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Introducing GOFIO: a DRS for the GIANO-B near-infrared spectrograph

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Introducing GOFIO: a DRS for the GIANO-B near-infrared spectrograph

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ABSTRACT

The NIR echelle spectrograph GIANO-B at the Telescopio Nazionale Galileo is equipped with a fully automated online DRS: part of this pipeline is the GOFIO reduction software, that processes all the observed data, from the calibrations to the nodding or stare images.

GOFIO reduction process includes bad pixel and cosmic removal, flat-field and blaze correction, optimal extraction, wavelength calibration, nodding or stare group processing.

An offline version of GOFIO will allow the users to adapt the reduction to their needs, and to compute the radial velocity using telluric lines as a reference system.

GIANO-B may be used simultaneously with HARPS-N in the GIARPS observing mode to obtain high-resolution spectra in a wide wavelength range (383-2450 nm) with a single acquisition. In this framework, GOFIO, as part of the online DRS, provides fast and reliable data reduction during the night, in order to compare the infrared and visible observations on the fly.

Keywords: High resolution spectroscopy, echelle spectroscopy, NIR, DRS, Data Reduction Software, GIANO-B, python

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1. INTRODUCTION

GOFIO is a data reduction software (DRS) written for the GIANO-B infrared spectrograph,[1,2] an high-resolution ($R = 50,000$) infrared echelle spectrograph that covers the wavelength range 900-2450 nm.

GOFIO is part of the online reduction pipeline[3] running at the Telescopio Nazionale Galileo (TNG): in this context, it interfaces with the ramp-processor database and reduces the data as soon as they are created. It can work also as a standalone offline DRS without a graphical interface, which allows the user to reduce the ramp-processed raw files available in the TNG archive.

GOFIO processes all the calibration files (darks, flat-fields and wavelength calibration lamps) and the scientific images, observed both in the nodding and stare mode. The reduction process includes bad pixel and cosmic removal, flat-field and blaze correction, optimal extraction, wavelength calibration with Uranium-Neon (U-Ne) lamps, nodding or stare group processing. A logfile of the whole reduction process is created and stored in the reduction directory.

The reduced calibration files are stored in a dedicated folder and inserted in the calibration database. The calibration database will be accessed by the online version of GOFIO in case the night calibrations do not pass the quality checks, and by the offline version in order to match them with the scientific frames to be reduced.

In the offline mode, the reduction process can be completely customized, but it is suggested to use only the command line options, unless having a great familiarity with the instrument and its settings.

2. INSTALLATION AND CONFIGURATION

GOFIO can be downloaded from the webpage https://atreides.tng.iac.es/monica.rainer/gofio. It is written almost completely in python 2.7 (with the exception of a single fortran77 subroutine), and it requires the following python packages: NumPy, SciPy, AstroPy, ccdproc, watchdog, docopt. The fortran77 program will need to be compiled with a fortran77 compiler (either f77 or gfortran are suitable), and it requires the CFITSIO library (available at https://heasarc.gsfc.nasa.gov/fitsio/fitsio.html).

An installation and user manual is available at the same webpage: the manual explains also how to configure GOFIO in order to customize the reduction process.

3. REDUCTION PROCESS

GOFIO reduces the data by working on a whole night of observations. The online version at the TNG reduces the frames in the order they are observed, while the offline version is meant to work on an already complete night, and it provides greater adaptability.

When using the offline version of GOFIO, it is recommended to reduce first all the calibration files of the night and then the scientific ones, regardless of the order in which they were taken. This is due to the fact that the calibration U-Ne lamps are observed at the end of the night, due to the persistence of the signal on the detector that prevents from observing them before the scientific observations. As such, reducing the frames in the order they are observed (as done by the online DRS at the TNG) forces GOFIO to use an older U-Ne lamp to calibrate in wavelength: depending on the time gap between the older U-Ne lamp and the observations, the instrumental drift could be quite large and the wavelength calibration not optimal.

