Data Reduction Protocol for Ground Based Observation of Spectrophotometric Standard Stars. II. Spectroscopy Pre-reduction up to extraction and wavelength calibration

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Abstract

When building a large set of ground based Spectro-Photometric Standard Stars (SPSS) for calibrating Gaia BP/RP spectra and G-band images to a few percent in absolute flux, it is essential to maintain the maximum homogeneity in data quality, acquisition and treatment. The procedure followed to pre-reduce the data, extract 1D spectra and perform the wavelength calibration is here described step by step. This procedure can be applied to any telescope, with a few exceptions: special ”tips” are discussed for the CAFOS@CAHA2.2 and DOLoReS@TNG instruments in the Appendices.

Document History

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1	0	18-May-2009	GA	Creation.

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1 Introduction

The task of our survey is to build a grid of *Spectrophotometric Standard Stars* (SPSS) to ensure the absolute calibration of Gaia BP/RP spectra and G passband observations within a few percent with respect to Vega (see MBZ-001). Such a grid needs to be built using ground-based observations of SPSS, using different telescopes and instruments, see (LF-001; GA-002). The details of the SPSS selection have been outlined in (GA-001; GA-003; JMC-001; JMC-002). In order to ensure the maximum homogeneity in the data quality, we adopted a well defined observational strategy ((EP-001; EP-003; EP-006), and planned the so-called *Instrument Familiarisation Plan* (IFP) aimed at studying both the peculiar characteristics of each telescope/instrument combination (GA-004; GA-005), and the instrumental effects that can affect the high precision required for the Gaia SPSS grid (SMR-002).

All the aforementioned documentation can be obtained through Livelink or SVN, and more information can be found in our local Wiki pages (hereafter Wiki-Bo[1]) in the ”documentation” section.

In this protocol we present the procedure to pre-reduce spectra, up to the extraction of the 1D spectra, and their accurate wavelength calibration. The following steps of spectra reductions, including corrections for second-order contamination, differential slit losses, telluric absorption, and (relative) flux calibration will be detailed in two forthcoming protocols (GA-005; GA-006). Following the strategy of MBZ-001, we will use both spectra observed under photometric conditions and spectra obtained in *“grey nights”*, i.e. nights where the extinction variations are grey. In this approach all data, also if acquired under non-photometric, but reasonably good, sky conditions will be fruitfully exploited.

For any doubt or need, please contact the authors. In particular, you will need help for:

- obtaining user-name and passwords to access our internal Wiki-Bo pages and DB&A (Section 3);
- downloading/uploading data (Sections 3 and 7).

2 Check-list

The following check-list, summarized in Table 2, serves as summary and reference for the observers once they are familiar with the details of each step. Each point is described in the corresponding Section, while in the appendices specific instructions on how to treat the data obtained by some of the instruments used in this campaign are discussed.

[1] `http://yoda.bo.astro.it/wiki`

TABLE 2: **Data Retrieval, Reduction Steps and Uploading of prereduced data**

Operation	Description	Sections
Data retrieval	Local Raw data archive	3
Pre Reduction Procedures		4
	Preliminary steps	4.1
	Overscan, trimming, bias and dark subtraction	4.2
	Bad pixel mask & QC	4.3
	Master Flat & QC	4.4
	Illumination calibration & QC	4.5
	2D scientific frames prereduction	4.6
	Note about fringing	4.7
Spectra extraction		5
	Seeing measurement and aperture width selection	5.1
	Narrow and wide spectra QC1	5.2
	Prereduced Spectra QC2	5.3.2
	Spectral extraction	5.3
Wavelength calibration		6
	Extract calibration lamps	6.1
	Determine the dispersion solution	6.2
	Assign the wavelength calibration lamp	6.3
	Apply the dispersion solution	6.4
	Wavelength calibration of wide slit spectra	6.5
	Wavelength Calibrated Spectra QC3	6.6
Data delivery	Local Reduced data archive	7
	Compiling reduction logs & Wiki-Bo pages	7.1
	Summary of QC criteria	7.2

3 Data retrieval

All data obtained in our Pilot Project (testing phase), Main Campaign (mainly devoted to spectroscopic observations) and Variability campaign (devoted to photometric observations) are archived in our local raw data archive[2], so that they can be easily retrieved by anyone working on them. The description of our local archive, as well as basic instruction on how to download data, can be found in EP-008, and in our local Wiki-Bo pages.

Details of each observing night (logs of the observations, target summaries etc.) can be retrieved from Wiki-Bo, from the web pages related to each observing run, accessible through the *"Summary of Observing Runs and Proposals"*[3] section, see Fig. 1. The *"SPSS Reduced Data*

[2] `http://spss.bo.astro.it/`
[3] `http://yoda.bo.astro.it/wiki/index.php/SPSS_Runs_Table`

M-005	La Palma	TNG	DoLoRes	EP	17-Oct-07	TAC_3 (AOT17/08A)	Observations completed	May 25-31, 2008 (logs)	Obs, Red
M-006	CAHA	2.2m	CAFOS	C. Jordi	14-Mar-08	H08-2.2-041	Observations completed	Sept. 3-11, 2008 (logs)	Obs, Red
M-007	La Silla	NTT	EFOSC2	EP	31-Mar-08	182.D-0287	Observations completed	26 Nov - 1 Dec 2008 (log)	Obs, Red
M-008	La Palma	TNG	DoLoRes	EP	18-Apr-08	TAC_14 (AOT18)	Observations completed	Oct. 16-21 2008 (logs)	Obs, Red
M-009	La Palma	TNG	DoLoRes	EP	24-Oct-08	TAC_14 (AOT19)	Observations 1st run completed	16-20 Mar 09; 5-9 Jun 09 (logs)	Obs, Red
M-010	La Silla	NTT	EFOSC2	EP	31-Mar-08	182.D-0287	Observations 1st run completed	5-10 Apr 09; 28 Aug - 4 Sep 09 (log)	Obs, Red
M-011	CAHA	2.2m	CAFOS	C. Jordi	15-Mar-09	H09-2.2-039	Proposal Submitted	??? (logs)	Obs, Red

FIGURE 1: Portion of the *"Summary of Observing Runs and Proposals"* Table in Wiki-Bo, showing runs already performed, to be performed and submitted, with hyper-links to the telescopes and instrument official pages (columns 2, 3 and 4), and links to the specific *"Run Pages"* (First columns).

Archive"[4] should be checked to see if master-frames related to the selected run are already available and if the selected nights have already been partially or completely reduced.

4 Pre-reduction procedures

In the following sections we describe, step by step, the procedure to be followed for the data reduction up to the wavelength calibration of the extracted spectra. Even if the reduction steps are similar for all adopted instruments, in some cases particular care and/or tricks are required. These cases will be mentioned in the following sections and described in more detail in the Appendices.

The primary aim of CCD data pre-reduction is to remove any peculiar effect due to the detector and the telescope, the so called "instrumental signature". The main concepts involved in this operation are listed in Tab 2. Our procedures are based on the Image Reduction and Analysis Facility (IRAF[5]) *imred*, *specred*, *twodspec*, *onedspec* and *rv* packages. An extensive description and examples can be found in Massey (1997).

[4] `http://spss.bo.astro.it/red.cgi/`
[5] `http://iraf.noao.edu/`
IRAF is distributed by the National Optical Astronomy Observatories (NOAO), which are operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

4.1 Preliminary steps

Using the official log of each night (that can be found in Wiki-Bo, Section 3) and standard Linux commands it is possible to create useful lists of biases, flat-fields, sky-flats, spectra, calibration lamps. The official log of each night can be also useful to check exposure times, airmass, instrumental set-ups and so on.

From the *"Spectroscopy Reduction and Analysis"* pages in Wiki-Bo users can find, for each instrument, scripts that must be used in order to configure the IRAF tasks before each pre-reduction step. All these scripts start with the command *unlearn task-name*, then for each task some of the fields are configured in order to optimize all the reduction steps and to minimize the human errors in the task configuration, as described in the following sections.

4.2 Overscan, trimming, bias & dark subtraction

The procedure to build the Master-bias and Master-dark is fully described in SMR-001. Semi-automatic pipelines producing the Master-bias and performing the necessary quality check are available in dedicated pages in our Wiki-Bo[6] [7]. In Fig. 2, we show the trimming and overscan sections used for the different telescope/CCD combinations: for some telescopes the CCD has been changed during the survey, as well as the trimming and overscan section, so the observations date should be used to select the appropriate CCD section. Details can be found on the pages of Wiki-Bo, from the web pages related to each observing run,*"Summary of Observing Runs and Proposals"*[8] and the web pages dedicated to the *"Instrument Familiarization Plan"* [9].

4.3 Bad-pixel masks

It is not uncommon that a CCD might contain faulty single pixels or columns. A bad-pixel mask (hereafter BPM) is a frame of the same dimension as the CCD to which it is associated, where good pixels are identified by zero value and bad pixels by non zero values (see SMR-001); when applied to scientific frames, the bad pixels are replaced by linear interpolation between the nearest good pixels. All the BPMs for the CCDs used during the spectroscopic campaign are available in Wiki-Bo[10] dedicated pages. If needed, new BPMs can be produced following the procedures described in SMR-001. The *ccdproc* IRAF task (see Sect. 4.4,4.6) will apply the BPM to all the frames before processing them.

[6] http://yoda.bo.astro.it/wiki/index.php/MasterBiaspipe
[7] http://yoda.bo.astro.it/wiki/index.php/QC_MasterBiaspipe
[8] http://yoda.bo.astro.it/wiki/index.php/SPSS_Runs_Table
[9] http://yoda.bo.astro.it/wiki/index.php/IFP_Calibration_Frames_Summary
[10] http://yoda.bo.astro.it/wiki/index.php/BPM

CCD Sections

CCD SECTIONS FOR PRE-REDUCTION			
	OVERSCAN SECTION	TRIM SECTION for PHOTOMETRY	TRIM SECTION for SPECTROSCOPY
BFOSC@Loiano	no overscan	[1:1335,1:1300] old CCD [7:1340,1:1300] new CCD	[1:1335,1:1300] old CCD [7:1340,1:1300] new CCD
CAFOS@CAHA	no overscan	[10:1120,10:1120] for run P003 [10:1014,10:1014] for all runs M (*)	[10:1190,10:1640] for all runs
DoLoRes@TNG	[15:2085,2065:2085]	[25:2089,25:2045] until M009a [55:2085,25:2045] from M009b	[25:2089,25:2045] until M009a [55:2085,25:2045] from M009b
EFOSC2@NTT	no overscan	[20:2000,10:2000] --> BIN 1x1	[47:985,1:1015] --> BIN 2x2 [100:1960,10:2000]--> BIN 1x1
LaRuca@SPM	[1020:1070,1:1024] (SITE1) [2110:2150,1:2048](Marconi e2vm)	[15:1013,15:1024] (SITE1) [60:2095, 5:2045] (Marconi e2vm)	no spectroscopy
ROSS@REM	no overscan	[*,*]	no spectroscopy

FIGURE 2: Portion of the *"Instrument Calibration Frames"* Table in Wiki-Bo, showing overscan sections and trimming sections for all the telescopes used in the prereduction steps

4.4 Master flats

Once all instrumental signatures are removed (bias, dark, overscan) the data values for each pixel are related to photon hits, but there are still non-uniform relations between the number of incident photons and the detected electrons because of pixel-to-pixel sensitivity variations. Flat fielding correction accounts for the non uniform CCD response to the incident light that can show large scale (across the whole CCD) and small scale (pixel-to-pixel) variations. The basic idea of flat-field correction is to divide the data by a "sensitivity map" (flat-field) created from calibration exposures. The effect of dust on the filters or on the detector, the vignetting and other variations in the throughput of the instrument optics are also corrected by flat fielding. Since the detector efficiency changes with the wavelength, flats are needed for all the grism-slit combinations used for the scientific frames. Also in this case "master-flats" are built by making a median of a number of flats (usually 10) in order to have a better statistics, to reduce the read-out noise and to get rid of cosmic rays.

Spectroscopic flat fields (see Fig. 3) differ from direct imaging because even when observing uniformly illuminated fields (sky or dome lamp), it is not possible to get a uniform illumination on all pixels of the detector. This is due to the fact that the source spectral energy distribution and the transmission variation with wavelength of the spectrograph both contribute to the shape of the observed spectrum (large scale pattern). Therefore, the large scale pattern is removed by appropriate modelling in order to "flatten" the calibration image without wiping out the small scale variations (which we want to correct for). The low signal and the strong lines in the dispersed sky light make it difficult to use blank (twilight) sky for flat fields (the image is essentially the solar spectrum plus telluric absorption features). For this reason a smooth dome lamp spectrum is preferred. Nevertheless, sky flats can be used to build up a correction function ("illumination correction") when necessary (see Sect. 4.5).

