Fusion of hyperspectral and multispectral infrared astronomical images

Claire Guilloteau$^{(1,2)}$, Thomas Oberlin$^{(1)}$, Olivier Berné$^{(2)}$ and Nicolas Dobigeon$^{(1)}$
$^{(1)}$University of Toulouse, IRIT/INP-ENSEEIHT, Toulouse, France
$^{(2)}$University of Toulouse, IRAP, CNRS, CNES, University Paul Sabatier, Toulouse, France
`firstname.lastname@enseeiht.fr, firstname.lastname@irap.omp.eu`

***Abstract*—In this contribution, we introduce a multispectral and hyperspectral image fusion method in an astrophysical observation context. We define an observation forward model and solve a approximate regularized inverse problem in the Fourier domain by a conjugate gradient algorithm. The fusion model is evaluated on simulated observations of the Orion Bar by the NIRCam imager and the NIRSpec spectrometer, embedded on the James Webb Space Telescope.**

I. INTRODUCTION

The James Webb Space Telescope (JWST) [1] will be launched in 2021 and will provide multispectral images (with low spectral resolution) on wide fields of view (with high spatial resolution) and hyperspectral images (with high spectral resolution) on small fields of view (with low spatial resolution). This contribution aims at developing a fusion method that will combine those images to reconstruct the astrophysical scene at high spatial *and* spectral resolutions. This fusion process is illustrated in Fig. 1. This fused product will allow an enhanced scientific interpretation of the data. For instance, we will be able to derive high spatial resolution maps of physical tracers in the interstellar medium and conditions (i.e. density of gas, dust temperature, etc.), that would otherwise be inaccessible. This project will benefit from data of the Early Release Science observing program “Radiative Feedback of Massive Stars” [2] which will be conducted in the first months of the JWST scientific operations. Hyperspectral images provided by the JWST will be composed of approximately 3000 spectral bands and 30 × 30 pixels for a 3” × 3” field of view, while multispectral images will contain up to 29 spectral bands (matching with narrow to wide filters) and 2040 × 2040 pixels for a 64” × 64” field of view. The general fusion problem has been deeply investigated for Earth observation [3], [4], [5]. The most powerful methods are based on an inverse problem formulation, consisting in minimizing a data fidelity term complemented by a regularization term. The data fidelity term is derived from a forward model of the observation instruments. The regularization term can be interpreted as a prior information on the fused image. In the particular context of JWST astronomical imaging, the main challenges are due to the very large scale of the fused data, considerably larger than the typical size of data encountered in remote sensing, as well as complexity of both instruments.

II. PROBLEM STATEMENT

Let $\hat{\mathbf{X}}$ denote the recovered high spatio-spectral resolution image, where each row (resp., column) is associated to a spectral band (resp., pixel). The problem to solve can be written

$$\hat{\mathbf{Z}} = \underset{\mathbf{Z}}{\operatorname{argmin}} \frac{1}{2}\|\mathbf{Y}_{\mathrm{m}} - \mathbf{L}_{\mathrm{m}}\mathcal{M}(\mathbf{V}\mathbf{Z})\|_{\mathrm{F}}^2 + \frac{1}{2}\|\mathbf{Y}_{\mathrm{h}} - \mathbf{L}_{\mathrm{h}}\mathcal{H}(\mathbf{V}\mathbf{Z})\mathbf{S}\|_{\mathrm{F}}^2 + \mu\|\mathbf{Z}\mathbf{D}\|_{\mathrm{F}}^2 \quad (1)$$

