Forward modeling to measure atmospheric transmission

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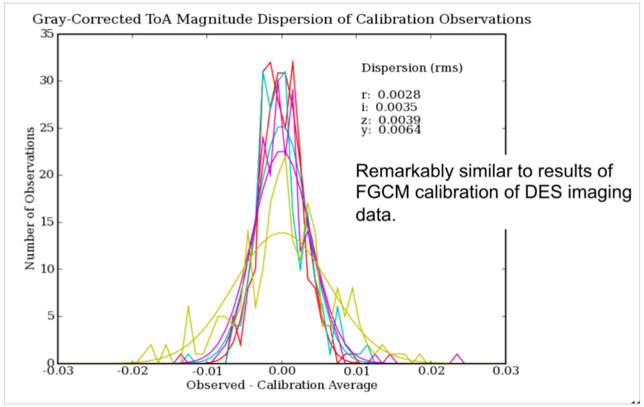
IPNL: Yannick Copin

Context

- LSST: millimag level for photometric uncertainites
- Auxtel: get spectra from photometric standards
  - to constrain atmospheric transmission
  - to propagate to LSST photometry

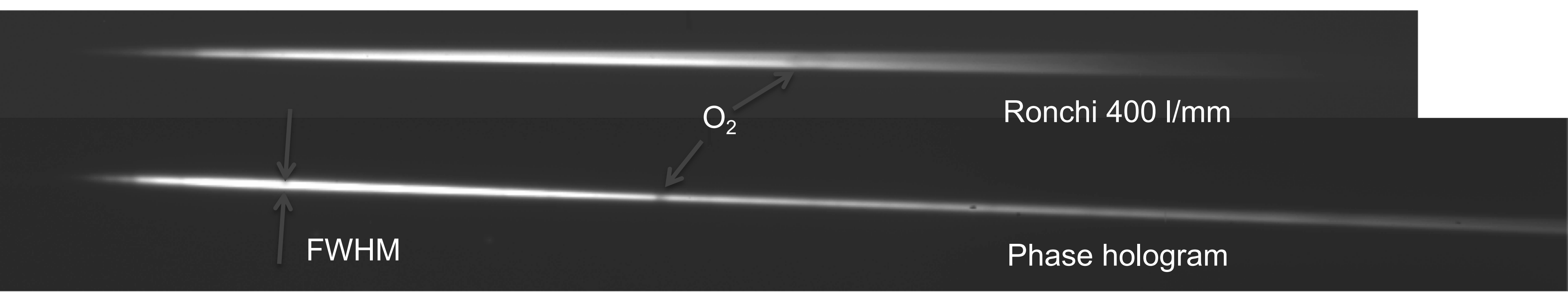


- But Auxtel Spectropgraph is slitless and produces defocused spectra
  - What do we call a spectrum in this context ? Mixing of spatial and spectral information
  - Y. Copin proposition: go to forward modelling

No spectrum extraction but direct atmospheric transmission measurement

Context

- Data and instrument:
  - CTIO data: 16 nights in June 2017, multiple CALSPECs
  - Ronchi, blazed disperser and hologram dispersers
- Primary objectives:
  - Build a forward model of the 2D spectrogram
  - Measure the atmospheric transmission



