Slitless spectroscopy and AuxTel

LSS-France 26/05/2021

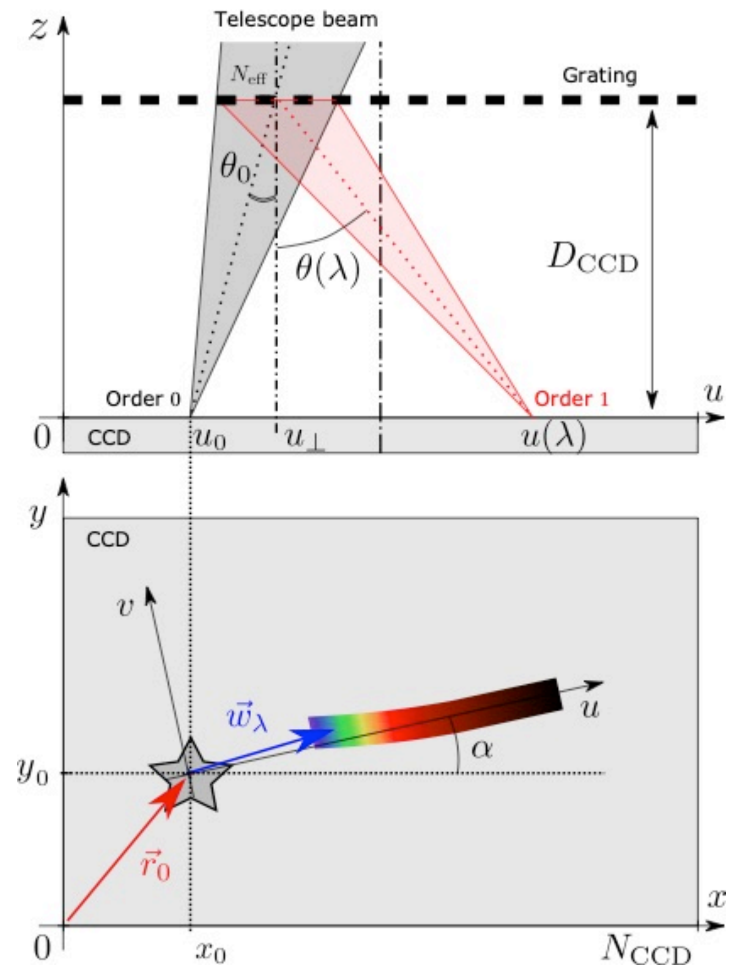
Outline

- **Slitless spectroscopy for newcomers**
- **Spectractor: new features**
- **CTIO instrumental transmission**
- **CTIO atmospheric transmission**
- **And AuxTel ?**

Slitless spectroscopy for newcomers

Simple slitless spectrograph

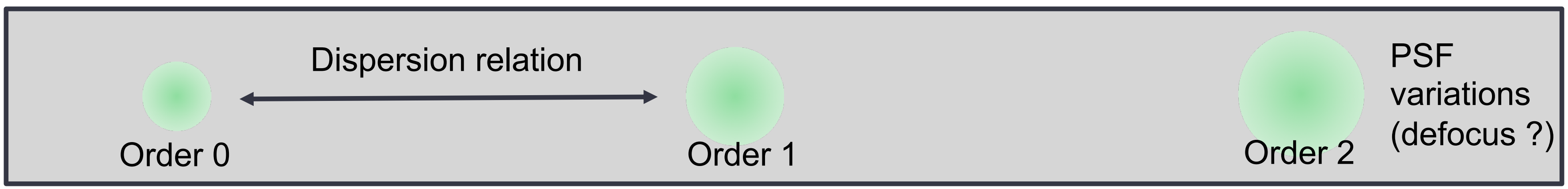
- Disperser inserted into the telescope beam, used with convergent or parallel wavefront
- Diffraction orders recorded on a CCD of size (N_{CCD}, N_{CCD}), at D_{CCD} behind the disperser
- Order 0 centroid position $\mathbf{r_0}$ can set the zero of the wavelength solution
- Optical system is a priori astigmatic: PSF evolves with λ but still obey to the grating formula



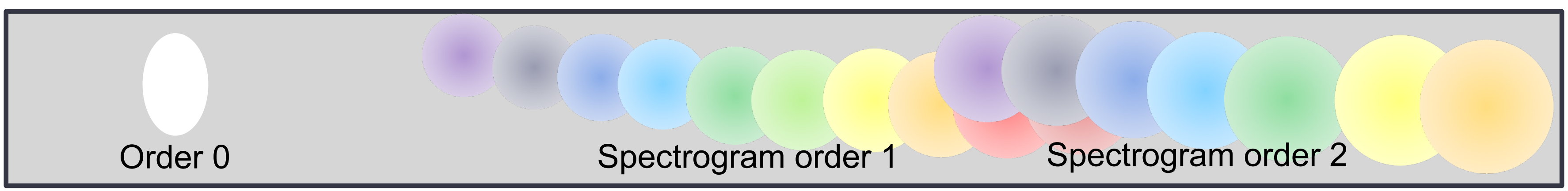
Spectrogram: a dispersed image

Observation of a monochromatic (green) star without a disperser:

Observation of a monochromatic (green) star with a disperser:



Observation of a polychromatic star with a disperser and ADR:



Spectrogram forward model

- Observation of astrophysical source with spatio-spectral flux density

$$C_p(\vec{r}, \lambda) = [T_{\mathrm{inst},p}(\lambda)\, T_{\mathrm{atm}}(\lambda|\theta_a)\, S_*(\lambda)] \times \delta\left(\vec{r} - \vec{r}_0\right)$$

with p the diffraction order, θ_a the atmospheric parameters

- Image is a stack of diffraction orders, which are a stack of monochromatic PSF kernels $\phi_p(\vec{r}|\lambda)$ dispersed by the grating:

$$I(\vec{r}) = \sum_p \int \mathrm{d}\lambda \iint \mathrm{d}^2\vec{r}'\ C_p(\vec{r}', \lambda)\, \phi_p(\vec{r} - \vec{r}'|\lambda)$$

- For a point source, the convolution product becomes:

$$\boxed{I(\vec{r}) = \sum_p \int \mathrm{d}\lambda\ S_p(\lambda)\phi_p\left(\vec{r} - \vec{\Delta}_p(\lambda)|\lambda\right)}$$

Dispersion relation

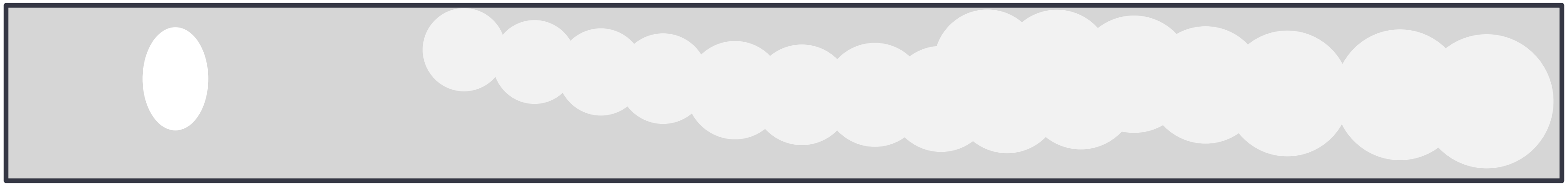
$$\vec{\Delta}_p(\lambda) = (x_{c,p}(\lambda), y_{c,p}(\lambda))$$

Spectrum

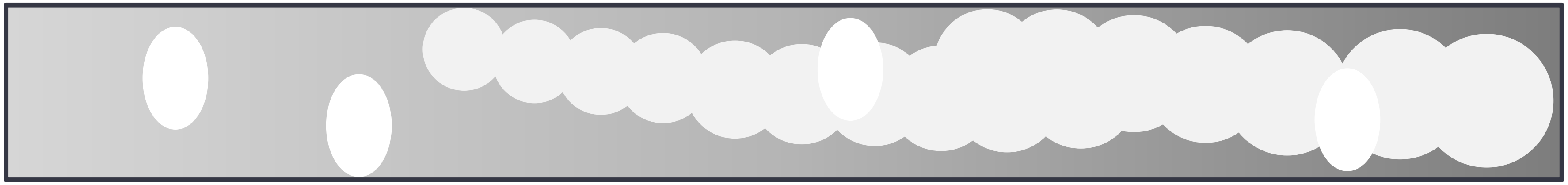
$$S_p(\lambda) = T_{\mathrm{inst},p}(\lambda)\, T_{\mathrm{atm}}(\lambda|\theta_a)\, S_*(\lambda)$$

From theory to reality

The CCD is a BW sensor:



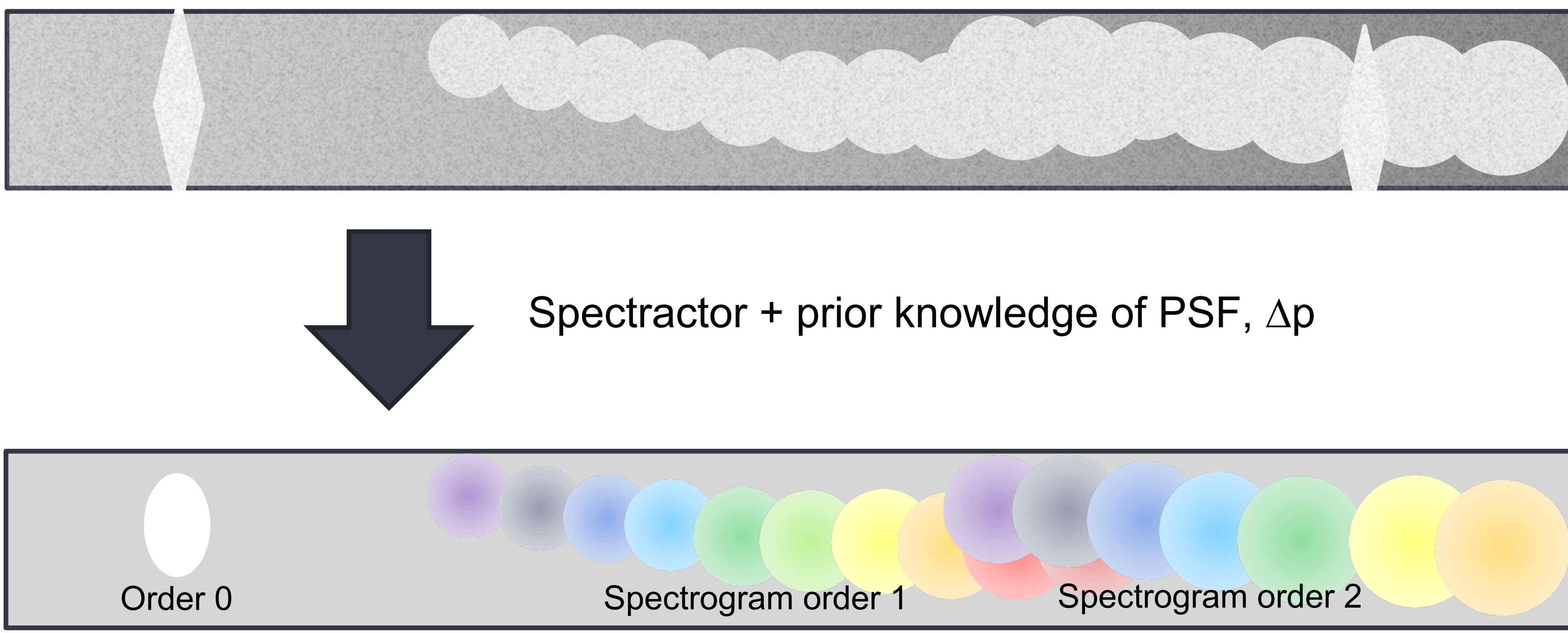
The background can be structured, with field stars:



CCD effects: saturation, noise…

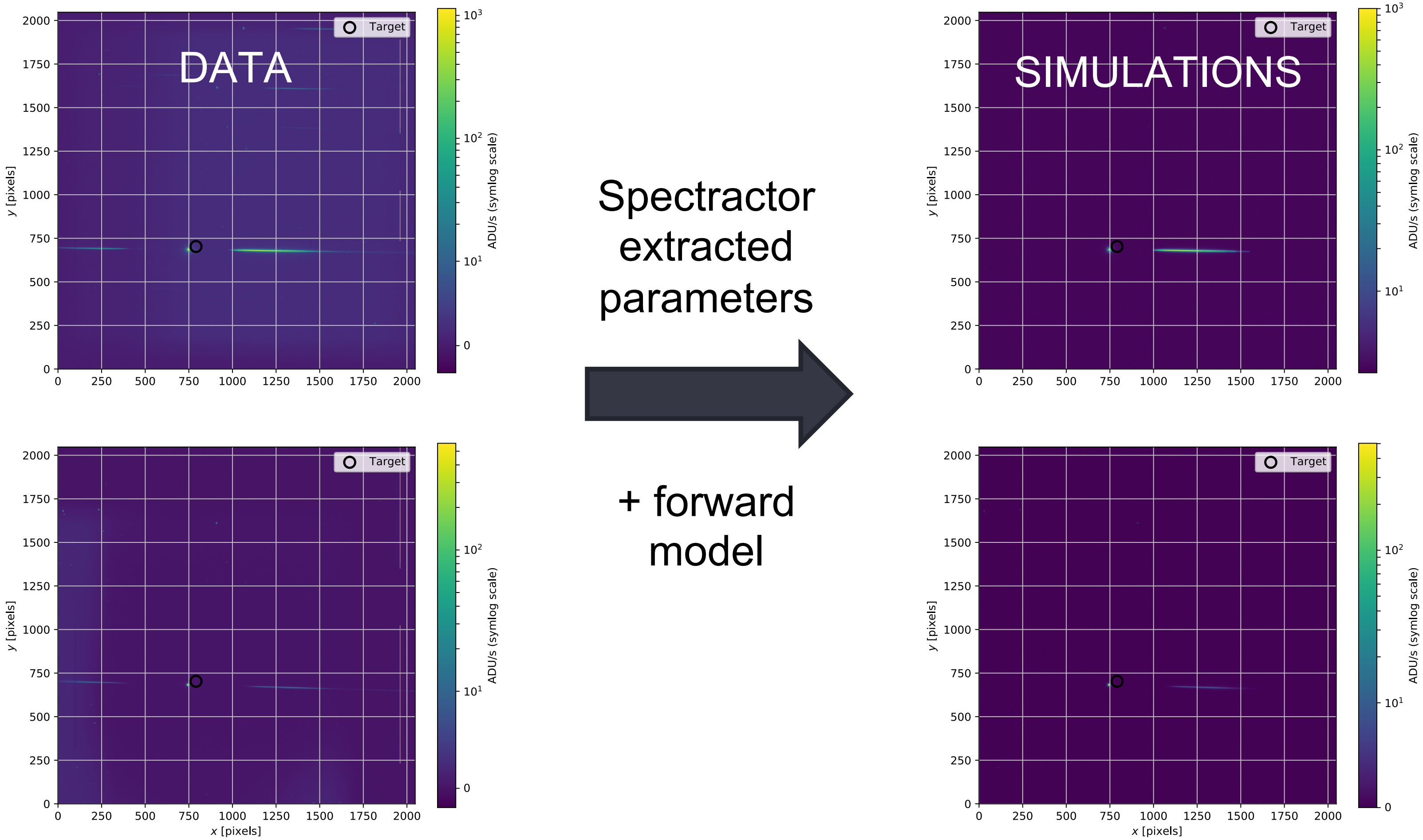
Spectrogram forward model

- Forward modelling of spectrograms opens the path to get atmospheric transmissions and other useful quantities
- Spectractor implements a way to extract and fit spectrograms and spectra, tested on CTIO simulations and data



Data sets and simulations

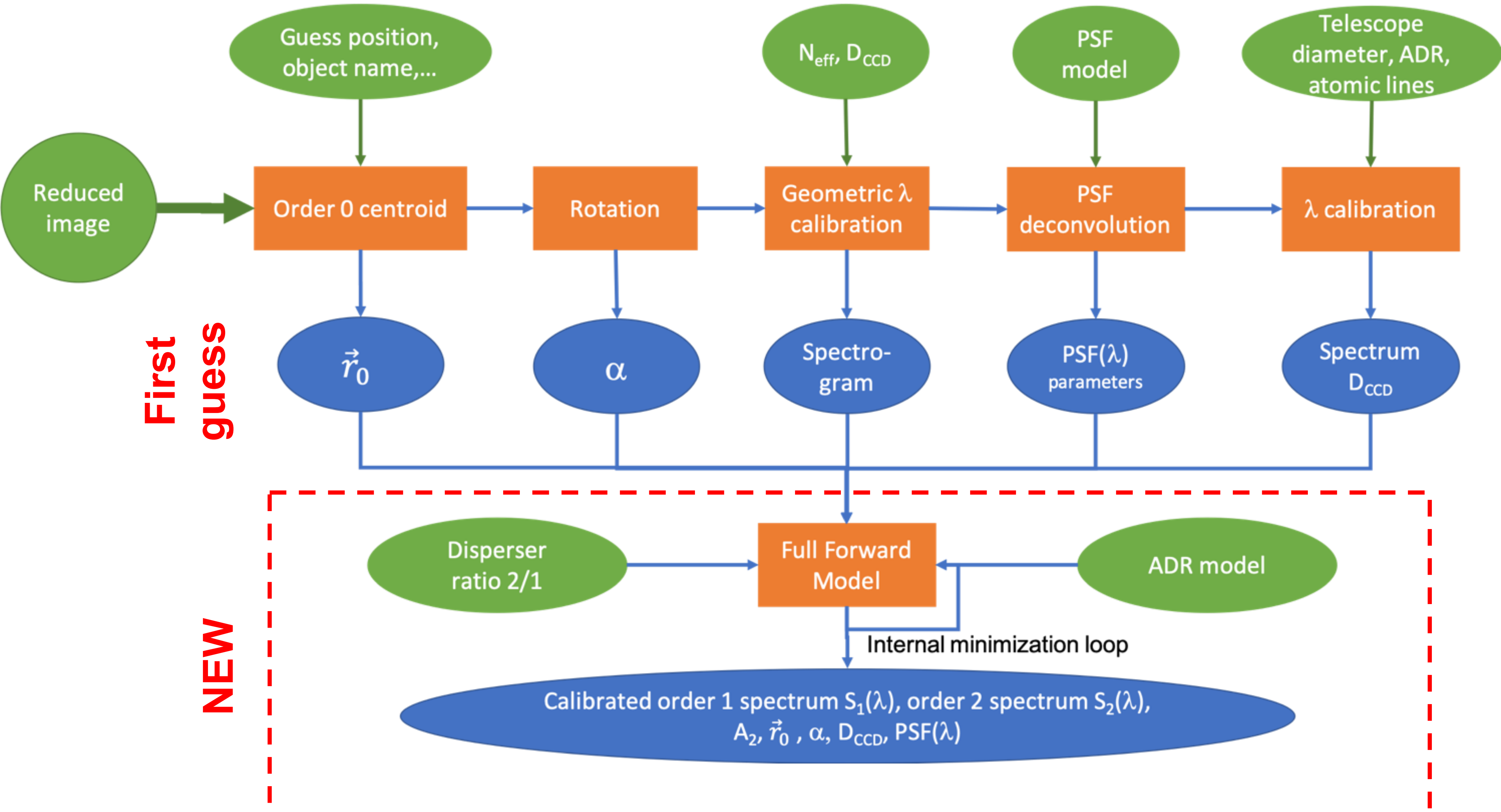
- Mainly CTIO images from June 2017 campaign (18 nights) with CALPSEC stars and different dispersers



