สถาบันวิจัยดาราศาสตร์แห่งชาติ (องค์การมหาชน)
National Astronomical Research Institute of Thailand (Public Organization)

MRES: technical evaluation of the spectrograph

Technical Report

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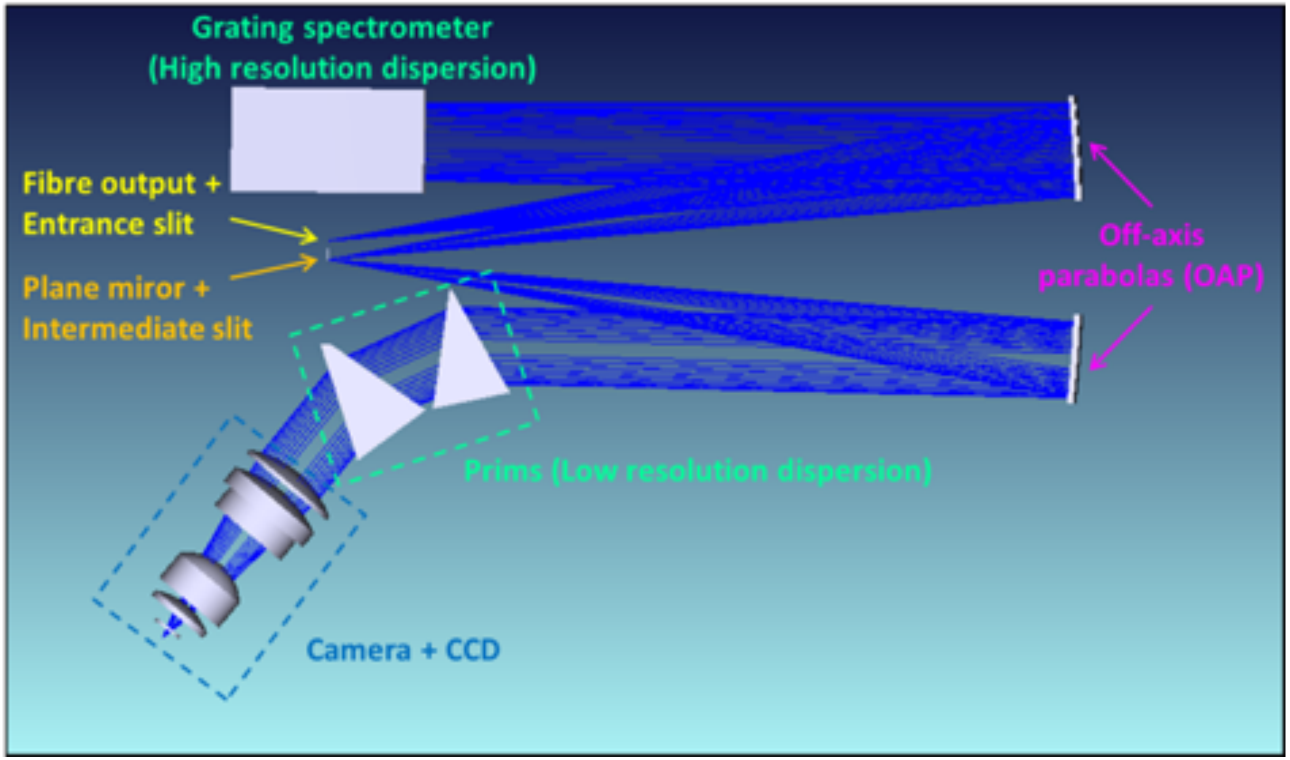
Introduction

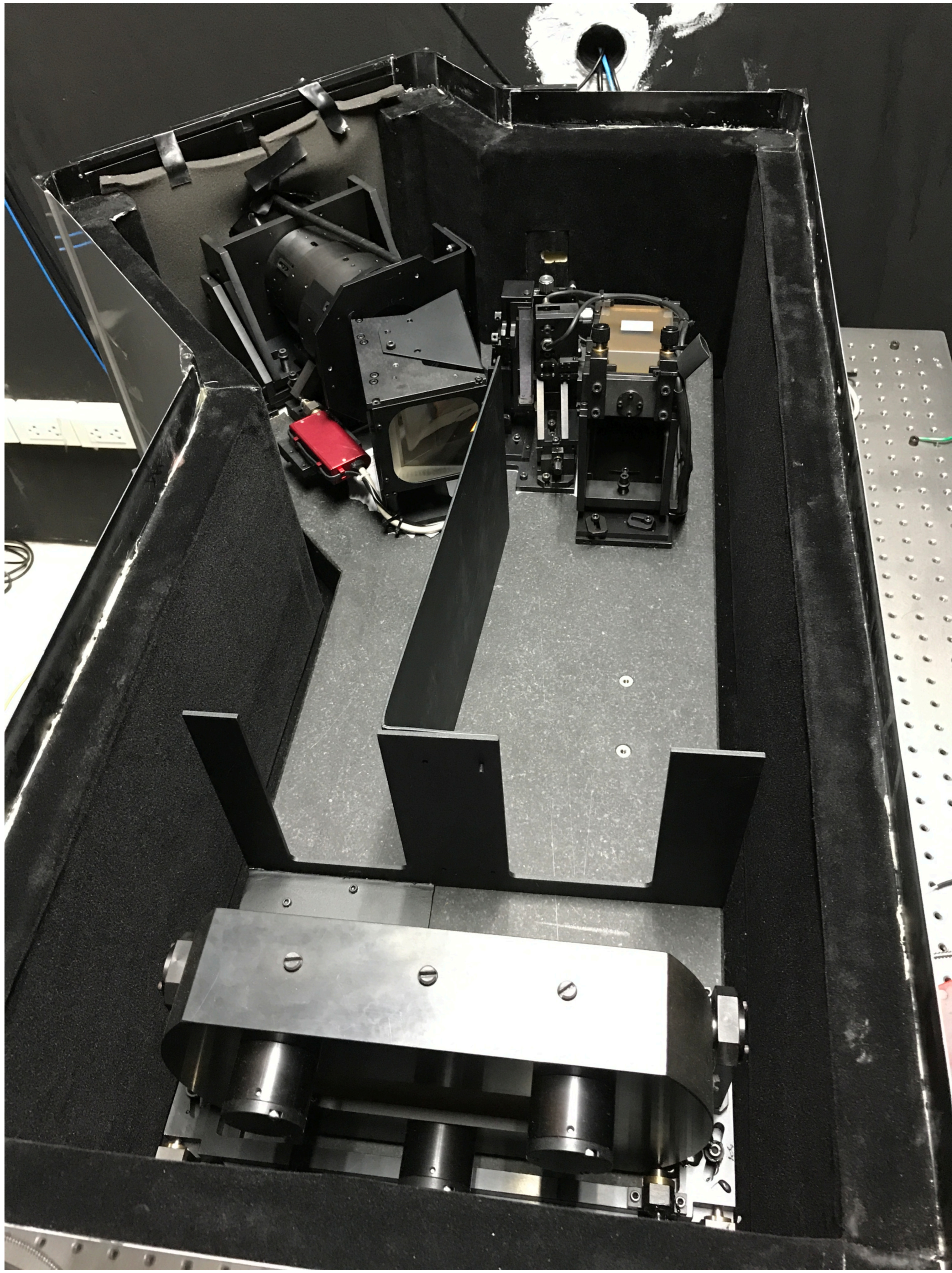
Description

- MRES (**M**iddle **R**esolution **E**chelle **S**pectrograph) was built by Nanjing Institute of Optics and Technology, National Astronomical Observatories, CAS (China) and NARIT.
- Resolving power *R* = 15,000 in the spectral range 390-880 nm (slit 1.4″, sampling approx. 2.1 px), two-pixel resolution is 17,000
- Cross-dispersed echelle spectrograph fed by fibre from one of the Nasmyth foci of the 2.4-m telescope of NARIT
- White-pupil design of the spectrograph with echelle grating at the pupil
- Peak efficiency of the spectrograph is 30% (w/o fibre)

Introduction

Description





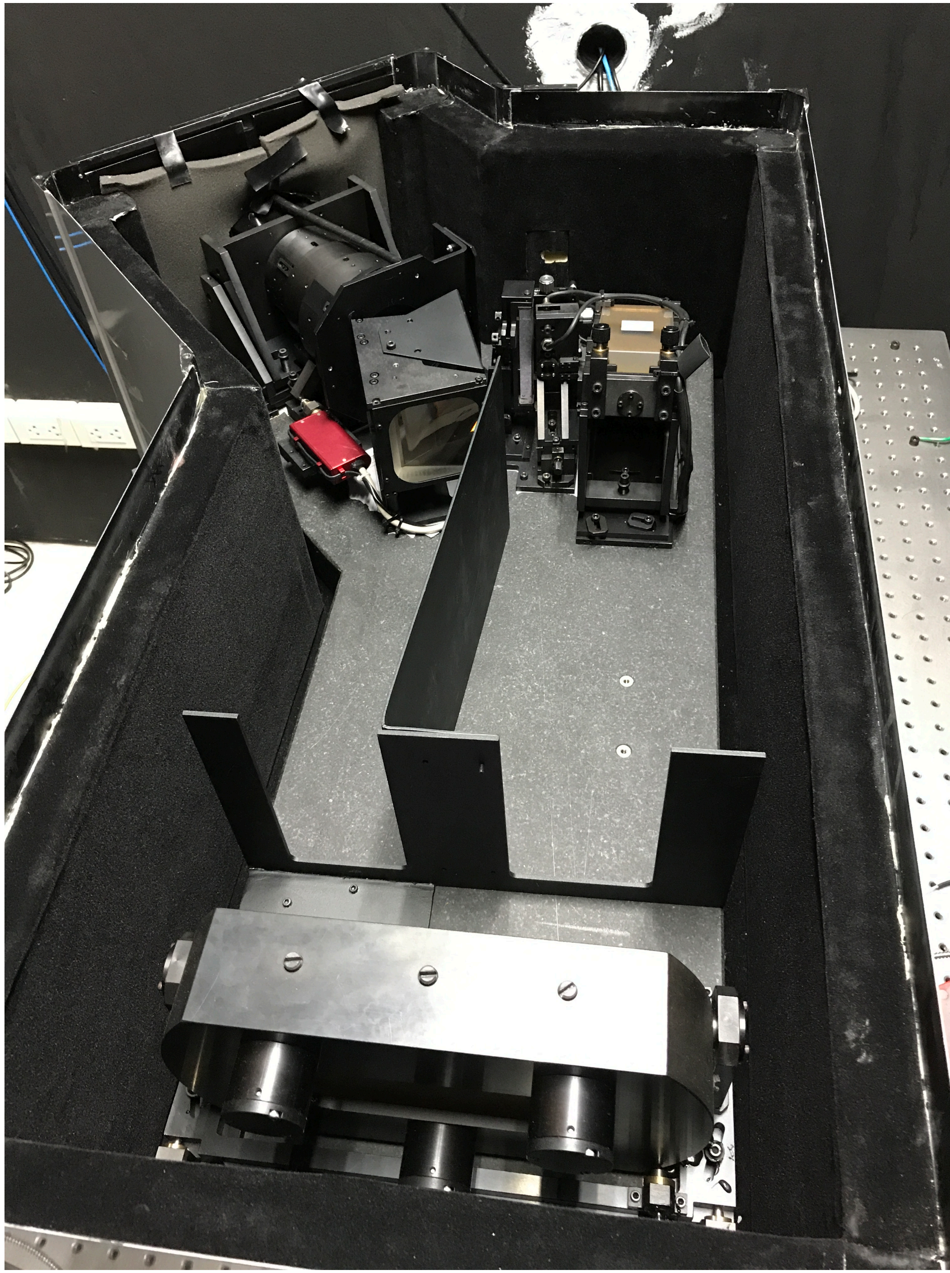
General view of the spectrograph (right) and its optical scheme

