Forward modeling to measure atmospheric transmission

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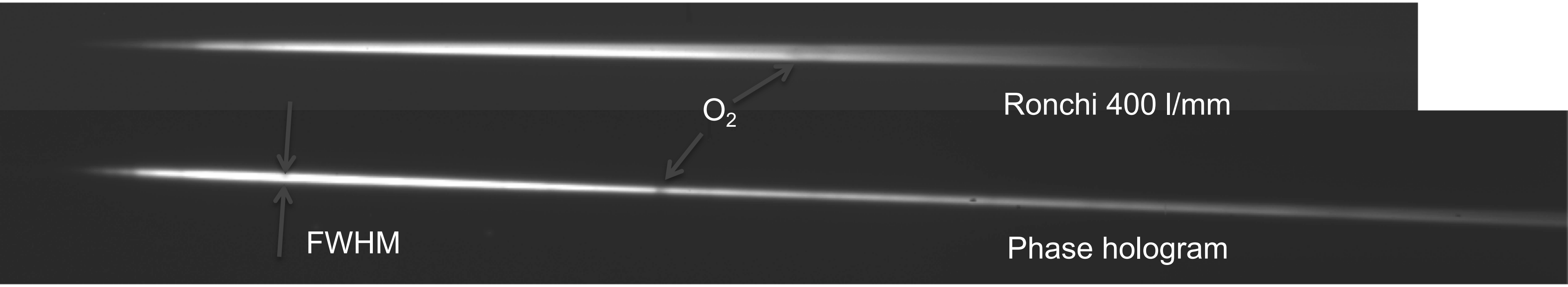
LSST DESC
Dark Energy Science Collaboration

Context

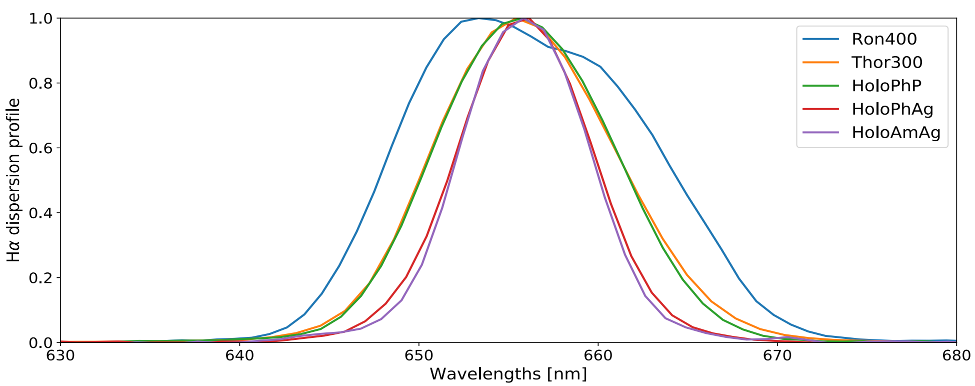
- Primary objectives:
  - Build a forward model of the 2D spectrogram
  - Measure the atmospheric transmission
- Data and instrument:
  - CTIO data: 16 nights in June 2017, multiple CALSPECs
  - Ronchi, blazed disperser and hologram dispersers

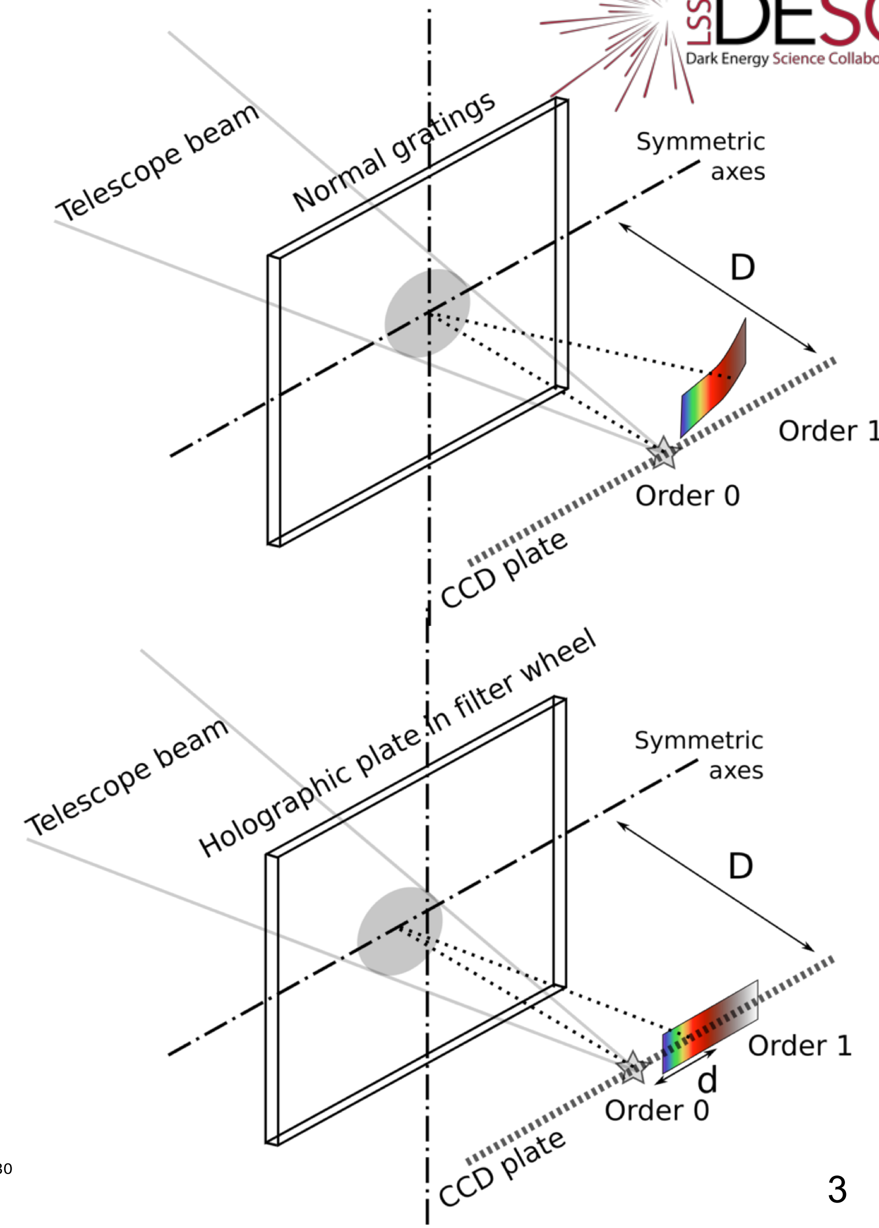


Holograms for slitless spectro

- **Usual gratings (Ronchi…):** when used in a convergent beam, all wavelengths not focused simultaneously on the focal plane
- **Holograms:** force the focus on the focal plane at almost all wavelengths → hardware solution for the focus