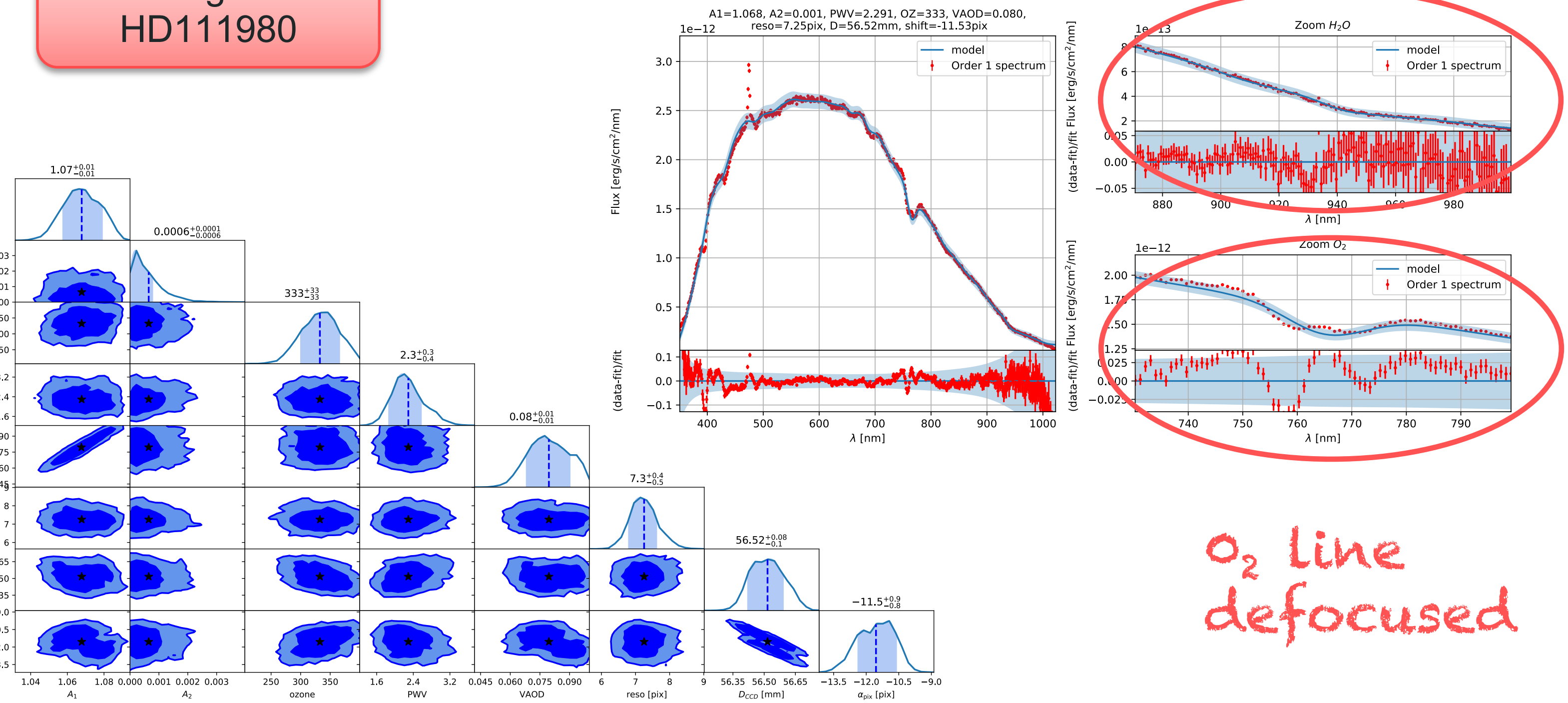
Traditional approach: cross spectrum

- Cross spectrum = sum across the transverse direction of the dispersion axis

Ronchi 400: #130 2017/05/31 02h45 UTC

H_2O information washed out

Target:
HD111980



O_2 line defocused

Y. Copin's slide

Dispersed imaging

- Slitless spectroscopy
  - P_0 = Point/Line Spread Function
  - $P_\Delta(\mathbf{r}, \lambda) = \delta(\mathbf{r} - \mathbf{\Delta}(\lambda))$ where $\mathbf{\Delta}(\lambda)$ is the dispersion law
  - Dispersed image: $\boxed{I(\mathbf{r}) = \int d\lambda\, (C \otimes P_0)(\mathbf{r} - \mathbf{\Delta}(\lambda), \lambda)}$ Direct approach
  - In spatial Fourier domain:

$$\boxed{\hat{I}(\mathbf{k}) = \int d\lambda\, \hat{C}(\mathbf{k}, \lambda)\, \hat{P}_0(\mathbf{k}, \lambda)\, e^{-i2\pi\, \mathbf{k}\cdot\mathbf{\Delta}(\lambda)}}$$

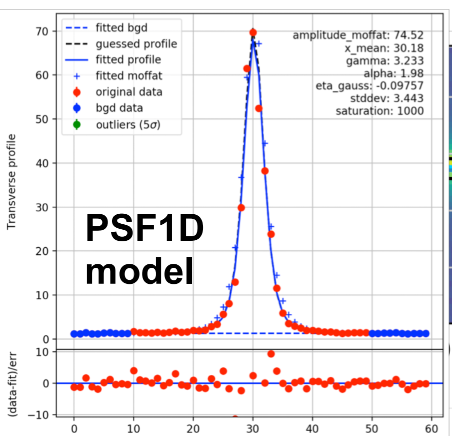
Fourier approach
-> FFT faster

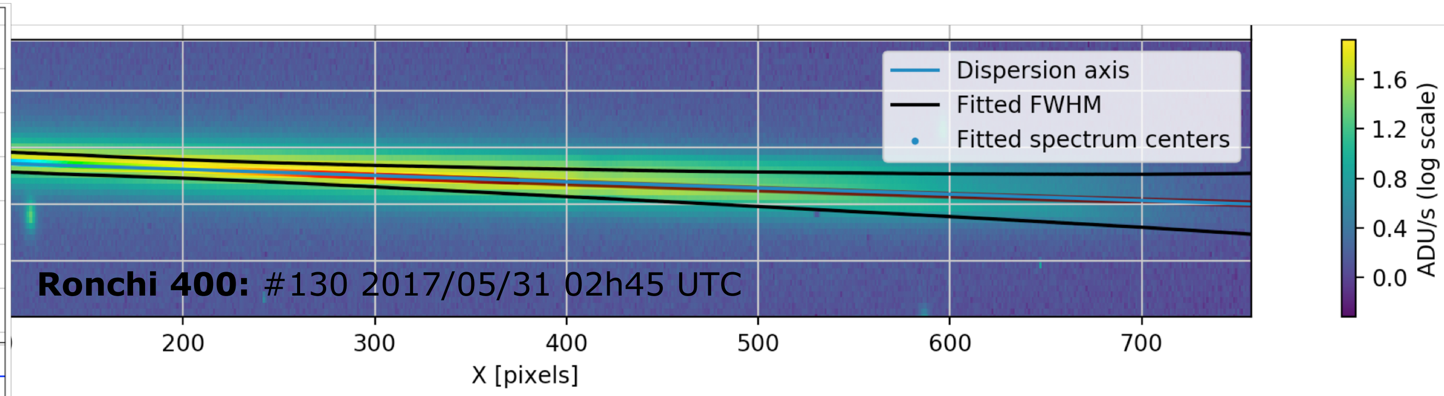
- Source: $C(\mathbf{r}, \lambda) = [T_{\mathrm{instrument}}(\lambda) \times T_{\mathrm{atm}}(\lambda|\theta) \times S_{\mathrm{star}}(\lambda)] \times \delta\left(\mathbf{r} - \mathbf{r}_{\mathrm{order}\ 0}\right)$
- Chromatic PSF: $P_0(\lambda)$
- Disperser law: $\mathbf{\Delta}(\lambda) = (x_{\mathrm{order}\ 1}(\lambda), y_{\mathrm{order}\ 1}(\lambda))$

Application to CTIO images

- Determination of $P_0(\lambda)$ and $\mathbf{\Delta}(\lambda)$ directly on the spectrograms:
  - Find the order 0 and spectro lines to calibrate λ
  - Rotate the image to fit spectrogram centers and derotate

$\Bigg\}\ \mathbf{\Delta}(\lambda)$





  - Fit transverse empirical 1D PSF(λ) = A(Moffat – ηGauss)
    - Smooth polynomial evolution of the shape parameters
    - To feed $P_0(\lambda)$ 2D PSF with same shape parameters (first guess)