During the night, the online reduction provides a fast quality check of the observations and the ability to compare on the fly the GIANO-B infrared spectra with the HARPS-N visible ones when the instruments are used in the simultaneous GIARPS mode.[4,5]

3.1 Calibration frames

When GOFIO is launched for the first time, the calibration database will be empty. It is important to populate it with at least one calibration per type, in the following order: dark frames, flat-field frames and U-Ne frames. We inform here that GIANO-B has two different calibration lamps (an U-Ne lamp and a Fabry-Perot), but at the moment the stability of the Fabry-Perot is still being studied, and so only the U-Ne lamp is used for the wavelength calibration.

3.1.1 Darks

The dark frames are ramped in such a way to create raw files with different exposure times, *i.e.*, from a dark frame with an exposure time of 600 s, $7 \times n$ frames with exposure times of 10, 30, 60, 100, 200, 300, and 600 s will be created. As such, GOFIO expects $7 \times n$ frames from a sequence of n observed dark frames: if the original exposure time is less than 600 s, less frames will be created and GOFIO will simply reduce the existing ones.

Each dark frame undergoes a quality check: if its exposure time is different from the expected values or the average signal in at least one of the quadrants of the image is larger than the defined threshold, then the frame is discarded (see Fig. 1 to see the detector's quadrants).
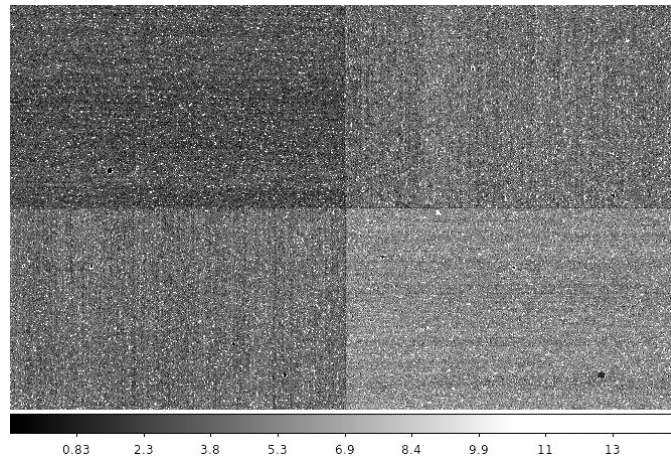

Figure 1. A 100 s masterdark, showing the differences between the detector's quadrants, and the bad pixels.

If enough frames of a particular exposure time have passed the quality check, they are averaged to create a masterdark. The masterdark is then inserted in the calibration database. If not, the masterdark for that exposure time will be taken from the calibration database according to the nearest date and a warning message will be given.

3.1.2 Flat-fields

The flat-field frames are reduced by group. Each frame undergoes a quality check by computing the mean signal over all the image and comparing it to a threshold value: if the value is lower than the threshold, the frame is discarded.

If no flat-field passes the quality check, the masterflat is taken from the calibration database and a warning message is given, otherwise the following reduction steps are performed:

1. the masterdark with the appropriate exposure time is subtracted;

2. the bad pixels are removed using a fixed bad pixel mask: the frame is filtered using a rectangular filter 41-pixel wide and 1-pixel high and then the bad pixel mask is used to define the bad pixel positions and substitute their values with the filtered ones (see Fig. 2);

