Advanced Data Reduction for the MUSE Deep Fields

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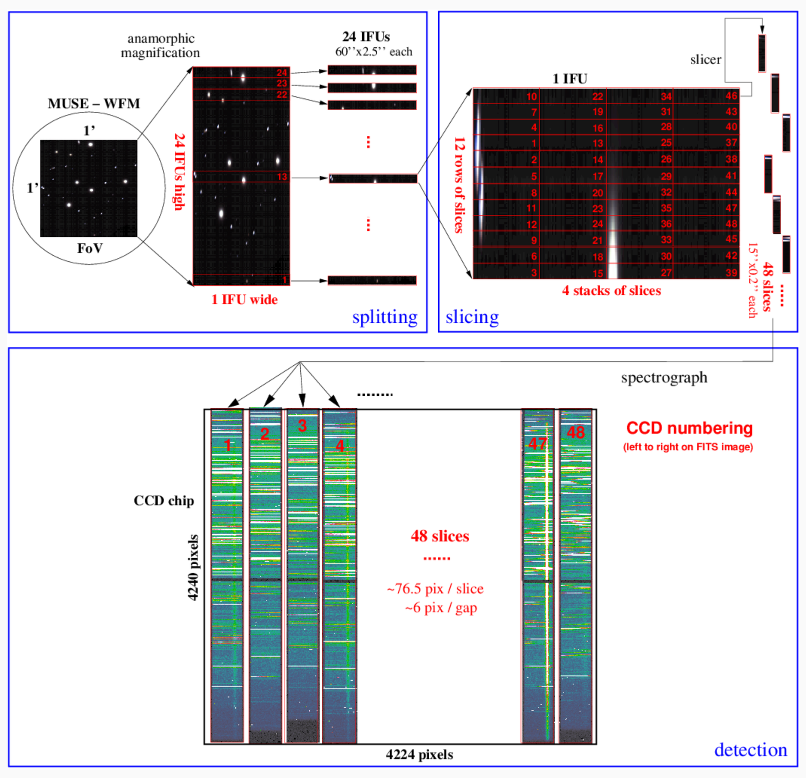
MUSE – the Multi Unit Spectroscopic Explorer

The official MUSE pipeline is available from ESO. However, for the data reduction of the Deep Fields program (Bacon et al., in prep.), we present a more sophisticated reduction pipeline that we have built with additional reduction tasks (or "recipes"), to extend the official one.



- MUSE is an integral-field spectrograph installed at the Very Large Telescope (VLT).
- First light on 31 January 2014.
- 24 Integral-field units (IFU) operating in the visible wavelength (4650–9300 Å).
- Currently only Wide-Field Mode without adaptive optics, but AO is coming !
- Field of view: $1' \times 1'$.
- Spatial sampling: $0.2'' \times 0.2''$.

- *Figure:* Splitting and slicing procedures.

Data Reduction System – MUSE Pipeline

- **Goal:** Converts raw data from the 24 CCDs into a combined datacube, corrects for instrumental and atmospheric effects.
- Many steps, computationally expensive, in terms of processing speed, memory usage, and disk input/output.
- Code and docs available [2], C code, OpenMP, ESO CPL (Common Pipeline Library).
- Run with Esorex (CLI), Python-CPL [4] (Python wrapper), or MuseWise.
- MuseWise: data management system for MUSE data, based on AstroWise. Distributed computing and storage, + Quality Control.

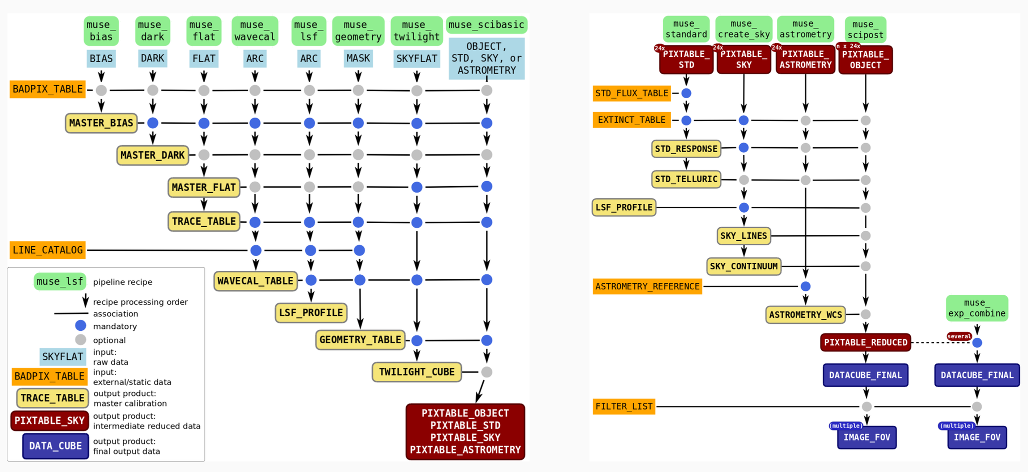


Figure: Schematic view of the pipeline.