Hα filter profile



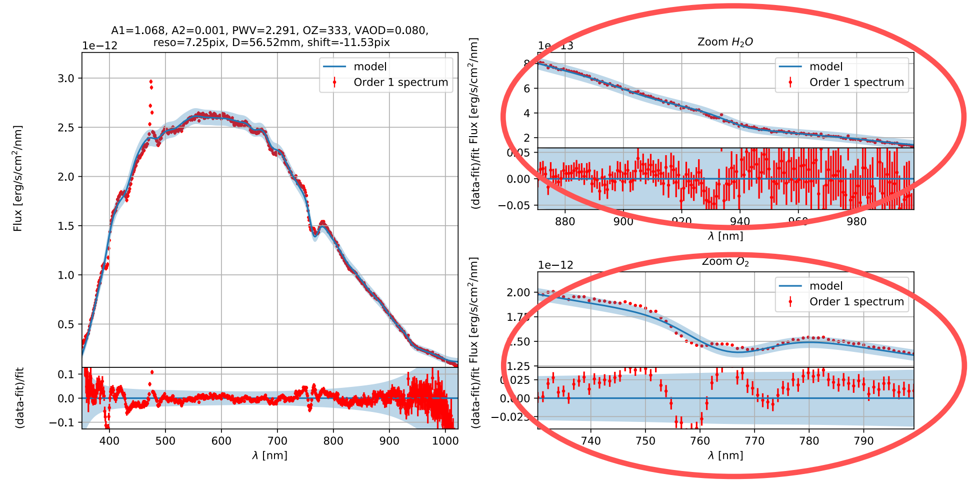


Traditional approach: cross spectrum

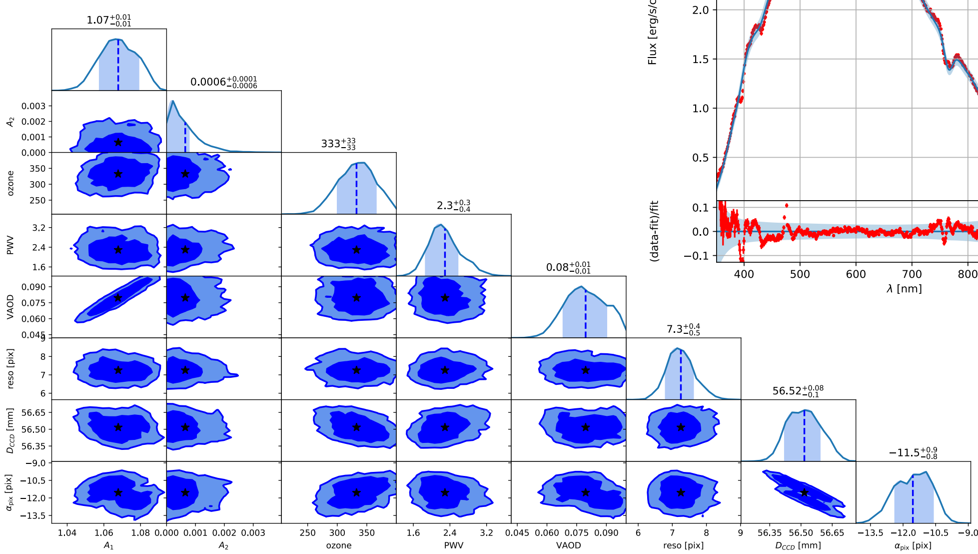
- Cross spectrum = sum across the transverse direction of the dispersion axis

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

Target:
HD111980



H_2O information washed out



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: $I(\mathbf{r}) = \int d\lambda\, (C \otimes P_0)(\mathbf{r} - \mathbf{\Delta}(\lambda), \lambda)$ Direct approach
  - In spatial Fourier domain:

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

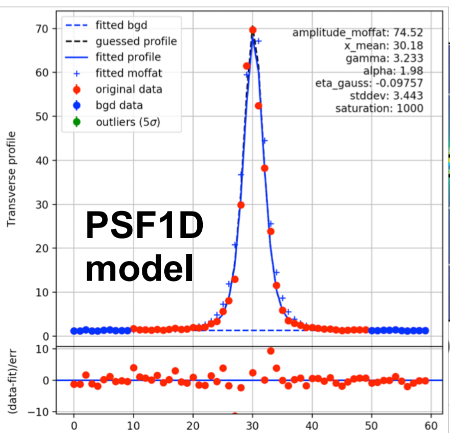
Fourier approach
-> FFT faster

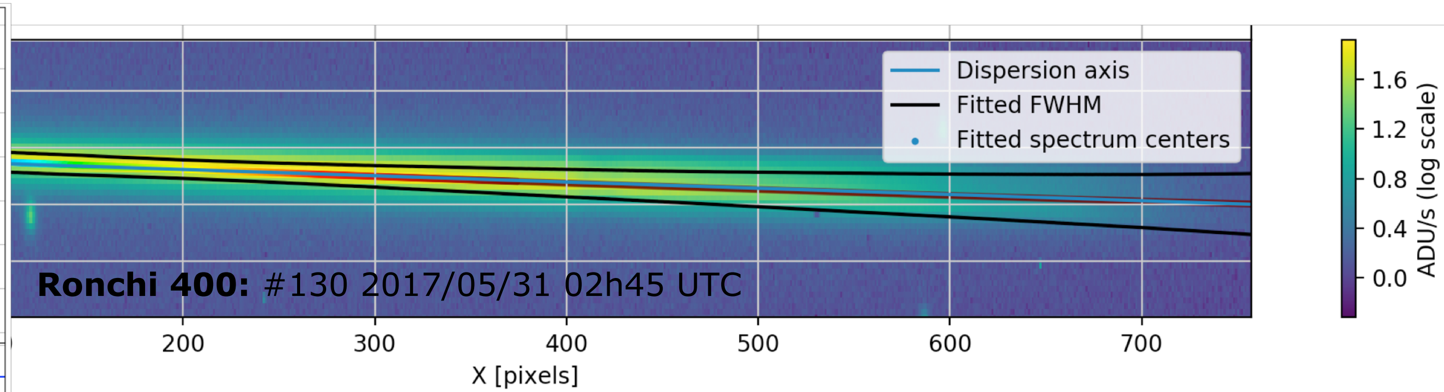
- Source: $C(\mathbf{r}, \lambda) = [T_{\text{instrument}}(\lambda) \times T_{\text{atm}}(\lambda|\theta) \times S_{\text{star}}(\lambda)] \times \delta\left(\mathbf{r} - \mathbf{r}_{\text{order 0}}\right)$
- Chromatic PSF: $P_0(\lambda)$
- Disperser law: $\mathbf{\Delta}(\lambda) = (x_{\text{order 1}}(\lambda),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