such that $\hat{\mathbf{X}} = \mathbf{V}\hat{\mathbf{Z}}$, i.e., $\hat{\mathbf{X}}$ is supposed to live in a subspace whose dimension is much smaller than its spectral dimension. The two first terms refer to data fidelity terms, derived from accurate forward models of the hyperspectral and multispectral instruments. The third term acts as a spatial resolution by promoting smooth content in each band. More precisely, $\mathbf{Y}_{\mathrm{m}}$ and $\mathbf{Y}_{\mathrm{h}}$ are the multispectral and the hyperspectral images respectively. The operators $\mathcal{M}(\cdot)$ and $\mathcal{H}(\cdot)$ are wavelength-dependent 2D spatial convolutions defined by the point-spread functions (PSF) of both instruments [6]. The spectral degradations induced by the multispectral and hyperspectral acquisitions are denoted by $\mathbf{L}_{\mathrm{m}}$ and $\mathbf{L}_{\mathrm{h}}$, whose rows are the spectral responses of the filters of the instruments [7]. Finally, the hyperspectral instrument has a low spatial resolution, which is understood as a sub-sampling matrix multiplication by $\mathbf{S}$, of factor d. Right multiplying by $\mathbf{S}$ means keeping one pixel over an area of $d \times d$ pixels. We assume here that both observation images are corrupted by a white Gaussian noise. If not, a stabilization pre-process is conducted.

III. PROPOSED METHOD

The spatial wavelength-dependent convolution operators $\mathcal{H}$ and $\mathcal{M}$ are computationally heavy to handle but can be approximated in the Fourier domain by a term-wise multiplication by the Fourier transform of the $\mathcal{H}$ and $\mathcal{M}$ kernels. The sub-sampling operator $\mathbf{S}$ can be formulated in the Fourier domain as an operator which sums spatial frequencies with modulo the spatial dimension over d. The 1^{st} order 2D finite differences operator $\mathbf{D}$ can be seen as a convolution operator with particular kernels. This convolution is approximated by a cyclic convolution operator, which can be formulated in the Fourier domain as a term-wise multiplication by the Fourier transform of those kernels. Thus, as all spatial operator can be expressed or approximated in the Fourier domain, the problem (1) can be approximately yet efficiently solved.

Alternatively, a vectorized counterpart of the problem (1) can be derived. By combining the spatial and spectral operators, it amounts to minimize a criterion of the form $\frac{1}{2}\mathbf{z}^T\mathbf{A}\mathbf{z} + \mathbf{b}^T\mathbf{z} + c$, where $\mathbf{A}$, $\mathbf{b}$ and c are appropriate combinations of operators, multi- and hyperspectral images, and $\mathbf{z}$ is a lexicographically vectorized version of $\mathbf{Z}$. In the considered applicative context, the matrix $\mathbf{A}$ is composed of about 10^{11} entries, but it is highly sparse and consequently easily storable in memory. The main benefit of this reformulation is to combine, as a pre-processing step, operators and especially every PSFs instead of applying the convolution operators at each iteration of a gradient descent algorithm spectral band by spectral band.

IV. RESULTS

The proposed fusion method has been tested on simulated JWST data of the Orion bar. The noise has been stabilized as a pre-processing step. The regularization parameter μ is set to $2 \cdot 10^4$. The $\mathbf{V}$ matrix has been chosen as the first components identified by a principal component analysis conducted on the observed hyperspectral image. The reconstruction is shown Fig. 2. The gain in spatial resolution with respect to the hyperspectral image is clearly noticeable, but some thin spatial details are not well reconstructed, mainly due to the smooth regularization. Reconstructed spectra are much closer to the original ones than hyperspectral ones, the noise is clearly reduced and almost every ray is restored, even those of low energy. However, the continuum is either over- or under-estimated.