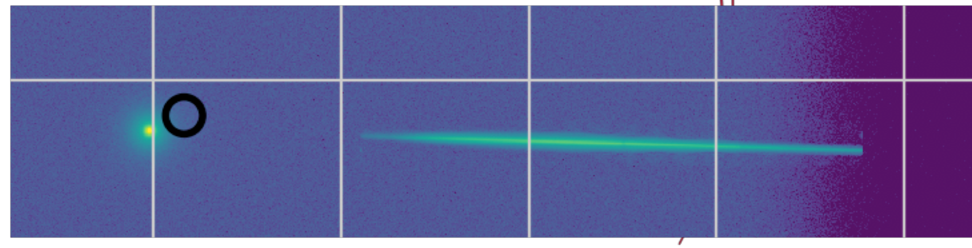
Spectrogram simulation

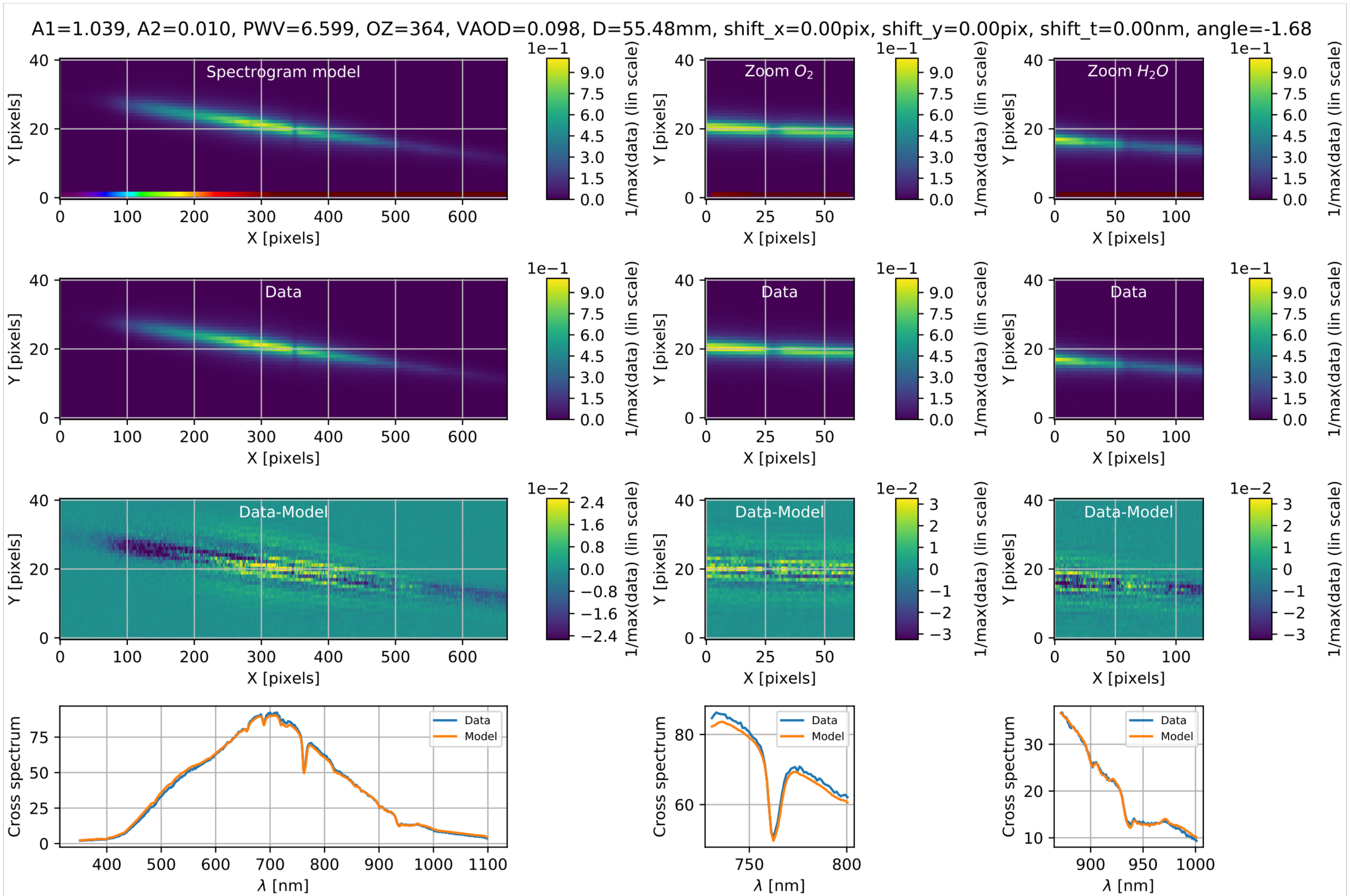
- Use Fourier formalism to simulate order 1 and order 2

$$I(\mathbf{r}) = \sum_{p=1,2} \mathrm{FFT}^{-1}\left[\int \mathrm{d}\lambda\ \hat{C}(\mathbf{k},\lambda)\ \hat{P}_0(\mathbf{k})e^{-i2\pi\mathbf{k}\cdot\boldsymbol{\Delta}_p(\lambda)}\right]$$

- Simulation and fitting procedure implemented in Spectractor
  https://github.com/LSSTDESC/Spectractor
- Fixed input: $T_{\mathrm{instrument}}(\lambda) \times S_{\mathrm{star}}(\lambda)$
- ~30 parameters to fit with ~3e4 pixels: $\chi^2 = \sum_{i=0}^{\text{all pixels}} \left(\frac{D(\mathbf{r_i}) - I(\mathbf{r_i})}{\sigma(\mathbf{r_i})}\right)^2$
  - **Atmospheric parameters**
  - A1: order 1 amplitude, A2: order 2 relative amplitude
  - $\Delta(\lambda)$ and $P_0(\lambda)$ parameters