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

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





  - 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)

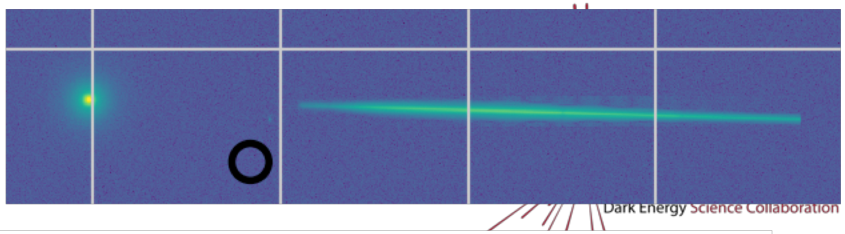
Spectrogram simulation

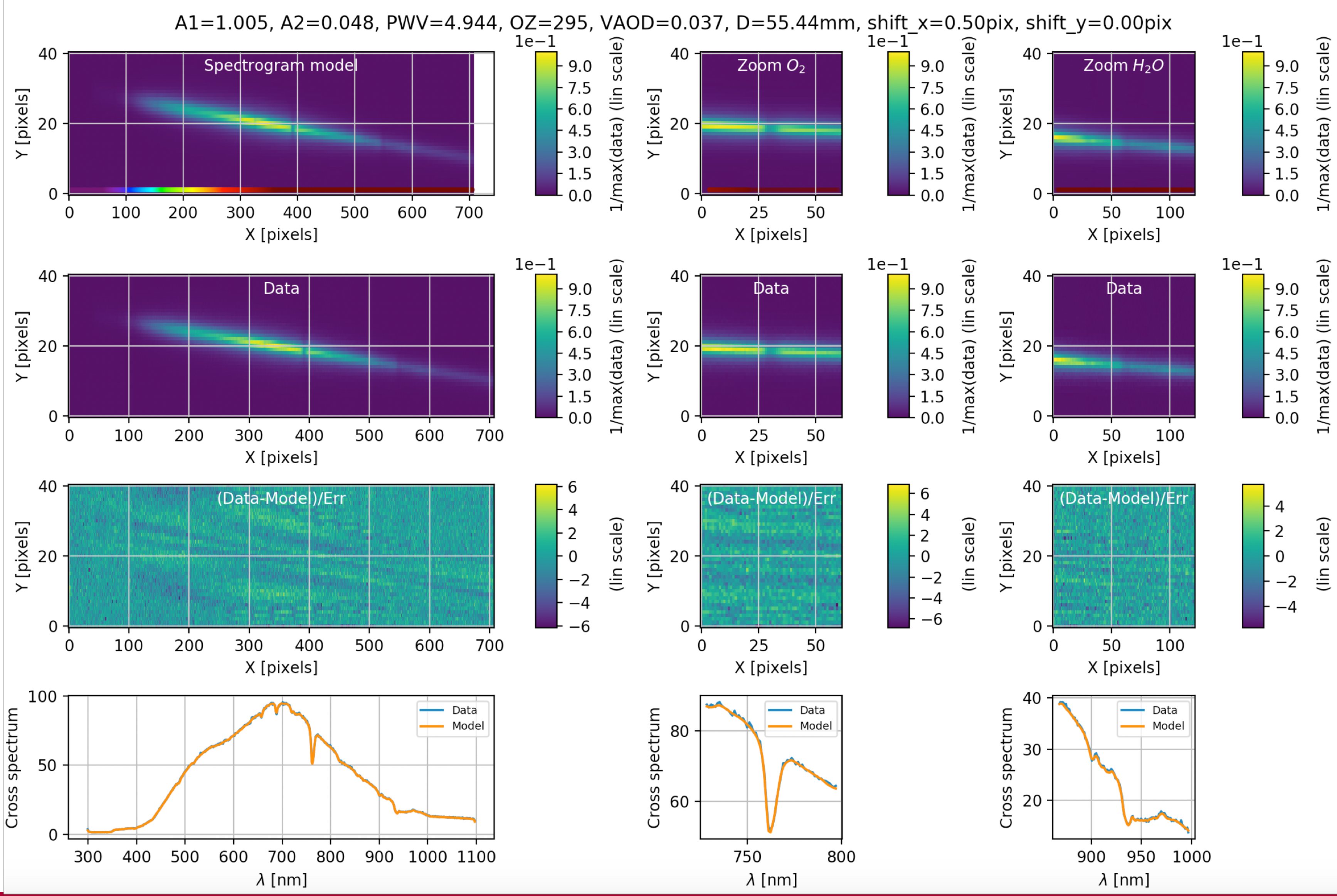
- Use Fourier formalism to simulate order 1 and order 2