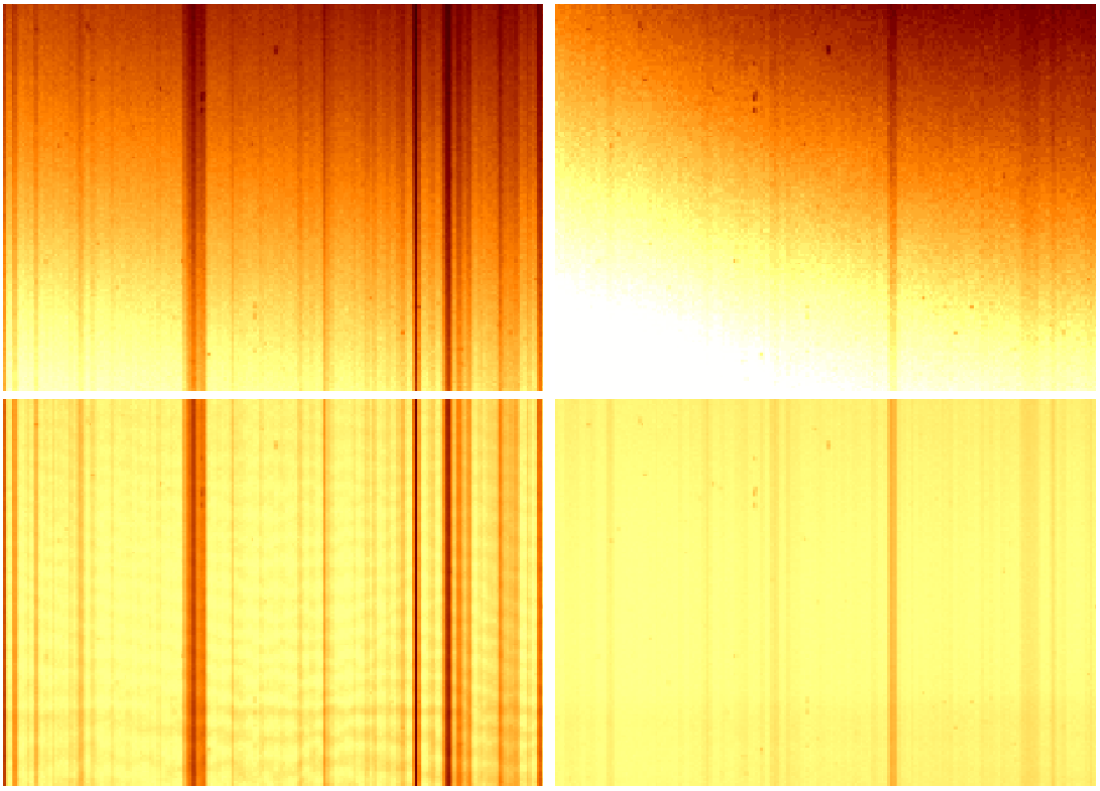


FIGURE 3: Spectroscopic lamp flat fields obtained with BFOSC and a slit of 1.5" (left panels) and 5"(right panels). Upper panels show flats obtained with grism 3, lower panels with grism 5. The black vertical stripes depend on the slit, and they are probably due to dust and imperfections (for a given slit the pattern is the same irrespective of the grism used). All the images show the same CCD area).

4.4.1 Raw Flat pre-reduction

The procedure to produce Master-flats starts by creating useful files containing the list of the spectroscopic lamp flats taken on the same night (with the same CCD sections). There must be a list file for each slit/grism combination used. We assume here that the set of spectroscopic flats to use are listed in the files `specflatlist` (for a given slit width and grism). Running first the script *setccdproc.cl* some of the fields will be automatically configured. Each instrument used in our survey has its own script, and the following example shows how the script configures the *ccdproc* IRAF task in order to pre-reduce data acquired at TNG, using the command:

```
cl < TNG_setccdproc.cl
```

The script will execute the following commands inside the task:

```
unlearn ccdproc
```

```
ccdproc.ccdtype=""
ccdproc.fixpix=yes
ccdproc.overscan=yes
ccdproc.trim=yes
ccdproc.zerocor=yes
ccdproc.darkcor=no
ccdproc.flatcor=no
ccdproc.readaxi="column"
ccdproc.fixfile="m.M009-TNG-DoLoRes_20090731_BPM_newCCD.pl"
ccdproc.biassec="[15:2085,2065:2085]"
ccdproc.trimsec="[55:2085,25:2045]"
ccdproc.functio="spline3"
ccdproc.order=5
```

The input list of flats will be corrected for overscan, trimmed, corrected for zero (with the masterbias created following the recipe described in Sect. 4.2 and in SMR-001), and corrected for BPM (see Sect. 4.3 and SMR-001) simultaneously, by running the *ccdproc* IRAF task with the command:

```
epar ccdproc

images="@specflatlist"       (the file containing the list
                              of flats to process, see above)
output="@specflatlist_corr" (list with the same flats in
                              the input list, preceded by "r.")
zero= "masterbias"           (the name of the masterbias appropriate
                              for the night)
```

4.4.2 Raw Flat Quality Control

We now consider the statistics of the processed flat fields. In order to build the master-flat we should avoid to use frames with a very low signal to noise ratio, or frames in CCD non-linearity or saturation regime. To do this we need to check first the typical shape of the flat field frames, which is different for each set-up, by plotting one row (or column), located in the middle of the frame, identifying the region of the CCD with the maximum S/N ratio.

For example we show in Fig. 4 the typical shape of the spectroscopic flat field, acquired with the instrument DoLoRes at the TNG, using the Blue grism (LR-B) and the 10” width slit.

Then we can check the statistic limited to the brightest area to identify frames close to saturation, or with few counts and low S/N, by using separate lists for each combination of slit-grism used to acquire the spectra.

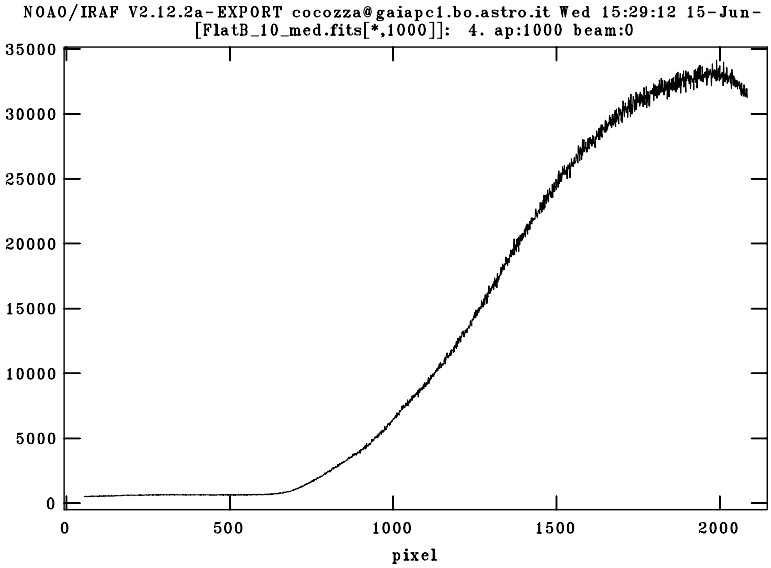


FIGURE 4: Spectroscopic flat field (DoLoRes@TNG, grism LR-B, slit width of 10"). Trace along dispersion axis. This plot shows that the counts for this set-up reach a maximum at the right edge of the frame. The statistics limited to the brightest area can be used to identify frames close to saturation, or with few counts and low S/N.

TABLE 3:

Instrument	**Blue Grism useful area** [x1:x2,y1:y2]	**Red Grism useful area** [x1:x2,y1:y2]	**Lower limit (ADU)**	**Upper limit (ADU)**
DoLoRes@TNG	[1500:2000,500:1500]	[850:1350,500:1500]	15000	60000
CAFOS@CAHA	[250:750,200:700]	[250:750,900:1400]	15000	55000
EFOSC2@NTT	[250:750,700:1000]	[250:750,250:650]	15000	55000
BFOSC@Cassini	[400:900,850:1250]	[400:900,500:1000]	15000	60000

If we suppose that the file "*specflatlist_corr*" lists all the frames obtained with the blue grism and a 10" width slit, corrected for bias and overscan, using the command:

```
imstat @specflatlist_corr[x1:x2,y1:y2]
```

we can check the counts in the area [x1:x2,y1:y2] with the maximum S/N. To create the master-flat, we recommend to avoid using flats with less than ∼15000 at the peak, as well as frames with counts beyond the limits of the CCD linear behaviour (see Tab. 3). The upper limit can change with the CCD used, as tested in GA-004. Lower and upper limits for each instrument and for each set-up used in our surveys are shown in Tab. 3, together with useful areas to better check the statistics of single flats. It could also be useful to visually inspect the flats, to identify

flats with significant shape variations which should be excluded from the subsequent steps.

4.4.3 Median 1D flat

The median flat can now be created, using first the script:

```
cl < setflatcom.cl
```

then running the task *flatcombine*:

```
epar  flatcombine

input="@specflatlist_corr",    (list of processed flats which passed
                                the QC)
output="medianflat"            (name of the median flat)
```

The median flat obtained must be corrected for the instrument response and for the lamp spectrum shape, thus leaving only the small scale variations in the normalized master-flat. This can be done by properly fitting the median flat shape and by dividing the median flat by the fit. The resulting frame will be the normalized one. The IRAF task to be used is *response* :

```
unlearn response
epar response

calibrat="medianflat"           (name of the median flat)
normaliz="medianflat"           (name of the median flat)
response="medianflat.n"         (name of the median flat fit)
interactive=yes
order=30
functio="spline3")
```

At this point we suggest to use the task in the 'interactive' mode which gives the opportunity to check and modify the spectral fit (see Fig. 5); we also recall that the list of commands is always available for each IRAF task with interactive window, just typing `?`. Once the task is running, it asks for `Dispersion axis`. We must select the option `1=along lines` or `2=along columns` according to our data. Usually a `spline3`, order $\simeq$ 30 − 40 fitting function produces a good result: remember that only large scale structures of the flat fields have to be removed. Depending on the used Lamp/grism/CCD, the order of the fitting function can

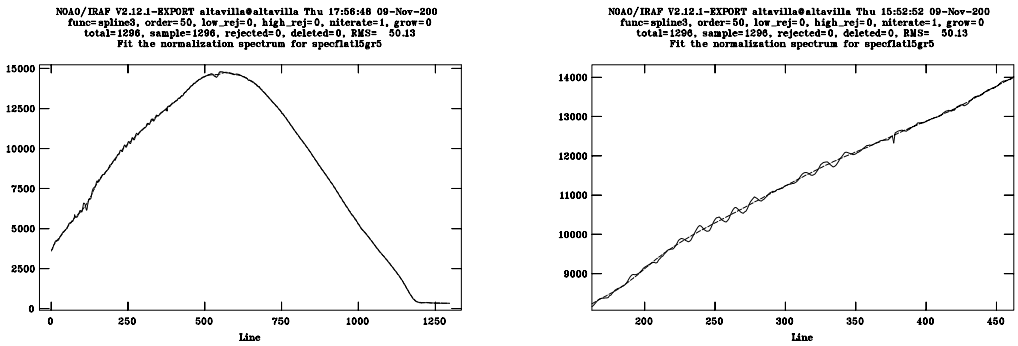


FIGURE 5: Fit of the large scale shape in the spectroscopic flat field due to the lamp spectral shape and the instrumental response (BFOSC, gr 5, slit 5”). A detail is shown in the right panel: fringes are *not* fitted, only large scale features must be fitted.

change slightly. High order fitting functions will have of course a lower RMS, but also a higher risk to remove small scale variation, like fringes, that should not be fitted and removed. On the other hand, a lower order of the fitting functions will have higher RMS.