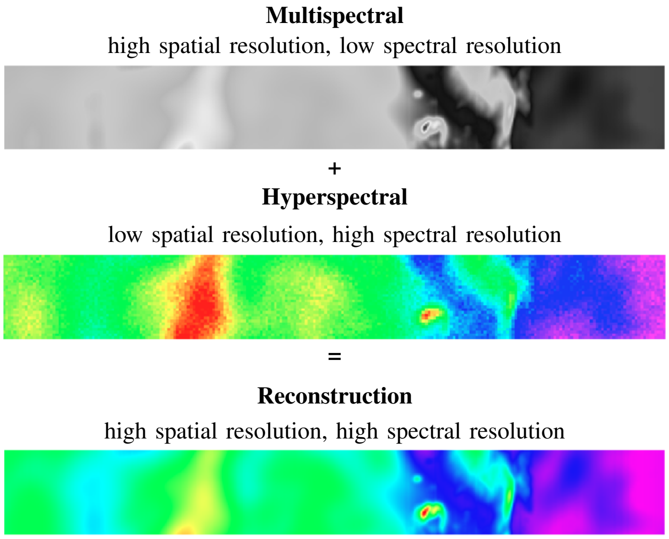

Fig. 1. Hyperspectral and multispectral data fusion

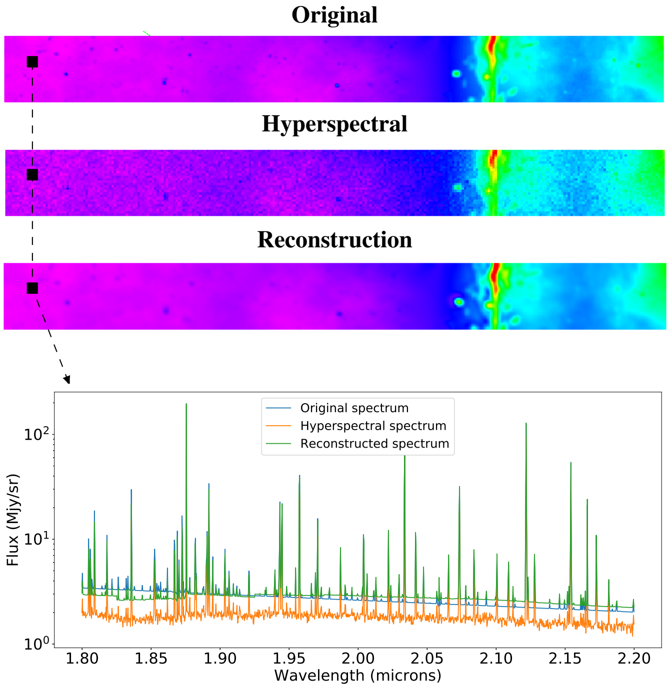

Fig. 2. Result of data-fusion for the wavelength 1.8765 μm (on the top) and spectra for a single pixel (on the bottom).

REFERENCES

[1] J. Gardner, J. Mather, and M. C. et al., “The James Webb Space Telescope,” *Space Science Reviews*, vol. 123, 2006.

[2] O. Berné et al., “Radiative feedback from massive stars as traced by multiband imaging and spectroscopic mosaics,” JWST Proposal ID 1288, Cycle 0 Early Release Science, 2017.

[3] Q. Wei, N. Dobigeon, and J.-Y. Tourneret, “Fast fusion of multi-band images based on solving a Sylvester equation,” *IEEE Trans. Image Process.*, vol. 24, no. 11, pp. 4109–4121, Nov. 2015.

[4] N. Yokoya, T. Yairi, and A. Iwasaki, “Coupled nonnegative matrix factorization unmixing for hyperspectral and multispectral data fusion,” *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 2, pp. 528–537, Feb. 2012.

[5] M. Karoui, Y. Deville, F. Benhalouche, and I. Boukerch, “Hypersharpening by joint-criterion nonnegative matrix factorization,” *IEEE Trans. Geosci. Remote Sens.*, 2017.

[6] R. Makidon, S. Casertano, C. Cox, and R. van der Marel, “The JWST point spread function : Calculation methods and expected properties,” Space Telescope Science Institute, Tech. Rep., 2007.

[7] B. Hilbert and J. Stansberry, “Nircam filters, weak lens and coronographic throughputs,” Space Telescope Science Institute, Tech. Rep., 2016.