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

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

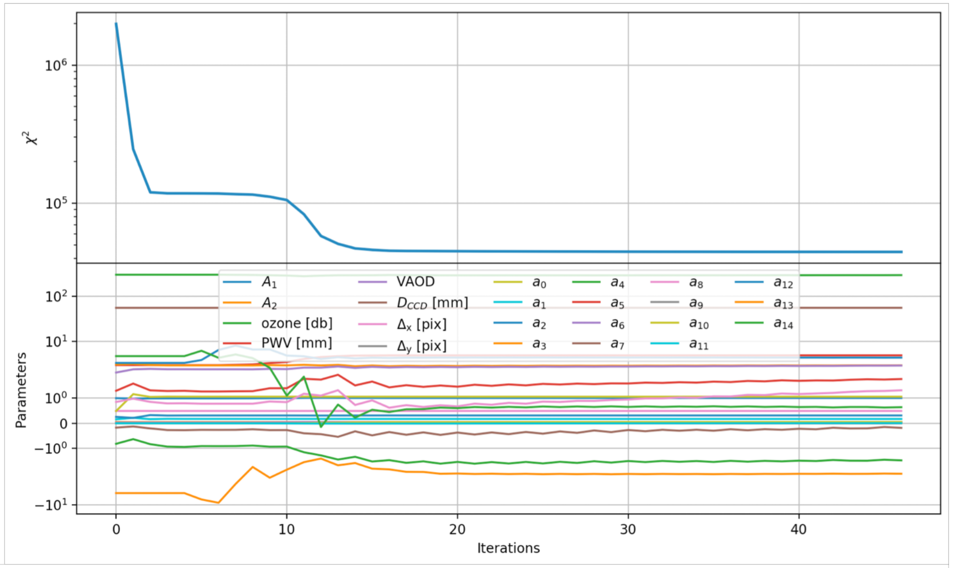
Fit: test model

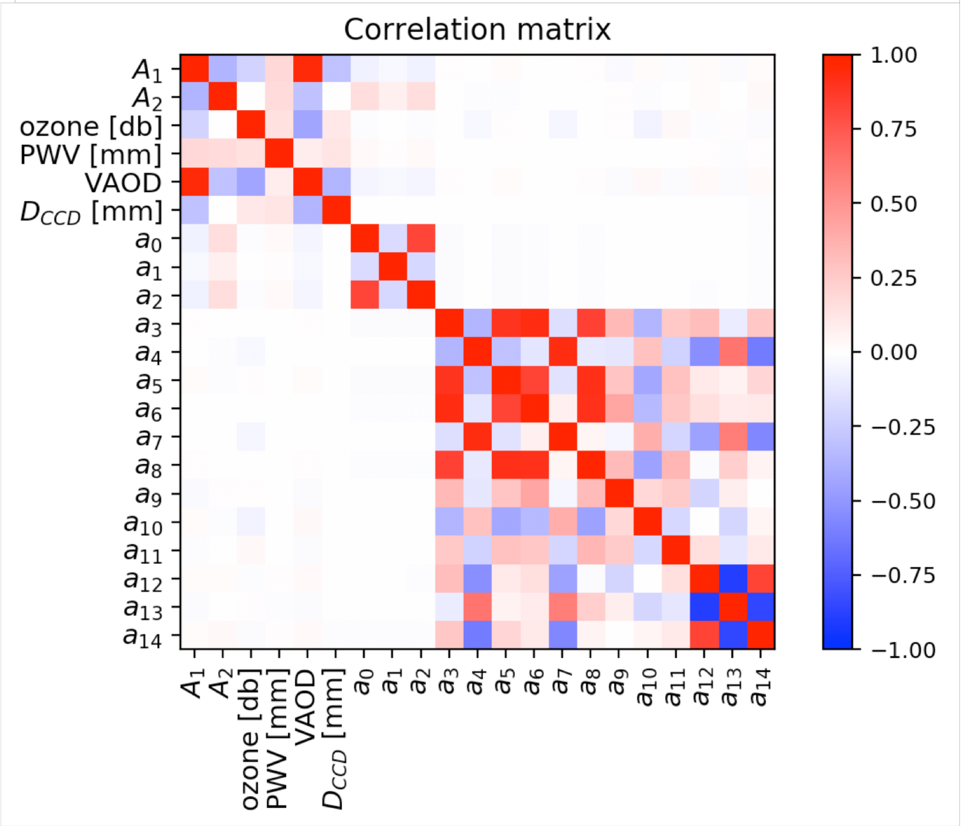




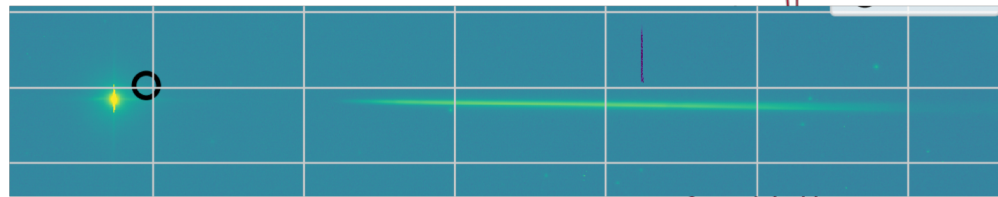
Fit: test model

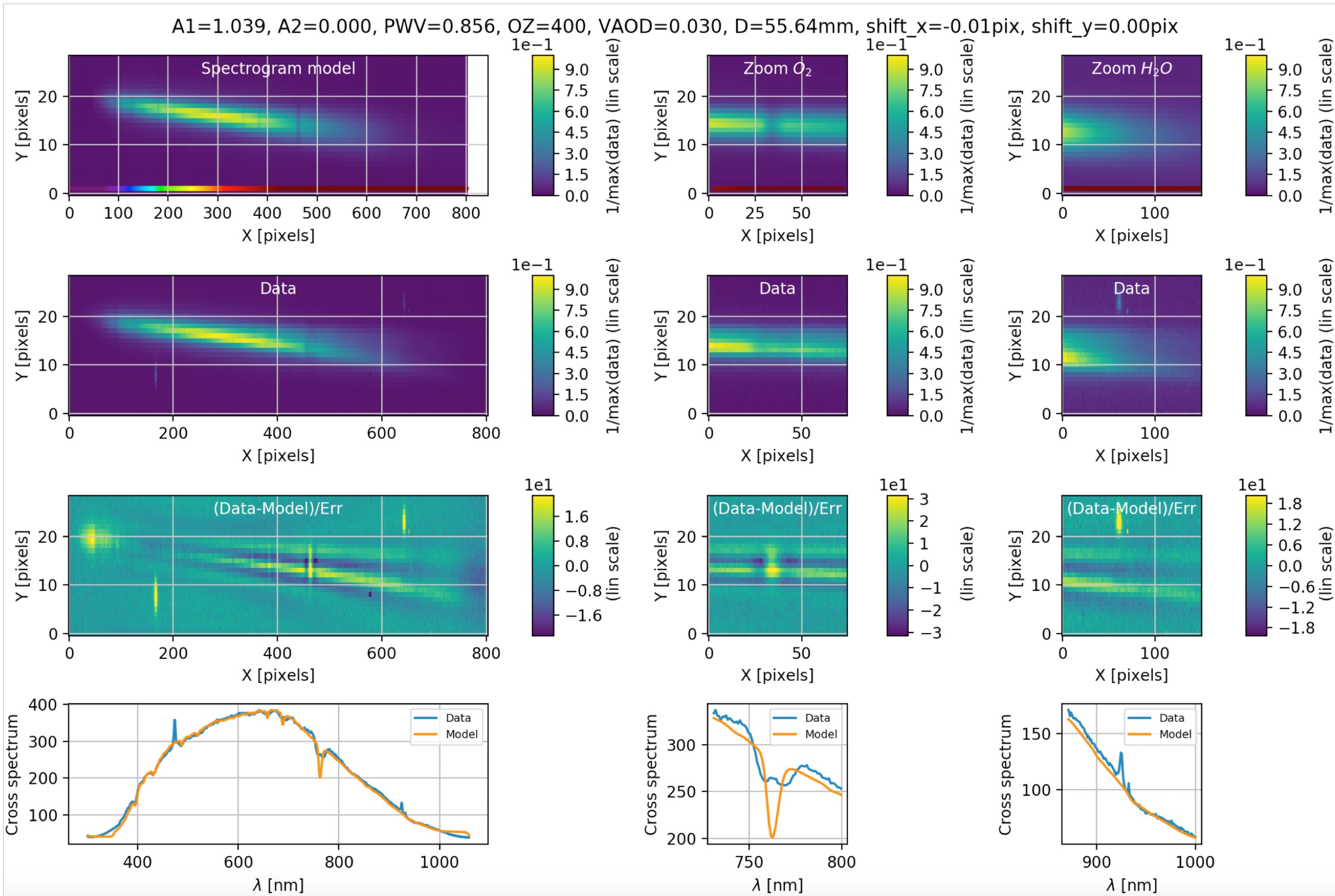
chisq=44505.996	Truth
A1: 1.005 +0.002 -0.002	1
A2: 0.0482 +0.0004 -0.0004	0.05
ozone [db]: 295 +8 -8	300
PWV [mm]: 4.94 +0.05 -0.05	5
VAOD: 0.037 +0.002 -0.002	0.03
D_CCD [mm]: 55.444 +0.002 -0.002	55.45
a0: 1.060 +0.001 -0.001	
a1: 0.174 +0.002 -0.002	
a2: 0.311 +0.003 -0.003	
a3: 2.97 +0.01 -0.01	
a4: -1.48 +0.02 -0.02	
a5: 1.76 +0.02 -0.02	
a6: 2.93 +0.02 -0.02	
a7: -0.18 +0.02 -0.02	
a8: 1.31 +0.03 -0.03	
a9: 0.0387 +0.0002 -0.0002	
a10: 0.0531 +0.0004 -0.0004	
a11: 0.0081 +0.0002 -0.0002	
a12: 4.396 +0.01 -0.01	
a13: -2.03 +0.02 -0.02	
a14: 0.64 +0.01 -0.01	