3. the flat-fields are combined to create the masterflat:
   - the flat-fields are masked by sigma-clipping using the median and the standard deviation modified by the read-out-noise (RON) and gain;
   - the sigma-clipped flat-fields are averaged to create the masterflat;
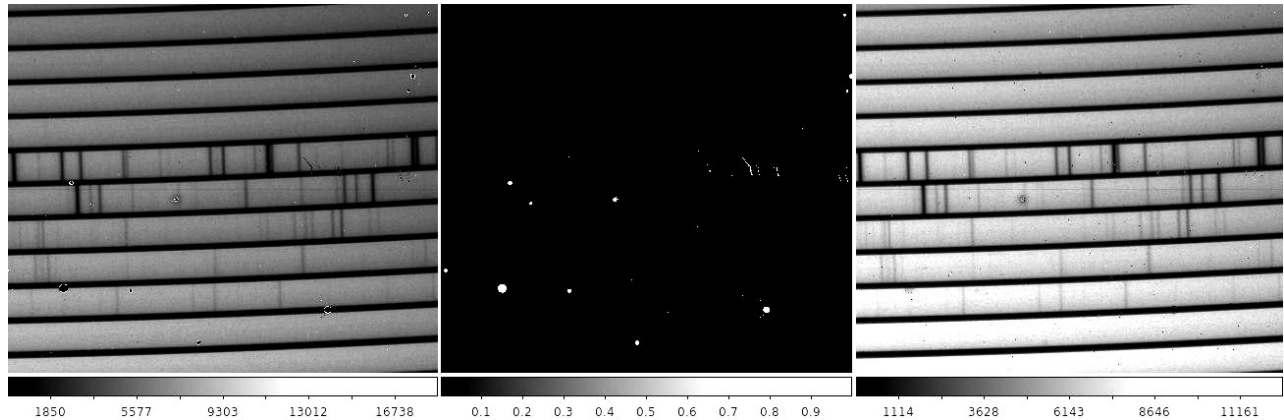   - RON and gain of the resulting masterflat are adjusted accordingly;

Figure 2. Flat-field with bad pixels (left), bad pixel mask (center), and flat-field with bad pixels removed (right)

4. the vertical position of the orders on the detector is computed by finding the bottom pixel of the flat signal in the lowest order (order 32) and the leftmost column of the detector. The value is then stored in the calibration database, and may be used in the following step.

5. the echelle orders of the masterflat are straightened using a fortran77 procedure,[6] which takes into account the slit-tilt and interpolate the signal. The curvature of each order can be represented by a parabolic function:

$$Y(X, N) - Y_0(N) = C(N) \times [\frac{X - X_0(N)}{2048}]^2 \tag{1}$$

where the parameters are:

- N is the echelle number (from 32 to 81);
- X is the horizontal pixel coordinate (from 1 to 2048);
- $Y(X, N)$ is the vertical pixel coordinate of the bottom of the trace at the given X coordinate;
- $Y_0(N)$ is the vertical pixel coordinate of the minimum of the order;
- $X_0(N)$ is the horizontal position of the minimum of the order, and can be approximated as $X_0(N) = 833.2 - 24.51 \times N + 230.3 \times \sqrt{(N - 25)}$;
- $C(N)$ is the curvature parameter, defined as $C(N) = 120.5 + 0.765 \times N$

For more details on the procedure, see Ref. 6.

The geometry of the orders is an intrinsic property of the GIANO-B spectrometer and it is always the same, but a shift of the spectral image may happen following major maintenance work of the cryogenic spectrograph (e.g. warm-up cycles, or manual movements of the slit wheel). As such, the straightening procedure accepts as input parameter a vertical shift in pixels. This parameter may be given directly from the configuration files (config.py or gofio.cfg), otherwise it will be taken from the calibration database (see previous step);

6. the straightened masterflat is normalized by fitting each row with a 5th order degree polynomial and then dividing the row by the polynomial;

7. the straightened masterflat is used to create the extraction mask with the position and the width of the echelle orders;

8. masterflat, straightened masterflat and normalized masterflat are inserted in the calibration database.

3.1.3 U-Ne lamps

The reduction of the U-Ne lamps follows these steps:

1. the appropriate masterdark is subtracted from each U-Ne frame;

2. the bad pixels are removed using the bad pixel mask (see Sec. 3.1.2);

3. if there is more than one U-Ne frame, they are combined after sigma-clipping them (see Sec. 3.1.2), creating the masterlamp;

4. the masterlamp is straightened (see Sec. 3.1.2) and inserted in the calibration database;

5. 20 central pixels of each order are extracted and a default wavelength calibration is performed (details below);

6. the extracted and calibrated U-Ne masterlamp is inserted in the calibration database.

