The Journal of Open Source Software

ASSET: A package for slit spectroscopy spectral extraction

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DOI: 10.xxxxxx/draft

Software

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Editor:

Submitted: 02 October 2025
Published: unpublished

Summary

Based on the maximum a posteriori likelihood criterion, ASSET is a Julia package providing an optimized, robust spectral extraction method that can be used across various slit spectrographs, ensuring high-quality data extraction independent of the specific instrument. Thanks to its generic structures, different PSF and background models can be easily defined by the user to adapt the estimation process to the instrument. Fitting of the background, of the instrument's PSF and refinement of the spatio-spectral calibration of the detector are already possible if wanted.

Statement of need

Spectroscopy is a powerful tool for characterizing the chemical components of celestial bodies, including stars, planets and smaller objects in our solar system. Slit spectroscopy is particularly valuable for faint object observations that may otherwise be challenging with integral field spectroscopy. Many instruments have been developed in that regard. For example, the SPHERE-IRDIS instrument (Beuzit et al., 2019), with its near-infrared long-slit spectroscopy mode (Dohlen et al., 2008), allows for detection and characterization of high contrast Dwarfs companions (Cheetham et al., 2018; Hinkley et al., 2015; Mesa et al., 2020) at small angular separation (0.5''). The James Web Space Telescope (JWST) contains two instruments equipped with slit mode: the NIRSpec (near-infrared) (Böker et al., 2023; Jakobsen et al., 2022), allowing for the characterization of faint solar system small bodies (Denneulin et al., 2023; Guilbert-Lepoutre et al., in prep.; Thomas et al., 2025) and faint stars or galaxies, and MIRI (mid-infrared) (Kendrew et al., 2015; Wright et al., 2023), allowing for the characterization of solar system objects (Müller et al., 2023) or, combined with a coronograph, the detection and characterization of exoplanets (Danielski et al., 2018; Henning et al., 2024). The future ELT instrument METIS should be equipped with a long-slit as well, allowing for the observation potential earth-like planet at very low separation (Maire et al., 2021).

To exploit the full potential of slit spectroscopy data, it is important to account for any element involved in their acquisition process, such as:

- the shape of the chromatic point spread function (PSF) profile,
- a thoroughly calibration of the spatial and spectral coordinates of each pixel in order to map correctly the PSF,
- an accurate estimation of the noise statistics and of the artifacts (bad pixels, cosmic rays,…).

The Inverse problems framework is widely used in astrophysics (Berdeu, 2024; Michalewicz et al., 2023) and offer the possibility to account for all this elements. Based on such an approach, an optimal auto-calibrated spectral extraction method (in the sense of the maximum of likelihood) was developed in (Thé et al., 2023) and adapted in (Denneulin et al., 2023).

The goal of `ASSET` is to generalize this method in an easy to use package, fully implemented in Julia, adaptable to any slit spectroscopy instrument. It relies on a thorough modeling of the data using different customizable structures of parametric or non-parametric PSF, which can be fitted via an alternated algorithm during the spectrum extraction. With the same versatility, a custom background model can be defined, fitted and subtracted in the estimation scheme. Finally, the package includes several regularization structures via the use of `InverseProblem`.

Estimation Framework

The method used in the `ASSET` package requires the following maps as inputs:

- data maps $(d_\ell)_{\ell \in 1:L}$, where L is the amount of dithers/acquisitions/frames;
- weights maps w_ℓ, where each element can be computed as the inverse variance of the pixel, forming the matrix $W_\ell = \Sigma_\ell^{-2}$. We assume that a defective pixel or artifacts have an infinite variance, i.e. a zero entry in W_ℓ;
- spatial coordinate maps X_ℓ where 0 should correspond to the center of the studied object;
- spectral coordinate maps Λ_ℓ.

The method outputs are the extracted spectrum z, sampled over a given regular wavelength grid $(\lambda_n)_{n \in 1:N}$, and the parameters θ of the fitted PSF model. They are obtained by solving:

$$z, \theta \in \operatorname{argmin} \Big\{ \sum_\ell \| d_\ell - (m_\ell(z,\theta) + b) \|^2_{W_\ell} + \mu_z \mathcal{R}_z(z) + \mu_\theta \mathcal{R}_\theta(\theta) + \mu_b \mathcal{R}_b(b), \Big\}$$

where $\mathcal{R}_z$, $\mathcal{R}_\theta$ and $\mathcal{R}_b$ are respectively the regularization of the extracted spectra, of the PSF parameters if required and of the background, with hyperparameters μ_z, μ_θ and μ_b. The spatial distribution maps X and the background map b are auto-calibrated in the process. The model of the data