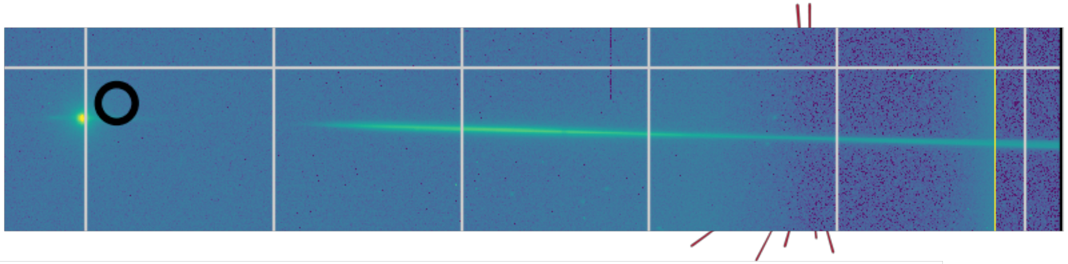
Fit: CTIO Ron#130

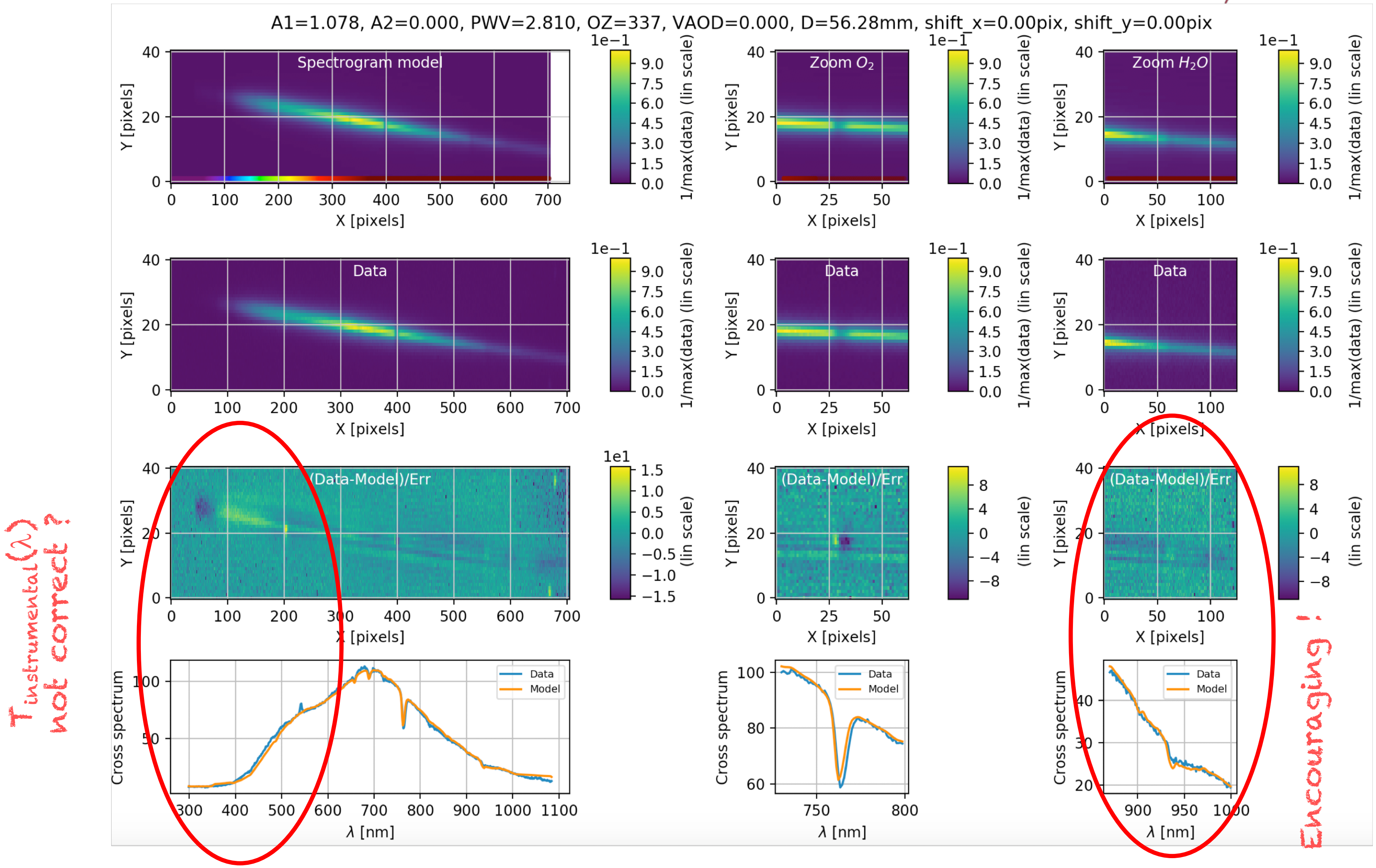




PSF model Moffat-Gauss not sufficient to model the defocus

Fit: CTIO holo#134





Lessons

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

- Work by Vincent Brémaud (L3) to get the “correct” instrumental throughput
- Work by Maxime Rey (M2) to implement the ADR and a defocused instrument model
- PhD 2019-2022 on Auxtel