The wavelength calibration is performed using an atlas of U-Ne lines. We selected as a starting point 743 prominent and isolated lines, for which both the position on the detector and the wavelength are well known.[6]

For each echelle order, the lines are found using the pixel position, fitted with a Gaussian function and discarded if the fit fails or if the parameters of the Gaussian are very far from the expected central position and width. The remaining lines are used to perform a preliminary calibration using a modified 3rd order degree polynomial:

$$\lambda = \lambda_0 + k_1 \times (x - x_c) + k_2 \times (x - x_c)^2 + k_3 \times (x - x_c)^3 \tag{2}$$

where k_1, k_2 and k_3 are derived from an ab-initio model of the echellogram that yields:[6]

$$
\begin{aligned}
k_1 &= -0.849(1/order - 1/2150) \\
k_2 &= -3.560 \times 10^{-5}/order \\
k_3 &= 1.780 \times 10^{-9}/order
\end{aligned}
\tag{3}
$$

with the order numbers going from 32 to 81.

This polynomial has only two free parameters (λ_0 and x_c), which is very useful considering that some echelle orders have very few U-Ne lines available.

Once this first calibration is done, GOFIO searches for all the other lines in the atlas and repeats the Gaussian fitting and quality check, and then the calibration. The polynomial parameters and the RMS of the fit are written in the header of the extracted masterlamp FITS file for each echelle order.

If the calibration fails, a warning message is given: the user may either observe another lamp or fall back to the calibration database.

3.2 Scientific frames

The GIANO-B spectrograph may be used with two different observing modes:

1. the nodding mode is the main observing mode for point-like sources. The target is observed first in the A position of the slit (roughly in the middle of the lower half of the slit), then in the B position (middle of the upper half of the slit), or vice versa (see Fig. 3). The two observations have the same exposure time and are combined during the reduction process in order to to eliminate the sky and detector contributions to the observation;

2. the stare mode is mainly used for extended objects, that span the whole slit, and therefore do not allow the observer to perform the nodding strategy (see Fig. 4). The object is placed in the center of the slit (C position). Stare observations should be coupled with sky observations in order to eliminate the sky and detector contributions.

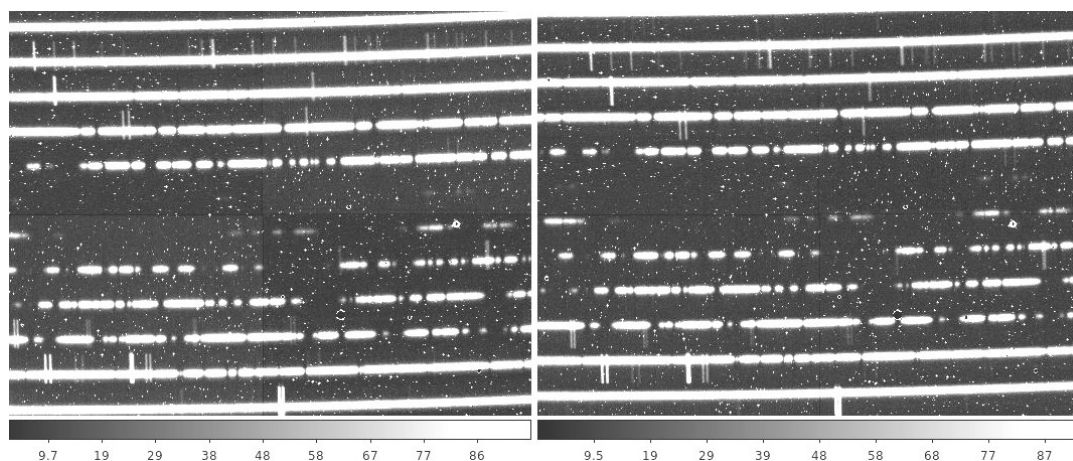GOFIO reduced automatically both nodding and stare images.

