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M. N'Diaye, A. Siebert, N. Lagarde, O. Venot, K. Baillié, M. Béthermin, E. Lagadec, J. Malzac, J. Richard (eds)

A NEW NEONARVAL PIPELINE WITH PYREDUCE

K. Thomson-Paressant[1], C. Gutteridge[1], C. Neiner[1] and C. Catala[1]

Abstract. After the upgrade of the Narval instrument at TBL to NeoNarval, concerns have been raised regarding the quality of results in polarimetry and precision in velocimetry. Investigations into the topic have hinted at both instrumental and software issues that must be resolved in order to accurately exploit the data. We present our discoveries of issues and subsequent work performed to improve the reduction of NeoNarval data. We aim to provide comparisons between the DRS and a pipeline utilised for similar instruments, as well as initial attempts to implement new methods. PyReduce, an open-source reduction pipeline for echelle spectrographs, has modules already designed for a variety of currently-used instruments as well as initialisation of a number of options allowing for the evolution and expansion of its functions, which is of great benefit for integrating the specifics of the NeoNarval instrument.

Keywords: instrumentation, spectropolarimeter, stellar magnetism

1 Introduction

1.1 The NeoNarval instrument

After 13 years of operation, the Narval spectropolarimeter installed at the Télescope Bernard Lyot (TBL) in the Observatoire Midi-Pyrénées was upgraded to NeoNarval in 2019. The aim of this upgrade was to achieve increased stability in radial velocity measurements (< 3 m.s^{-1} goal), at the cost of reduced instrumental resolution (68,000 →53,000). This would allow the instrument to obtain high precision velocimetry for exoplanet research, in addition to the stellar spectropolarimetric studies it was already performing. To achieve this, efforts were focused on improving calibration, as well as thermal and mechanical stability (Böhm et al. 2016).

The data taken by the previous Narval instrument was reduced by the LibreEsprit pipeline (Donati et al. 1997), however this software is not open-source and modifications were necessary for operation with NeoNarval. In particular, a super-resolution algorithm was required to theoretically recover the resolution lost by the upgrade of the hardware. As a result, it was decided that a new open-source pipeline should be designed from the ground up for NeoNarval, called the Data Reduction Software (DRS).

Since the upgrade of the instrument, concerns have been raised regarding the quality of the spectropolarimetric results and the precision in velocimetry. Independent investigations hint at both instrumental and software issues, both of which would require correction in order to accurately exploit the science data coming from the instrument. A workshop was organised in January 2023 to discuss the instrument and the problems being observed, during which a science team was formed to assess these concerns, and we were tasked with investigating software-related issues. To this end, we elected to utilise PyReduce to diagnose these problems and to perform reduction of the spectropolarimetric data in an isolated environment, independent of the DRS.

A new release of the DRS (version 3) became operational in May 2023. However all comparisons between our adaptation of PyReduce and the DRS presented here will be regarding DRS version 2.

1.2 PyReduce software

PyReduce is a data reduction pipeline designed for echelle spectrographs (Piskunov et al. 2021), based on the IDL Reduce package (Piskunov & Valenti 2002) that has been ported to Python3. It is open source

[1] LESIA, Paris Observatory, PSL University, CNRS, Sorbonne University, Université Paris Cité, 5 place Jules Janssen, 92195 Meudon, France

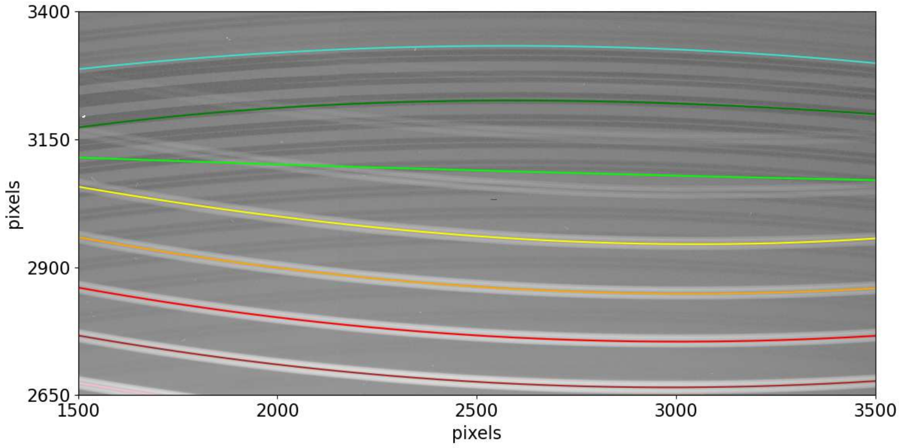

Fig. 1. Example of the order tracing method performed by the DRS version 2. Note the blue and green curves at the top of the image that are incorrectly tracing the ghost orders.

and available on GitHub*, albeit with limited support from the original authors. Nevertheless, it is under development by a number of independent groups, each with their own goals e.g. SALT (Crause et al. 2022) and MIKE (Das & Banyal 2021). The software already operates for a variety of spectroscopic instruments (e.g. UVES, XSHOOTER, HARPS, NIRSpec, etc.), and was designed with the intention of eventually adding polarimetric methods, though they had yet to be implemented. Using this tried and tested tool, we are steadily progressing on implementing polarimetry, in addition to the instrument configuration for NeoNarval.