4.4.4 2D flattening and Master-flat building

Because the two-dimensional flats can sometimes have 2D structures, like internal reflections of the lamp, the result of normalizing the median flat with a fit of a “collapsed” 2D frame (as explained in the previous section), is not a *flat* image with mean value of ~ 1, but it depends on the Lamp shape and the set-up. See for example the results obtained with normalized flat built using DoLoRes@TNG datasets acquired during the Run M-009 in Fig. 6. The large scale 2D residual structures can be easily removed using the task *boxcar*, which performs a smooth fit in a box of dimensions xwindow $\times$ ywindow pixels:

```
unlearn boxcar
epar boxcar

input   = medianflat.n            (Input images to be fit)
output  = medianflat.n_box        (Output images)
xwindow =                   50    (X dimension of box)
ywindow =                   50    (Y dimension of box)
(boundar=               nearest   (Boundary)
(constan=                     0   (Constant for boundary extension)
```

the output frame (a 2D fit of the flat) must be applied to the normalized flat, by dividing the normalized flat by the smoothed one. Since we would remove only large scale 2D structures we have to set the dimension of the box in an appropriate way. Usually a square region of $\sim 50-75$

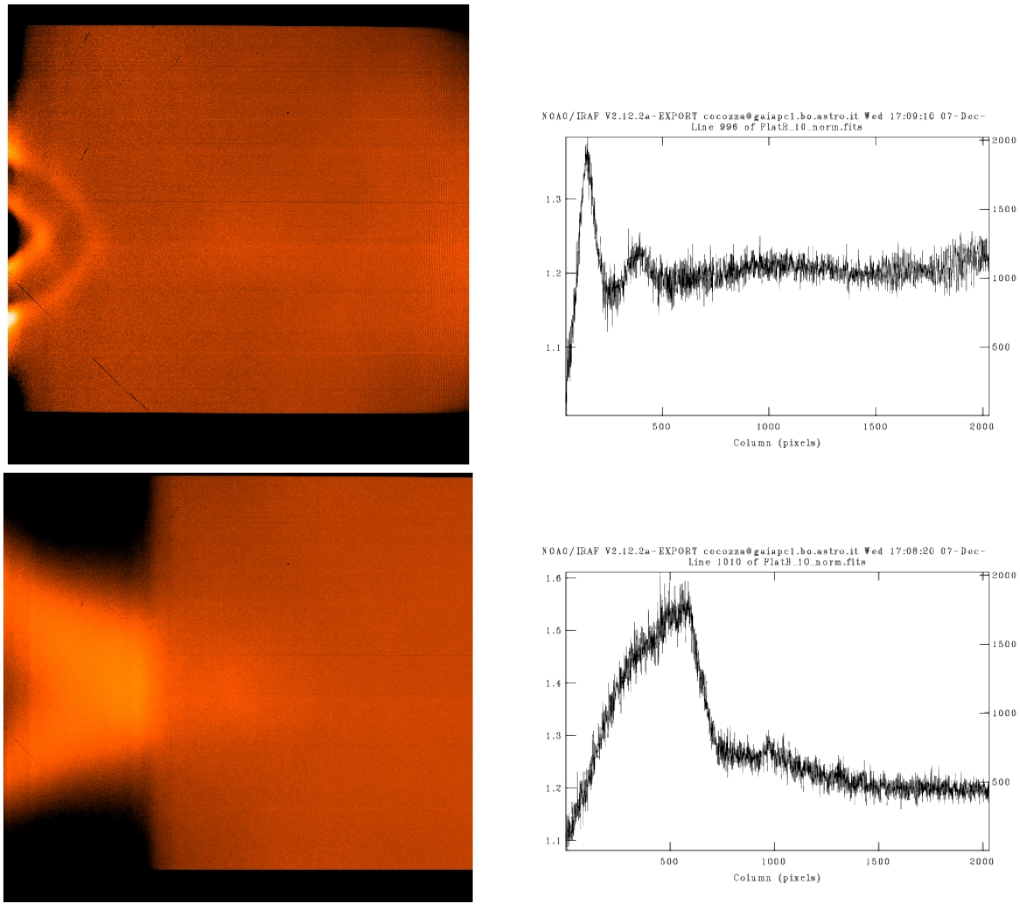


FIGURE 6: Spectroscopic flat field obtained with DoLoRes, slit width of 10”, grism LR-R (top left panel) and LR-B (bottom left panel); horizontal cut of one line shows the normalized flat shape (top right panel for LR-R, bottom right panel for LR-B): a strong internal reflection is clearly visible on the left side of the flats. The images are on the same intensity scale.

pixels on each side provides the best results. Especially for the redder Grisms, users have to be careful and choose a large enough window size, in order to ensure that the fringing pattern is not removed or altered. We can build now the master-flat using the task:

```
imarith medianflat.n \ medianflat.n_box masterflat.fits
```

the *masterflat.fits* must be renamed following the appropriate naming convection (see Sect. 7). The result is shown in Fig. 7, where the 2D residual structures in the normalized median flat are corrected, the effect of the internal lamp reflexion is reduced by a factor ∼10 and the residuals of the correction are tipically below ∼3%.

4.5 Illumination calibration

Scientific spectroscopic frames, after overscan, bias and flat field correction, are expected to be flat across dispersion. If not, Sky Flat Field images can be used to create an illumination calibration frame, to flatten the scientific images, removing the residual deviation from a flat image.

We assume here that, for each combination of grism/slit, we have a list of skyflat images, `skyflatlist`. The first step consists in processing this list applying the overscan, bias and dome flat-field correction using the *ccdproc* task:

```
epar  ccdproc

input=   @skyflatlist      (imput file list)
```

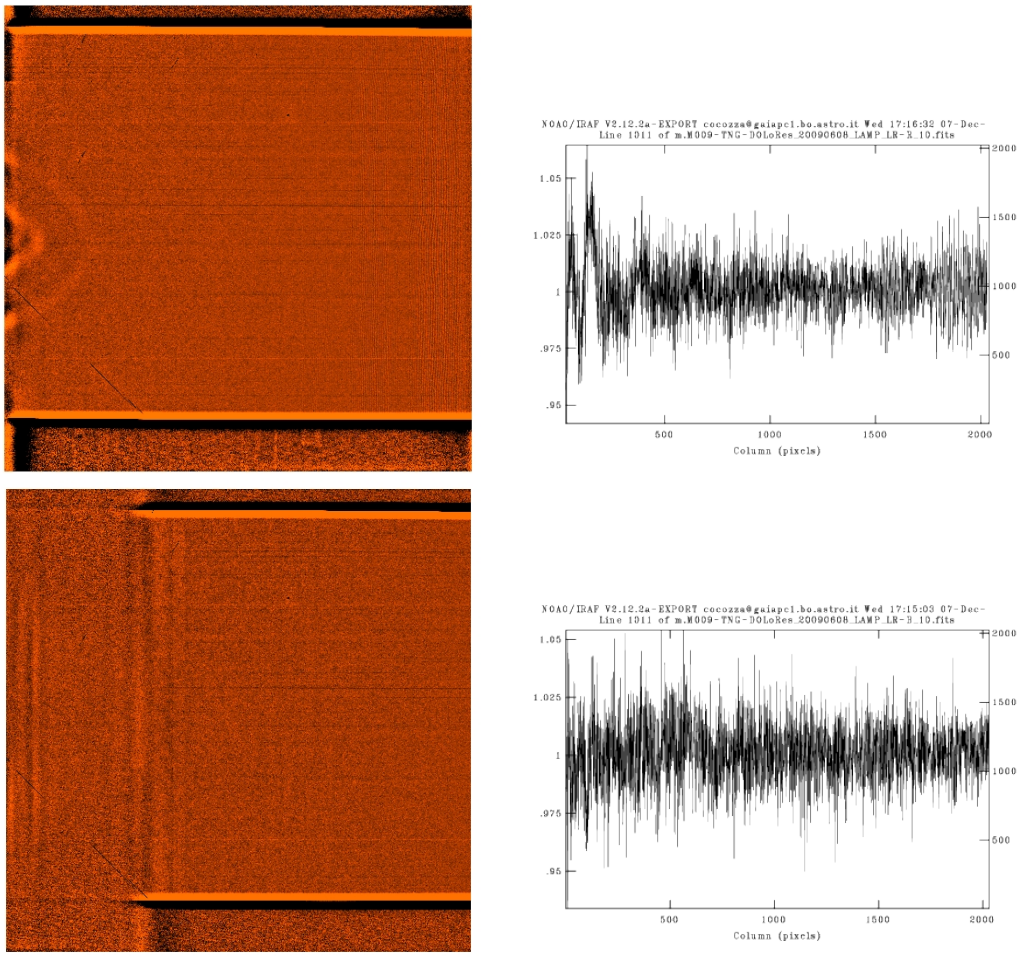


FIGURE 7: Spectroscopic Master flats, built using the normalized Flats shown in Fig. 6 and the task boxcar for the smoothing. The plots are shown using the same colour scale as in Fig. 6

```
output=  @skyflatlist_corr (output file list )
flatcor= yes
zero="masterbias"          (name of the appropriate masterbias)
flat="masterflat"          (name of the appropriate masterflat)
```

Note that this time we set `flatcor=yes` because now we have the masterflat available, while the other parameters have been already configured using the script *TNG_setccdproc.cl* (Sect. 4.4). Masterdark correction is neglected, because it is not necessary for any of the four instruments used (see SMR-001).

Using *imstat* as already done for the dome flats, we can check the statistics of the corrected sky-flats, in order to be sure that sky-flats are not too faint or not saturated (see Tab. 3). Once bias and flat-field corrected, the illumination correction flat can be obtained, making first a median of the corrected skyflats using the task *flatcombine*:

```
epar  flatcombine

input="@skyflatlist_corr,       (list of processed skyflats which passed
                                the QC)
output="median_skyflat"         (name of the median sky flat)
```

and then using the IRAF task *illumination*:

```
unlearn illum
epar  illumination

image=" median_skyflat",       (name of the median sky flat)
illumina="illuminationflat"    (appropriate name for the illumination
                                correction flat)
nbins=10
order=10)
```

This task defines `nbins` intervals along dispersion in the sky-flat spectra. In principle, the values in these strips (i.e. across dispersion) should be flat. If they are not, they can be fitted to create a 2D illumination frame to be used to remove the flatflielding residuals.

The task allows to select the interactive mode to determine illumination. Also the dispersion axis must be properly selected. Then the task shows each bin (`nbins`) in order to fit it properly. The fit order of each bin can be changed when necessary. Typing `q` the task moves on to the next strip to be fitted. The output of the task is the illumination correction frame (some smoothing is performed within the image to avoid discontinuities from strip to strip).

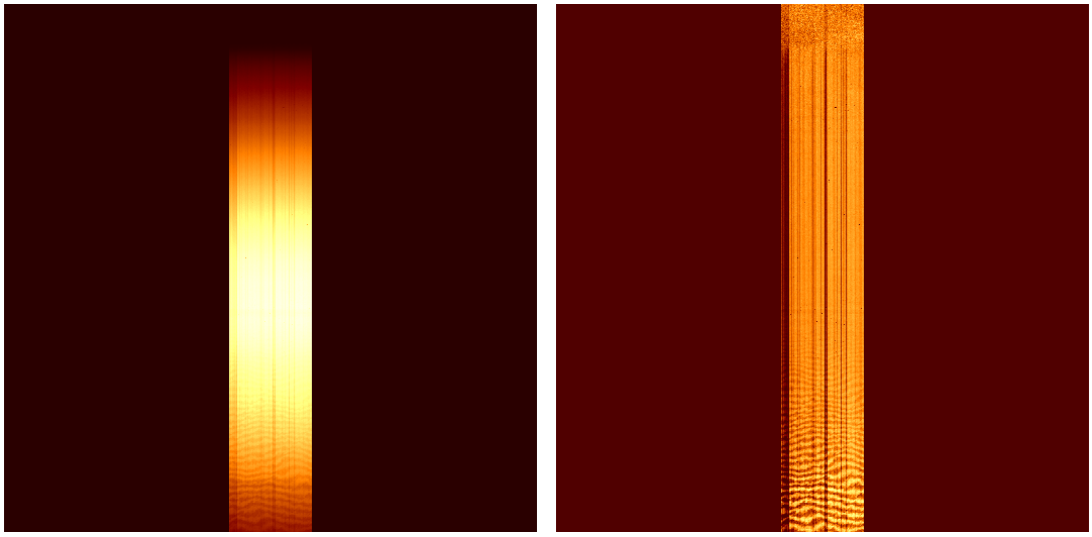


FIGURE 8: BFOSC, gr5, slit 5", wavelength range: 4800 - 9800Å. Left image: median spectroscopic flat field (5 images used); Right image: as before but after "normalising" the image by removing the overall lamp spectrum shape. The typical fringing pattern is visible in the lower part of both panels (corresponding to $\lambda > 7000$Å); it is caused by interference of multiple reflections between the two surfaces of the CCD. Even if the fringing pattern is visible in the spectroscopic flat, it is not fully removed by it, since it is an additive component and not a multiplicative one.

4.6 2D Scientific Frame pre-reduction

Once all calibration images are prepared, all images (both spectra and calibration lamps) must be corrected for BPM, overscan (if possible), trimmed, and then corrected for bias, flat and illumination. This can be done simultaneously, for example for a list of scientific spectra, using the usual IRAF task *ccdproc*, and all Masterframes created previously:

```
epar ccdproc

images="@speclist"        (list of all the scientific spectra)
output="@speclist_corr"   (list with the same files in
                          the input list, preceded by "r.")
zero="masterbias"         (appropriate masterbias name)
flat="masterflat"         (appropriate masterflat name)
illum="illuminationflat" (appropriate illumflat name)
```

When all science and wavelength calibration lamps are processed, they are uploaded to the reduced data archive (see Sect. 7 and EP-008) together with the newly created master calibration frames, following the appropriate naming convention. The 2D reduced frames are our first level of data product.