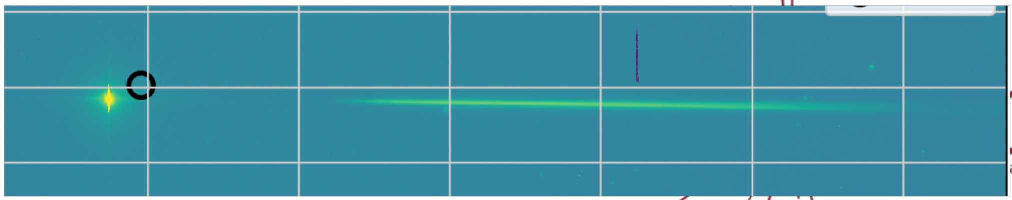
Fit: test model

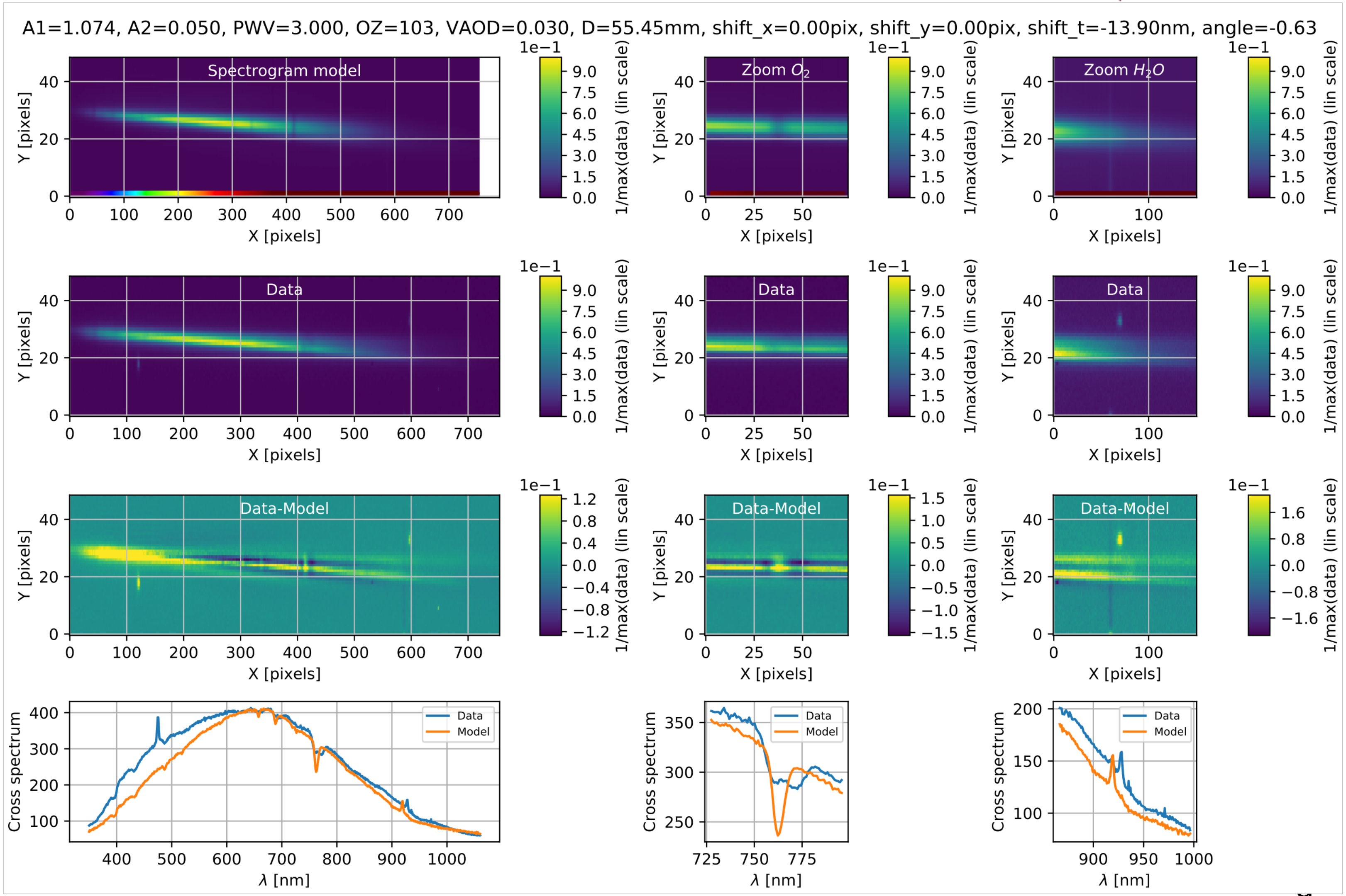




NOT CONVERGED !
Minuit have not finished its job

Fit: CTIO Ron#130





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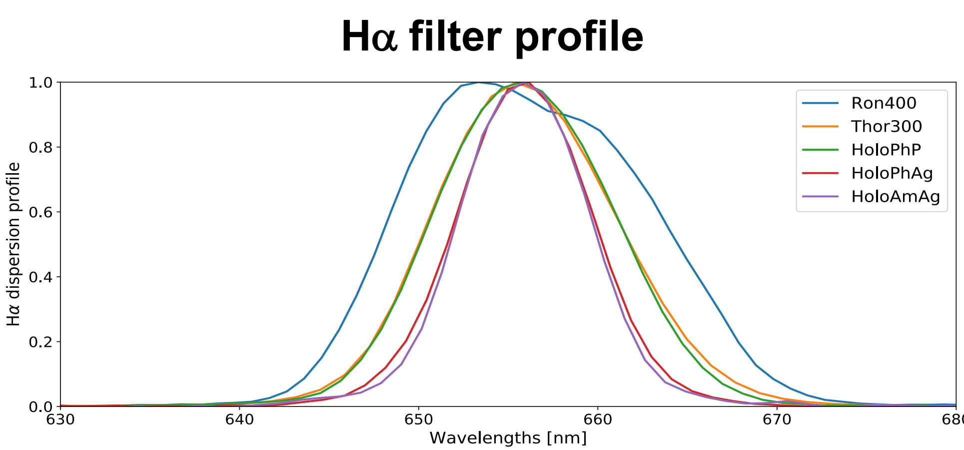