2 Issue resolution

During the process of applying PyReduce to the NeoNarval data, a number of key issues have arisen on which we have elected to focus our efforts. These are detailed in the following sections, but this is far from an exhaustive list of areas we are currently investigating in the operation of the DRS and the NeoNarval instrument.

2.1 Spurious Inverted Orders

Visible on the CCD, most clearly on the flat field exposures, are inverted ghost orders. This instrumental issue originates from an electronic crosstalk between the 4 amplifiers, but ultimately needs to be considered in the data reduction as it causes errors in the flux recorded in the far blue orders and in the order tracing as seen in Fig. 1. This ultimately led to DRS version 2 having large errors in the wavelength calibration for the bluest orders, as these spurious orders were being calibrated rather than the true orders.

To solve this problem, we identify clusters of points along the bright beams and fit a second-order polynomial to each region. Any fit with an inverted sign in the leading term, with respect to the majority, is isolated and removed from the list. Additionally, each fit is only allowed minor variations to those around it, preventing any deviations where the spurious orders intercept. Unfortunately, the proportion of overlap of true and ghost orders results in the inability to extract quality data from the far blue orders. A potential solution to maximise the extracted data would be to trace these inverted orders to mask out the regions they interfere with.

2.2 Background scatter subtraction

When looking at the raw data files, it becomes quickly apparent that there is flux that appears between the spectral orders. This is a result of scattered light inside the instrument, and causes issues when attempting to determine the flux ratio in each order as it contributes unevenly across the beams. This feature is particularly

*See `https://github.com/AWehrhahn/PyReduce`

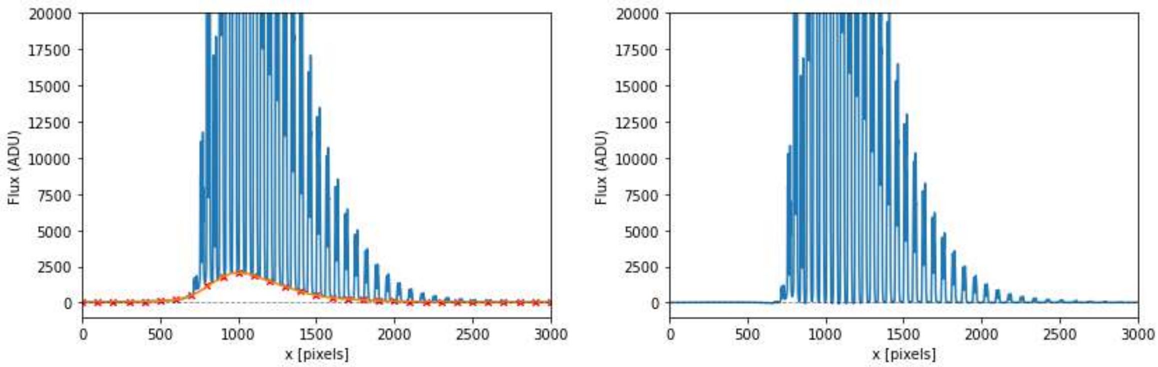

Fig. 2. Slice of a CCD image perpendicular to the orders (blue), before (left panel) and after (right panel) subtraction of the fit to the background scatter (red and orange).

visible when looking at the flat-field calibration files, as the overall flux in the image is larger, and so too is the amount of scattered light, but it is also present in all illuminated exposures.

To resolve this issue, we utilise a window function that runs perpendicular to the orders to search for local minima. These minima correspond to the zero-points between orders, from which we can perform a 2D fit over the entire image to determine the overall contribution of background scatter to the image. We utilise a linear combination of four Gaussian profiles, as this was the most consistently performing shape. A least-squares algorithm determines the best fit parameters, which we then use to subtract the fit from the image.

We first perform this fit to the flat-fields, then apply the given parameters as a first guess for the fit on the science files. While the amplitude will differ, the overall shape of the function should remain roughly constant. As an example, a 2D slice of this fit is shown in Fig. 2. One should note that the NeoNarval DRS currently only performs this step on science files and not on the calibration files.