Finally, the reduction logs in each run page in Wiki-Bo must be compiled as described Sect. 7.

4.7 A note about fringing

Fringing is caused by the multiple reflection and interference of the night-sky emission lines in the CCD substrate. This usually has the appearance of a series of "ripples" in the images. The fringing pattern is an additive effect and must be subtracted. Because strong sky emission lines are present at long wavelengths, the effect is particularly strong in the red, both in imaging (especially in the I band, while in the R band it is much fainter or negligible, depending on the CCD) and in spectroscopy. In spectroscopy, fringing is greatly reduced by flat fielding, but it is never completely removed because it is an additive and not a multiplicative component (see Fig. 5 and Fig. 8). Tests performed on the instruments used in our survey (see SMR-002) show that the fringing pattern is stable within one observing run for all the flat fields acquired with the instruments DoLoRes@TNG and EFOSC2@NTT. The EFOSC2 Users Manual suggests also to acquire internal flats with the red grism (Gr16) after each red spectrum in order to reduce the fringing pattern amplitude. For these two instruments, if flat fields were missing in a given night, Masterflats produced in other nights of the same run could still be used to prereduce the spectra. The same tests performed on the Mastreflats acquired with the CAFOS@CAHA instrument show that the fringing pattern is not stable during one run, and thus we recommend not to use Masterflats produced during one night to prereduce spectra acquired during other nights (see Appendices of SMR-002).

Our strategy requires that narrow slit spectra must be acquired for the wavelength calibration; these spectra can be in principle used also to reduce the fringing, because the fringing pattern strongly depends on the width of the slit and on the position of the star within the slit. Moreover, for a large fraction of our SPSS sample, observations will be repeated with different telescopes. In this way the final amplitude of the fringing pattern will be strongly reduced by median averaging all the spectra acquired for each SPSS, after the absolute calibration step.

5 Spectra extraction

After pre-reduction, scientific frames are now ready to be extracted. Next paragraphs describe how to perform operationally this task, along with some preliminary steps, such as the aperture width estimate. The procedure described below is fairly standard, and is fully described by Massey et al. (1992).

5.1 Aperture width estimate

The goal of our survey is to get an accurate spectral flux calibration for all the SPSS. Our observational strategy requires both narrow and wide slit spectra: the narrow slit spectra (one for each grism, usually acquired using a 2" wide slit) are used to perform accurate wavelength calibration, while the wide slit spectra (three for each grism, aquired using a 10" or 12" wide slit depending on the instrument capability) are used for the flux calibration. The wide slit ensures that:

- if the spectra are taken in photometric nights, we can gather all flux recorded on our frames;
- if the spectra are taken under non-optimal sky conditions (but grey extinction), we do not suffer *differential* light loss, and can recover the correct spectral shape. In this case the spectra will be flux calibrated using photometric data, following a subsequent protocol (GA-006).

In both cases we want to measure all the recorded flux and avoid differential (wavelength dependent) light loss, therefore we must estimate with great care the extraction width, to make sure that the faint wings of the spectrum are properly included.

Under the simple assumption that the 2D profile of the spectrum along the dispersion axis is described by a Gaussian function, most of the flux (99.7%) falls within the $\pm 3\sigma$ interval. The full width at half maximum (FWHM) of a Gaussian function is related to σ by the formula σ=FWHM/2.3548. This means that an aperture equal to ~ 2.55 FWHM (i.e. 6σ) contains 99.7% of the recorded photons. Nevertheless a real star can be better approximated by a Moffat function (or a linear combination of Moffat functions, see Racine 1996). A Moffat function looks similar to a Gaussian, but is a better representation of the PSF because of its higher (and thus wider) "wings" (Moffat, 1969). For this reason, supported also by tests on real spectra, a wider aperture is recommended to extract both narrow and wide slit spectra. An aperture equal to $6\times$FWHM allows us to extract more than 99% of the flux and does not introduce additional wavelength dependent light loss. Much larger extraction apertures, on the other hand, can be more easily affected by close sources falling in the slit or by background irregularities, spurious defects or cosmic rays.

The FWHM can be measured at several positions across the spectrum and used to estimate the extraction aperture width. Since the seeing is higher at shorter wavelengths, we recommend to measure the FWHM in the blue side of the spectrum, in order to minimize wavelength dependent light loss. The seeing measurement can be done with IRAF task *splot*, included in the *specred* package and its profile fitting key `k`:

```
splot r.spectra.fits
```

The output of this command, the FWHM of the Gaussian fit and the centroid of the fit, will be automatically written by IRAF in the file splot.log. Because the atmospheric conditions are not always perfectly stable, the FWHM should be measured for each image, in order to use the best aperture size for each image. Users can found in Wiki-Bo, in the *"Spectroscopy Reduction and Analysis"* pages, tar files containing simple scripts (*TELNAME_grism_seeing.cl* and *TELNAME_grism_contin.curs*) useful to automatically measure the seeing. Before running the scripts *TELNAME_grism_seeing.cl* users should first edit the field :

```
list="speclist.lis" (using different name for different grisms)
```

where the file speclist.lis, for each grism list the name of all the spectra needing seeing measurement. The script measures the FWHM and sets the most suitable extraction aperture, saving this information in a text file called *Aperture_GRISMNAME.txt*. The two files produced (one for each grism) should be combined together in a file called *Aperture_seeing_YYYYMMDD.txt*, as in the example below, and uploaded in the observing log pages, as explained in Sect. 7.

```
#Filename          seeing(px)   seeing(arcsec)  aperture(pixels)
#LR-B Spectra
r.KLTA0105.fits     3.544        0.886            22
r.KLTA0106.fits     3.669        0.91725          23
r.KLTA0107.fits     3.418        0.8545           21
r.KLTA0114.fits     2.982        0.7455           18

#LR-R Spectra
r.KLTA0108.fits     3.363        0.84075          21
r.KLTA0109.fits     3.238        0.8095           20
r.KLTA0110.fits     3.355        0.83875          21
r.KLTA0120.fits     2.812        0.703            17
```

TABLE 4:

Slit width	R (slit/seeing)	Spectrum type
≥ 10" (wide slit)	$R \geq 6$	wide
≥ 10" (wide slit)	$1.5 \leq R < 6$	narrow
≥ 10" (wide slit)	$1.5 \leq R$	fail
< 2.5" (narrow slit)	$1.5 \leq R \leq 6$	narrow
< 2.5" (narrow slit)	$R < 1.5$	wavecal only

5.2 Narrow and wide spectra QC1

A first Quality Control (QC) on the spectra should be performed at this level. Since we adopt a wide slit to acquire spectra (10" or 12", depending on the instrument capability) each spectrum is considered *wide*, and hence suitable to perform accurate flux calibration, only if the ratio (R) between the slit width and the seeing measured is greater than 6. If all the spectra obtained with a wide slit for each SPSS pass this QC, the corresponding SPSS can be labelled in blue in the Reduction Logs, if the SPSS spectra also pass the Signal to Noise QC, as explained in Sect. 5.3.2, Sect. 6.6 and Sect. 7.2; if one or more spectra of a single SPSS dataset has $1.5 < R < 6$, the SPSS will be labelled in purple and moved to the *narrow* spectra sample. If all the spectra acquired with the wide slit have $R < 1.5$, the QC1 should be considered failed and the SPSS will be labelled in red in the Reduction Logs. In this case a note should be added in the Reduction Logs and the observation must be repeated.

Similarly, spectra obtained with a narrow slit (usually < 2.5"), and primarily acquired to obtain accurate wavelength calibration, should be classified as narrow only if $R > 1.5$, because in this case a simple correction can be applied to recover differential light losses (GA-006) and these narrow spectra could be used to increase the S/N ratio of the final flux tables. If they do not pass this QC step, a note should be added in the reduction logs (as explained in Sect. 7.2) and those spectra will be only used to perform the wavelength calibration (see Sect. 6). Tab. 4 summarizes the QC criteria above, where R is the ratio between the slit width and the seeing measured as in Sect 5.1.

5.3 Spectra extraction

Single slit spectra can be extracted with IRAF task `apall`. This is quite a complex task that, as explained in the IRAF help page, *"provides functions for defining, modifying, tracing, and extracting apertures from two dimensional spectra. The functions desired are selected using switch parameters. When the task is run interactively queries are made at each step allowing additional control of the operations performed on each input image"*. We summarize here the main steps that are needed for our spectra reduction:

5.3.1 Frame Inspection

For each SPSS spectrum frame, using for example the IRAF task `display` and the ds9 tool, find out where the target is located in the frame and whether the target is well isolated or if there are other sources which can contaminate it. Spectra which are found to be contaminated by companions or other disturbing effects should be labelled purple in the data reduction logs (see Sect. 7). SPSS stars are usually bright (Fig. 9), and are generally located in the middle of the frame, although in few special cases there are two SPSS in the same frame.

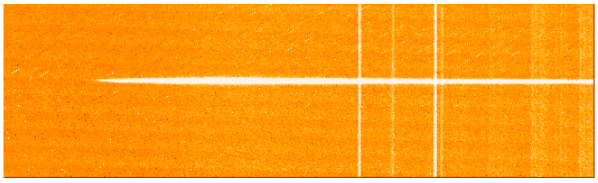


FIGURE 9: Two-dimensional spectrum, ready to be extracted.

5.3.2 Pre-reduced 2D Spectra QC2

The second quality check on the spectra should be performed after the pre-reduction steps. Since the final goal of our survey is to achieve precise and accurate flux calibration, we should ensure that all the spectra acquired have a Signal to Noise good enough for this purpose. At the same time we should be careful to use spectra near the saturation or with counts beyond the limits of the CCD linear behaviour (see Tab. 3). As already done for the Flat Fields QC, users can check the number of counts of the pre-reduced 2D spectra by using the command:

```
imstat  @preredspectra.lis [x1:x2,y1:y2]
```

limiting the statistics in a narrow strip ($\sim 20 - 30$ pixels) along the dispersion axis including the spectra.

We can distinguish three different cases for the results of the QC2 performed on the pre-reduced 2D spectra:

- If the number of counts per pixel is below the limit of the CCD linear behaviour along the whole dispersion axis in all the spectra acquired for each SPSS, the SPSS can be labelled in blue in the reduction logs, if the same SPSS also passes the QC1 and the QC3 (see Sect. 5.2 and Sect. 6.6), following the prescription summarized in Sect. 7.2.

- If the number of counts per pixel exceed the limit of linear behaviour in a region smaller than 100 pixels in one or more of the spectra of a single SPSS, the same SPSS will be labelled in purple in the reduction logs.
- If the number of counts per pixel exceed the limit of linear behaviour in a region wider than 100 pixels for all the spectra of a single SPSS the QC2 should be considered failed. In this case, the SPSS will be labelled in red in the reduction logs and a note should be added advising that the observation must be repeated

5.3.3 Parameters setting

Before running the *apall* IRAF task, some of the parameters can be configured automatically, running the script *setapall.cl*; different versions of the script for each instrument and grism can be found on Wiki-Bo. After running the script, there are only a few parameters left to configure, as shown below:

```
epar apall


input    =  r.imagename.fits      (input spectrum)
(output  =  r.imagename_ap.fits   (output spectrum)

                            # DEFAULT APERTURE PARAMETERS

(lower   =      -3xFWHM       (Lower aperture limit relative to center)
(upper   =       3xFWHM       (Upper aperture limit relative to center)

                            # DEFAULT BACKGROUND PARAMETERS

(b_order=                 3)       (Background function order)
(b_sampl=-x2:-x1,y1:y2    )        (Background sample regions)
```

A description of the principle parameters of the `apall` task is given in Section 3 of Massey et al. (1992).

5.3.4 Review the aperture and the background

Some parameters should be defined before running the task: the parameters `lower` and `upper` set the aperture width. As discussed above, we want to gather as much of the light from the target as possible, so we set the total aperture to 6×FWHM. When running *apall* interactively,

it is possible when necessary to review the aperture using the `d` (delete), `n` (new), and `g` (new fit) keys. In case of doubt, it is better to overestimate the aperture size, especially if there are no other objects near the target and the background looks smooth and regular: the "optimal extraction" algorithm employed by *apall* will weight each pixel appropriately, based on the signal-to-noise.