Introduction

Description

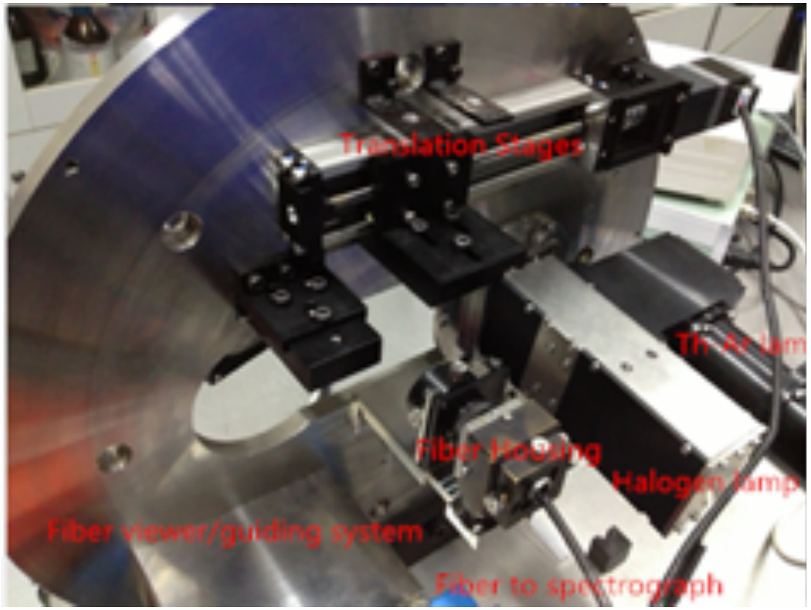
Slit	Physical dimension	Dimension error
1	0.3 mm × 0.3 mm	±4μm
2	0.3 mm × 0.17 mm	±4μm
3	0.17 mm × 0.17 mm	±4μm

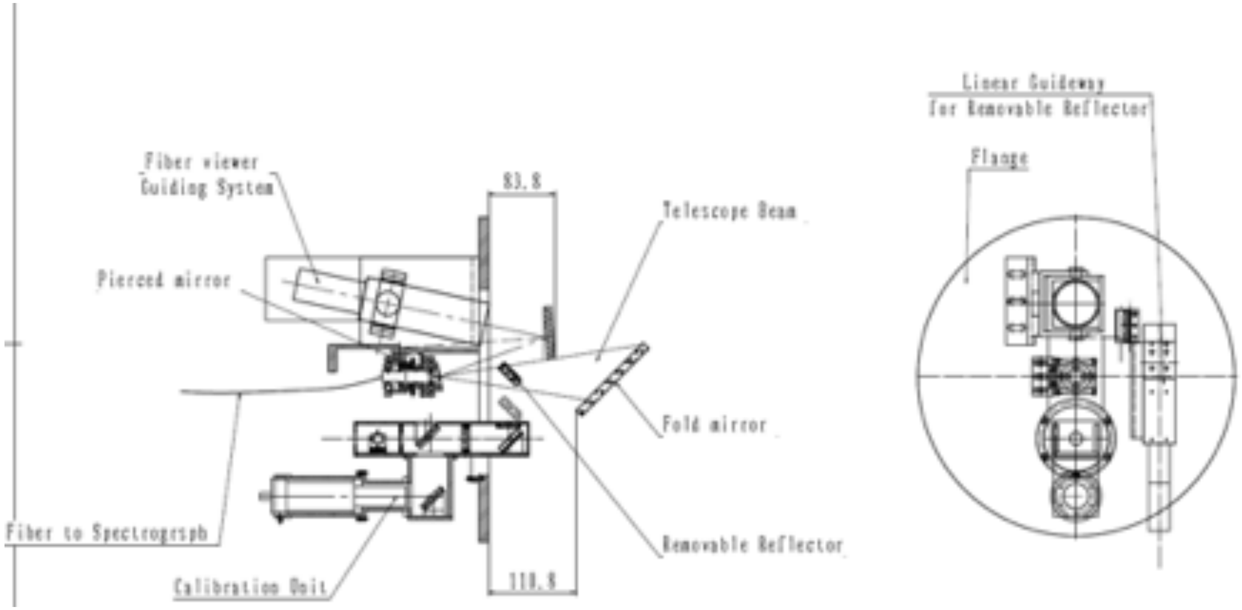
Manually changeable slits



Introduction

Description





The Nasmyth unit and its optical scheme.

Calibration unit contains a halogen lamp for flat fielding and a hole cathode Th-Ar lamp for wavelength calibration

Problems

solved in this study

1)To measure of the spectral resolution with different slits

2)To study the influence of the scattered light on the results and to construct a model for the SL subtraction

3)To evaluate the total throughput of the spectrograph

4)To create an exposure calculator

Material and tools

- Observations with 2.4-m telescope in Dec 2019 and Jan 2020 (my programme), and technical nights in Nov 2020 (with David)
- Observed sources: stars with calibrated flux (HD 92558, HD 215012, HD 218045), hot stars with fast rotation (HD 88960, HD 188001), evening sky
- Data reduction: IRAF, REDUCE, HiFLEX or … something custom

Pipeline

Requirements

- Flexibility and modularity (scripting language, multiplatform, easy to modify the sequence of operations)
- High speed of reduction (multiply repeated reduction)
- Optimal method of data extraction (few implemented methods are preferable)
- Potential for adaptation to changes (new detector, different format of input data, etc)

⇒ a python-based pipeline written by Vadim Krushinskiy (UFU, Russia) was chosen for modification

Pipeline

Structure

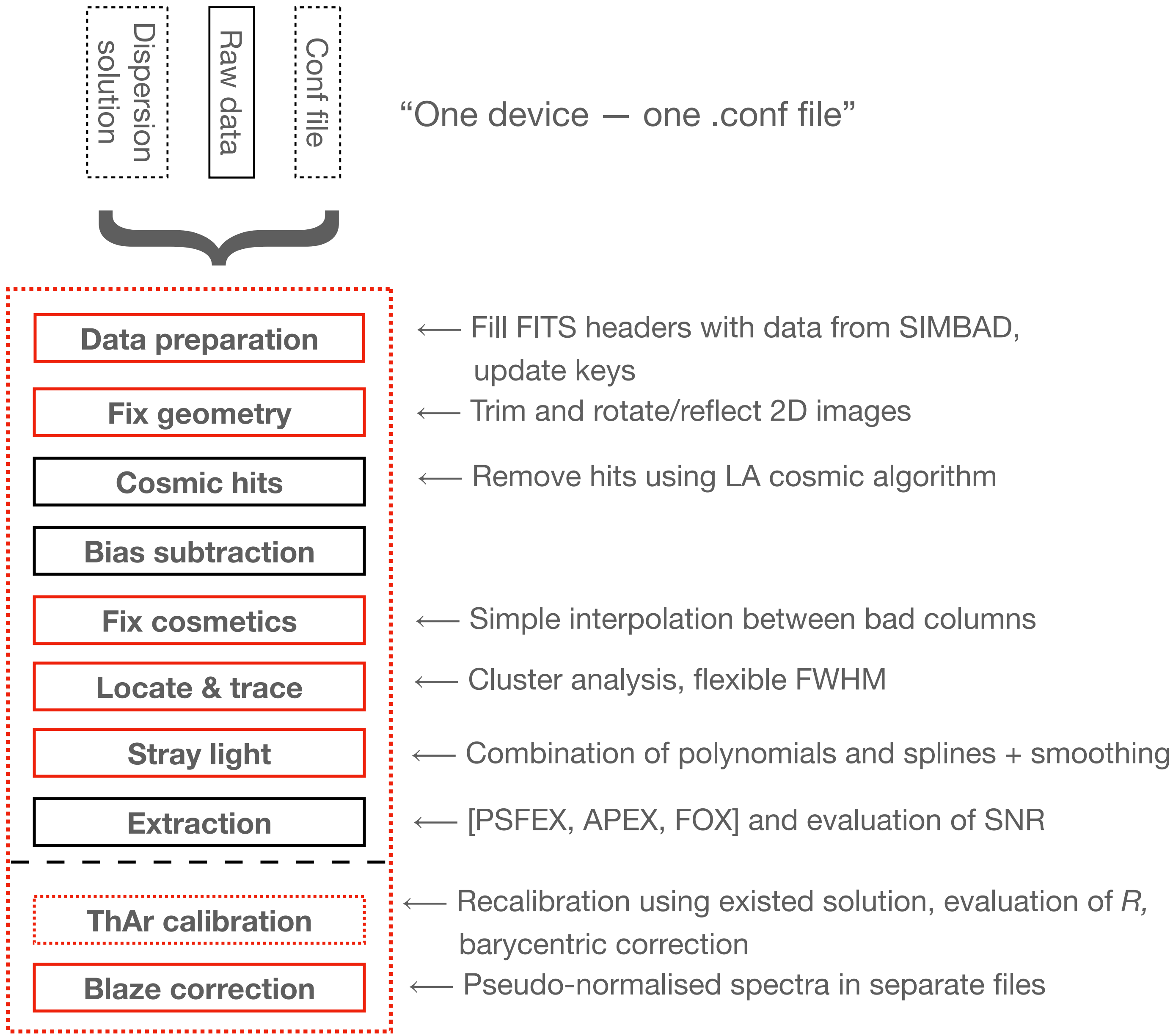
1) Python 3.8+

2) Short list of external packages available for installation with PIP

3) Each procedure is a single .py-file

4) Very simple installation

5) Works on Mac, Linux, and should work on Windows-based computers



Pipeline

Test and performance

Observational night

30 files — bias

20 files — flat

10 files — ThAr

37 files — stars

Hardware (laptop)

CPU Intel Core i5-6200U (@2.3 GHz)

RAM 8 GB

SSD 256 GB

Software

Debian Sid (latest)

Python 3.9.1 with the latest versions of packages installed using PIP

PSFEX: PSF-based extraction took 7 min 54 sec

APEX: Aperture-based extraction in 5 min 43 sec

FOX: Flat-based extraction in 6 min 13 sec

PSFEX: 1986PASP…98..609H, 1998MNRAS.296..339N

FOX: 2014A&A...561A..59Z

Parameters

Graphical output is off

Frame section [660: 1580, 1:393]

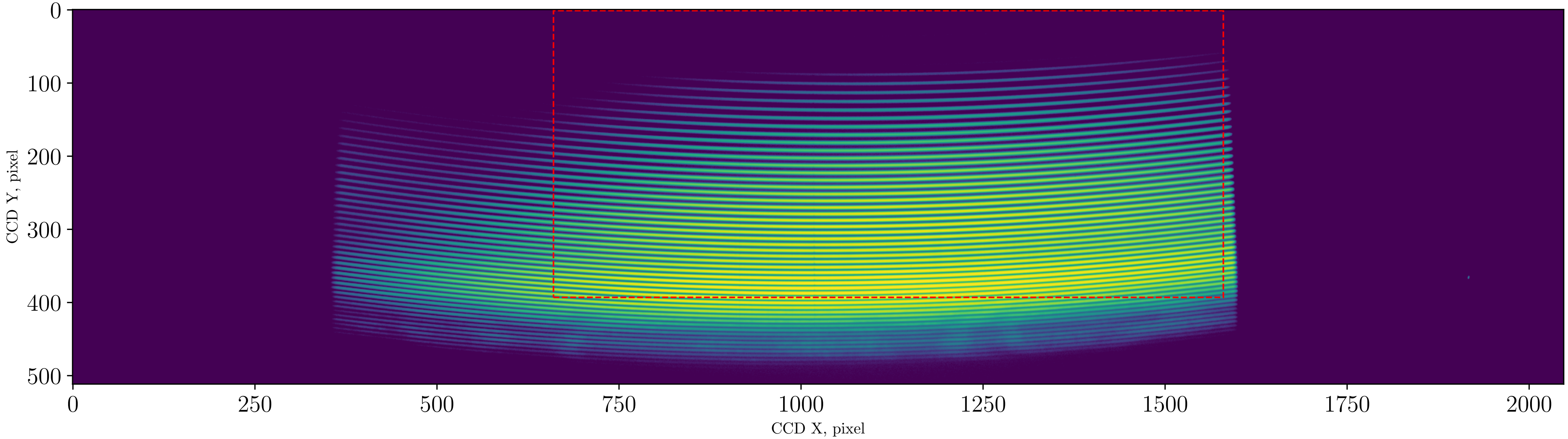
Aperture size is 1.1 of FWHM

Does not include ThAr calibration

SL subtraction if off (otherwise + approx. 50 sec)

Parameters of extraction

Trim area, aperture, etc



Inter-order space at least 0.07 mm or 5.1 pix

Aperture 1.6 FWHM: overlapped spectra

from order #19 (5113 - 5225 Å)

Section of frame: [660, 1580, 1, 393]