Data Processing

The key requirements of our pipeline are to:

- Be able to process a big number of exposures (∼300, 2–3Tb of raw data, dozens Tb of intermediate data).
- Build automated and reproducible procedures for tasks like associating multiple calibration files with a specific observation.
- Keep track of the results and output logs of the different steps and versions.

It is based on several key components:

- **doit**: a task management and automation tool [1]. doit is a flexible tool which allows to define task dependencies, to remember task execution, and to use parallel execution.
- **sqlite** database to store information about all the files (raw, calibration, outputs) and all the outputs: file paths, logs, etc.
- **Jupyter notebook**: used for the quality analysis. It is an easy way to explore the data and plot the relevant information, while running directly onto the computing server and accessed remotely. Once the notebook is ready, we use it to generate HTML pages for each exposure.

References

[1] Doit. `pydoit.org`.

[2] Muse pipeline at eso. `www.eso.org/sci/software/pipelines/muse/muse-pipe-recipes.html`.

[3] Muse science website. `http://muse-vlt.eu/science/`.

[4] Python cpl. `https://pythonhosted.org/python-cpl/`.

[5] R. Bacon et al. The MUSE 3D view of the Hubble Deep Field South. *Astronomy & Astrophysics*, 575:A75, March 2015.

[6] L. Piqueras, S. Conseil, M. Shepherd, and R. Bacon. In A. R. Taylor and J. M. Stil, editors, *ADASS XXVI*, volume TBD of *ASP Conf. Ser.*, page TBD, San Francisco, 2016. ASP.

[7] K. T. Soto, S. J. Lilly, R. Bacon, J. Richard, and S. Conseil. ZAP - enhanced PCA sky subtraction for integral field spectroscopy. *Monthly Notices of the Royal Astronomical Society*, 458:3210–3220, May 2016.

Deep fields: HDFS, UDF

Hubble Deep Field South (HDFS) Commissioning data, $1' \times 1'$ field observed to a 26.5h depth (53×1800 s). See [3, 5].

Hubble Ultra Deep Field (UDF) The MUSE-Deep GTO survey has observed a 9 field mosaic that covers the UDF. $3' \times 3'$ field observed to a depth of ∼10h (in exposures of 1500 s each). Extra-deep $1' \times 1'$ portion of the mosaic that reaches ∼31h. This data will be appear in Bacon at al. (in prep.), the redshifts in Brinchmann et al. (in prep.) and the full catalogue in Inami at al. (in prep.).