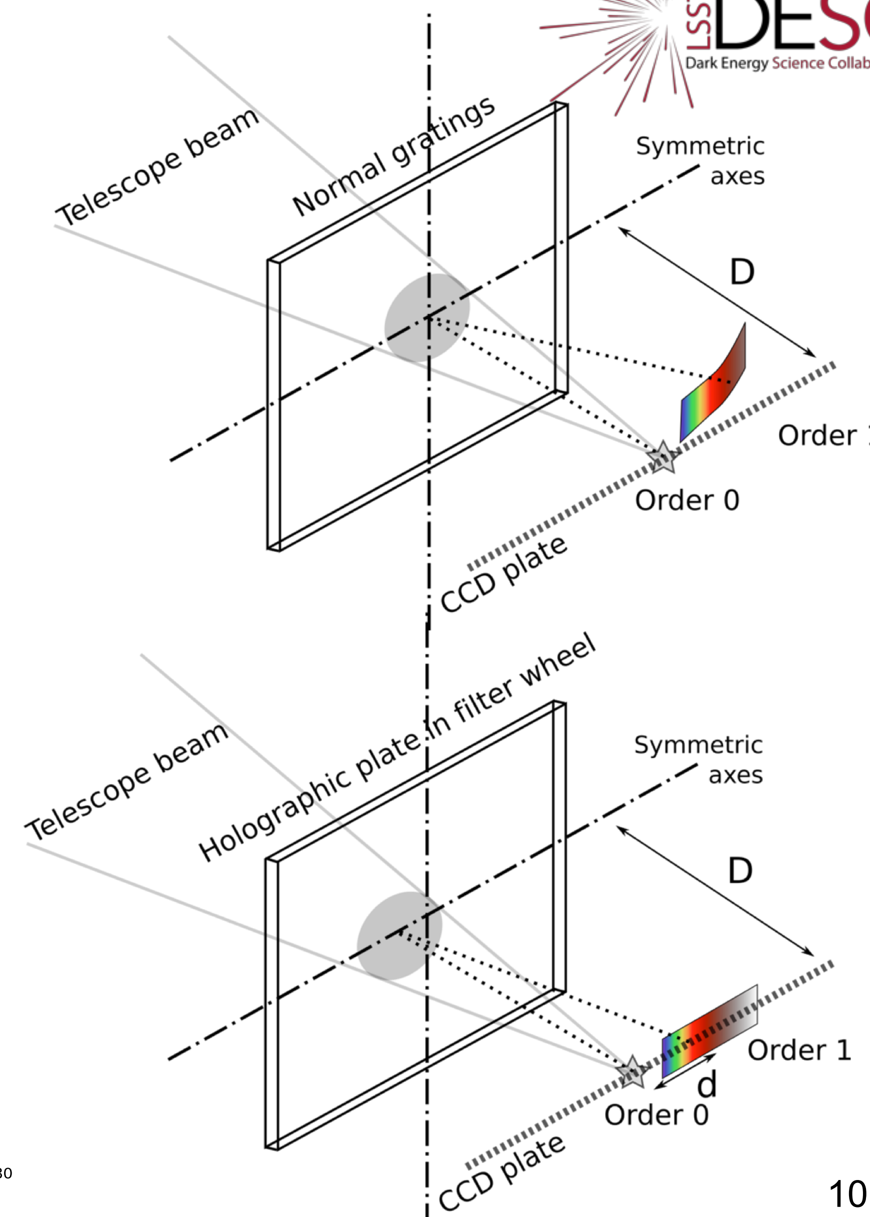
Holograms for slitless spectro

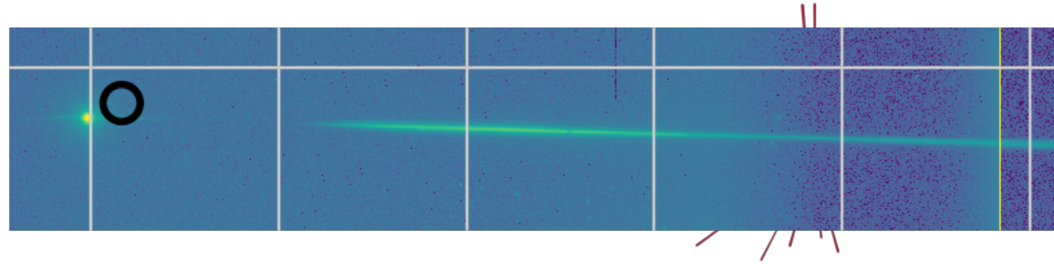
- **Usual gratings:** all wavelengths not focussed simultaneously on the focal plane because used with a convergent beam