$$m_\ell(z,\theta) = \alpha_\ell Z(\Lambda_\ell, z) \odot H(\theta, X_\ell, \Lambda_\ell)$$

is the Hadamard (element-wise) product of the spectrum interpolated in the camera plane

$$Z(\Lambda, z)_{j,k} = \sum_n \phi\Big(\frac{\Lambda_{j,k} - \lambda_n}{\delta_\lambda}\Big) z_n$$

with ϕ an interpolation kernel, and of the chromatic PSF H (parametric or non-parametric). The package provide several `ParametricPSF` and `NonParametricPSF` and the users can easily implement their own. A `ParametricPSF` H is a function parametrized by a few unknown variables θ_m, thus with low degrees of freedom, *e.g.* a Gaussian chromatic with a minimum width model:

$$H(\theta, X_\ell, \Lambda_\ell)_{j,k} = \big(2\pi(\theta_1 \Lambda^2_{j,k\ell} + \theta_2)\big)^{-1} \exp\Big(- \frac{X^2_{j,k,\ell}}{2(\theta_1 \Lambda^2_{j,k,\ell} + \theta_2)} \Big).$$

It does not require any regularization. See Thé et al. (2023) and Denneulin et al. (2023) for more details.

A `NonParametricPSF` is parametrized directly by some profile $(\theta_m)_{m \in 1:M}$, thus with high degrees of freedom , *e.g.* taking o order of the speckles expansion model (Devaney & Thiébaut, 2017) which is the interpolation of the profiles θ_o in a reference plane of the spatial coordinates $(x_m)_{m \in 1:M}$:

$$H(\theta, X_\ell, \Lambda_\ell)_{j,k} = \sum_o \gamma(\Lambda_\ell)^o \sum_m \phi\Big(\frac{\gamma(\Lambda_\ell) X_\ell - x_m}{\delta x}\Big) \theta_{m,o}(x_m).$$

For such a PSF, θ must be regularized. The hyperparameter is auto-calibrated in the method (see Thé et al. (2023) for and references therein for more details).

Usage Examples

For these examples, we use the G dwarfs reference star GSPC P 330 E observed with JWST instruments (Program ID 1538). NIRSpec's data were observed the 08/30/2022 with the S1600A1 Fixed Slit, PRISM grating, CLEAR filter, and a 5 dithers pattern. MIRI's data were observed the 08/14/2022 with the MIRI LRS Slit, P750L filter, and a 2 dithers pattern. For each example, we present ASSET extracted spectra, the reference spectrum (Bohlin et al., 2014), resampled to the same resolution, and the JWST pipeline extractions. We also present the fitted chromatic PSF models for different wavelength.

The results for NIRSpec FS (Figure 1 and Figure 2) are obtained with `ParametricPSFs` (chromatic Gaussian and Moffat with a minimum width) and a `NonParametricPSF` (with only 1 order). These data have the particularity that under 3.25μm the PSF is "blured" by the pixel, because it is larger than the PSF FWHM. The `ParametricPSF` account for this blur, with the minimum width, and allow for a good extraction of the spectrum. The PSF profile fitted by the series expansion is more precise, however it does not yet account for the PSF blur which affect the slope of the spectra under 1 μm. The ASSET spectral extraction is also more robust to outliers compared to the JWST pipeline extractions.

The results for MIRI LRS (Figure 3 and Figure 4) are obtained with `ParametricPSFs` (chromatic Gaussian and Moffat) and a `NonParametricPSF` (with 1 and 2 orders). For this wavelength range the target is very faint, hence a bright background for the largest wavelength due to a longer integration time. The PSF profile fitted by the `NonParametricPSF` are more precise, and the slop fits more accurately the reference spectrum above 5 μm. It is also more robust to the background brightness than the pipeline method, but it remains perfectible. Moreover there is an issue to be fixed under 5 μm.

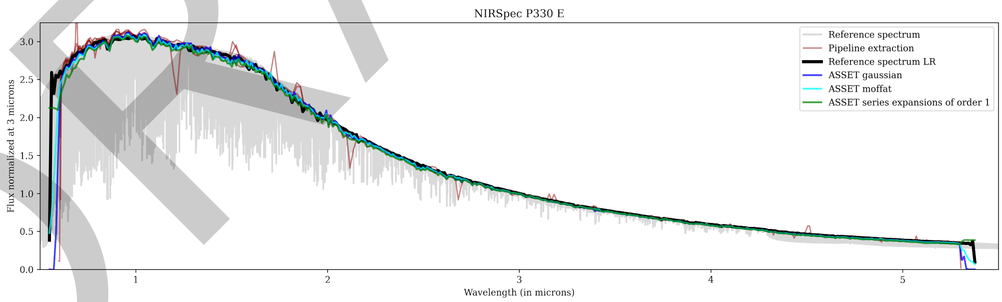

Figure 1: Comparison of the spectra extracted with the pipeline and ASSET for different PSF models