The `b_sample` field sets the background region: the background windows should be as close as possible to the object aperture, to be representative of the sky below the object, but far enough to avoid contaminating light from the object wings. A suitable first guess could be a background region of $\simeq 50$ pixels on both sides of the spectrum, $\simeq 10$ FWHM far from the object. The background position can be modified interactively, using the `b` key (background) in the interactive window, the `t` key to delete the existing sample regions, the `s` key to define two new regions on both sides of the object aperture, and `f` to fit the new background regions.

5.3.5 Trace the spectrum

Spectra are never perfectly parallel to the CCD lines or columns, and often they are curved or distorted. Tracing takes care of this, by "following" the object and the background aperture along the dispersion axis. To do this, answer "yes" to the queries *Trace spectra?*, *Fit curve to aperture 1 of the spectrum interactively?* If your object is bright, as expected, the tracing automatically performed by IRAF will be well fitted as shown in Fig. 10. If IRAF reports that it

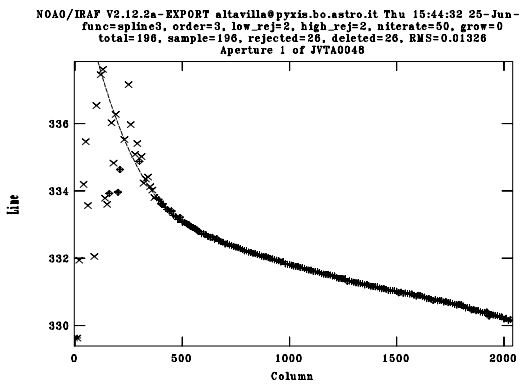


FIGURE 10: Spectrum tracing as shown by the graphic interface of `apall`.

lost the trace, try increasing the `nsum` parameter (e.g., `:nsum 50`). The resulting fit should be very good with an RMS usually much smaller than 1. Delete outlying points and all points in the CCD region outside the spectral range of the grism with the `d` key, if the automatic rejection is not enough and type `f` to make a new fit. When a suitable fit is achieved, type `q` to quit and answer "yes" to the following questions: *write aperture to database?*, *extract aperture spectra?* and *review extracted spectra?*.

5.3.6 The extracted spectra

The default output of *apall* is a one-dimensional spectrum. In our case, we set the parameters with setapall.cl, and this produces an output file which contains four spectra (see Fig. 11) which can be plotted with the *splot* command:

- band 1 is the optimally extracted, sky-subtracted spectrum[11];
- band 2 is the same as band 1, but without optimal extraction;
- band 3 is the sky background;
- band 4 is an estimate of the noise associated to the band 1 spectrum.

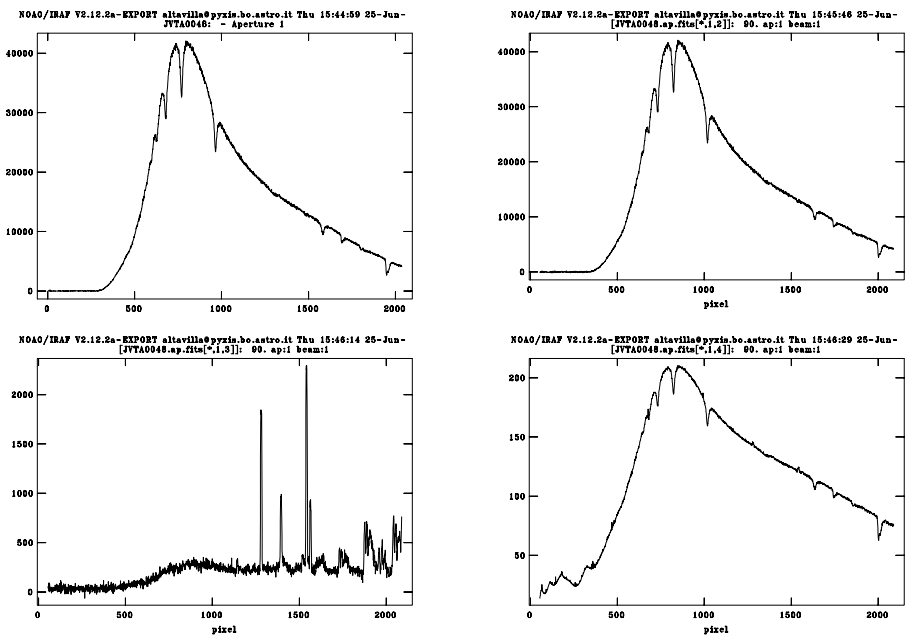


FIGURE 11: The results of the spectra extraction with apall. Top left: optimally extracted, sky-subtracted spectrum. Top right: non-optimally extracted, sky-subtracted spectrum. Bottom left: sky background. Sky emission lines, which are useful for wavelenght calibration, are clearly visible. Bottom right: signal-to-noise spectrum.

[11]The optimal extraction (selected setting `weights = variance` in `apall`) gives more weight to high signal-to-noise pixels than to the low signal-to-noise pixels. You can imagine that the profile of an object on a 2D frame looks something like a Gaussian. The centroid is well above the noise, and the wings are not much above the noise. A smart extraction would place more weight on the bright, high signal-to-noise pixels rather than on the faint, low signal-to-noise wings. The weights are based on the noise statistics, in particular optimal extractions are weighted by the variance based on the data values and a Poisson/CCD model using the gain and readout noise parameters. Variance weighting is often called "optimal" extraction because it produces the best unbiased signal-to-noise estimate of the flux in the two dimensional profile (Horne, 1986; Kinney et al., 1990).

The difference between optimal and non-optimal extraction is generally negligible for high signal-to-noise spectra (Valdes, 1992) (see also the two top spectra shown in Fig. 11, and their ratio shown in Fig. 12). We configured apall with the *setapall.cl* task, which imposes

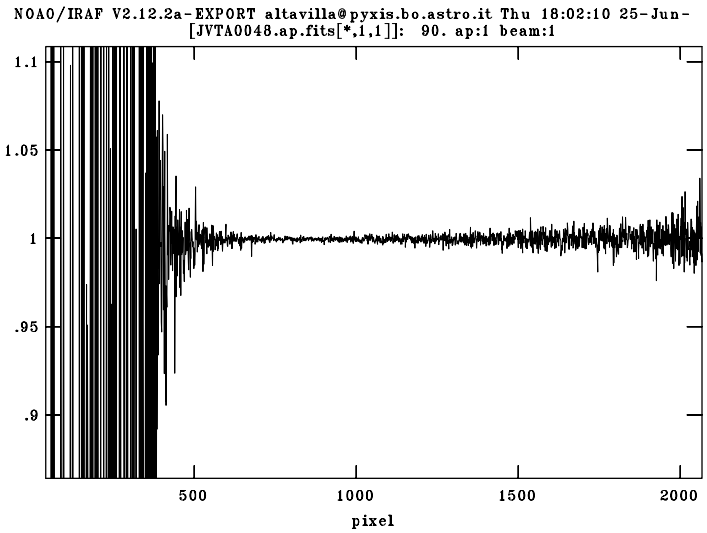


FIGURE 12: Ratio between optimal and non-optimal extraction of a high S/N (S/N≈250) spectrum.

`clean=yes`[12] This is the best choice if the spectrum is characterized by broad absorption lines. If the target spectrum is characterized by very narrow lines, the `clean = no` option could be a better choice to avoid rejecting true features along with bad pixels.

We recall that the extracted spectra, before being calibrated in wavelength, are not one of the intermediate data products and thus they do not need to be uploaded into the reduced data archive.

6 Wavelength calibration

Extracted spectra are now ready to be wavelength calibrated. The concepts for mapping pixels onto wavelengths are described in the next paragraphs, while an extensive discussion and more examples can be found in Massey et al. (1992).

In our strategy, the narrow spectra (usually taken with the 2" slit) are calibrated in wavelength using the procedure described below, and they are later used to calibrate the wide spectra (usually taken with the 10" or 12" slit) by means of cross-correlation.

[12] If the `clean = yes` is set, then the weights used are "variance" regardless of the weights specified by the `weights` parameter.

6.1 Extract wavelength calibration lamp

Adopting the observational strategy described in (EP-006) each narrow-slit spectrum must have a corresponding calibration lamp, observed at the same position on the sky. The first step of the wavelenght calibration is to extract the calibration lamps[13] spectra with the same aperture and tracing of the spectrum to be calibrated. This can be done running the script *setapall_lamp.cl* first and then editing the IRAF task *apall*:

```
cl < setapall_lamp.cl
epar apall

input    =      r.lampname   (List of input images)
(output =   r.lampname_ap)   (List of output spectra)
(apertur=                 )  (Apertures)
(format =        onedspec )  (Extracted spectra format)
(REFEREN=     r.reference )  (List of aperture reference images)
```

The reference frame is the narrow slit spectrum acquired soon before (or soon after) the calibration lamp: in this way the parameters used to find, recentre and resize the apertures, and trace the reference spectrum, can be used to extract the lamp spectrum. Of course the background must not be subtracted: if the `backgro` parameter is switched on, the task would subtract the lamp spectrum from itself. Fig. 13 shows as example of an extracted Helium calibration lamp.

6.2 Determine the dispersion solution

The dispersion solution, for a given spectroscopic set-up, is determined by assigning to a sufficient number of pixels, properly distributed along the dispersion axis, their corresponding wavelength. This can be done by comparing the position of the emission lines in the extracted spectrum of the calibration lamp (as the one shown in Fig. 13) with line Atlases or tables reporting laboratory rest wavelength of that calibration lamp (see Fig. 13)[14]. All the lamp line Atlases and tables necessary for our survey can be found in Wiki-Bo[15].

A little care must be applied when comparing extracted spectra with template spectra and tables, for example the direction of the wavelength axis may be flipped. The extracted spectrum of a calibration lamp generally shows lines of different intensity with respect to the laboratory

[13]The observational strategy, and the wavelength calibration procedure at TNG is a bit more complex, and will be discussed in Appendix B.

[14]from `http://www.tng.iac.es/instruments/lrs/oldtable.html`

[15]`http://yoda.bo.astro.it/wiki/index.php/Main_Page{#}Spectroscopy_Reductions`

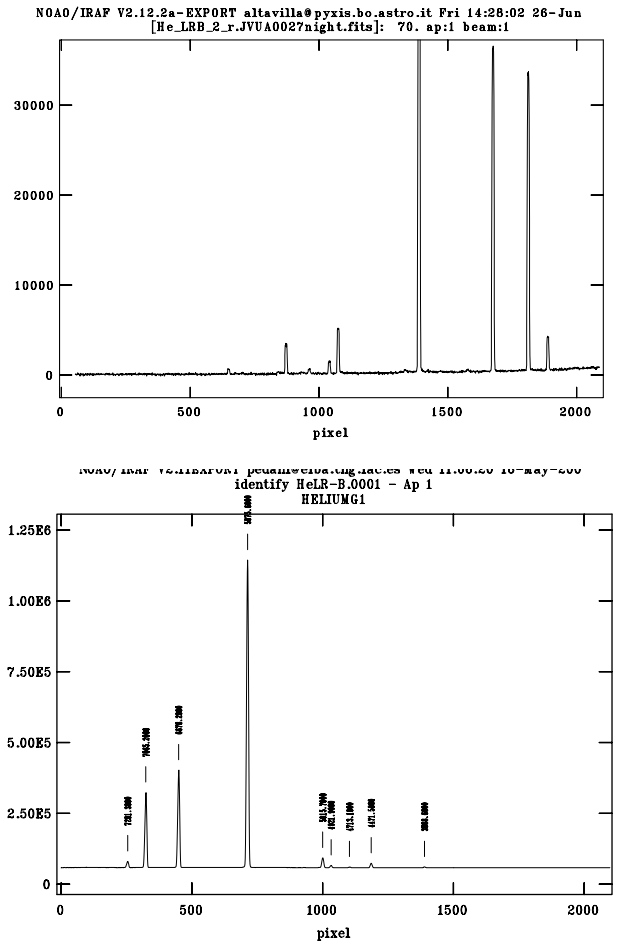


FIGURE 13: Top panel: one-dimensional extracted Helium calibration arc. Bottom panel: atlas of the Helium lamp with rest frame wavelength of the emission lines.

spectrum (see Fig. 13), this happens when the lamp operating temperatures are different. Also, if lamps of different elements are observed together, a given exposure time has a different effect on the line intensity of different elements, making the pattern somewhat more difficult to recognize.