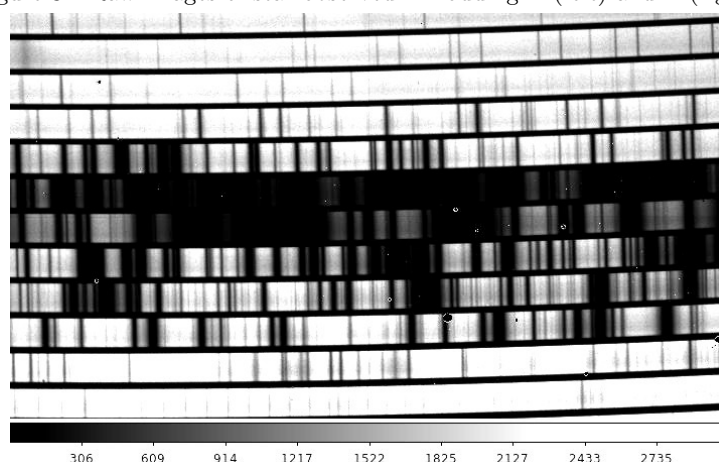Figure 3. Raw images of star observed in nodding A (left) and B (right).

Figure 4. Raw image of Mars observed in stare mode: the signal covers the whole slit width.

3.2.1 Nodding

The nodding images are reduced in pairs (A and B images). They immediately undergo a check to be sure that the exposure times of the two frames are the same, otherwise they will not be reduced. Once the images pass the quality check, the reduction follows these steps:

1. the bad pixels are removed (see Sec. 3.1.2);

2. the image A-B is created, which takes care of the sky and dark subtraction. From this point on, all the reduction is performed on this image, while the separate A and B images are used only for the information stored in the headers;

3. the image is straightened (see Sec. 3.1.2). The straightened images are saved in the STR directory nested in the night reduction directory;

4. the image is divided by the straightened masterflat. By default, the division is performed on the 2D images order by order: each order region of the masterflat is first divided by its mean value, then the same order region of the nodding is divided by this normalized masterflat. The values of RON and gain are updated accordingly. In the offline version of GOFIO it is possible to choose different procedures: either divide by the masterflat normalized by its global mean value, or divide by the normalized masterflat (and skip the blaze correction), or not divide by the masterflat at all;

5. extraction of the signal A from A-B and the signal B from -(A-B) with an optimal extraction algorithm.[7] The extraction is done order by order and follows these steps:

- a mean order profile is created by averaging the order columns along the whole order length and setting all the negative, infinite or NaN values to zero;

- the order profile is fitted by a Gaussian. If the x_0 position of the Gaussian is very different from the expected position of the object on the slit, the expected position is used. If the half-width-at-tenth-maximum (HWTM) is smaller than 3 pixels (probably a cosmic is driving the fit) or larger than the configuration value (risk of overlapping between A and B traces), then the configuration value is used;

- the x_0 and the HWTM of the Gaussian profile are used to define the extraction window and to perform a standard extraction. The results are the standard flux and its variance;

- a spatial profile is built by dividing the data for the standard flux. The profile is then corrected by setting all the negative, infinite and NaN values to zero, and normalized;