Spectractor: new features

Order 2 decontamination and regularized deconvolution

Full forward model



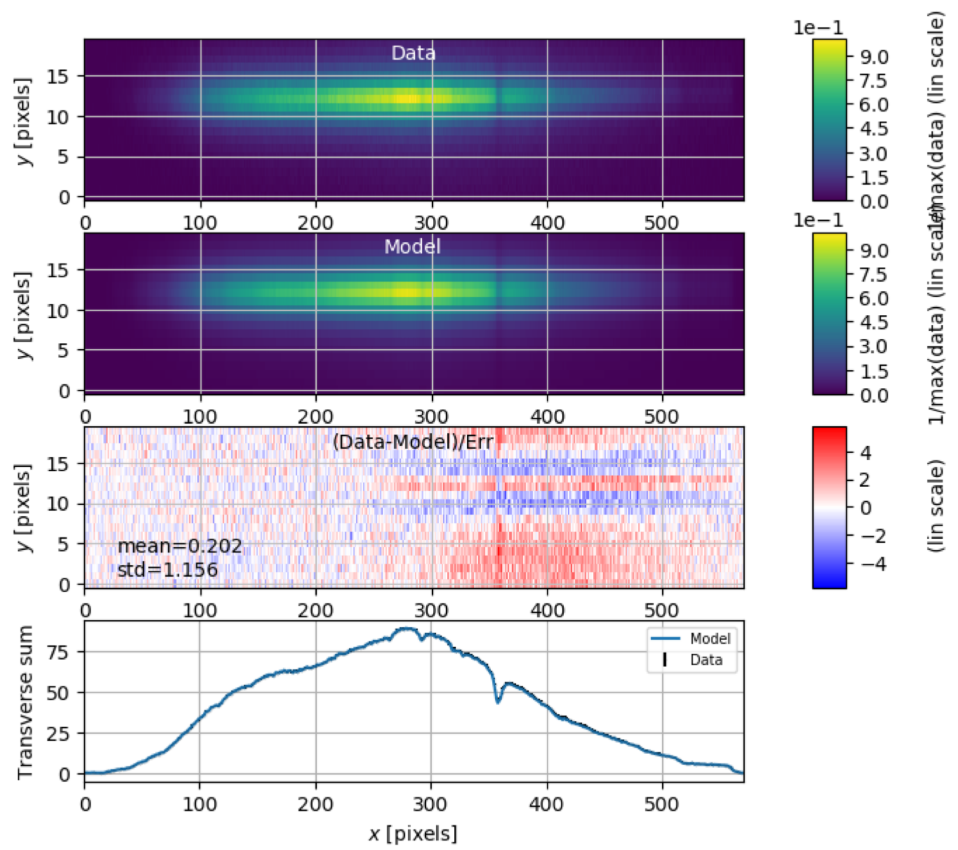
PSF deconvolution: 1D fit

- To start the PSF deconvolution, we first estimate the cross-spectrum A^{1D} with 1D transverse PSF $\phi^{(1D)}$ fit (Moffat)

$$\vec{I}_1^{(1D)}(\vec{r}|\vec{A}^{(1D)}, \vec{r}_c, \vec{\theta}) = \sum_{i=0}^{N_x} A_i^{(1D)} \phi^{(1D)}(\vec{r}|\vec{r}_{c,i}, \vec{\theta}_i)$$