2.3 Beam separation and order extraction

Illuminated images taken by NeoNarval exhibit curved spectral orders consisting of two beams, one for each perpendicular polarisation state. Unfortunately, there is a slight overlap in the areas illuminated by each beam. While this is not an issue for spectroscopy, it is problematic in polarimetry, as one polarisation state pollutes the other. We therefore opted to design a new extraction algorithm to minimise the contribution of each beam to the other.

Each beam is split into 3 separate peaks due to the slicer it passes through. The central peak of each beam is the brightest, and one (and always the same one) of the side lobes is brighter than the other. Looking at the left panel of Fig. 3, we can see that a simple double-Gaussian profile does a poor job of fitting these peaks, and that rather two sets of three Gaussians (labelled 'Hex Gaussian') is a much more accurate representation. This can be extrapolated quite easily to 2-dimensions to fit the two beams of an entire order at once, as seen in the right panel of Fig. 3.

Once the fit to the flat-corrected science files has been determined, we can then exclude all pixels between the two beams with $\geq$5% contribution from both beams. Typically, this corresponds to an exclusion region of up to three columns (out of $\sim$ 30 columns per order).

3 Conclusions

We are implementing polarimetry into PyReduce, with new and improved methods for e.g. order tracing, blending removal, background scatter subtraction, wavelength calibration, and Stokes profiles generation. Here, we present preliminary results of our efforts to integrate some of these into the software, taking into account the specific configuration of the NeoNarval instrument.

PyReduce produces encouraging results, though there is still work to be done in order to accurately and precisely exploit the spectropolarimetric data coming from NeoNarval. The next steps in this process are:

- Consider vignetting at the extremities of each order to prevent error being introduced into the order tracing and background scatter steps.

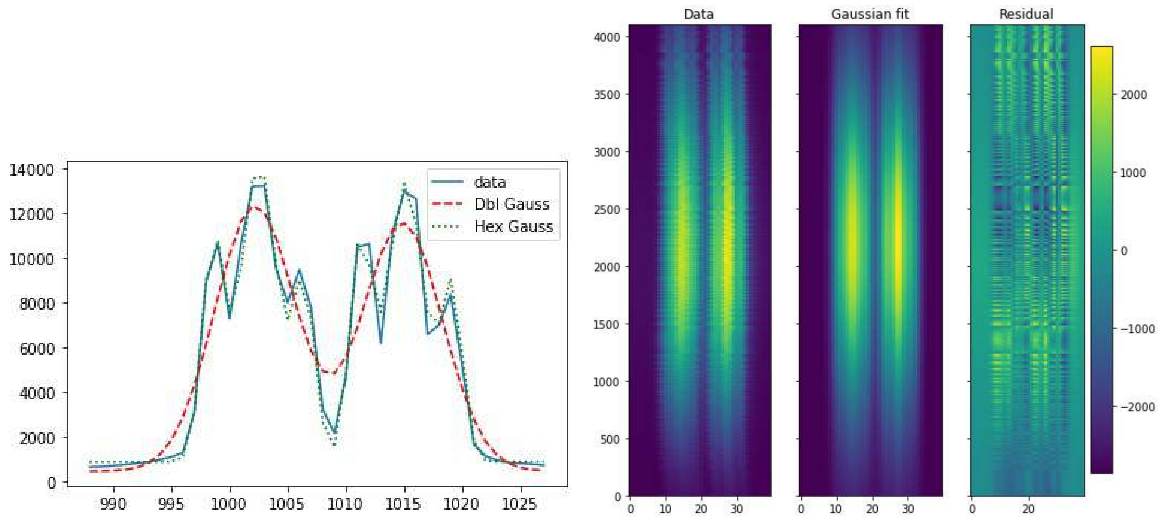

Fig. 3. Gaussian fits to the two beams of a given order, **left:** in one dimension and **right:** in two dimensions. The latter also provides the residuals of the fit to the data, with corresponding value range.

- Transition from the rigid pixel grid currently in operation to a non-linear grid to improve precision of order tracing.
- Integrate 2D wavelength calibration, to be performed on each polarisation state separately.
- Ensure the validity of the cosmic ray removal method inside of PyReduce on NeoNarval data.
- Implement multi-threading/parallelisation for the most computationally expensive steps, particularly the various fitting steps such as background scatter and inter-beam exclusion.
- Ensure universality/portability of packages for Python 3.X, so that the code operates on a maximum of devices.

We emphasise that the implementation of these methods into PyReduce will not solve the instrumental problems, but rather will help to diagnose such issues and improve the operation of the instrument as a whole, while maximising the quality of both past and future reduced data.

The branch of PyReduce that we are currently working on is not yet openly available, but can be made so for anyone willing to test the methods on their own data, and will be open access in the future, with the hopes that other members of the community can contribute to its operation and improve its function.

We thank the TBL team for providing us with the DRS source code and raw data, as well as for useful discussions. We also thank the PyReduce team for making their code publicly available.

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