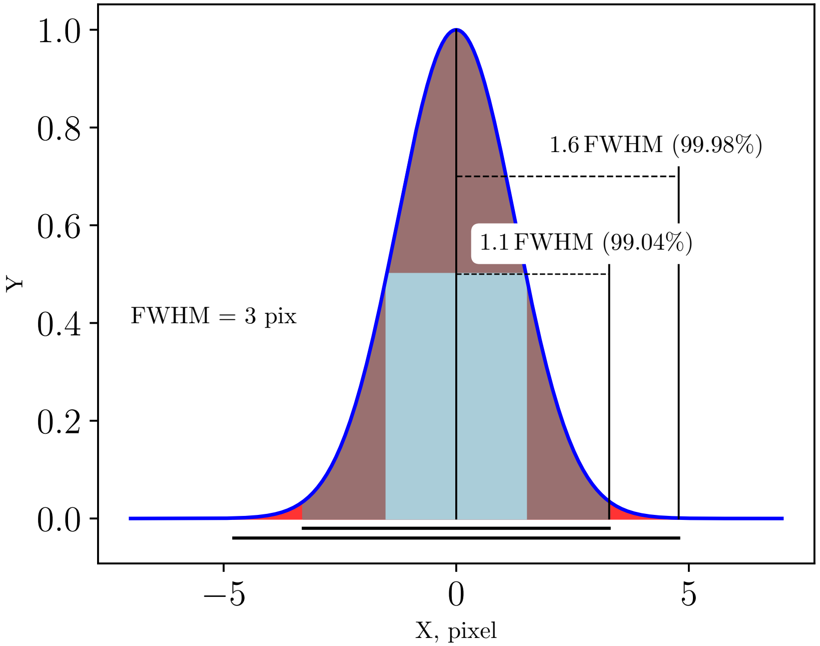
Orders: 37

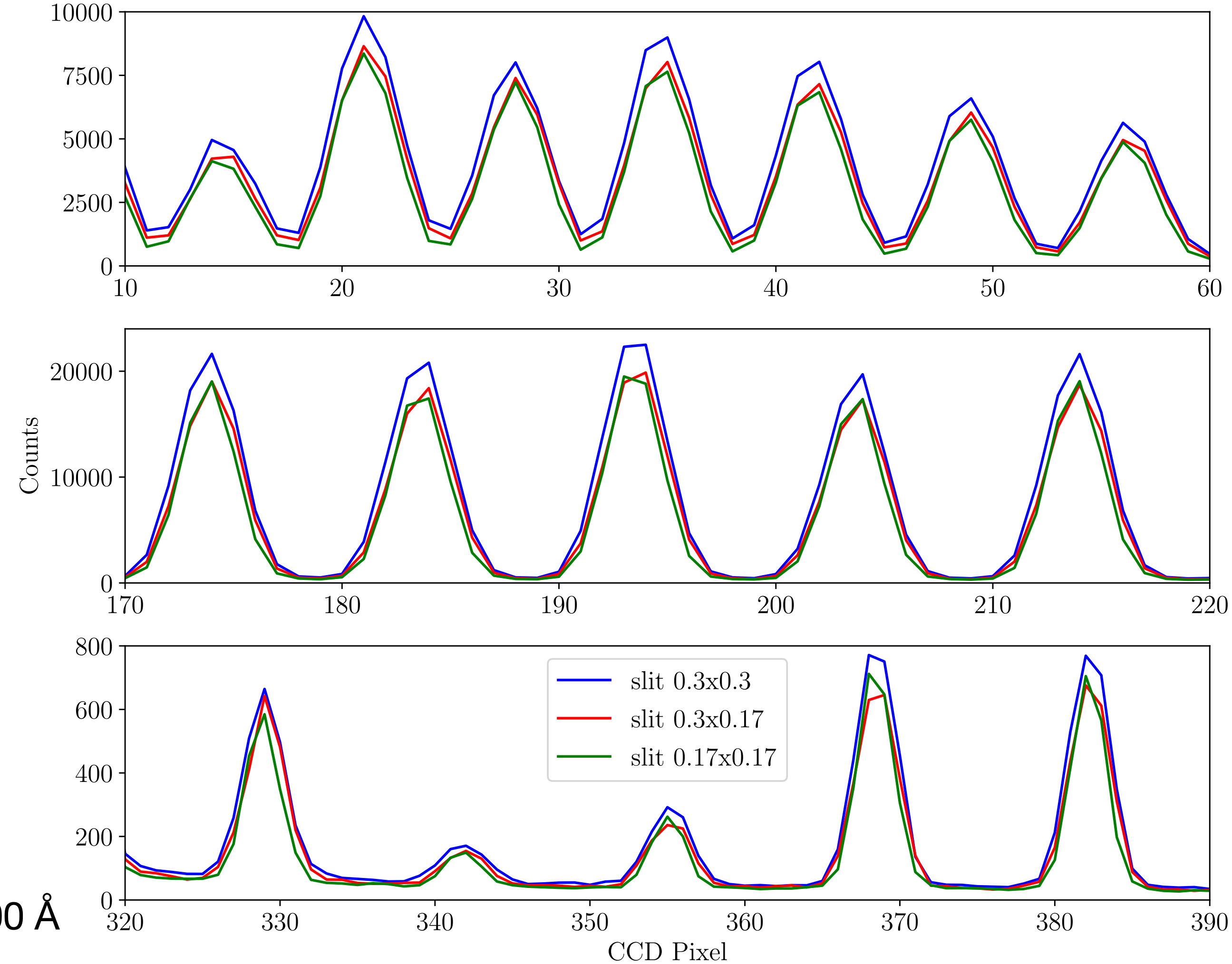
Wavelengths: 4054 - 7068 Å

Aperture: 1.1 FWHM: no overlapping up to 7100 Å

Parameters of extraction

Crop size, aperture, etc





Section of frame: [660, 1580, 1, 393]

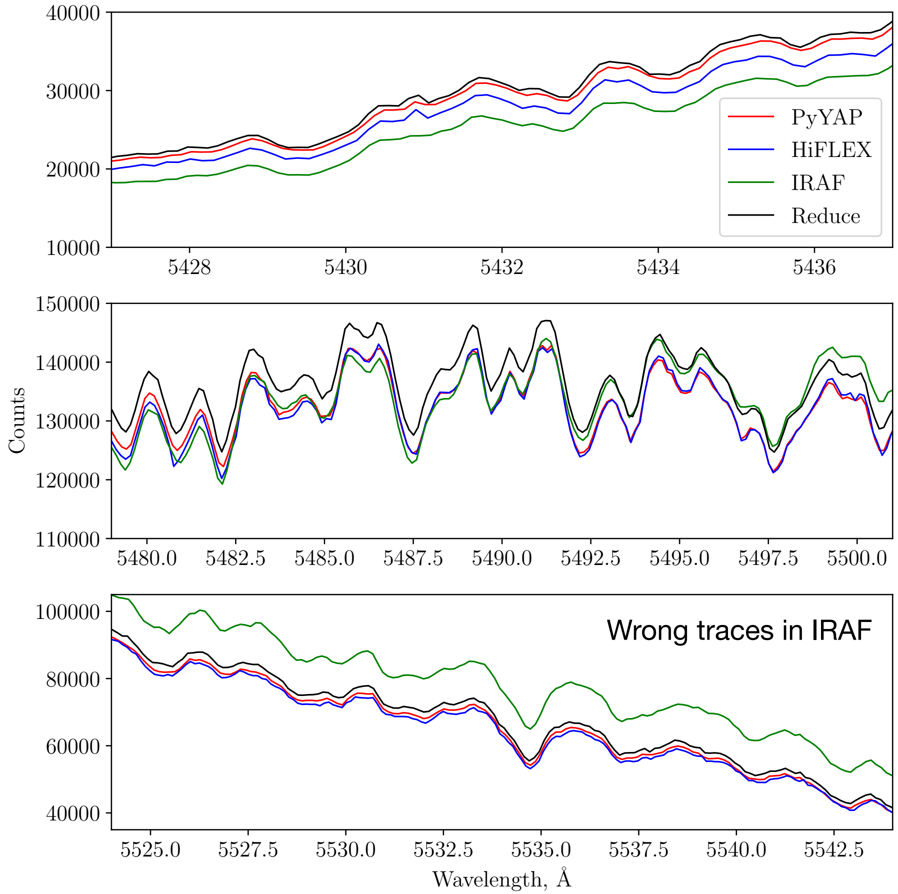
Orders: 37

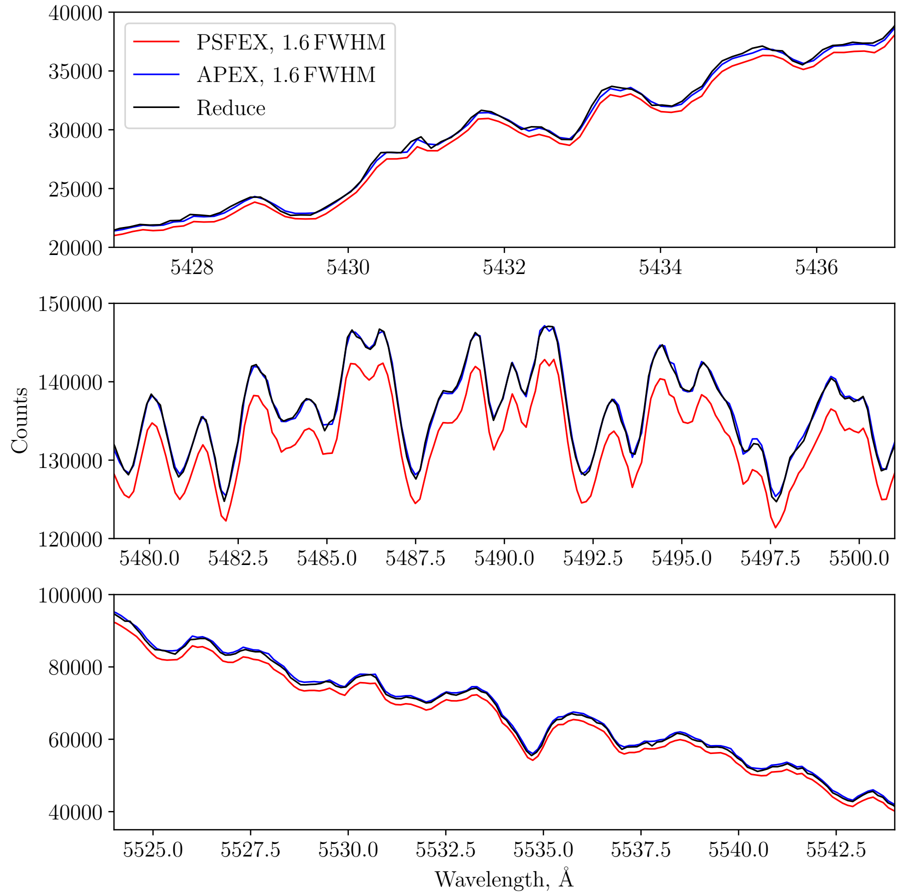
Wavelengths: 4054 - 7068 Å

Aperture: 1.1 FWHM: no overlapping up to 7100 Å

Comparison

IRAF, Reduce, HiFLEX





Orders location and shape

basic principles

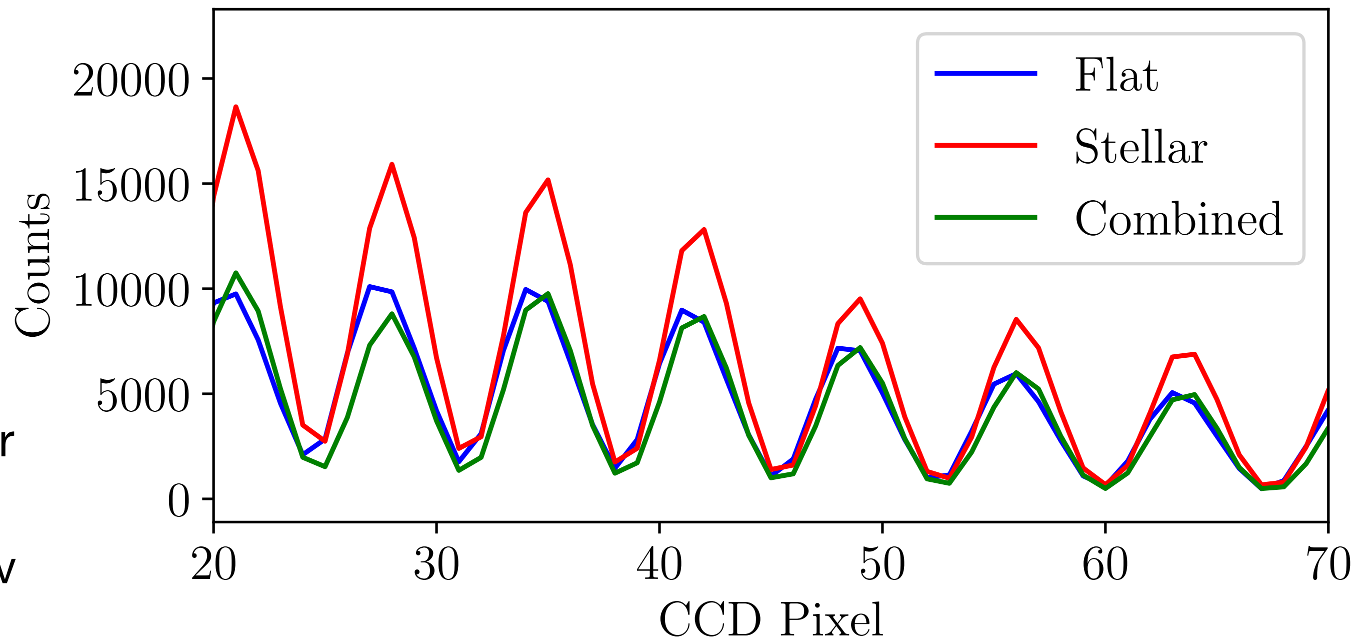
- Average all flats and stellar spectra collected during the night (to eliminate effects of low SNR)