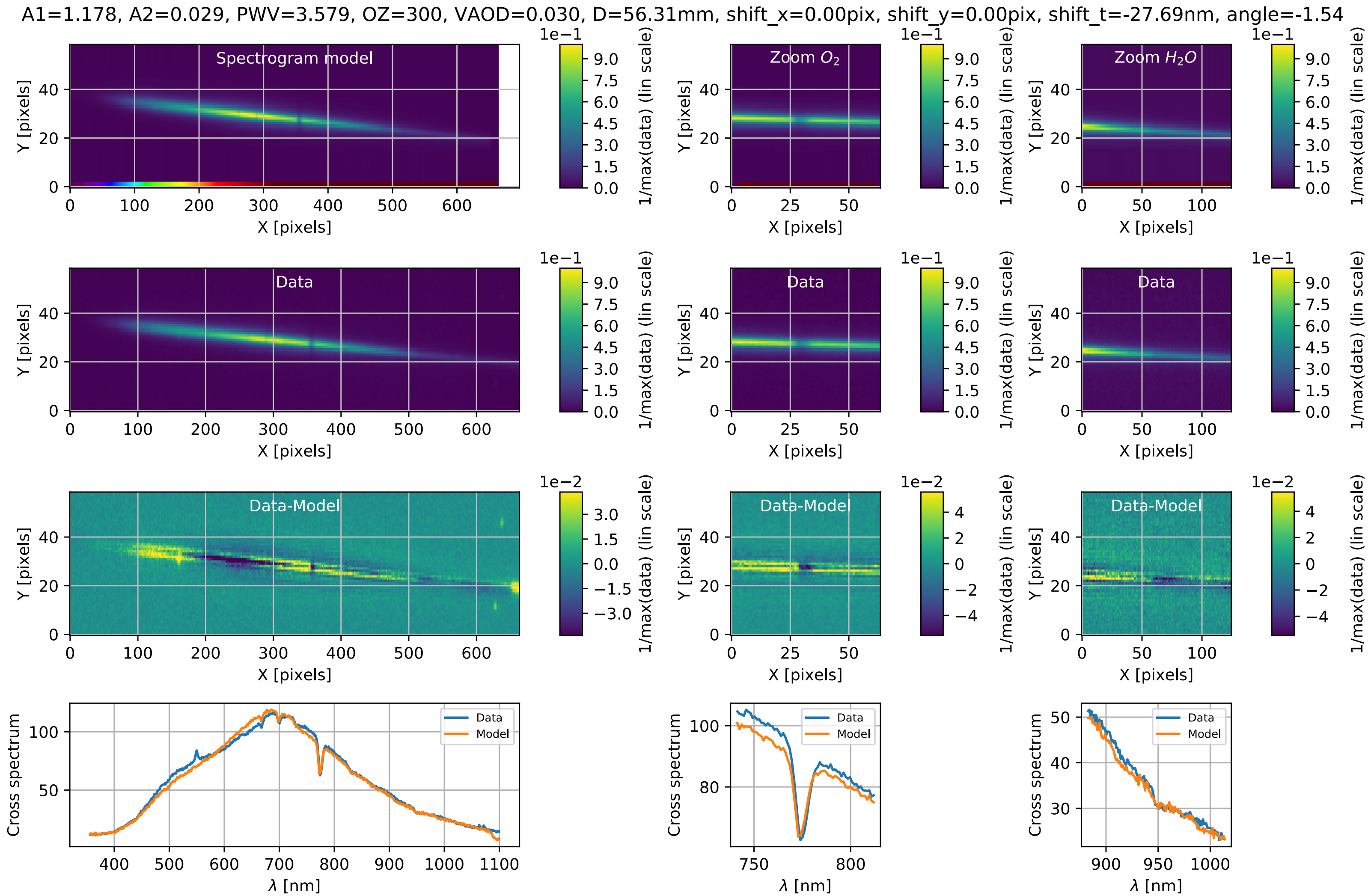
- **Holograms:** forced focussing on the focal plane at almost all wavelengths → hardware solution for the focus





Fit: CTIO holo#134





NOT CONVERGED !
Minuit have not finished its job

Lessons and outputs

Software solutions	Hardware/data solutions
1. Accurate model of a defocused PSF can not be empirical	
Optical model for ATS defocused PSF	Holograms
2. Instrument transmission must be known accurately	
Simultaneous fit of many spectrograms to get constant throughput	Nights of observation, CBP
3. Contribute to the observational strategy for Auxtel	
Use forward model to simulate nights and strategies	Use existing data sets and go on sky

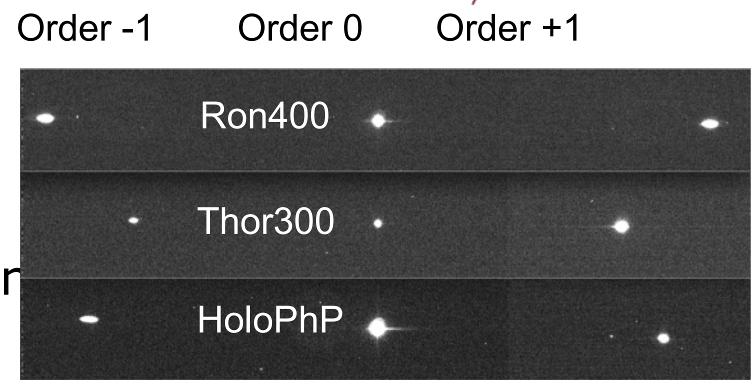
- Lots of work ! Y. Copin and S. Bongard have a master student
  - Hopefully will be able to continue in PhD on Auxtel

Back-up slides

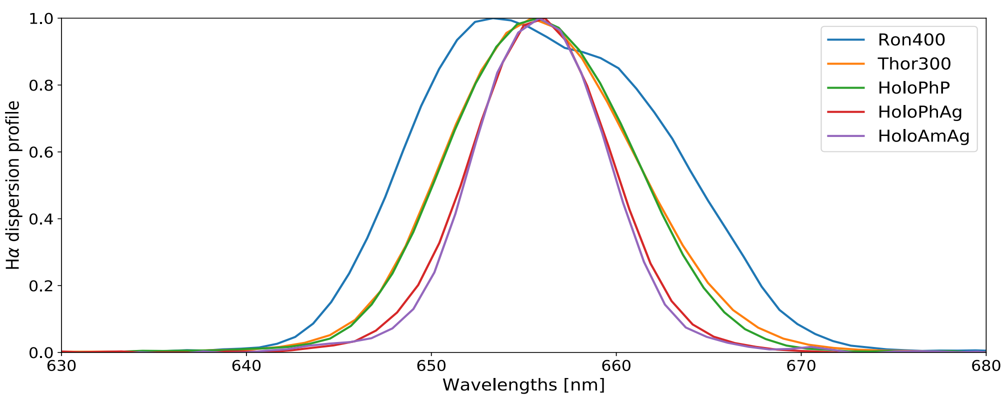
Hologram resolutions

- Determination of effective grooves per mm number
  - With H-alpha 655.9 nm
  - Calibration of D distance with known Thor300 et Ron400

D = 55.5 +/- 0.2 mm



- Comparison of the different resolutions



Filter	λ/δλ order +1	λ/δλ order -1	FWHM transverse (pix)
Ronchi 400	72	69	6.0
Thorlabs 300	124	114	4.0
HoloPhP	131	62	4.1
HoloPhAg	283	30	4.4
HoloAmpAg	367	38	4.1