- Get a first guess of the amplitude A and on the PSF parameters $\{r_c, \theta\}$ with a polynomial evolution

- But strong and structured residuals



PSF deconvolution: spectrogram model

- Discretized version of the spectrogram forward model with 2D PSF kernels

$$\vec{I}_1(\vec{r}|\vec{A},\vec{r}_c,\vec{\theta}) = \sum_{i=0}^{N_x} A_i\,\phi(\vec{r}|\vec{r}_{c,i},\vec{\theta}_i) \Longrightarrow \vec{I}_1(\vec{X}|\vec{A},\vec{r}_c,\vec{\theta}) = \mathbf{M}(\vec{X}|\vec{r}_c,\vec{\theta})\,\vec{A}$$

$$\mathbf{M}(\vec{X}|\vec{r}_c,\vec{\theta}) = \begin{pmatrix} \phi(x_1|\vec{r}_{c,1},\vec{\theta}_1) & \phi(x_1|\vec{r}_{c,2},\vec{\theta}_2) & \cdots & \phi(x_1|\vec{r}_{c,N_x},\vec{\theta}_{N_x}) \\ \phi(x_2|\vec{r}_{c,1},\vec{\theta}_1) & \phi(x_2|\vec{r}_{c,2},\vec{\theta}_2) & \cdots & \phi(x_2|\vec{r}_{c,N_x},\vec{\theta}_{N_x}) \\ \vdots & \vdots & \cdots & \vdots \\ \phi(x_{N_xN_y}|\vec{r}_{c,1},\vec{\theta}_1) & \phi(x_{N_xN_y}|\vec{r}_{c,2},\vec{\theta}_2) & \cdots & \phi(x_{N_xN_y}|\vec{r}_{c,N_x},\vec{\theta}_{N_x}) \end{pmatrix}$$

- Minimization of $\chi^2(\vec{A}|\vec{\theta}) = \left(\vec{D} - \mathbf{M}(\vec{X}|\vec{X}_c,\vec{\theta})\,\vec{A}\right)^T \mathbf{W} \left(\vec{D} - \mathbf{M}(\vec{X}|\vec{X}_c,\vec{\theta})\,\vec{A}\right)$
  - Newton-Raphson gradient descent for $\{r_c,\theta\}$
  - Analytical solution for linear parameters A

$$\hat{\vec{A}} = (\mathbf{M}^T\mathbf{W}\mathbf{M})^{-1}\mathbf{M}^T\mathbf{W}\vec{D} \qquad \mathbf{C} = (\mathbf{M}^T\mathbf{W}\mathbf{M})^{-1}$$

PSF deconvolution: regularization

- Analytic solution: fast but very oscillatory if PSF kernel is "large" or noise is "important" => need to regularize the A solution assuming is should be "smooth"

$$\mathcal{E}(\vec{A}|\vec{\theta}) = \left(\vec{D} - \mathbf{M}\,\vec{A}\right)^T \mathbf{W} \left(\vec{D} - \mathbf{M}\,\vec{A}\right) + r(\vec{A} - \vec{A}_0)^T \mathbf{Q}(\vec{A} - \vec{A}_0)$$

$$= \chi^2(\vec{A}|\vec{\theta}) + r\chi^2_{\text{pen}}(\vec{A}|\vec{A}_0), \quad \vec{A}_0 = \vec{A}^{(1D)}$$