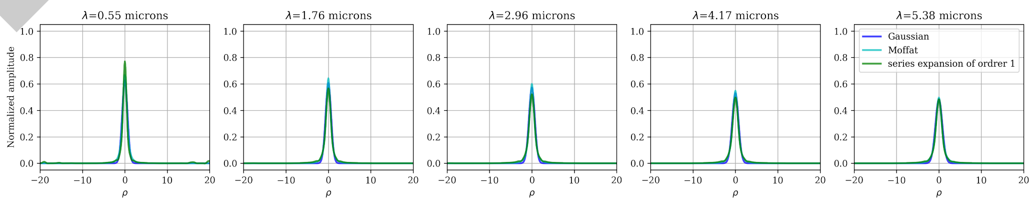

Figure 2: Comparison of the shape of the auto-calibrated PSF for each ASSET extracted spectrea

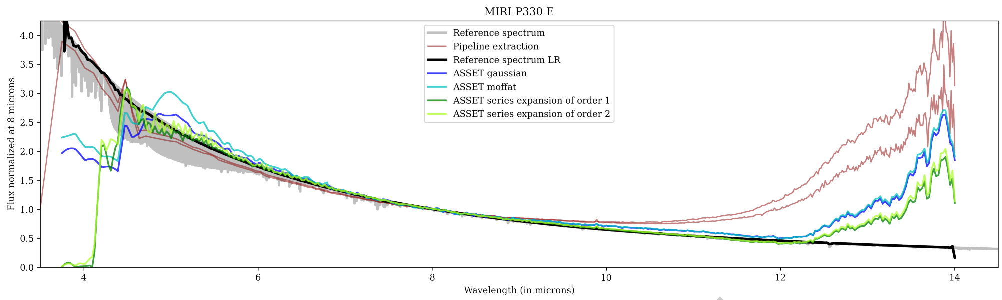

Figure 3: Comparison of the spectra extracted with the pipeline and ASSET for different PSF models

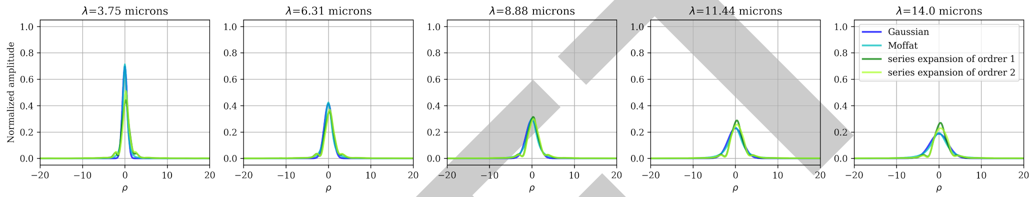

Figure 4: Comparison of the shape of the auto-calibrated PSF for each ASSET extracted spectra

Research projects using the package

The ASSET package can be used for many slit spectrograph data, such as the SPHERE/IRDIS-LSS (Thé et al., 2023), used to characterize exoplanets. In this context, speckles are forming a high-contrasted structural background where the extraction of the planet's spectrum is achieved by the method's joint estimation of this background and the instrument's PSF. The package is also currently used to extract spectra from JWST/NIRSpec data (Denneulin et al., 2023; Guilbert-Lepoutre et al., in prep.). This instrument involves a diverse set of slits, spectral resolution and positions on the detector, to observe a vast range of targets in terms of flux. The flexible and multi-frame approach of ASSET is particularly interesting as it provides a single methodology to all these problems.

A particular interest in ongoing work is to correctly extract the spectrum of interest from the strong, but smooth, background present in some MIRI data, the blurred PSF in NIRSpec data and finally, to generalized such an approach to Integral Field Units data.

Dependencies

`PointSpreadFunctions`, `InverseProblems`, `InterpolationKernels`, `LazyAlgebra`, `LinearInterpolators`, `OptimPackNextGen`, `PowellMethods`, `AMORS` and `SparseArrays`.

Acknowledgments

James Webb Space Telescope. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-03127 for JWST. These observations are associated with the calibration program #1538.

The authors would like to explicitly thank Bryan Holler (STSCI) for his unconditional help, for running the pipeline countless time in order to provide the calibrated data and to answering any minor question.

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