Spectrum model

- CALSPEC SED and atmospheric transmission from Libradtran

Atmospheric parameters:
PWV: water; VAOD: aerosols; OZ: ozone

$$\Phi(\lambda;\sigma,\mathrm{atm}) = [\boxed{SED(\lambda)} \times \boxed{T(\lambda,\mathrm{PWV},\mathrm{VAOD},\mathrm{OZ})}] * \boxed{G(\sigma)}$$

$$S(\lambda;\mathrm{params}) = \boxed{A_1}\left[\Phi\left(\lambda(D_{CCD},\alpha_{pix})\right) + \boxed{A_2}\Phi\left(\frac{1}{2}\lambda(\boxed{D_{CCD},\alpha_{pix}})\right)\right]$$

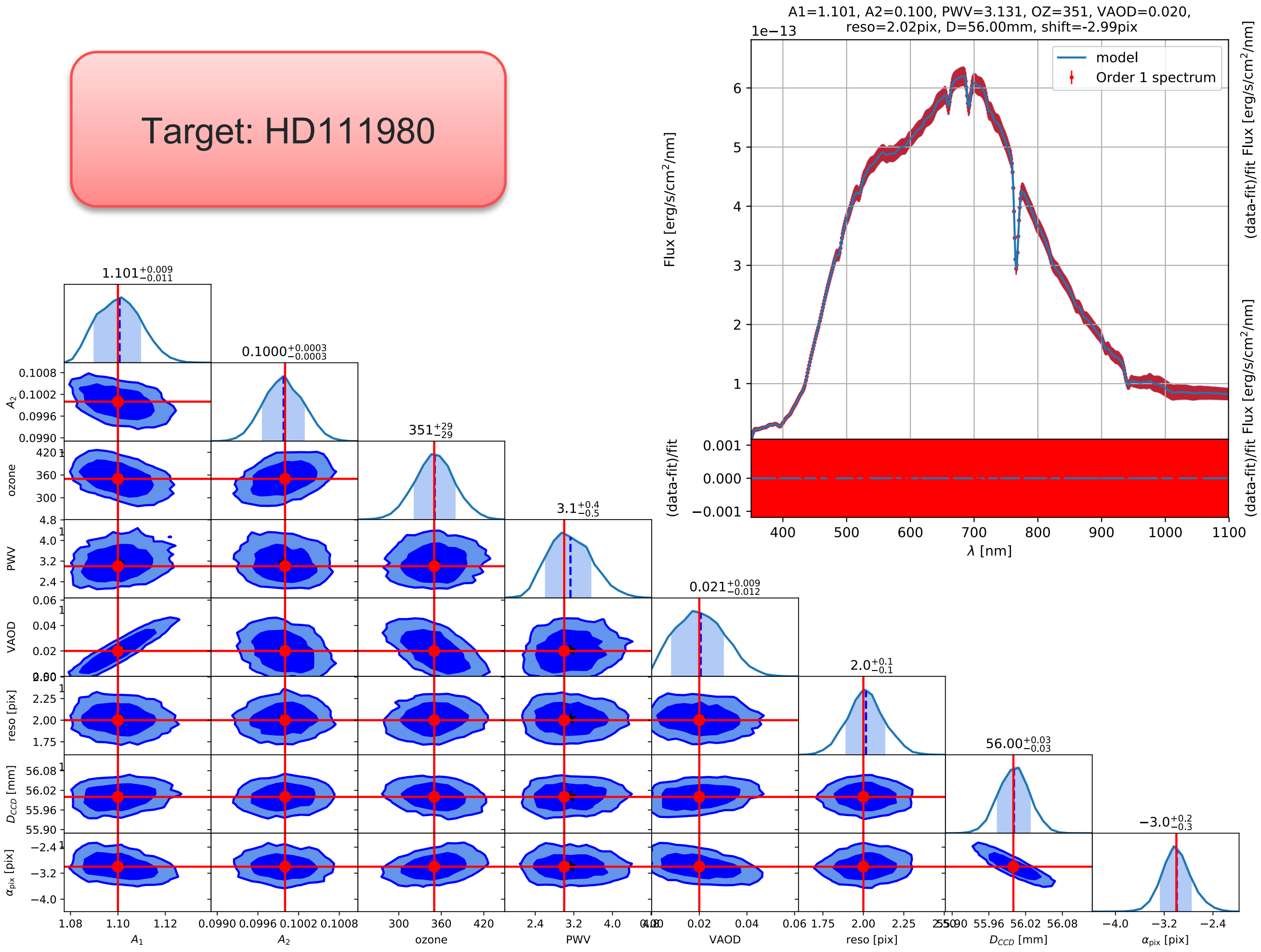
Instrumental effects:

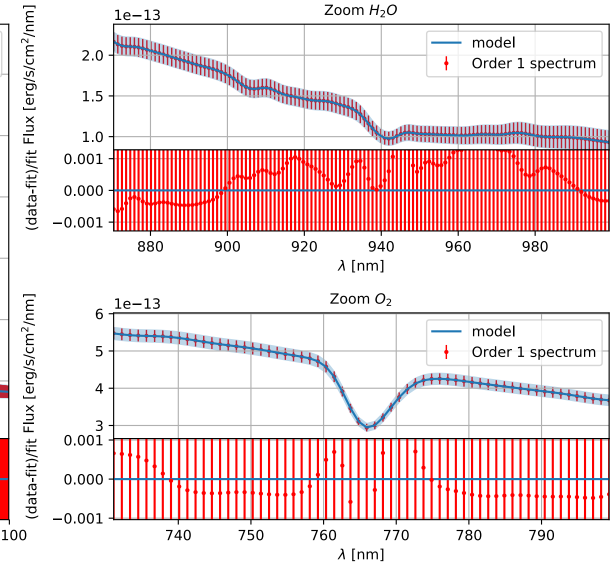
- A_1,: general amplitude of the spectrum
- A_2 : level of the order 2 contamination
- $G(\sigma)$: Gaussian convolution with σ modelling the resolution and the seeing
- D_{CCD}: the distance between the CCD and the disperser
- α_{pix}: shift in pixels on the order 0 position to calibrate the wavelengths