The fit of these data produce the dispersion solution. The IRAF task which performs this operation is *identify*. The parameters configuration can be obtained running first the script *setidentify.cl* and then the *identify* IRAF task:

```
cl < setidentify.cl
epar identify

images  =   r.lampname_ap Images containing features
                              to be identified
```

```
(coordli=  Atlas.dat        ) User coordinate list
```

The task is run interactively, and both the lamp Atlas and the list of laboratory wavelengths that can be found in Wiki-Bo (see above) are used to identify the lines. All the steps described are shown in Fig 14. As a first step we suggest to manually identify a few lines in the interactive window and perform a preliminary fit. The typical RMS using few lines is very low. Using now the reference table all the lines will be automatically added using the command `l`, and a new fit with all the lines can be computed. The RMS can be now much worse, because

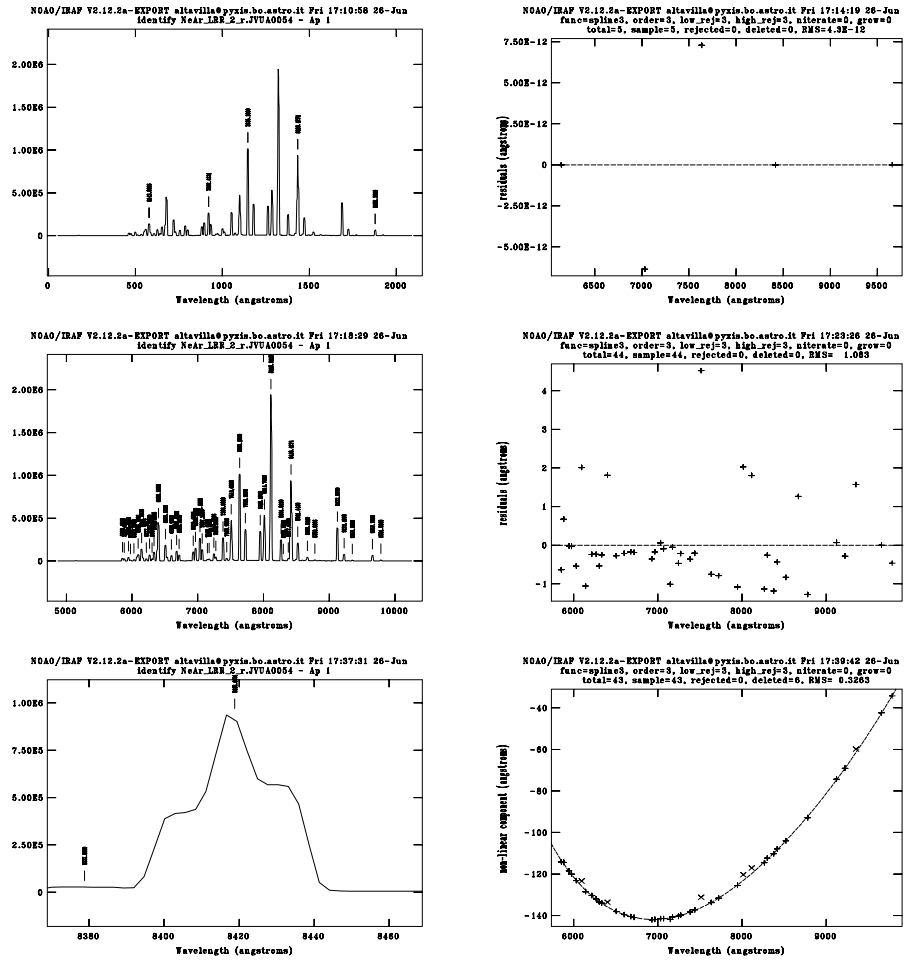


FIGURE 14: Upper left: a few lines are manually identified on the extracted arc spectrum. Upper right: a first fit is done. Middle left: using the reference table all the lines are automatically added. Middle right: a fit with all the lines is performed. The RMS is now much worse (1.08Å). Bottom left: lines are carefully inspected, and faint, noisy, blended or spurious features, such as the one in this plot, are deleted. Bottom right: the new fit is now computed with a better RMS, 0.33Å in this particular case, and the non linear part of the dispersion solution shows a plausible, smooth trend. Note that the shape of the non linear residual can change from instrument to instrument.

faint, noisy, blended, spurious or saturated features are included in the fit. After cleaning the line list, a new fit can be performed. The fitting function can be changed when necessary, but usually a cubic spline of order 2-3 gives good results. Residuals of 0.2-0.3Å can be considered satisfactory and at least 10-15 lines, distributed along the whole wavelength range, should be identified. Both the residual plot and the non-linear component plot (see Fig. 14) should show a smooth trend. Once the fit is satisfactory, the features will be automatically written in the database directory, simply quitting the task. It is important to note that the RMS of the fit is necessary to compute the wavelength calibration uncertainty, so it should be recorded in an ascii file containing all the narrow frames of a given night, with their RMS uncertainty: this file should be called *CalibrationWavelength_RMS_YYYYMMDD.txt*, as the file showed below in the example and must be saved in Wiki-bo as explained in Sect. 7.

```
#FILENAME                                RMS(Angstrom)
#Gr11 Lamp Spectra
r.EFOSC2_0156_ap.0001.fits                 0.168
r.EFOSC2_0183_ap.0001.fits                 0.137
r.EFOSC2_0183_ap_shift168.fits             0.143
r.EFOSC2_0183_ap_shift171.fits             0.144
r.EFOSC2_0192_ap_shift204.fits             0.135
#Gr16 Lamp Spectra
r.EFOSC2_0157_ap.0001.fits                 0.151
r.EFOSC2_0193_ap.0001.fits                 0.180
r.EFOSC2_0184_ap_shift173.fits             0.179
r.EFOSC2_0184_ap_shift174.fits             0.172
r.EFOSC2_0193_ap_shift213.fits             0.188
```

Usually, during the same run, many wavelength calibration lamps are acquired with the same configuration and the same exposure time. In this case all the lamp spectra but the first one can be processed with the IRAF task `reidentify`, which uses the output of `identify` as a guide to calibrate the subsequent lamp spectra in a fully automatic way. A typical set-up can be the following:

```
cl < setreidentify.cl
epar  reidentify

referenc=    r.lampname_ap      (Reference image)
images  =  r.otherlamps_ap      (Images to be reidentified)
shift =              INDEF      (default option)
(coordli=        Atlas.dat      (User coordinate list)
```

When necessary the task can be used in interactive mode, which allows the user to refine the

new solution following the same procedure described for the *identify* task. The RMS of the new dispersion solution is expected to be similar to that obtained for the reference image, and must be saved in the same text file. A faster result is obtained by fixing the parameter `shift` to the actual linear shift between the reference image and the image to be calibrated. The shift must be expressed in Å.

6.3 Assign the wavelength solution to the narrow slit spectra

After determining the dispersion solutions for the extracted calibration lamps and before applying them to the corresponding target spectra, IRAF requires an intermediate step, which consists in assigning to each spectrum that will be calibrated the corresponding wavelength calibration lamp. The task writes the reference calibration lamp into each input spectrum fits header, using a dedicated keyword.

```
cl < setrefspectra.cl
epar  refspectra

input    =        r.imagename    List of input spectra
(referen=         r.lampname_ap) List of reference spectra
```

6.4 Apply the wavelength solution to narrow slit spectra

The next step in the calibration procedure, i.e. assigning the dispersion solution to the narrow slit spectra, can be performed running first the script *setdispcor.cl*, then the task *dispcor*:

```
cl < setdispcor.cl
epar dispcor

input    =        r.specname_ap  List of input spectra
output   =      x.specname.fits  List of output spectra
```

The two most important parameters, automatically configured by the script, are: `linearize = yes`, which allows to re-sample the spectral pixels linearly, and `flux= yes`, which ensures to conserve the total flux of the spectrum rather than the flux density. The two options produce quite different spectra, as shown in Fig. 15.

At the end of the procedure the wavelength calibration can be checked, for example, using the strong emission sky lines such as the O I at 5577Å and 6300Å or the NaD at 5892Å.

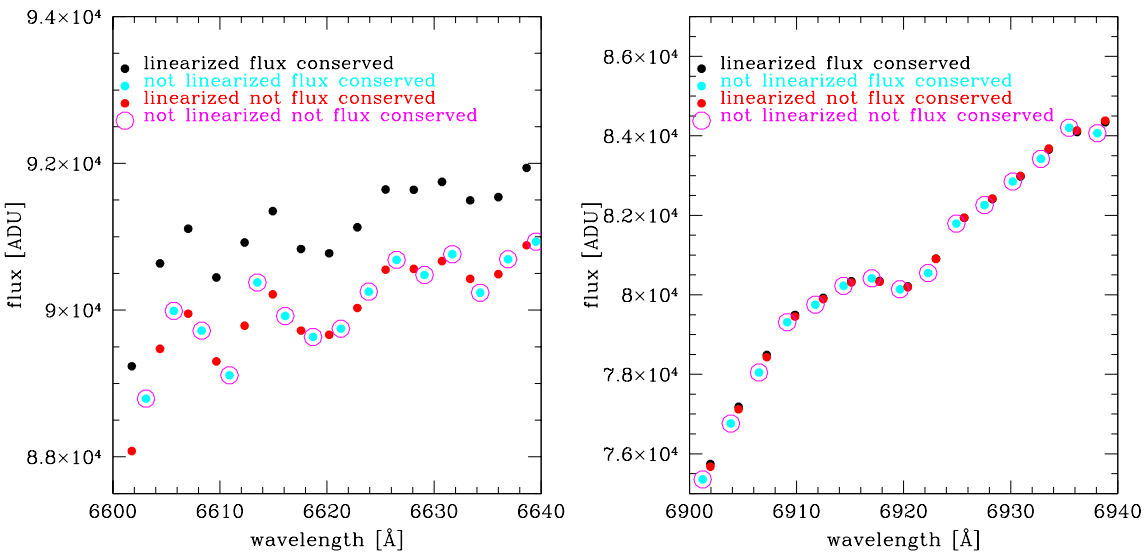


FIGURE 15: Left and Right panel: comparison between the different combinations of the parameter configuration for the dispersion solution, i.e. linearised and flux preserved wavelength calibrated data (black filled dots), the non-linearised flux preserved points (cyan filled dots), the linearised non-flux-preserved points (red filled dots) and the non-linearised non-flux-preserved points (magenta circles). Right Panel: the linearised flux-preserved points coincide with the linearised non-flux-preserved points when the wavelength step is the same (black and red dots in the right panel).Left Panel: at shorter wavelength, the linearised bins are bigger than the non-linearised spectrum, and the flux-preserved linearised points are higher because they represent the flux-integrated over a larger wavelet interval while the non-flux-conserved points are the average of the flux within the same wavelength interval.

A useful IRAF task to check the sky emission lines position is *splot*, and we recall that the 3rd aperture in the extracted spectra contains the sky spectrum.

6.5 Wavelength calibration of the wide slit spectra

The previous sections describe how to calibrate a narrow slit spectrum with the corresponding calibration lamps. A wide slit spectrum cannot be wavelength calibrated the same way, because lamp spectra taken with the same setup have lines which are too wide to provide the desired precision and are more affected by blending. Therefore lines cannot be easily identified and used to determine an accurate dispersion solution. Moreover the star centreing in a wide slit is less constrained than in a narrow slit, further degrading the precision of the wavelength calibration.

Because the central position (in pixels) of a narrow slit is generally different from that of a wide slit[16], it is not possible to apply the dispersion solution of a narrow slit spectrum directly to a

[16]The Calar Alto spectrograph is an extreme example of this problem, because the slit opens asymmetrically so the slit centre position on the CCD changes significantly

wide slit spectrum.

Our strategy consists in determining the offset in pixels between (almost) consecutive narrow and wide spectra of the same star, by cross-correlating them with the IRAF task `fxcor`, which performs a one-dimensional Fourier cross-correlation based on the standard Tonry & Davis (1979) algorithm:

```
cl < setfiltpars.cl
cl < setcontinpars.cl
cl < setfxcor.cl
epar fxcor

objects =     r.widespetrum_ap  Object spectrum
template=  r.narrowspectrum_ap  Template spectrum
```

Running *fxcor* interactively allows for the continuum normalization of each spectrum. Then the spectra are correlated and a series of plots are produced (see Fig. 16), including the correlation plot. Filtering of the data may be necessary to remove high frequency noise or low-frequency trends not removed by continuum subtraction.