- Cluster analysis for the initial tracing

- Re-trace the reference image for a big number of reference points in each order

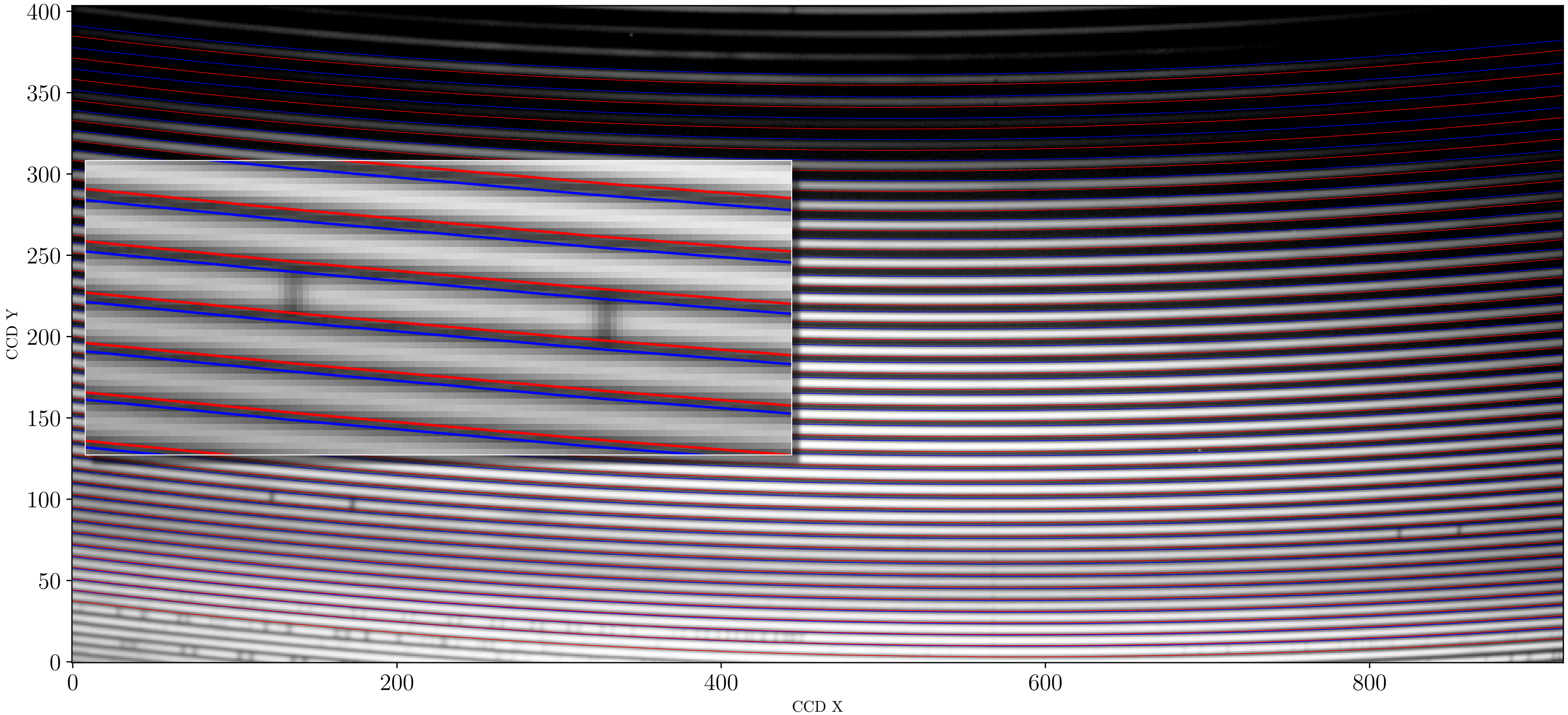
- Fit orders and FWHM using Chebyshev polynomials and Moffat function

- FWHM varies along the dispersion



Orders location and shape

results



Orders location and shape

results

FWHM is not uniform along the dispersion

Reasons:

- focus of the CCD camera

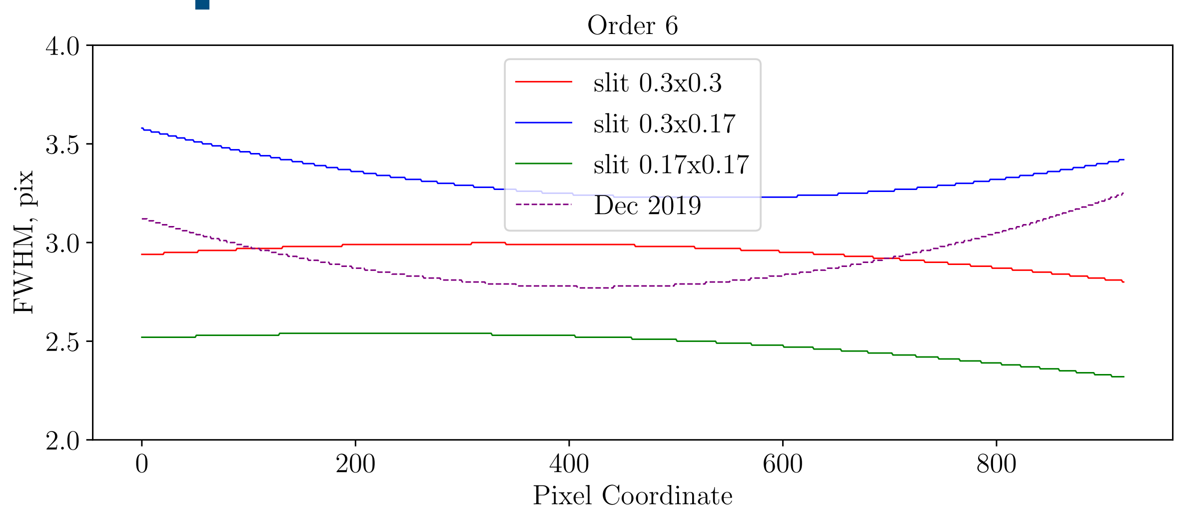
- optical aberrations of the CCD camera

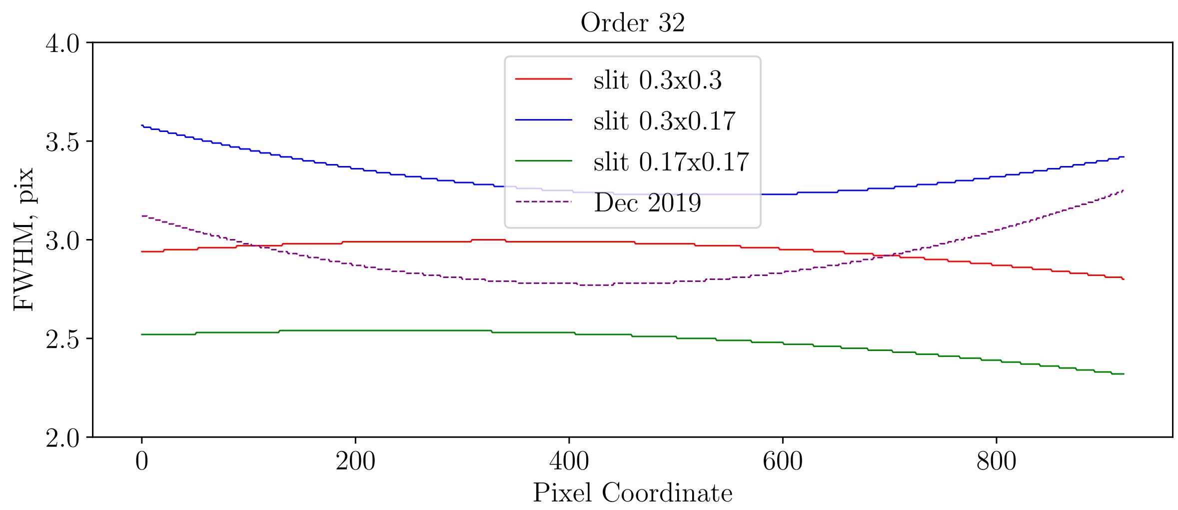
- other(?)

Conclusions:

1) different slits require re-focusing

2) narrower slit does not solve the problem of small inter-order space.





Scattered light

Sources and modelling

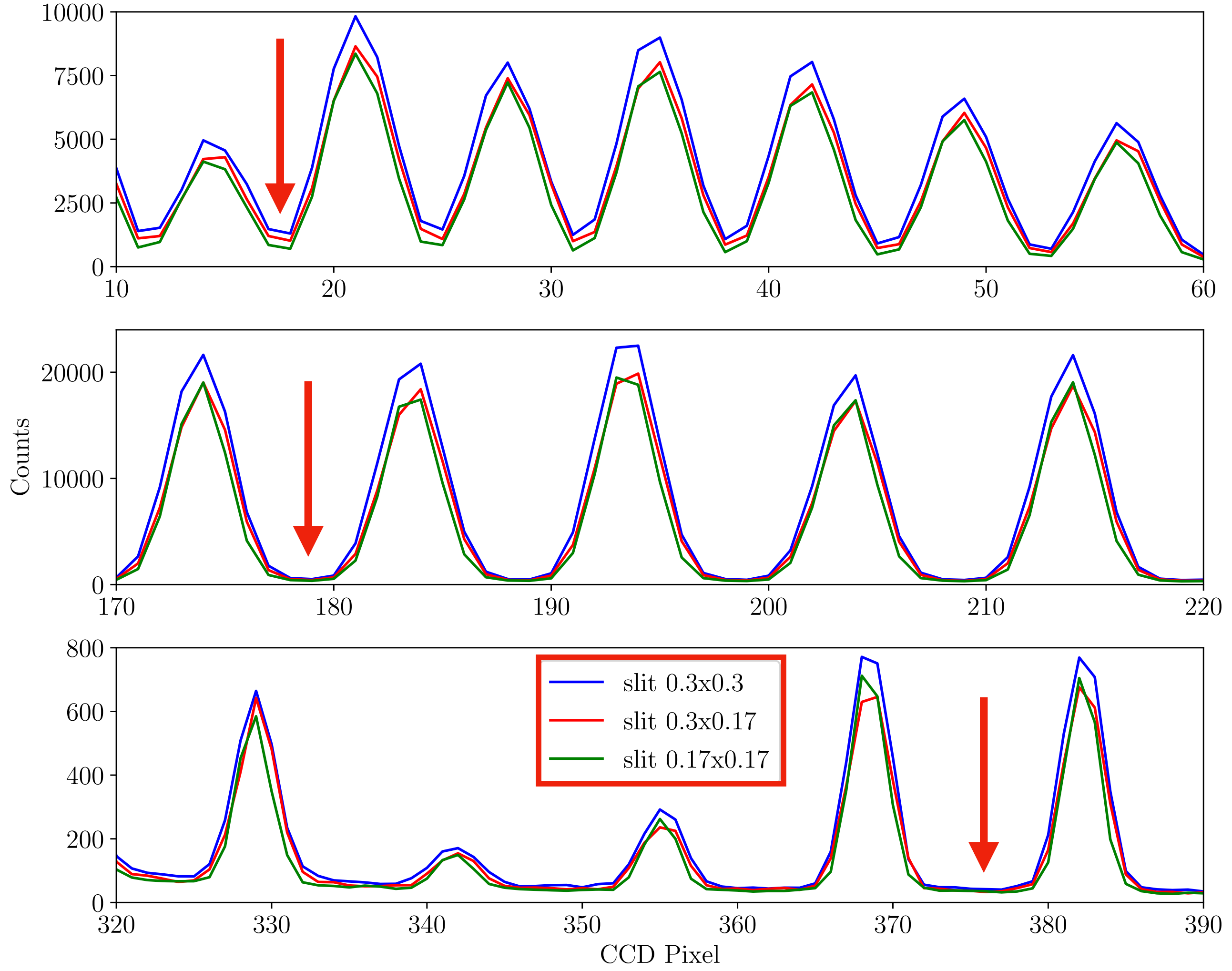
Sources of scattered light:

1) reflections and scattering on the optical and mechanical elements inside the 'box'

2) dust on the surfaces

3) accuracy of manufacturing of gratings

Model: smoothed combination of polynomials and splines



Scattered light

Practical evaluation

Observational tests:

1) bright stellar object or

2) uniformly illuminated fibre (flat field)

3) sky spectrum

1) - 3) for different slits

Observational sets:

- Flat, slit 0.3×0.3 mm, T_{exp} = 0.3 s
- Flat, slit 0.3×0.17 mm, T_{exp} = 0.7 s
- Flat, slit 0.17×0.17 mm, T_{exp} = 1.0 s
- Sky, slit 0.3×0.3 mm, T_{exp} = 8.0 s

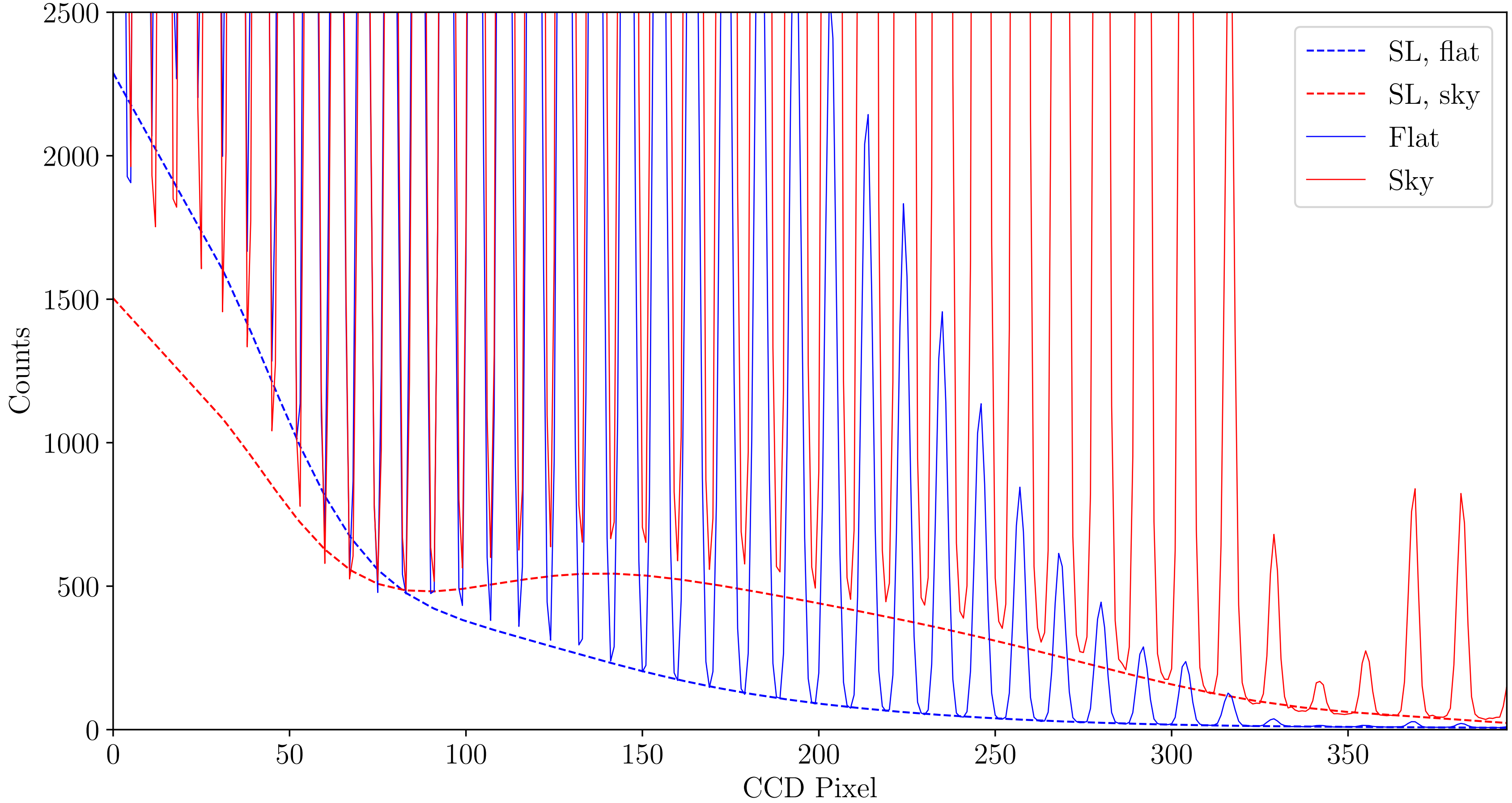
Scattered light

Practical evaluation

Flat field

Aperture 1.6 FWHM

Slit 0.3 × 0.3 mm



Scattered light

Practical evaluation

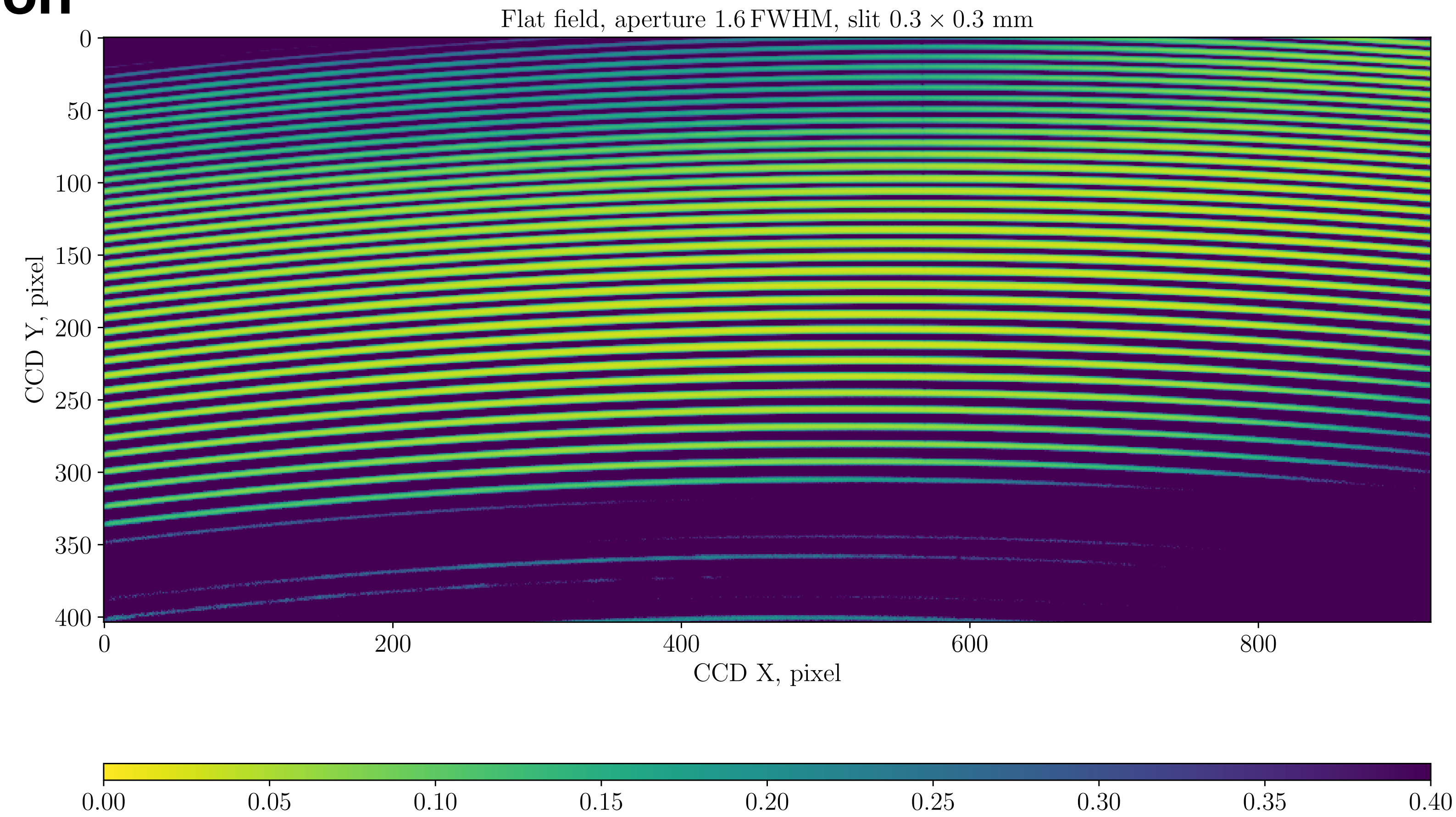
Flat field

Aperture 1.6 FWHM

Slit 0.3 × 0.3 mm

Level of SL varies from less than 5% to more than 40% (low SNR)

Averaged SL: 5-10%



Scattered light

Practical evaluation

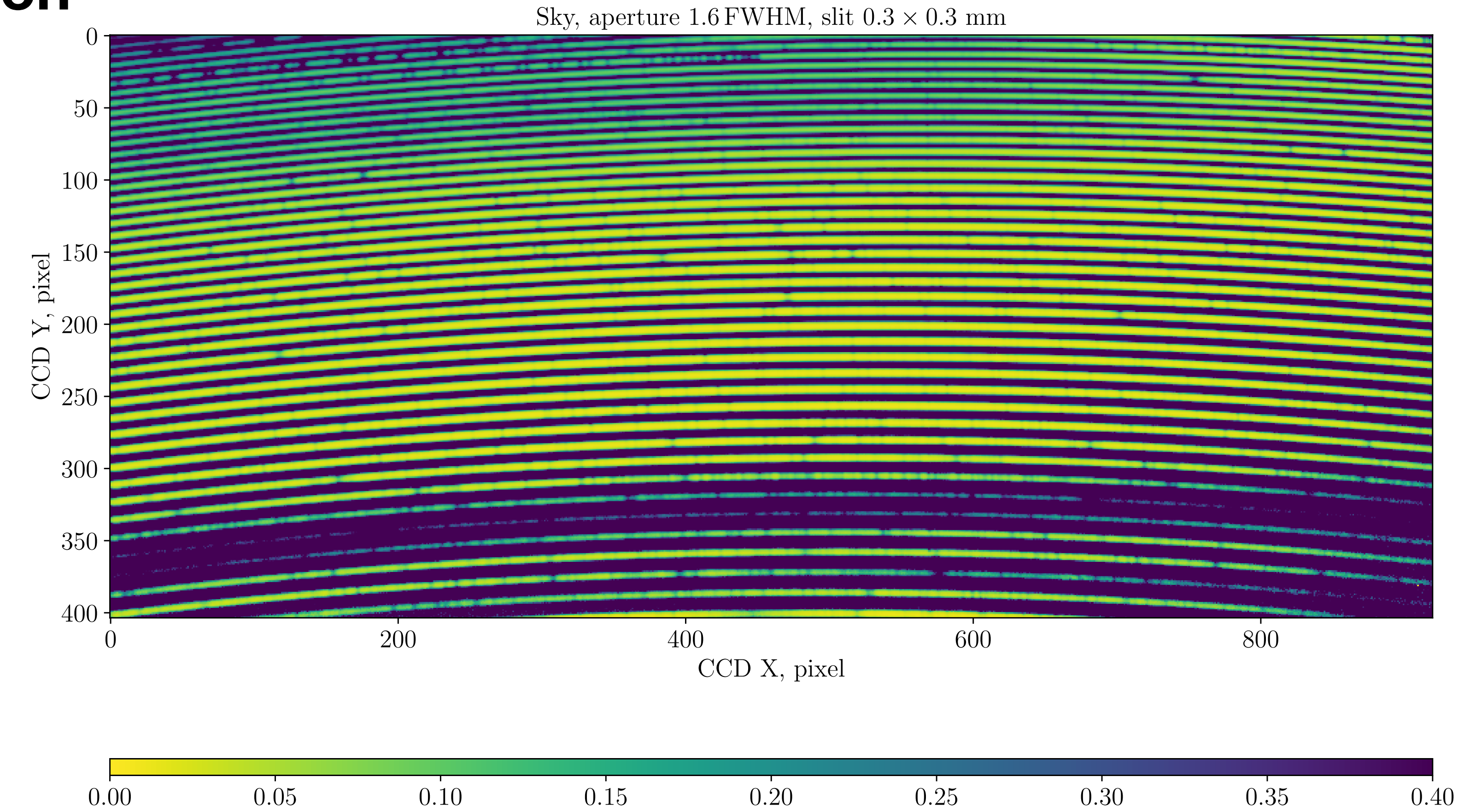
Sky spectrum

Aperture 1.6 FWHM

Slit 0.3 × 0.3 mm

Level of SL varies from less than 5% to about 30% (low SNR)