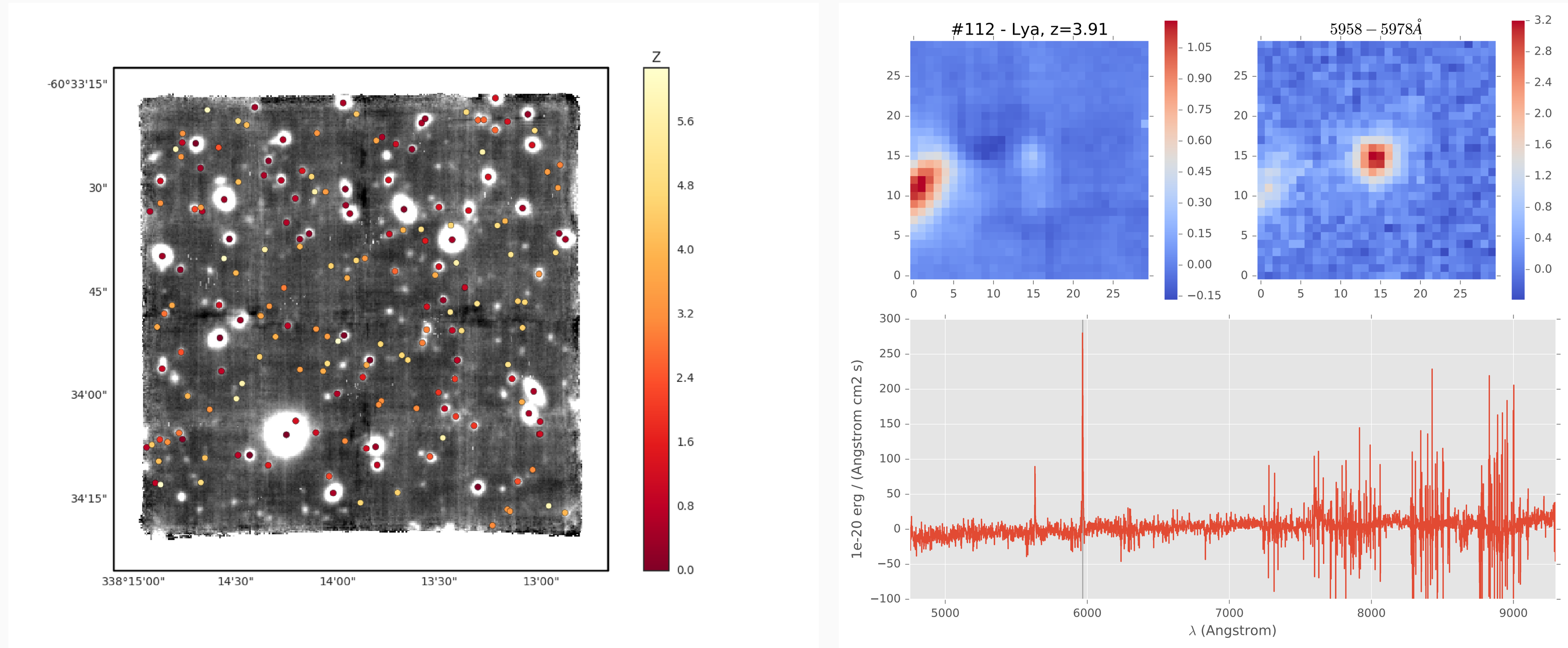


Figure: HDFS, white-light image with detected sources, and example of a Lyα emitter.

Additional reduction steps

The pipeline works well for the general case, but several things can be improved with some additional reduction steps. Most of these steps can be done with the recently released MPDAF Python package ([6], see the poster at ADASS).

Flat fielding We developed an automatic flat-fielding procedure, which computes and apply a correction to the slices level, using the sky level as a reference (thus this needs to be done before the sky subtraction). Part of the `mpdaf.drs.PixTable` class.

Sky subtraction Sky subtraction is performed with ZAP [7], a high precision sky subtraction tool, also released this year. The method uses *Principal Component Analysis* to isolate the residual features and remove them from the datacube. ZAP can also be run in addition to the sky subtraction of the MUSE pipeline.

Masking Various masking steps are applied, to remove instrumental artifacts that cannot be corrected. This is done both on pixtables and datacubes.