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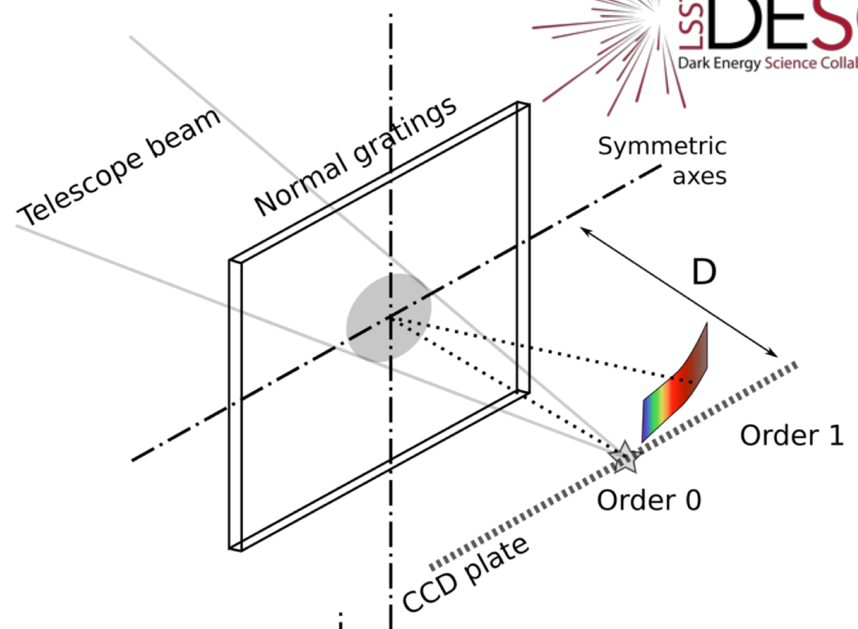
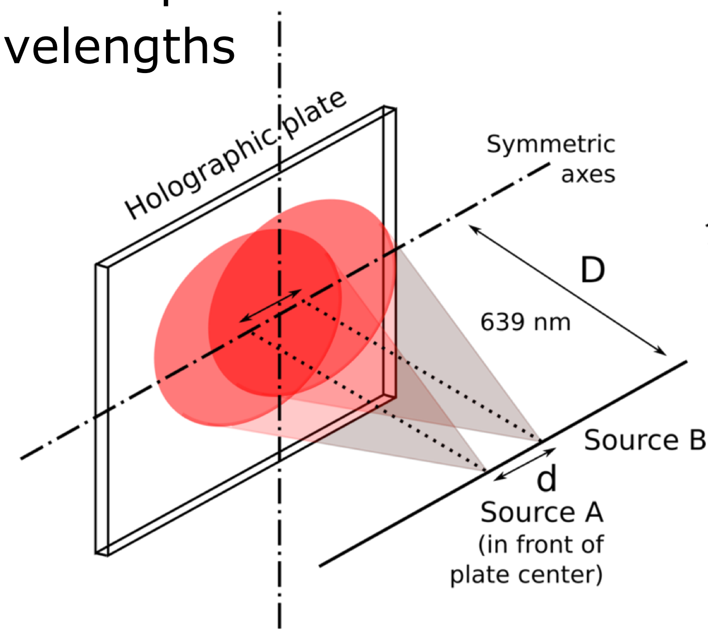
- Building of a 2nd generation of holograms:
  - Adapted to the Auxtel geometry
  - Higher 1st order transmission
  - Lower 2nd order transmission
  - Sealed and overall better quality