Averaged SL < 5%



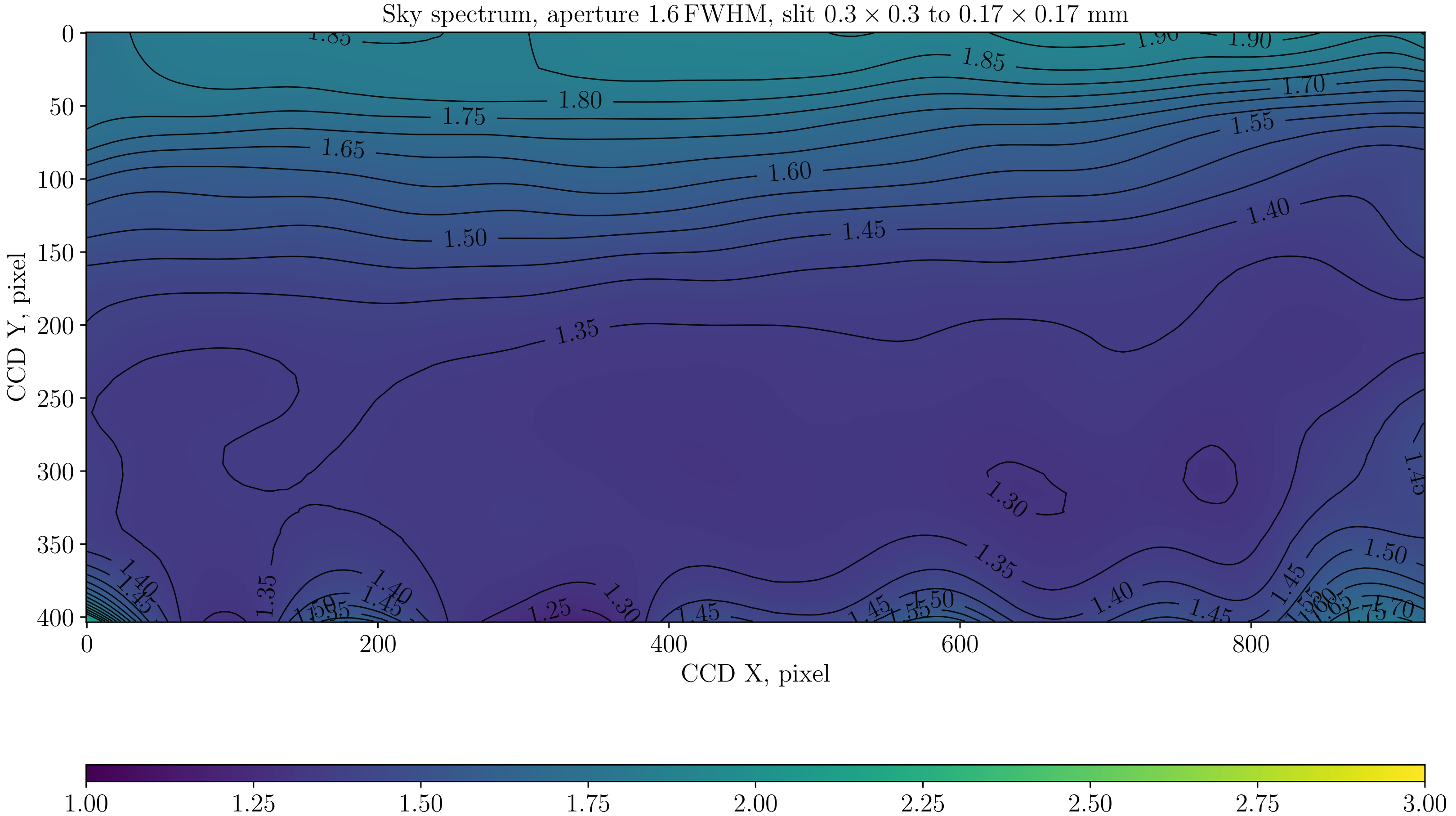
Scattered light

Practical evaluation

Model of the SL, extracted from spectra of the sky

High linearity, visible boundary effects

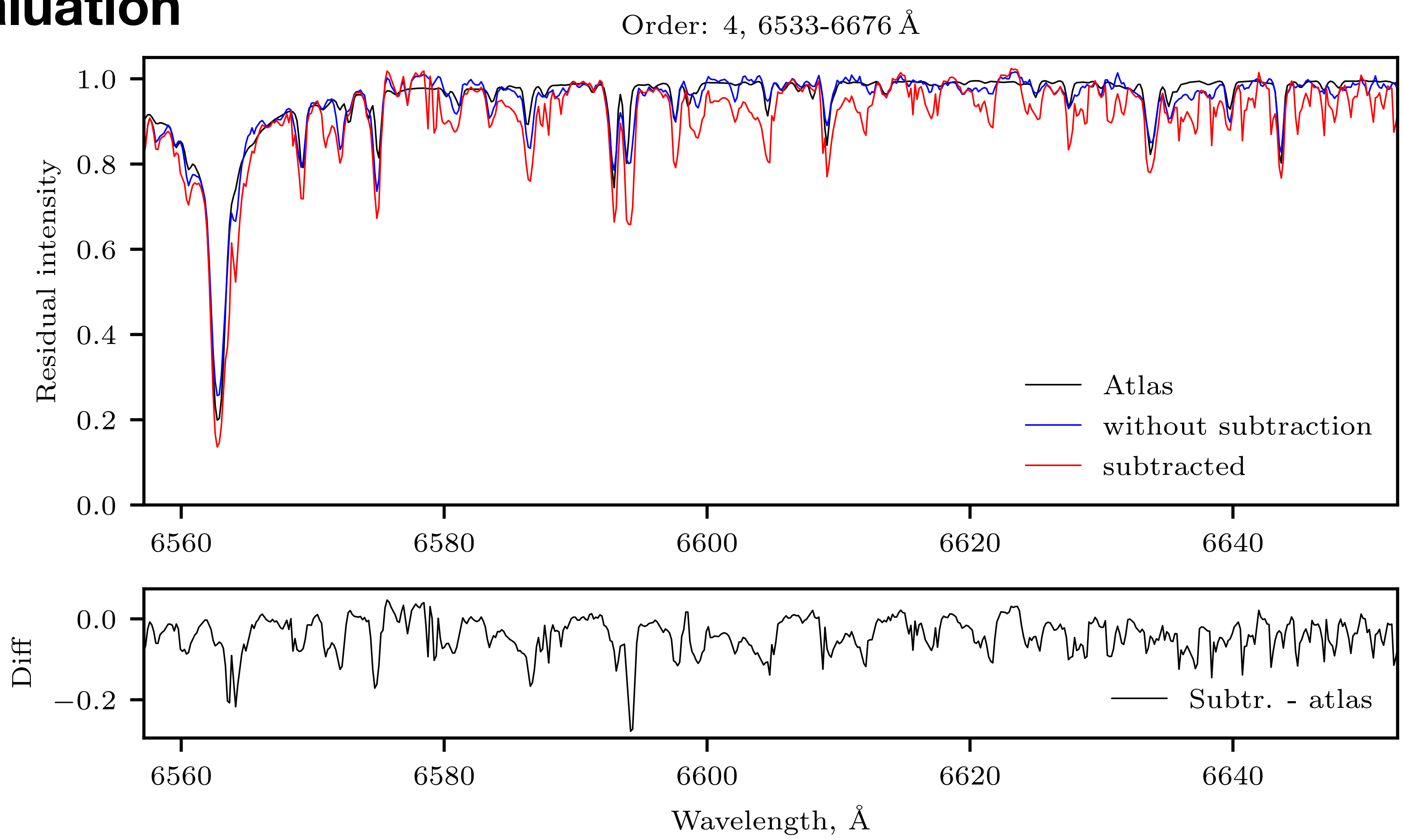
(low SNR zones)