Once the offset between the wide and the narrow slit spectra is known (with its uncertainty) it can be used to shift the corresponding wavelength calibration lamp, previously extracted, in order to match the pixel scale of the wide spectra. The first step consists in converting the fits file of the extracted lamp into an ASCII table, using the task *wspectext*:

```
unlearn wspectext
epar wspectext

input    =  r.lampname_ap.fits   (Input list of image spectra)
output   =   r.lampname_ap.dat   (Output list of text spectra)
(header =                   no   (Include header?)
```

now the shift can be applied, for example with a simple `supermongo` macro that is possible to find in Appendix C. The output of this procedure can be converted back to a fits file with the task *rspectext*:

```
unlearn rspectext
epar rspectext
```

```
input   = r.lampname_ap_shift.dat  ) Input list of text spectra
output  = r.lampname_ap_shift.fits ) Output list of image spectra
(title  =                          ) Spectrum title
(flux   =                      yes) Flux calibrated?
```

The shifted lamp can now be used for the wavelength calibration of wide slit spectra using the recipe already described in Sect. 6.2, 6.3, 6.4. The lines in the shifted calibration lamp can be easily identified with the task *reidentify*, specifying as reference image the one already calibrated and specifying a rough guess of the shift to add to reference feature: we recall that the shift must be in Ångström, and must be specified if positive or negative. The RMS of the dispersion solution must be recorded in the ascii file as described in Sect. 6.2. The task *refspec* adds the keyword of the reference calibration lamp to the wide slit spectrum, while the task *dispcor* assigns the dispersion solution to the spectrum.

The wavelength calibrated spectra (both narrow and wide) are one of the data products that need archiving and logging (see Sect. 7), and are the final data product of this particular protocol.

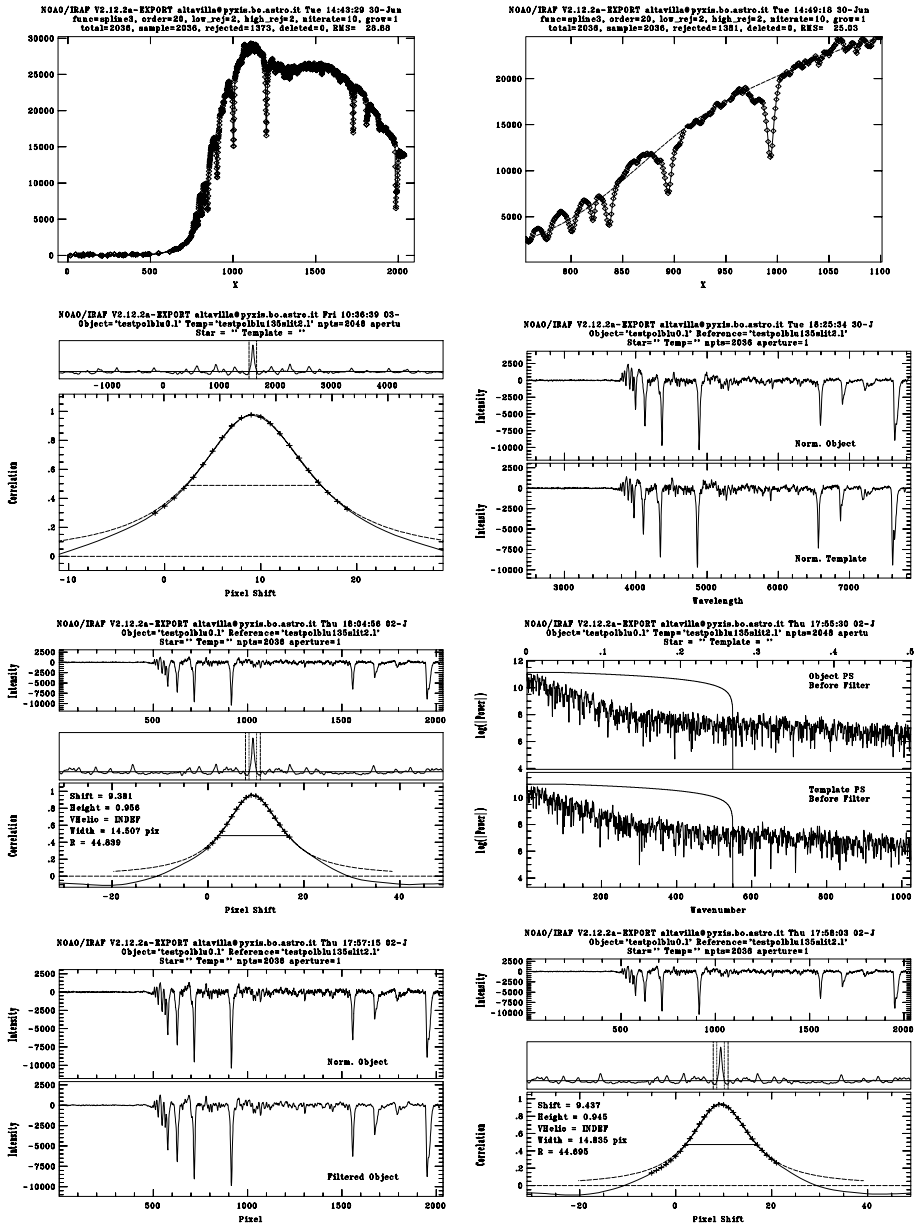


FIGURE 16: First row (from top to bottom): fitting of the continuum of the spectra (right image shows a small wavelength range in detail). Second row, left: correlation function (over a wide interval and a zoom around the peak). In this example the spectra are made to coincide with an offset of $\simeq$ 10 pixels. Second raw, right: spectra after continuum subtraction. Third row, left: summary plot. In this example the shift between the spectra is 9.381 pixels. Third row, right: a filtering of the high frequencies (noise) is applied; forth row, left: as a consequence, the spectral noise decreases. Forth row, right: the new correlation plot is shown. In this example the filtering does not affect significantly the result, the new offset is 9.437 pixels.

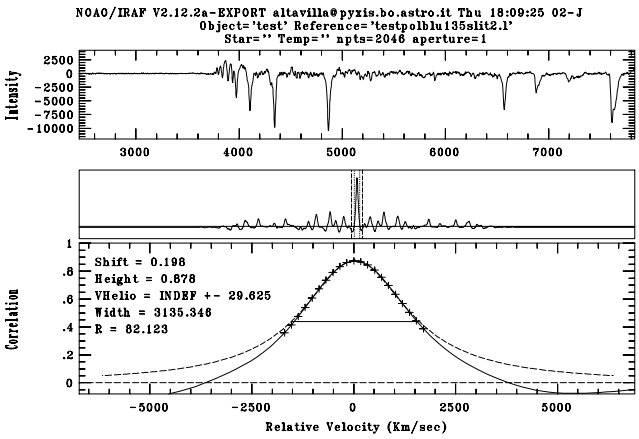


FIGURE 17: Cross-correlation of the wide and narrow slit spectra after the correction of the wavelength offset.

6.6 Wavelength Calibrated Spectra QC3

The third and last quality check should be performed after the wavelength calibration, for each spectrum. At this point we should ensure that all the spectra acquired have a Signal to Noise good enough for the purpose of our survey. We recall, as explained in Sect. 5.3.6, that each frame contains four spectra, being the *band 1* the optimally extracted and sky-subtracted spectra, while the *band 4* is the noise associated to the optimally extracted spectra. The S/N can be calculated using the command:

```
sarith x.spec.fits[*,1,1] / x.spec.fits[*,1,4] testS_N.fits
```

Each SPSS wavelength calibrated data set which passed both the QC1 and the QC2 (see Sect. 5.2 and Sect. 5.3.2) will be labelled in blue, in the reduction logs, if the S/N is larger than 100 in a region of at least 100 pixels around the peak, following the instruction summarized in Sect. 7.2. The SPSS dataset will be labelled in purple in the reduction logs, if one or more spectra have the mean value $50 < S/N < 100$ in a region of at least 500 pixels around the peak. If all the calibrated spectra of an SPSS have a mean value $S/N < 50$, the QC3 should be considered failed and the SPSS will be labelled in red in the reduction logs. A note will be added reminding that the observations must be repeated.

6.7 Difficult cases

In some special cases (for example featureless spectra) the result of the procedure described before can still have small errors, and some correction in these cases is needed.

The result of the calibration can be checked using the task *fxcorr* and the wavelength calibrated narrow slit spectrum as reference (template) image. Selecting the option `pixcorr =yes` the shift is expressed in pixels. If we assume that the small residual errors are just linear shifts, it is possible to modify the wide slit spectrum starting point of the wavelength scale by changing the *CRVAL1* keyword in the spectrum header. Because we computed the shift in pixels, it is necessary to convert it in Ångströms using the grism dispersion[17]. In the example reported in Fig. 16 we must subtract $9.437 * 2.52$ from *CRVAL1* =2471.957094568 (the scale of DOLORES is 2.52 Å pix^{-1}). The new value can be written in the header with *hedit*:

```
unlearn hedit
epar hedit

images  =      x.specname.fits  images to be edited
fields  =               CRVAL1  fields to be edited
value   =      2448.1758545688 value expression
(add    =                  yes) add rather than edit fields
(verify =                  yes) verify each edit operation
(update =                  yes) enable updating of the image header
```

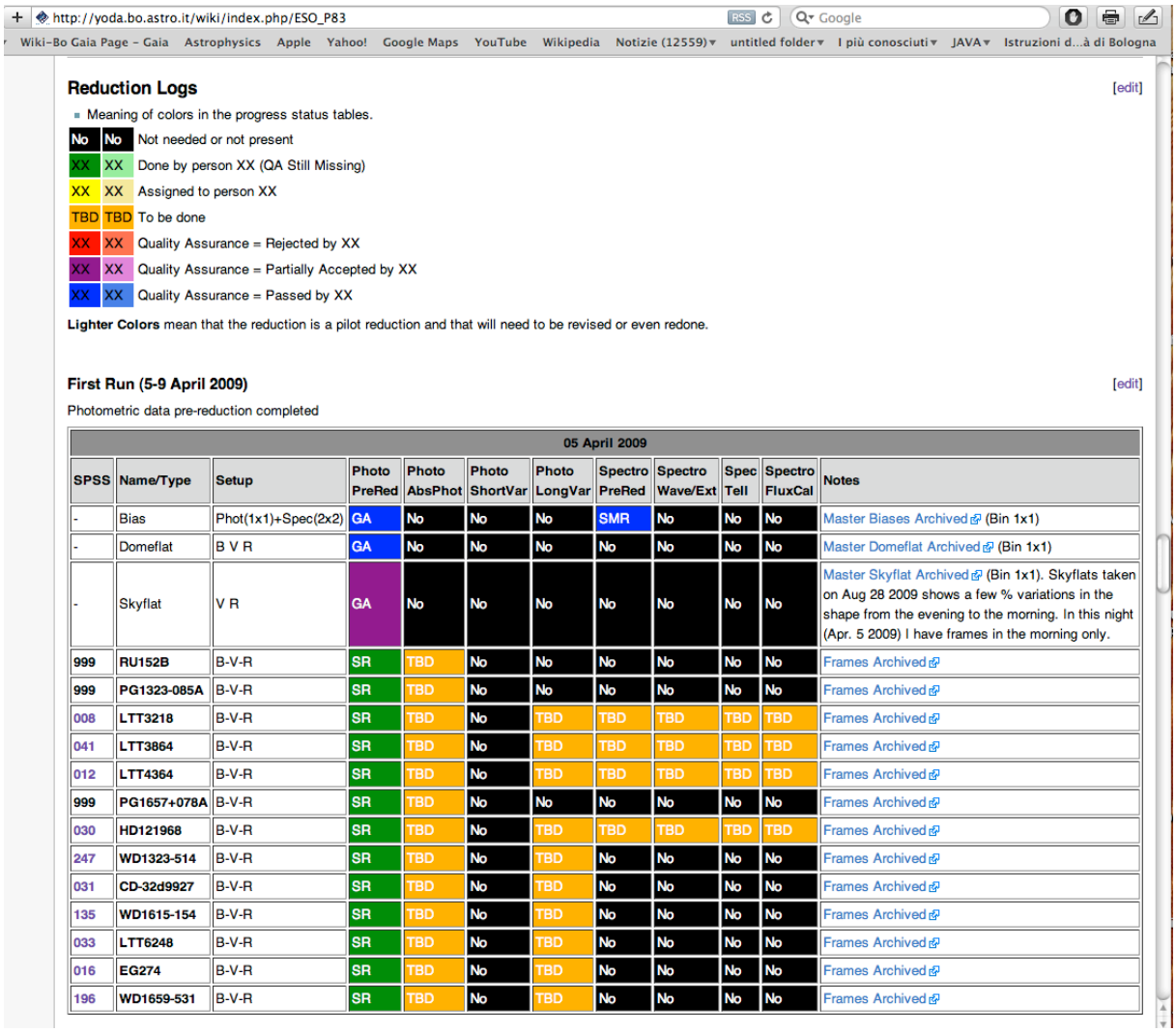
Since we modified the wavelength scale, if we want to check the result with `fxcor`, we must necessarily use `pixcorr= no`, see Fig. 17.

