}$, low rank assumption considering that the high spatio-spectral reconstructed image lives in a lower dimension subspace.
- **Spatial regularization** : $\|\mathbf{ZD}\|_{\mathrm{F}}^2$, smooth content promoting regularization, with $\mathbf{D}$ first order finite differences operator.

Problem statement

- Assumption : white Gaussian noise (after data whitening and/or variance stabilization).
- Inverse problem to solve :

$$\hat{\mathbf{Z}} = \underset{\mathbf{Z}}{\operatorname{argmin}} \underbrace{\frac{1}{2}\|\mathbf{Y}_{\mathrm{m}} - \mathbf{L}_{\mathrm{m}}\mathcal{M}(\mathbf{VZ})\|_{\mathrm{F}}^2 + \frac{1}{2}\|\mathbf{Y}_{\mathrm{h}} - \mathbf{L}_{\mathrm{h}}\mathcal{H}(\mathbf{VZ})\mathbf{S}\|_{\mathrm{F}}^2}_{\text{Data fidelity}} + \underbrace{\mu\|\mathbf{ZD}\|_{\mathrm{F}}^2}_{\text{Regularization}} \quad (1)$$

Proposed method

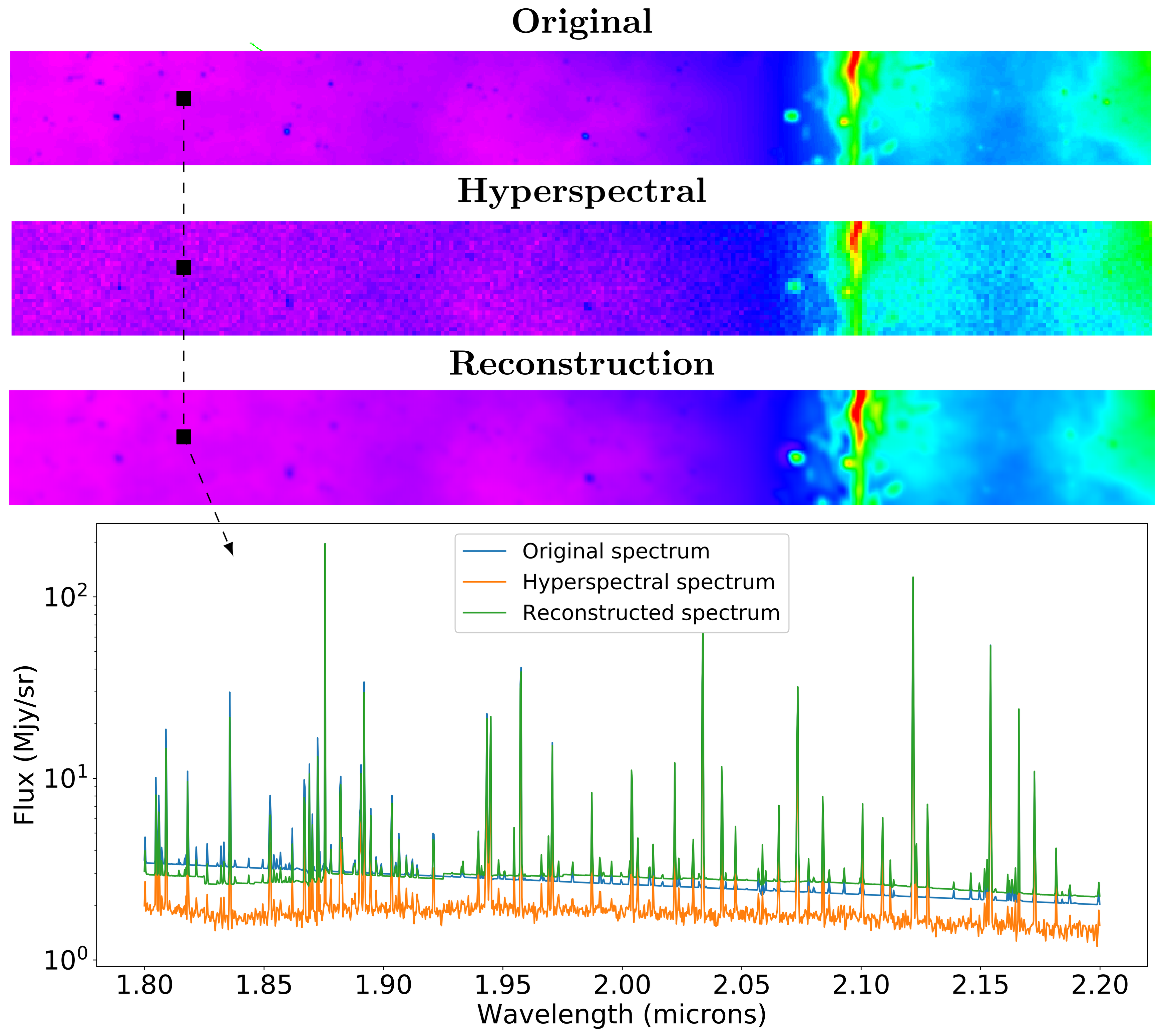
- **Approximation in the Fourier domain** to handle heavy wavelength-dependant 2D-spatial convolutions :
  – $\mathcal{H}$, $\mathcal{M}$ and $\mathbf{D}$ approximated by a term-wise multiplication.
  – $\mathbf{S}$ expressed as a well-chosen sum of spatial frequencies.
- **Vectorizing the problem** yields to solve :

$$\min_{\mathbf{z}} \tfrac{1}{2}\mathbf{z}^T\mathbf{A}\mathbf{z} + \mathbf{b}^T\mathbf{z}$$

– $\mathbf{A}$, $\mathbf{b}$ appropriate combinations of operators, multi- and hyperspectral images.
– $\mathbf{z}$ a lexicographically vectorized version of $\mathbf{Z}$.
✔ $\mathbf{A}$ (about 10^{11} entries) highly sparse and easily storable.
✔ Operators combined in a preprocessing step, instead of being applied at each iteration of a gradient descent algorithm.
- **Resolution with a conjugate gradient algorithm.**

Experimental Results

The proposed fusion method has been tested on simulated JWST data of the Orion bar.
- $\mu = 2 \cdot 10^4$.
- $\mathbf{V}$ chosen as the first components identified by a principal component analysis conducted on the observed hyperspectral image.



✔ Noticeable gain in spatial resolution with respect to the hyperspectral image.
✔ Reconstructed spectra much closer to the original ones than hyperspectral ones. Clear reduction of the noise and well restoration of almost every ray, even those of low energy.
✔ Computation time (s) : 340 (pre-processing) + 90 (problem solving)
✘ Some thin spatial details not well reconstructed, mainly due to the smooth regularization.
✘ The continuum either over- or under-estimated.

Future Work

- Design a tailored regularization.
- Take into account the specific noise statistics.
- Consider the fusion problem when the field of view is different for each image.

References

[1] J. Gardner et al., *The James Webb Space Telescope*, Space Science Reviews, 2006.
[2] Q. Wei et al., *Fast fusion of multiband images based on solving a Sylvester equation*, IEEE Trans. Image Process., 2015.
[3] N. Yokoya et al., *Coupled nonnegative matrix factorization unmixing for hyperspectral and multispectral data fusion*, IEEE Trans. Geosci. Remote Sens., 2012.
[4] P. Makidon et al., *The JWST point spread function calculation methods and expected properties*, STScI, Tech. Rep., 2007.
[5] B. Hilbert et al., *NIRCam filters weak lens and coronographic throughputs*, STScI, Tech. Rep., 2016.