- Tikhonov regularization using A^{1D} as a prior

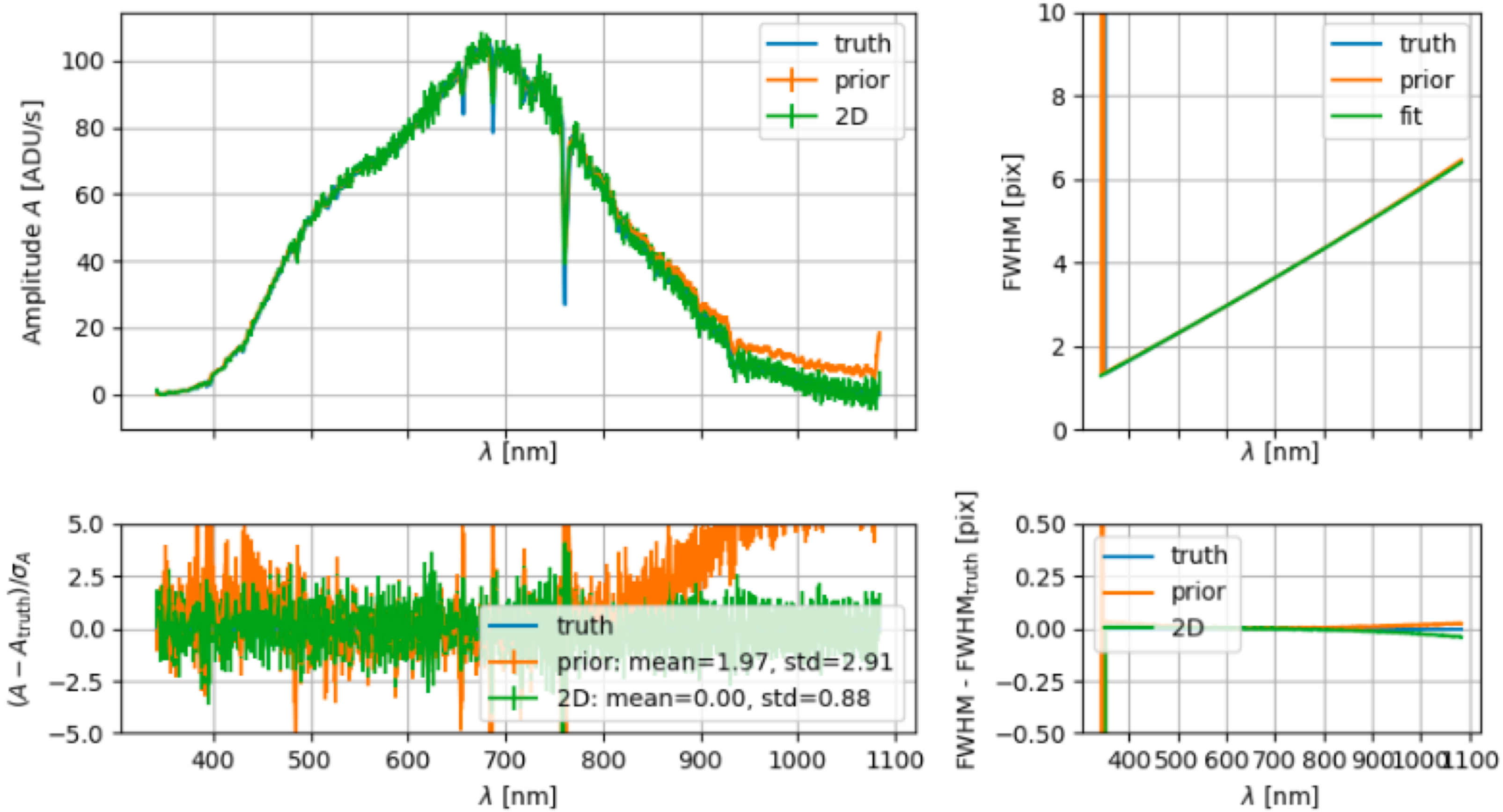
$$\hat{\vec{A}} = (\mathbf{M}^T\mathbf{W}\mathbf{M} + r\mathbf{Q})^{-1}(\mathbf{M}^T\mathbf{W}\vec{D} + r\mathbf{Q}\vec{A}_0) \qquad \mathbf{C} = (\mathbf{M}^T\mathbf{W}\mathbf{M} + r\mathbf{Q})^{-1}$$

- Many Q matrix tested, but best choice is to recover truth spectrum on simulations is

$$\mathbf{U} = \begin{pmatrix} 1/\sigma_{A_{1D}^{(1)}} & 0 & \cdots & 0 \\ 0 & 1/\sigma_{A_{1D}^{(2)}} & \cdots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & 1/\sigma_{A_{1D}^{(N_x)}} \end{pmatrix} \qquad \mathbf{L} = \begin{pmatrix} -1 & 1 & 0 & 0 & \cdots & 0 & 0 \\ 1 & -2 & 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & -2 & 1 & \cdots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots & \vdots & \\ 0 & 0 & 0 & 0 & \cdots & -2 & 1 \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 \end{pmatrix}$$

$$\mathbf{Q}(r) = \mathbf{L}^T\mathbf{U}^T\mathbf{U}\mathbf{L}, \qquad \vec{A}_0 = \hat{\vec{A}}_{1D}$$

Test on simulations with order 2



- Prior is biased because of order 2 contamination
- 2D FFM superimpose perfectly with the true spectrum (amplitude and PSF), without bias (mean of residuals =0)

Applications

- There are two main outputs:

1. **A deconvoluted spectrum** $S_p(\lambda) = T_{\mathrm{inst},p}(\lambda)\, T_{\mathrm{atm}}(\lambda|\theta_a)\, S_*(\lambda)$