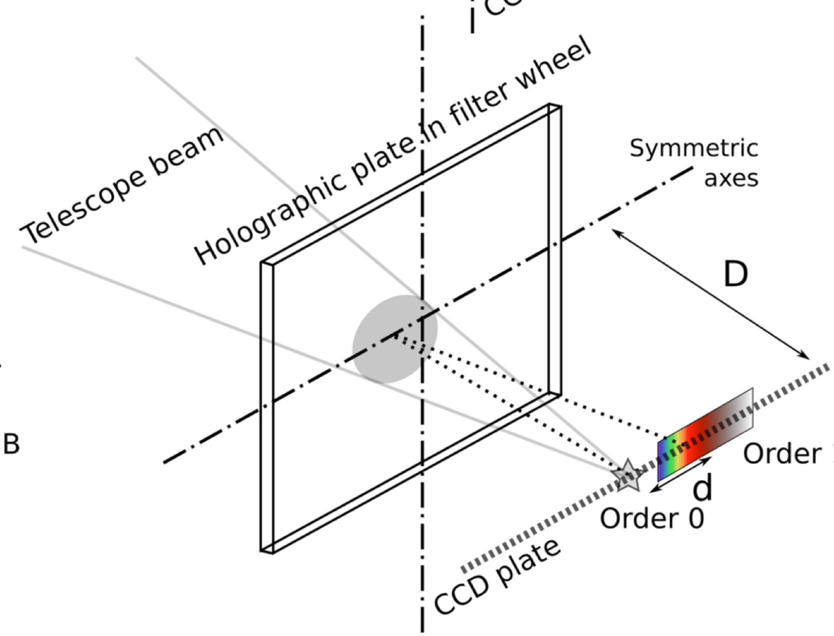
Back-up slides

Holograms for AuxTel

- **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

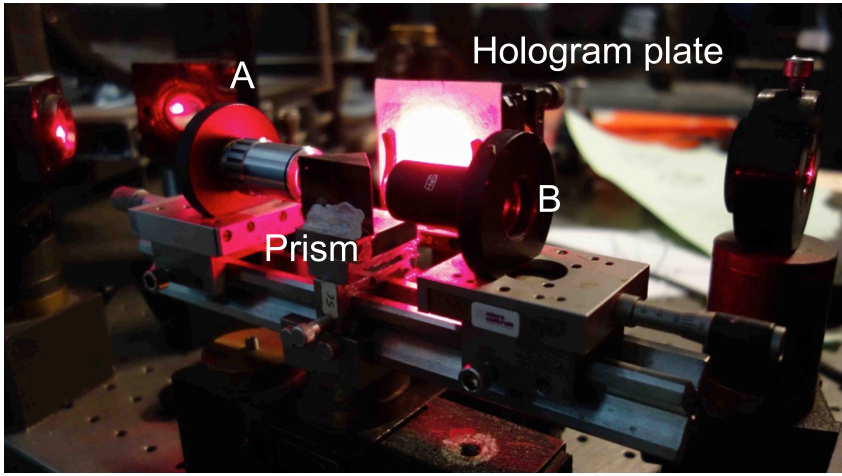


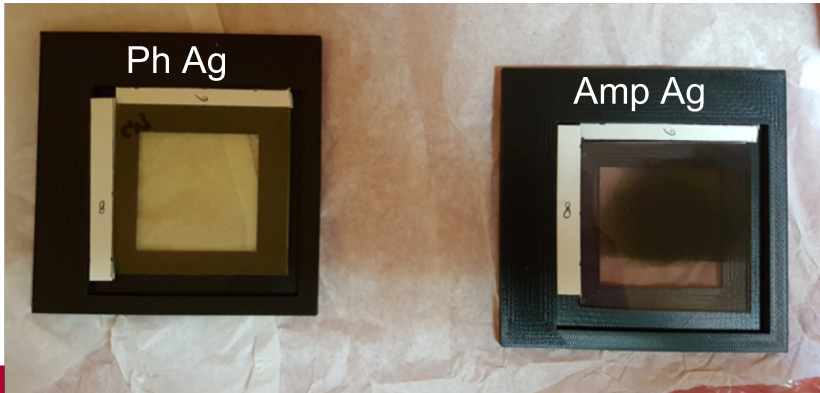




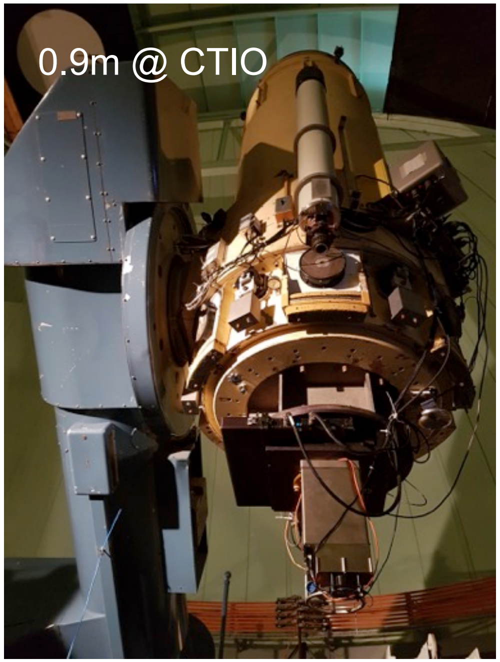
Holograms in a nutshell

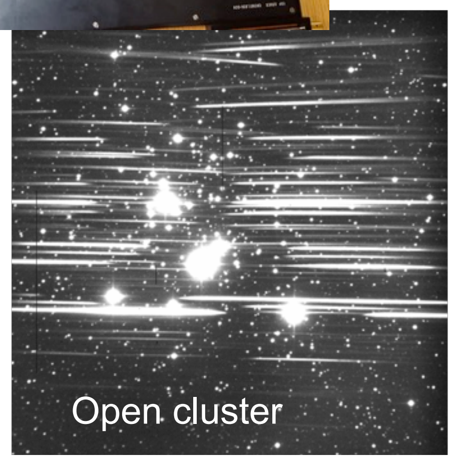
- Prototypes made in Bordeaux by Ultimate Holographics “Best holograms in the world”
- Three different technologies tested :
  - Phase with polymers
  - Phase with Ag
  - Amplitude with Ag
- Brought to CTIO for 18 test nights:
  - calibration, characterisation
  - Atmospheric studies
  - Compared with Ronchi 400 gr/mm and blazed grating 300 gr/mm