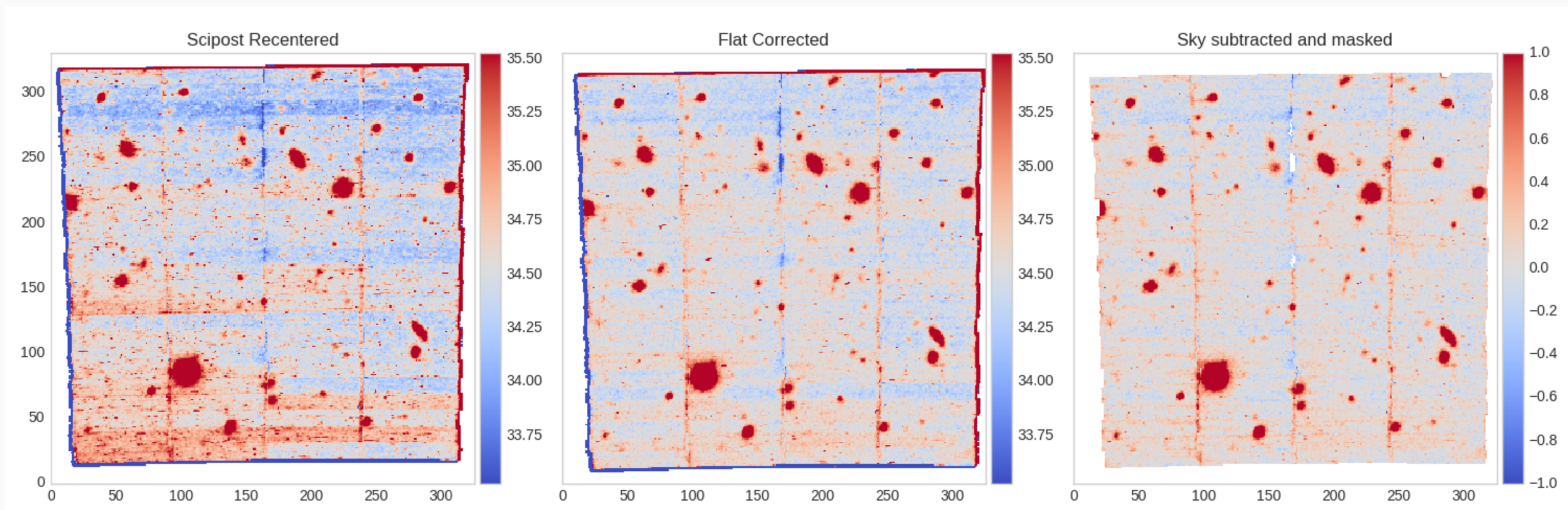


Figure: Top-left: white-light image after running the pipeline. Top-right: after recentering and correction of the slices level. Bottom-left: after the sky subtraction with ZAP. Bottom-right: after masking.

Combination Exposures combination is done on data cubes, which allow to run additional steps on the cubes before combining them. This is also part of MPDAF (the `CubeList` and `CubeMosaic` classes). Several combination algorithm are available (mean, median, sigma clipping), and it can be used to create a mosaic.

PSF estimation We developed a way to estimate the PSF parameters, calibration factors and pointing offsets, using HST as a reference: for each HST band, the image is resampled to the MUSE resolution, and fitted to a MUSE image computed on the same band.

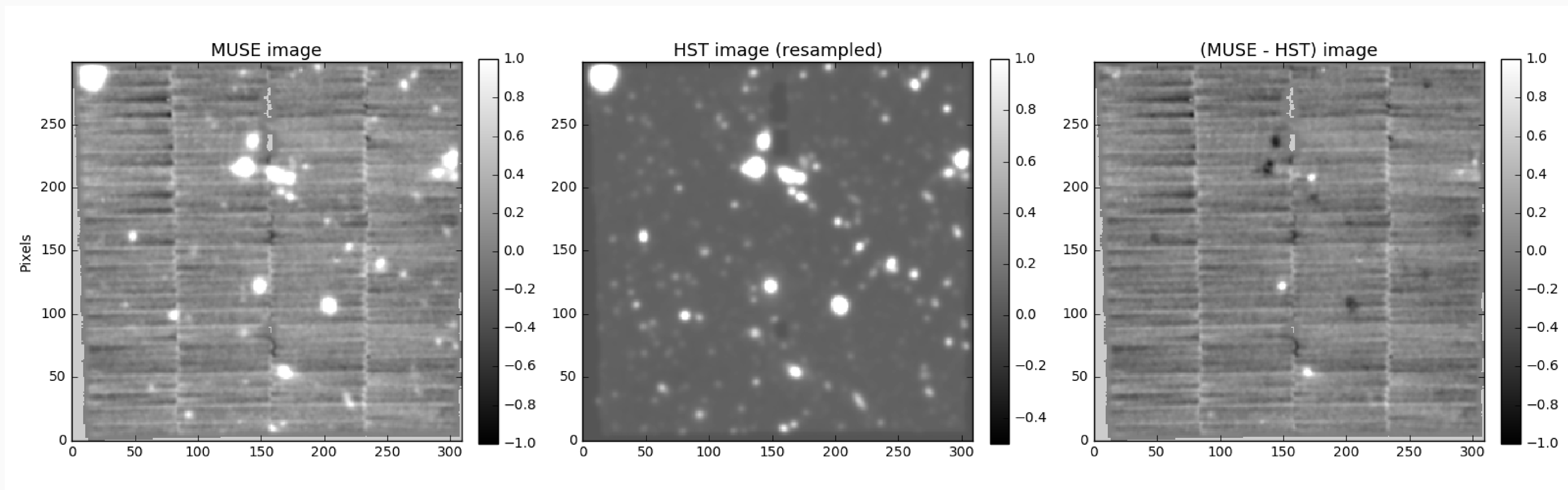


Figure: PSF estimation. Left: fitted MUSE image. Middle: Fitted HST image (resampled). Right: residual.