- 8 parameters to fit (3 atmospheric, 5 instrumental): python EMCEE

Test of the fitter on a simulated spectra

Target: HD111980

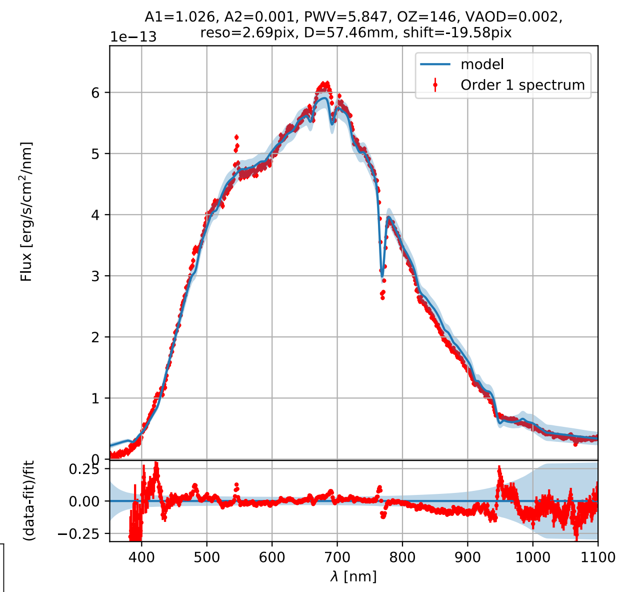


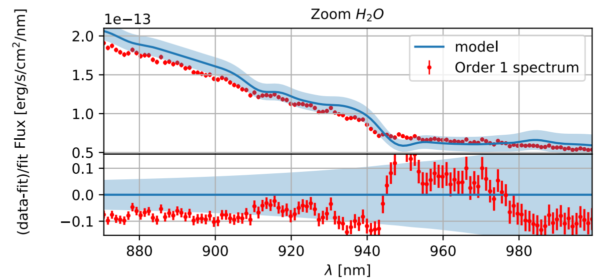


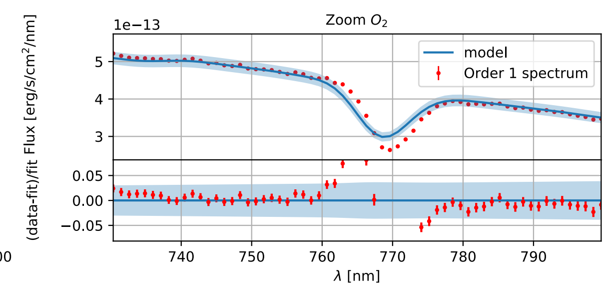
MCMC OK.

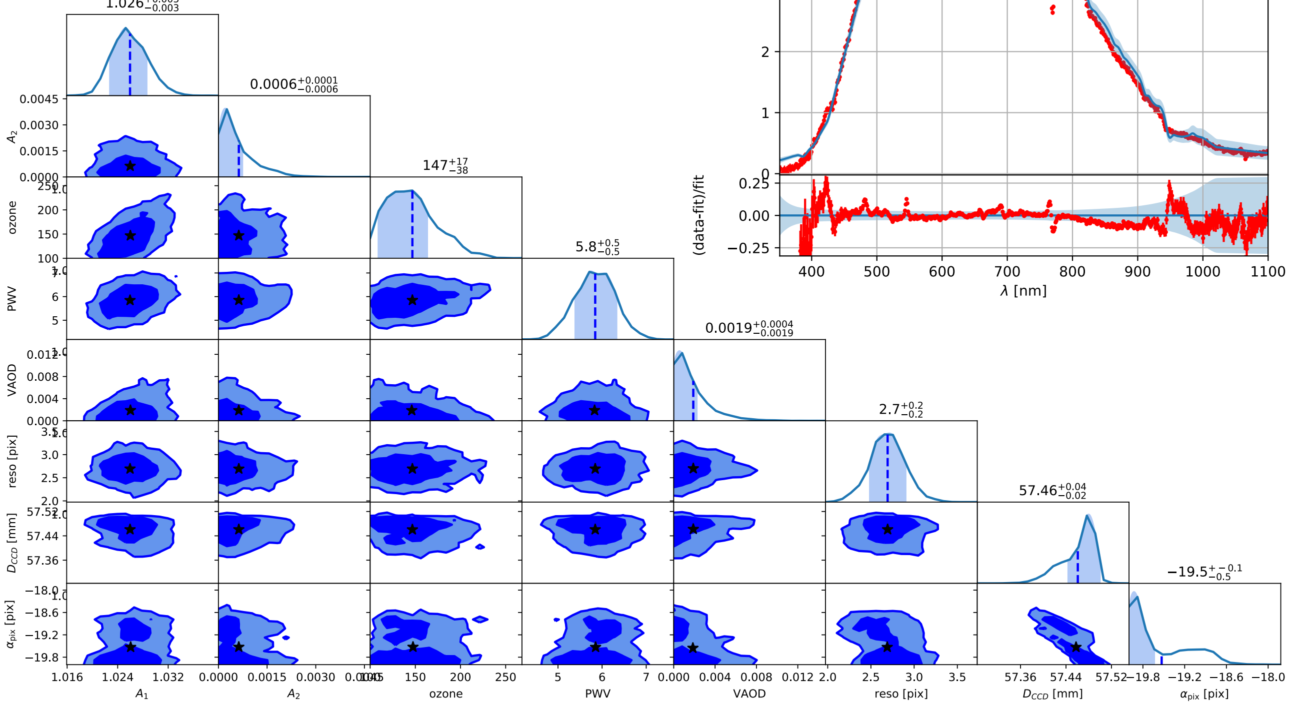
HoloAmAg: #134 2017/05/31 02h54 UTC

Target: HD111980









Best resolution but double minimum.