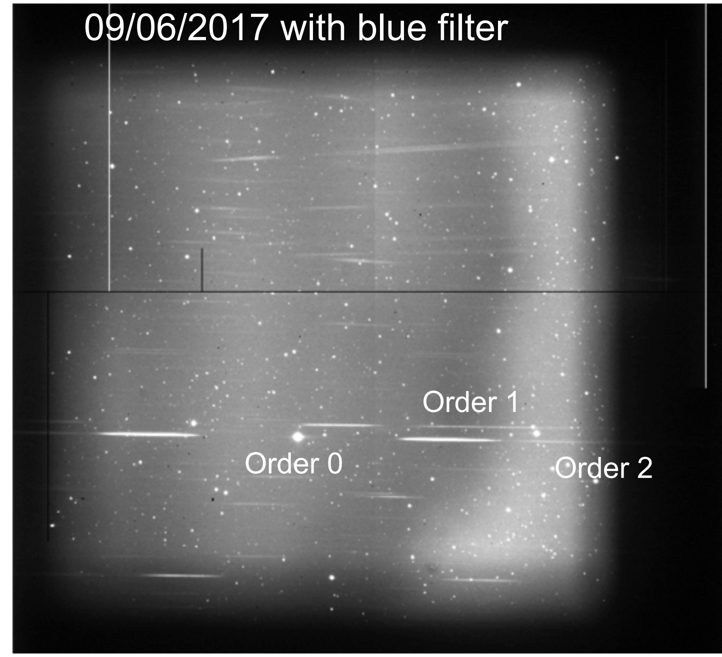


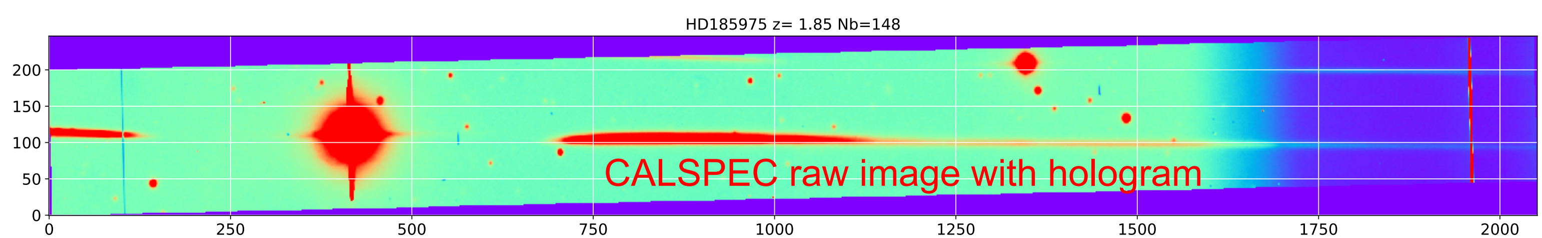


Holograms in a nutshell



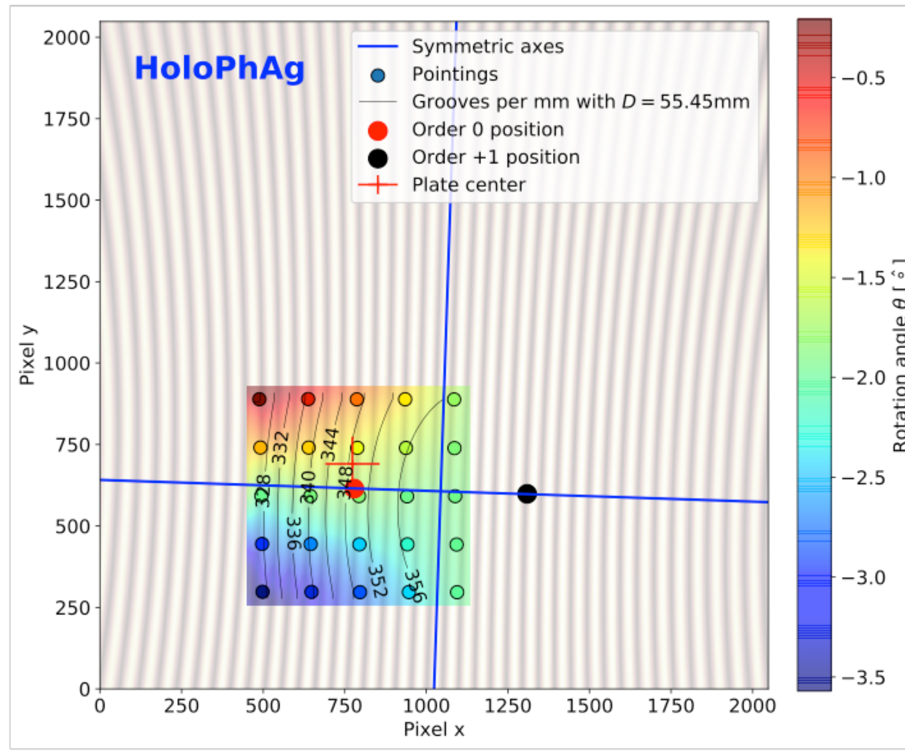






Tests at CTIO (18 nights in June)

- Scans of 25 pointings to calibrate and characterise the holograms
  - Rotation angle field
  - Effective grooves per mm
  - Transverse width
  - Order 2 contamination
- Observation of emission line objects and CALSPECs



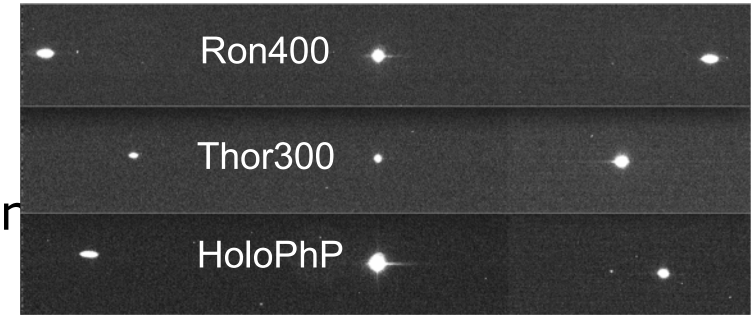
Hologram resolutions

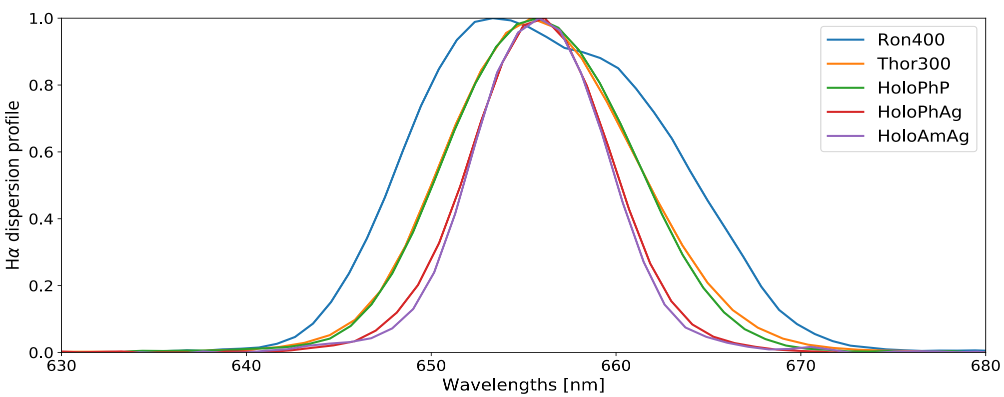
- Determination of effective grooves per mm number
  - With H-alpha 655.9 nm
  - Calibration of D distance with known Thor300 et Ron400

D = 55.5 +/- 0.2 mm

- Comparison of the different resolutions

Order -1 Order 0 Order +1





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

Improvements: minimisation algo

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- Minimization of χ^2 the vector (not summed)
- Implementation of a Newton-Raphson method to find the zeros of the gradient of the χ^2

$$\chi^2(\theta) = \left(\vec{M}(\theta) - \vec{D}\right)^T W \left(\vec{M}(\theta) - \vec{D}\right) = \vec{R}^T(\theta) W \vec{R}(\theta)$$

$$\vec{\nabla}_\theta \chi^2 \approx 2 J_0^T W \vec{R}_0 + 2 J_0^T W J_0 \delta\vec{\theta} \text{ with } \delta\vec{\theta} = \vec{\theta} - \vec{\theta}_0$$

J: Jacobian

$$\vec{\nabla}_\theta \chi^2 = 0 \Rightarrow \vec{\theta} = \vec{\theta}_0 - \left(J_0^T W J_0\right)^{-1} J_0^T W \vec{R}_0$$

$$\Rightarrow \vec{\theta}_{k+1} = \vec{\theta}_k - \alpha \left(J_k^T W J_k\right)^{-1} J_k^T W \vec{R}_k$$

$(J^TWJ)^{-1}$: covariance matrix

- Minimization of α with a line search method
- χ^2_{min}=36516 (with 27429 pixels) in 6 minutes (14 steps)