Scattered light

Practical evaluation

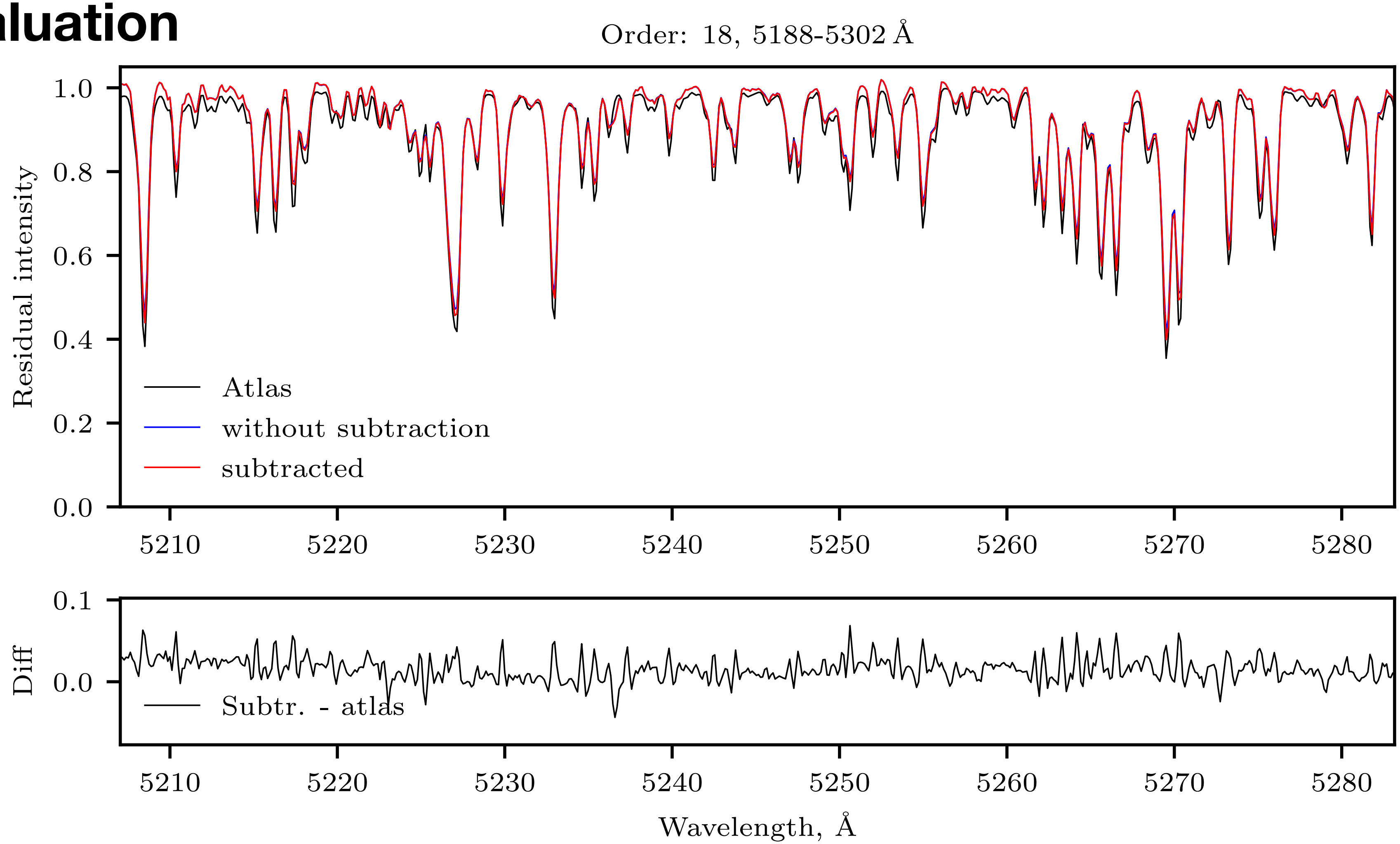
Spectrum of sky



Scattered light

Practical evaluation

Spectrum of sky

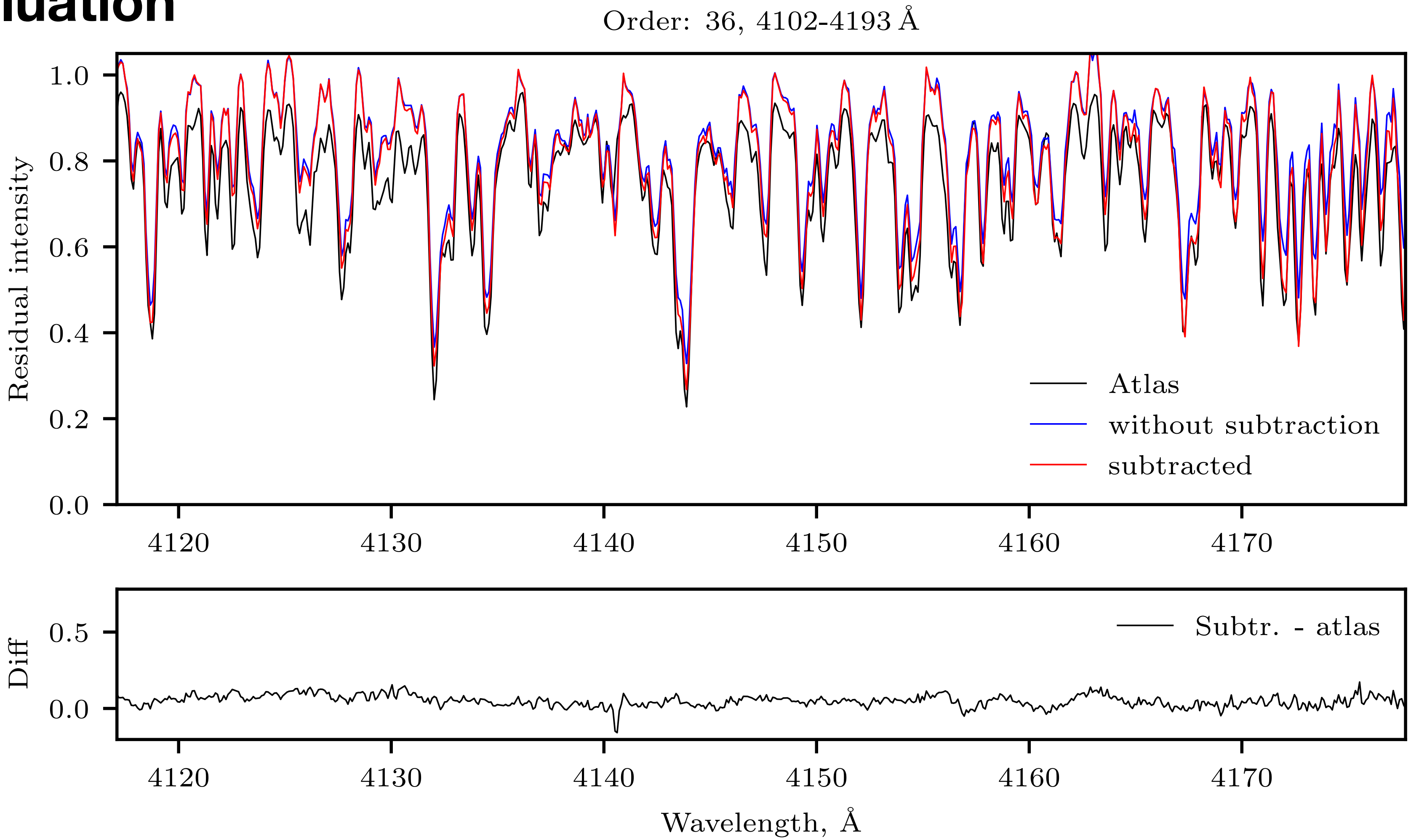


Scattered light

Practical evaluation

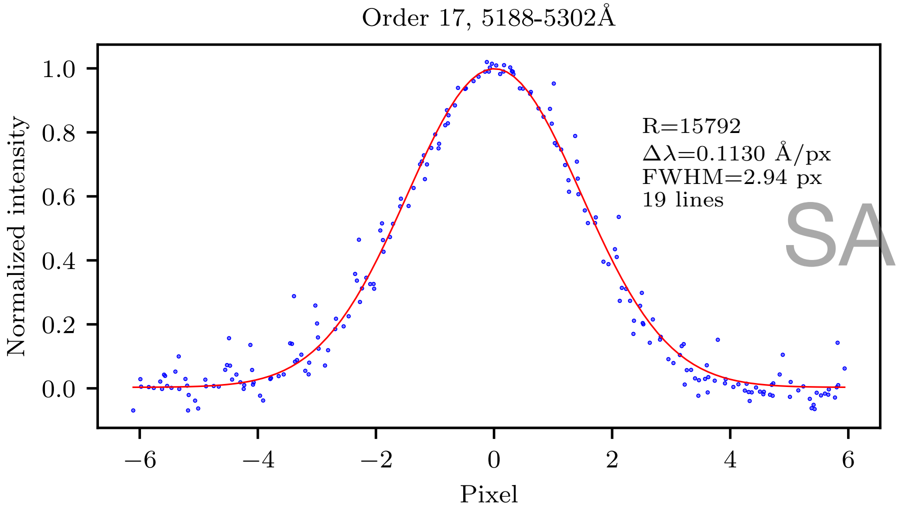
Spectrum of sky

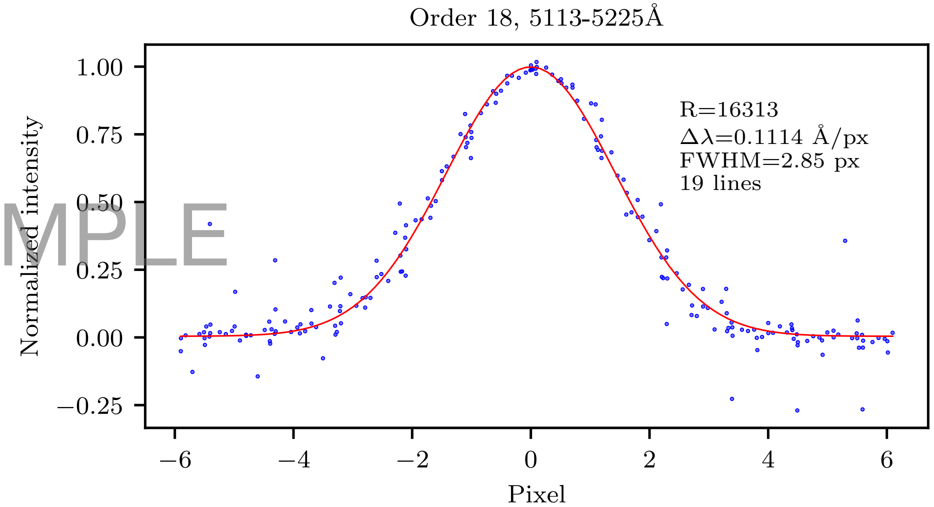
Conclusion: subtraction works with issues. The model needs for more detailed study



Spectral resolution

Built-in evaluation





ThAr lines

Aperture 1.1 FWHM

Slit 0.3 × 0.3 mm

Slit 0.3 × 0.17 mm

Slit 0.17 × 0.17 mm

- Evaluation of *R* for each order with at least one emission line
- Evaluation of an averaged *R* for the whole range (normally, hundreds of lines)
- Information about *R* is written in FITS-header
- PDF-document with report

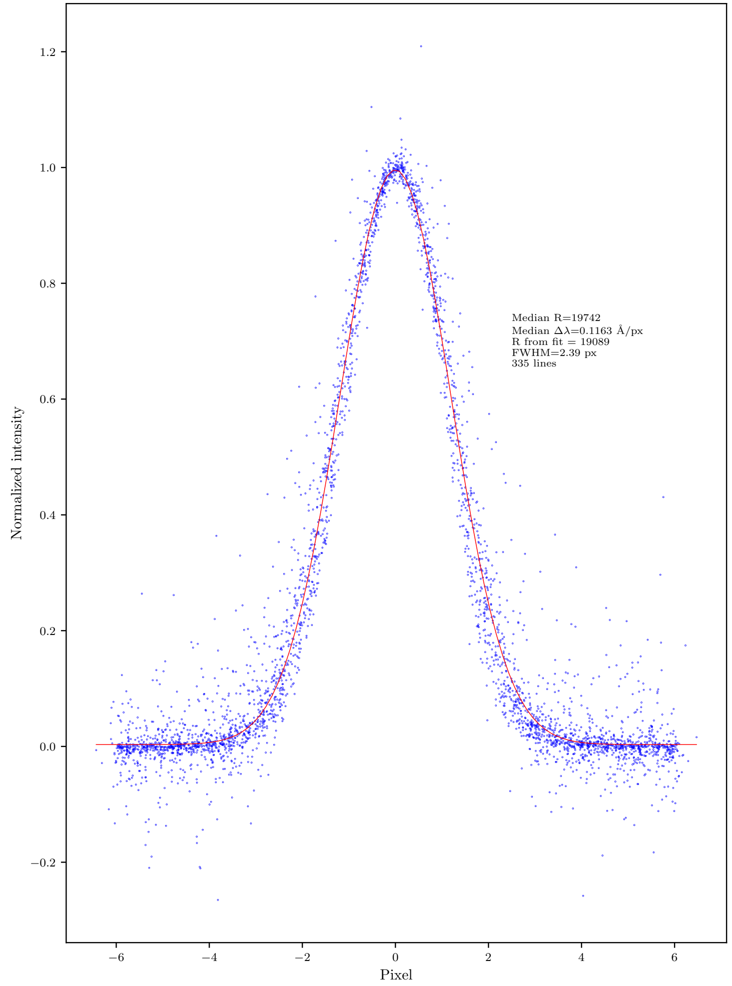
Spectral resolution

Results

Slit 0.3 × 0.3 mm	Slit 0.3 × 0.17 mm	Slit 0.17 × 0.17 mm
R = 16,000	R = 19,000	R = 18,000
FWHM = 2.85 pix	FWHM = 2.39 pix	FWHM = 2.49 pix
351 lines	335 lines	344 lines

Conclusions:

- Data sampling is almost perfect (~2.5 pix)
- Switch from the slit 0.3 × 0.3 mm to 0.17 × 0.17 mm requires re-focusing of CCD



Performance

Initial data

Observations of the flux calibrated objects:

1. 16/17 December 2019, HD 92558, A2, $V = 8.06$ mag, $z = 3\text{-}19°$, seeing ≈ 2.3″, in total, 7 spectra, Moon close to the last quarter (75%) in 12° from the target
2. 17/18 December 2019, HD 218045, B9III, $V = 2.48$ mag, $z = 40°$, seeing = 1.5″, 4 spectra, no Moon
3. 10/11 January 2020, HD 92558, A2, $V = 8.06$ mag, $z = 15\text{-}19°$, 3 spectra, no Moon
4. 10/11 November 2020, HD 215012, A0, V = 7.47, $z = 15\text{-}19°$, seeing ≈ 2″, 4 spectra (one pair for one slit), no Moon. Bad example: eclipsing binary with $\Delta m = 0.22$ mag

Fluxes from Alekseeva et al. (1997), ADS: 1997BaltA…6..481A; Biryukov et al. (1998), 1998A&AT…16...83B