- the spatial profile is optimized by fitting it row by row with a 2nd order degree polynomial, weighting the signal with the inverse of the square root of the variance. All the points more than 4σ from the fit are rejected and substituted with the fitted values (see Fig. 5);
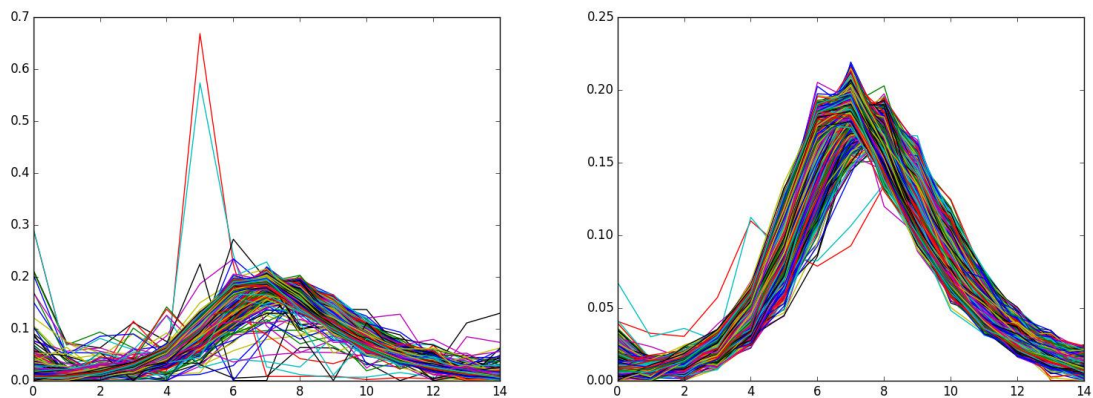

Figure 5. Sample extraction profile for order 32 before (left) and after (right) the optimization.

- the optimized profile is corrected for negative, infinite and NaN values, and normalized, the variance is updated;

- a first optimal extraction is performed with the optimized profile: the results are the optimized flux and its variance;

- a 2D model of data is created by multiplying the optimized profile by the optimized flux;

- the cosmic rays and other outliers are removed iteratively:
  - the outliers are found by comparing the difference between the data and the model with the square root of the variance;
  - only the strongest outlier is removed each time, and only if the above absolute value is greater than 5. The outlier is removed by substituting it with the median of a small interval around it, the same is done for the extraction profile in correspondence to the outlier;
  - the process is repeated until no more outliers are found or the maximum number of outliers per order (arbitrarily set to 50) is reached;

- the final optimal extraction is performed on the clean data;

6. the signal-to-noise ratio is computed for each pixel of the extracted spectrum. If the masterflat has been used, it will be extracted with the same optimized profile in order to correct the signal-to-noise ratio. The formulas used are the following:

$$SNR = \frac{1}{\sqrt{\epsilon_{sp}^2 + \epsilon_{flat}^2}} \tag{4}$$

where:

$$\epsilon_{sp} = \frac{\sqrt{RON_{eff}^2 + (gain_{eff} \times N_{sp} \times flux)}}{gain_{eff} \times N_{sp} \times flux}$$

$$\epsilon_{flat} = \frac{\sqrt{fRON_{eff}^2 + (fgain_{eff} \times fflux)}}{fgain_{eff} \times fflux} \tag{5}$$

with: RON_{eff}, $gain_{eff}$, = effective RON and gain of the detector for the spectrum;
N_{sp} = number of spectra combined to obtain the extracted spectrum;
$flux$ = flux of the extracted spectrum;
$fRON_{eff}$, $fgain_{eff}$ = effective RON and gain of the detector for the flat-field;
$fflux$ = flux of the extracted flat-field;

7. the same extraction profiles are used also to extract signal from the calibration masterlamp, then the extracted masterlamp is calibrated and the wavelength solution applied to the spectra. If the calibration fails, the default wavelength solution found during the U-Ne lamp reduction (see Sec. 3.1.3) will be used;

8. the wavelength calibrated A and B nodding are averaged to create the AB spectrum, adjusting RON, gain, slit position, airmass, and exposure time;

9. the barycentric correction is computed for each spectrum (nodding A, nodding B and combined nodding AB), both in radial velocity and in time (both the heliocentric Julian Date in UTC and the barycentric Julian Date in TDB are computed), and the results are written in the headers;

10. all the 3 spectra (A, B, and AB) are saved in two different formats:

    - ∗_ms1d.fits: binary table with 50 rows (one row for each order) and 4 columns (wavelength, flux, SNR, order number from 32 to 81). All the relevant information are in the header of the primary HDU, while the table itself is in the secondary HDU. The spectra have constant step in pixel, they are all 2048 pixel long. The barycentric correction is stored in the header, but it is not applied;

    - ∗_s1d.fits: monodimensional fits image with a constant step in wavelength of 0.001 nm, with the barycentric correction applied. As an option, these spectra can be normalized prior to the order merging;

11. in the case of the AB spectrum, the exposure times, the Modified Julian Date (MJD), and names of the A and B images are stored in the header.