7 Data delivery

At the end of the procedures described in the previous sections three kinds of new data product are ready to be uploaded in our local archive of reduced data:

- all the newly created master-frames which were used to pre-reduce 2D spectra, i.e. bias, flat, bad pixel mask and possibly dark and illumination correction frames (see Sec. 4);
- all the 2D pre-reduced frames, both spectra and calibration wavelength lamps, corrected for bias, flat, overscan and so on (see Sec. 4);
- the wavelength calibrated spectra, both wide and narrow (see Sec. 5).
- the text files containing the seeing measured and the RMS of the calibration lamp dispersion solution, as explained in Sect. 5.1 and in Sect. 6.2.

[17] In the *Summary table of Observing Runs* in Wiki-Bo it is possible to find a link to the web pages of all the telescopes, with the dispersion of all the grisms we have used.



http://yoda.bo.astro.it/wiki/index.php/ESO_P83

Wiki-Bo Gaia Page - Gaia | Astrophysics | Apple | Yahoo! | Google Maps | YouTube | Wikipedia | Notizie (12559) | untitled folder | I più conosciuti | JAVA | Istruzioni d...à di Bologna

Reduction Logs [edit]

- Meaning of colors in the progress status tables.

No	No	Not needed or not present
XX	XX	Done by person XX (QA Still Missing)
XX	XX	Assigned to person XX
TBD	TBD	To be done
XX	XX	Quality Assurance = Rejected by XX
XX	XX	Quality Assurance = Partially Accepted by XX
XX	XX	Quality Assurance = Passed by XX

Lighter Colors mean that the reduction is a pilot reduction and that will need to be revised or even redone.

First Run (5-9 April 2009) [edit]

Photometric data pre-reduction completed

05 April 2009											
SPSS	Name/Type	Setup	Photo PreRed	Photo AbsPhot	Photo ShortVar	Photo LongVar	Spectro PreRed	Spectro Wave/Ext	Spec Tell	Spectro FluxCal	Notes
-	Bias	Phot(1x1)+Spec(2x2)	GA	No	No	No	SMR	No	No	No	Master Biases Archived (Bin 1x1)
-	Domeflat	B V R	GA	No	No	No	No	No	No	No	Master Domeflat Archived (Bin 1x1)
-	Skyflat	V R	GA	No	No	No	No	No	No	No	Master Skyflat Archived (Bin 1x1). Skyflats taken on Aug 28 2009 shows a few % variations in the shape from the evening to the morning. In this night (Apr. 5 2009) I have frames in the morning only.
999	RU152B	B-V-R	SR	TBD	No	No	No	No	No	No	Frames Archived
999	PG1323-085A	B-V-R	SR	TBD	No	No	No	No	No	No	Frames Archived
008	LTT3218	B-V-R	SR	TBD	No	TBD	TBD	TBD	TBD	TBD	Frames Archived
041	LTT3864	B-V-R	SR	TBD	No	TBD	TBD	TBD	TBD	TBD	Frames Archived
012	LTT4364	B-V-R	SR	TBD	No	TBD	TBD	TBD	TBD	TBD	Frames Archived
999	PG1657+078A	B-V-R	SR	TBD	No	No	No	No	No	No	Frames Archived
030	HD121968	B-V-R	SR	TBD	No	TBD	TBD	TBD	TBD	TBD	Frames Archived
247	WD1323-514	B-V-R	SR	TBD	No	TBD	No	No	No	No	Frames Archived
031	CD-32d9927	B-V-R	SR	TBD	No	TBD	No	No	No	No	Frames Archived
135	WD1615-154	B-V-R	SR	TBD	No	TBD	No	No	No	No	Frames Archived
033	LTT6248	B-V-R	SR	TBD	No	TBD	No	No	No	No	Frames Archived
016	EG274	B-V-R	SR	TBD	No	TBD	No	No	No	No	Frames Archived
196	WD1659-531	B-V-R	SR	TBD	No	TBD	No	No	No	No	Frames Archived

FIGURE 18: Example of a Reduction log for run M-010, from our Wiki-Bo. For each new data product produced and archived, the log is upgraded following our colour convention.

Instructions on how to upload data can be found in EP-008 and in Wiki-Bo, in the section *"Reduced Data Archive Requirements"*[18]. The Wiki-Bo page contains instructions on the naming convention for the three data products that should be followed strictly.

7.1 Reduction logs

The reduction steps should be documented carefully in Wiki-Bo. The steps to follow are:

1. In the web pages dedicated to the observing runs, users should compile the *Reduction logs*, necessary to summarize and easily visualize the final result of the

[18] `http://yoda.bo.astro.it/wiki/index.php/Reduced_Data_Archive_Requirements`

reduction steps and the quality assurance achieved for each data product, following the colour code convention. An example of Reduction log is shown in Fig. 18.

2. In the same page, under the *"Other"* column of the *"Observing logs"* section (see Fig. 19), users should upload the text files produced, summarizing the seeing measured for each spectrum (see Sect. 5.1), the aperture width for the extraction, and the RMS of the dispersion solution for each calibration wavelength lamp (see Sect. 6.2).

3. In the Wiki-Bo pages of each SPSS users should compile the *"Reduction Summary"*, specifying which kind of data products have been produced and the quality achieved.

4. The status of the *"Summary table of all our Observing Runs"* must be updated for each run.

Observing Logs

1st Run (Sept 09)						
Night	Official	EON Report	Obs Log	Other	Weather	Data
24 Sept 2009	DU13 Logs	EON+targets	Elog pdf	-	Clear, seeing 0.8"-1.0"	raw data Archived
25 Sept 2009	DU13 Logs	EON+targets	Elog pdf	-	Veils, seeing 0.8"-1.4"	raw data Archived
26 Sept 2009	DU13 Logs	EON+targets	Elog pdf	-	Clear, seeing 0.74"-1.7"	raw data Archived
27 Sept 2009	DU13 Logs	EON+targets	Elog pdf	-	Too High humidity (all night lost)	raw data Archived
28 Sept 2009	DU13 Logs	EON+targets	Elog pdf	-	Rain/high humidity (all night lost)	raw data Archived
2nd Run (Dec 09)						
Night	Official	EON Report	Obs Log	Other	Weather	Data
06 Dec 2009	DU13 Logs	EON+targets	Elog doc	-	Low humidity, clear (no visible clouds), seeing 0.8"-2"	raw data Archived
07 Dec 2009	DU13 Logs	EON+targets	Elog doc	-	Low humidity, a few light cirri, seeing 1"-1.4"	raw data Archived
08 Dec 2009	DU13 Logs	EON+targets	Elog doc	-	Low humidity, clear, seeing 0.9"-2"	raw data Archived
09 Dec 2009	DU13 Logs	EON+targets	Elog doc	-	Low humidity, clear to cloudy, seeing 0.9"-1.5"	raw data Archived
10 Dec 2009	DU13 Logs	EON+targets	Elog doc	-	Very high humidity, clouds, seeing 1.5"-2.5"	raw data Archived

FIGURE 19: Example of an Observing log, from our Wiki-Bo. The text files with the seeing measurement and the RMS of the dispersion solution are saved here, in the column "Other".

7.2 Summary QC criteria and results

The 3 QCs performed on the prereduced and the wavelength calibrated spectra must be documented in Wiki-bo as illustrated in 5.2, 5.3.2 and 6.6. Here below we summirize the criteria that should be followed to correctly log and archive all the prereduced wide slit SPSS spectra and all the wavelength calibrated wide slit SPSS spectra.

- If all the wide slit spectra of a single SPSS pass the QC1, QC2 and QC3 as described in 5.2, 5.3.2 and 6.6, the SPSS will be labelled in blue in the reduction logs of the

web pages dedicated to each single run. The same SPSS will be labelled in blue in the Reduction Summary in the web pages dedicated to the single SPSS.

- If the wide slit spectra of a single SPSS fail one or more of the QCs described in 5.2, 5.3.2 and 6.6, the SPSS will be labelled in red in the reduction logs in the web pages dedicated to each single run. A note should be added to remind that the observations of this SPSS should be repeated. The same SPSS will be labelled in red also in the Reduction Summary of the web pages dedicated to the single SPSS, adding the same note.
- In all the other cases the SPSS should be labelled in purple in both the Reduction Log and in the Reduction Summary. A note should also be added, to better explain the result of the QCs

The same 3 QCs should be performed also on the spectra acquired with the narrow slit; if the spectra of a single SPSS do not pass one or more of the QCs, the SPSS will be labelled accordingly with the result of the QCs performed on the wide slit spectra. A note should be added in the Reduction Logs, to better explain the result of the QCs.

8 References

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A CAFOS@2.2m Detailed Instructions

Before processing the fits files acquired with the CAFOS instrument, it is necessary to delete the BIASSEC, DATASEC and CCDSEC fields in the fits headers. This is necessary because CAFOS headers are not in a format that IRAF can process.

As an example, the header DATASEC in the CAFOS format is "DATASEC = '[x1,y1:x2,y2]'/ image portion of frame", where [x1,y1] give the bottom-left corner and [x2,y2] gives the top-right corner pixel coordinates of that image, whereas the correct IRAF format (used for example by the `ccdproc` task for trimming, bias and dark correction) is [x1,x2:y1,y2].

The wrongly formatted keywords can be removed with the commands:

```
hedit(images="*.fits",fields="BIASSEC",delete+,verify-)
hedit(images="*.fits",fields="DATASEC",delete+,verify-)
hedit(images="*.fits",fields="CCDSEC",delete+,verify-)
```

One needs to add verify- to avoid being asked each time for confirmation. The correct header keywords (CCDSEC and BIASSEC) will be added back to the header in the IRAF format as soon as `ccdproc` is run, as explained in Sect. 4.

B DoLoRes@TNG Detailed Instructions

Before run M-008 (October 2008, see the SPSS runs table in Wiki-Bo[19]) the DoLoRes calibration lamps could not be switched on simultaneously. For this reason the lamps acquisition was quite time consuming. In order to reduce the calibration observing time, we decided to take multiple high S/N calibration lamps (Ne, He, Ar) during the afternoon and a single exposure of only one element per grism (He for LR-B and Ar for LR-R) during the night, with short exposure times, soon after or before each target spectrum. The wavelength calibration of the target spectra is then performed as follows:

- the calibration lamps spectra taken in daylight are used to derive the dispersion solution using the task `identify`, as described in Sect. 6;
- the nigh-time lamp spectra of a single element are extracted in a similar way and used to derive the shift (if any) with respect to the daytime corresponding lamp spectra (this is done by cross-correlating the lamp spectra, as explained in Sect. 6.5);

[19] `http://yoda.bo.astro.it/wiki/index.php/SPSS_Runs_Table`

- the wavelength scale of each target spectrum is assigned using the solution obtained from all the daytime calibration lamps, corrected by the shift derived in the previous step if necessary.

Starting from run M-008 all the lamps can be switch-on simultaneously, and to avoid saturation of the strongest emission lines a short exposure time must be used. However, some He emission lines, which are very useful for the calibration of the bluest part of the LR-B spectra, are too faint and useless. For this reason we decided to change the strategy to acquire the wavelength calibration lamp for the LR-B grism:

- in daytime, both the All-elements lamp (with a short exposure time) and the He calibration lamp (with a longer exposure time) are acquired, so as to have high S/N lamp spectra for both lamps;
- the He and All-elements lamps are cross-correlated and combined using the procedures described in Section 6, and the combined lamp is used as reference for the calibration of the All-elements lamp spectra acquired during the night;
- during the night only the All-elements lamp is acquired for each target. The corresponding spectra are then cross-correlated with the reference lamp spectrum to compute the shift (if any).
- the wavelength scale of each target spectrum is derived using the solution obtained from the daytime reference spectrum, corrected by the shift derived in the previous step, if necessary (as described in Sect. 6). .

C SuperMongo macro

Here below we propose a simple *SuperMongo* macro which can be used to compute the shift of the wavelength calibration lamps:

```
sm

   define filename ?
   {Filename? (r.lampname_ap.dat)}
   define outputname ?
   {Outputname? (r.lampname_ap_shift.dat)}
   define shift ?
   {Shift? (wide-narrow, in pixels, beware of the binning)}
```

```
#Use iraf wspectext to create the table to be used by this macro
#of course not integer shifts and integer shifts not integer multiple
#of the original binning produce a small data interpolation

   data $filename
   read {x 1 y 2}

   erase
   limits x y
   expand 1.5
   ctype black
   box
   xlabel x
   ylabel counts
   connect x y
   set xshift0=x+$shift
   ctype red
   connect xshift0 y

   interp2 xshift0 y x yshift
   ctype blue

   connect x  yshift
   print  $outputname {x  yshift}
   write standard "##############################################"
   write standard  New data in $outputname
   write standard use rspectext to create a fits
   write standard with CRVAL1 and CDELT1  of the original image
   write standard "##############################################"
```