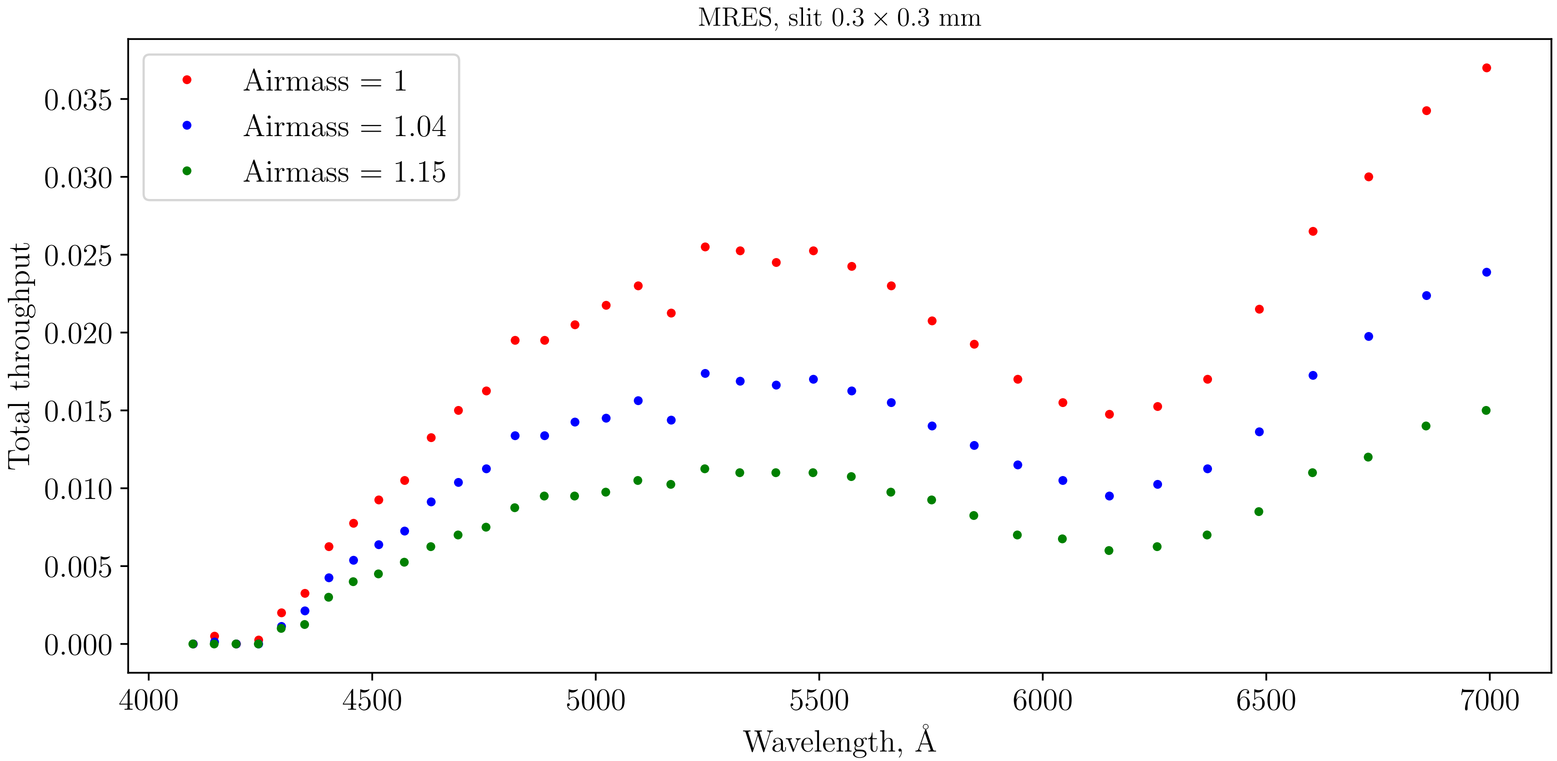
Parameters of extraction: aperture = 1.1FWHM, PSFEX, no correction for the scattered light

Performance

Total throughput

Atmosphere + telescope + fibre + spectrograph + CCD:

- Peak η is about 2.6% @5350 Å
- after 4290 Å η drops to 0.025%
- Changing the slit from 0.3 × 0.3 to 0.3 × 0.17 mm leads to the loss of 0.15 mag



Performance

Analysis

Possible sources of losses:

- seeing (AO, tip-tilt system)
- guiding errors (local guider, guiding with the injection unit)
- telescope focus (guiding mirror to be replaced)
- new fibre

Expected efficiency:

Atmosphere — 0.8 (?)

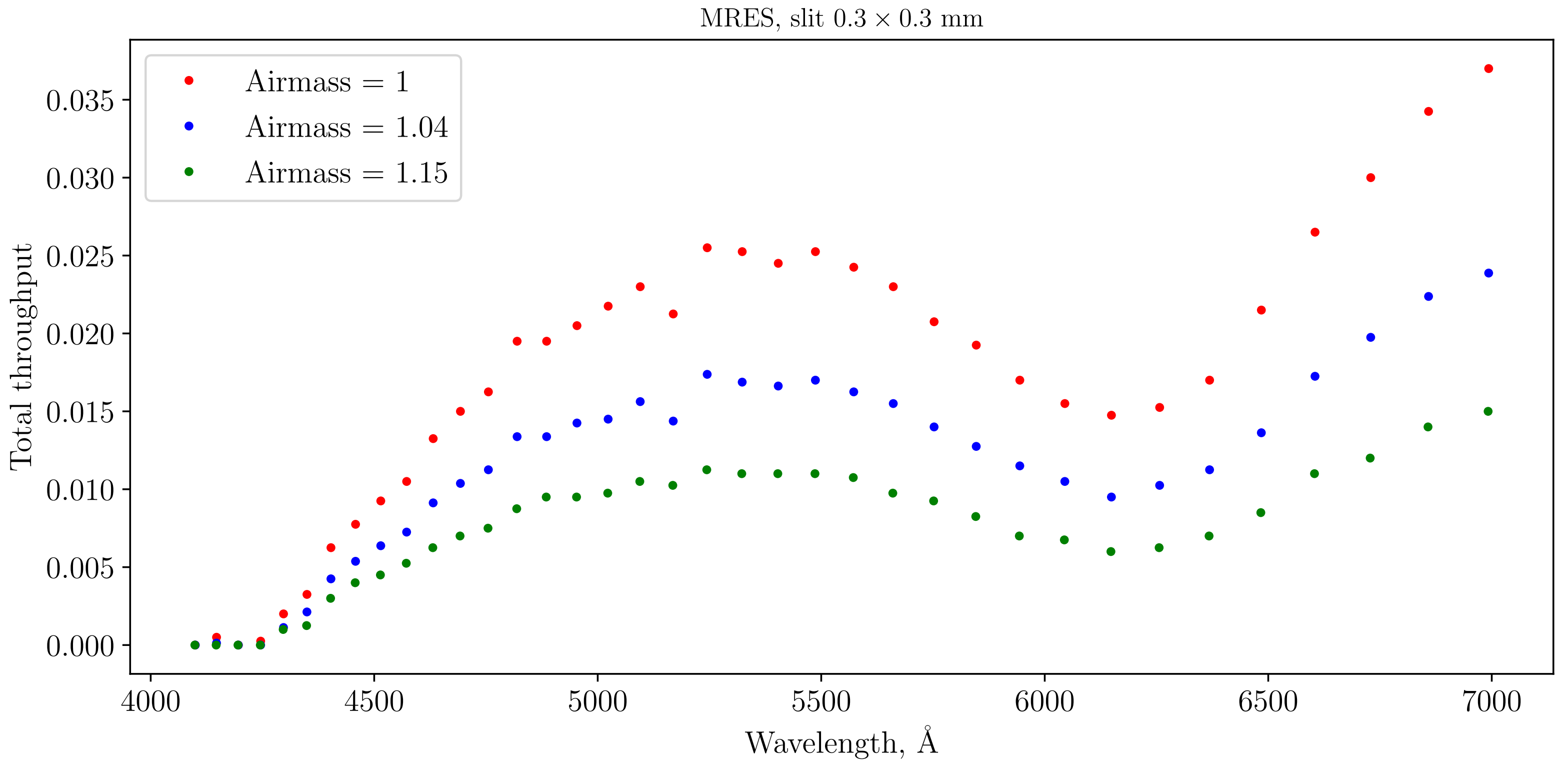
Seeing — 0.6 (?)

Fibre unit — 0.5 (?)

Telescope — 0.47 (?)

Spectrograph — 0.3

Total: 0.033



Exposure calculator

Python version

```
usage: mres_expose.py [-h] [--sptype SPTYPE] [--moon MOON] [--mag MAG]
                      [--wave WAVE] [--snr SNR] [--texp TEXP] [--showall]

optional arguments:
  -h, --help          show this help message and exit
  --sptype SPTYPE     Spectral type among available [O5, O9, B0, B2, B5, B8, A0,
                      A2, A5, A8, F0, F2, F5, F8, G0, G2, G5, G8, K0, K2, K5, M0,
                      M2, M5]
  --moon MOON         Lunar phase in days from new Moon. Available values are
                      ['new', 'quarter', 'full']
  --mag MAG           Magnitude in V band
  --wave WAVE         Reference wavelength in Agstroems
  --snr SNR           Compute time, required for specified SNR
  --texp TEXP         Compute SNR from specified time
  --showall           Plot the diagram for the full range of wavelengths
```

Initial data:

- measured throughput of MRES
- (very) rough model of sky brightness
- scaled to $V = 0^m$ flux density distribution for 24 stars with known sp. type (errors from 5 to 20%)

Modes:

- known T_{exp}, estimate SNR@λ
- known SNR@λ, find *T*exp
- display result for the whole range 4000-7000 Å

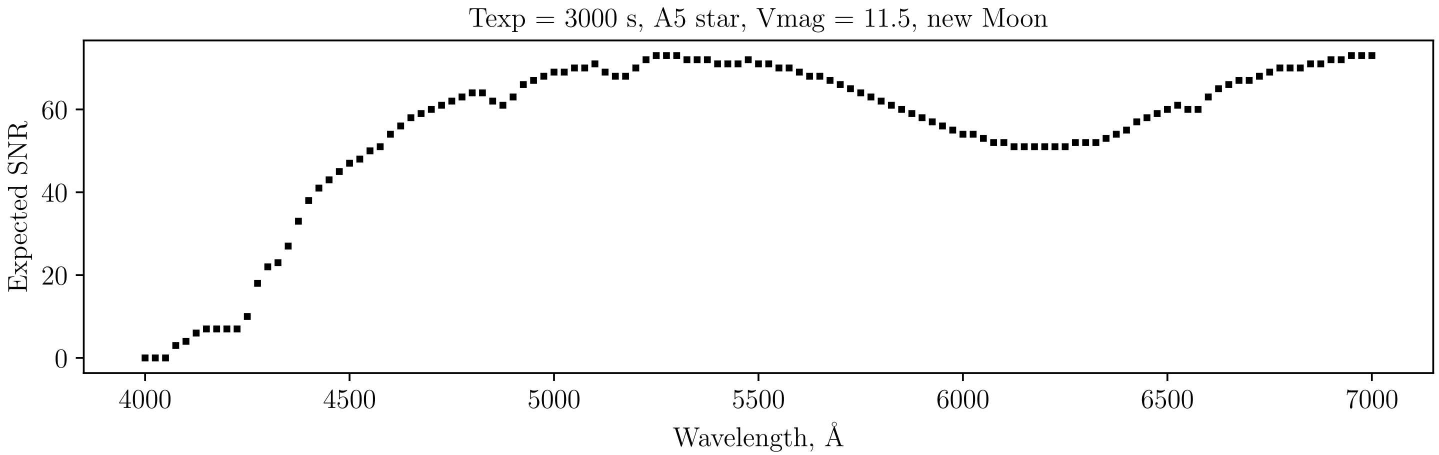
Example of usage:

./mres_expose.py --sptype A5 --moon new --mag 11.5 --texp 3000 --showall --wave 6000

Expected SNR(6000) = 53 in 3000 s

Exposure calculator

Python version



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Example of usage:

./mres_expose.py --sptype A5 --moon new --mag 11.5 --texp 3000 --showall --wave 6000

Expected SNR(6000) = 53 in 3000 s

Warning: Calibrations exist only for the central wavelength of orders

Final remarks

Summary and recommendation for the users

✓ Optimal parameters of extraction when is possible to neglect the effect of overlapped orders: region [x0:xn, y0, yn] = [660, 1580, 1, 393] and aperture width = 1.1FWHM. In this case the frame contains 37 orders within wavelengths 4054 - 7068 Å

✓ Spectrograph provides *R* from 16,000 (slit 0.3 × 0.3 mm) to 19,000 (slit 0.3 × 0.17 mm) while corresponding FWHM varies from 2.85 to 2.49 pix

✓ The full efficiency of the system in visible light reaches 2.5-3% and increases in IR

✓ Switch from the slit 0.3 × 0.3 mm to 0.3 × 0.17 mm leads to the loss of approx. 0.15 mag

✓ Scattered light cannot be removed completely with current setup

Possible ways to improved spectrograph:

- guiding (local guider, carriage, etc.
- control of the telescope focus (guiding 'mirror' must be replaced to the real mirror)
- new fibre
- switch to usage of different cross-dispersing element (prisms, grating, grism — better)

Thanks for your attention

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