If a group of noddings of the same targets is observed, GOFIO will reduce each nodding separately, but then it will perform a reduction on the whole group:

1. all the raw A noddings are averaged, adjusting RON, gain, and airmass. All the exposure times and MJD of the combined images are saved in the header;

2. all the raw B noddings are averaged, adjusting RON, gain, and airmass. All the exposure times and MJD of the combined images are saved in the header;

3. from here on, the reduction follows the standard steps of nodding reduction, with the average A as the nodding A and the average B as the nodding B;

4. the final output will have a 'grp.fits' suffix.

3.2.2 Stare

The reduction of a sequence of stare images and associated sky images (if any) follows these steps:

1. the exposure times of the target images are checked: if the images have different exposure times, the ones with the most common exposure times are kept, the others are discarded;

2. the exposure times of the sky images are checked: if different from the target images, they are discarded;

3. an average target image is created, the values of RON, gain, and airmass are adjusted accordingly;

4. an average sky image is created, adjusting the values of RON and gain;

5. the average sky image is subtracted from the average target image. If there is no available sky image, the masterdark is used instead. If there is no masterdark available, the reduction will continue anyways. A warning will be given for each of these situations. The values of RON and gain are adjusted accordingly;

6. the names and MJDs of every target and sky image used are written in the header of the sky-subtracted image;

7. the sky-subtracted image is straightened (see Sec. 3.1.2);

8. the image is divided by the masterflat (see Sec. 3.2.1);

9. the spectrum is extracted (see Sec. 3.2.1). The only difference with the nodding extraction is on the limits of the extraction profile, which in this case may span the whole slit width;

10. the SNR is computed (see Sec. 3.2.1);

11. the masterlamp is extracted, and used to calibrate the scientific image (see Sec. 3.2.1);

12. the barycentric correction is computed (see Sec. 3.2.1);

13. the reduced spectrum is saved in both ∗_ms1d.fits and ∗_s1d.fits format (see Sec. 3.2.1).

4. GOFIO AND YABI

GOFIO may be run on the user's proprietary data or on public data without installation using the Yabi[8] service deployed at IA2 Data Center (`http://ia2.inaf.it`). Yabi is a open source workflow 3-tier application stack to provide users with an intuitive, easy to use, abstraction of compute and data environments.

This kind of service results in several advantages for the final user. In particular, the users do not have to download and install GOFIO themselves, and they have the last version of GOFIO always available through Yabi web service. In addition, Yabi is integrated and synchronized with the TNG archive hosted at IA2 Data Center, so the users can access their proprietary data in a transparent manner and reduce them without having to first download the raw files locally.

Through Yabi web interface, the users can create in a very intuitive way their custom workflows for data reduction, configuring all input parameters of GOFIO such as: calibration files to be used, reduction of specific calibration files, options for flat-field removal, or normalization of s1d spectra.

5. FUTURE WORKS

As soon as the Fabry-Pérot lamps will be fully characterized, GOFIO will be modified in order to use them as wavelength calibrator along with the U-Ne lamps.

Meanwhile, we are working on implementing a radial velocity computation procedure to be used in the offline mode on whole spectroscopic time-series. This method will use the telluric lines in order to improve the precision of the wavelength calibration (see Ref. 9 for an overview of the method). When the gas-absorption cells[10] will be installed, a dedicated radial velocity software will be written.

We are also working on a containerized version of GOFIO with Docker to be used in Kubernetes clusters. This will allow to deploy GOFIO on Platform-as-a-Service private or public Cloud in order to get more extensive and flexible exploitation of computation capabilities.

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