   If two factors, one can get the third

   => find $T_{atm}(\lambda|\theta_a)$

   If more spectra are available, if one factor is known one can get the two others

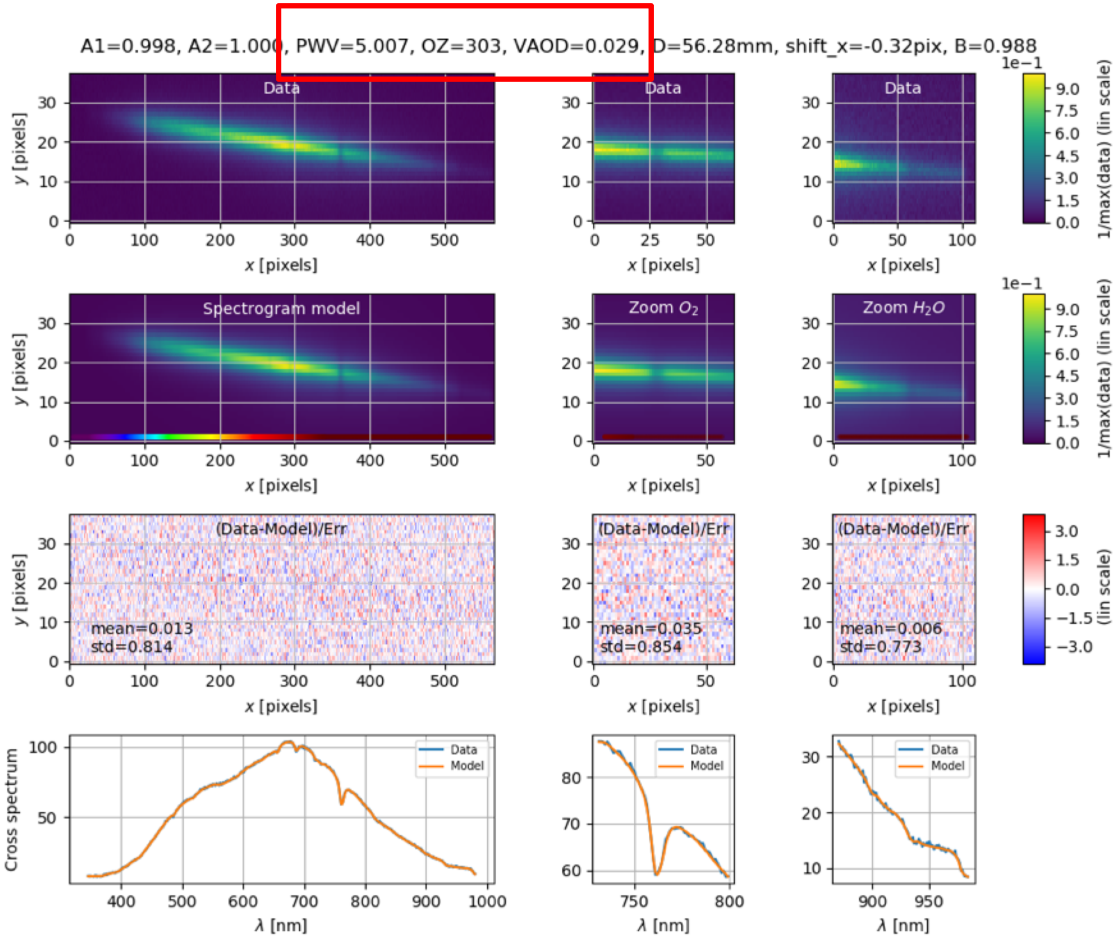
   => with a photometric night find $T_{atm}(\lambda|\theta_a)$ and $T_{inst,p}(\lambda)$

2. **A spectrogram** I(r)

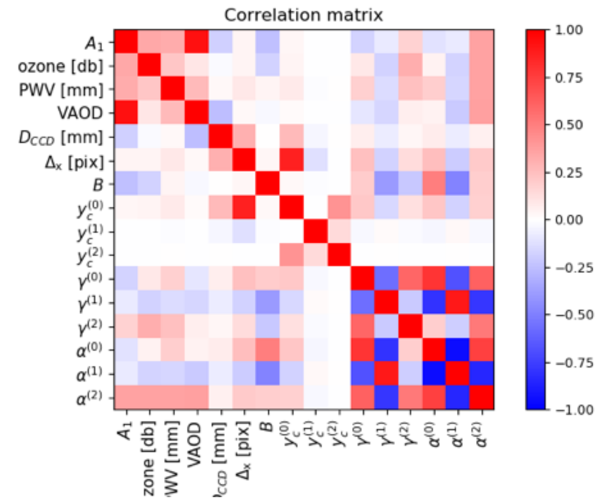
   Apply the forward model to find $T_{atm}(\lambda|\theta_a)$ if $T_{inst,p}(\lambda)$ is known

Forward model of spectrograms

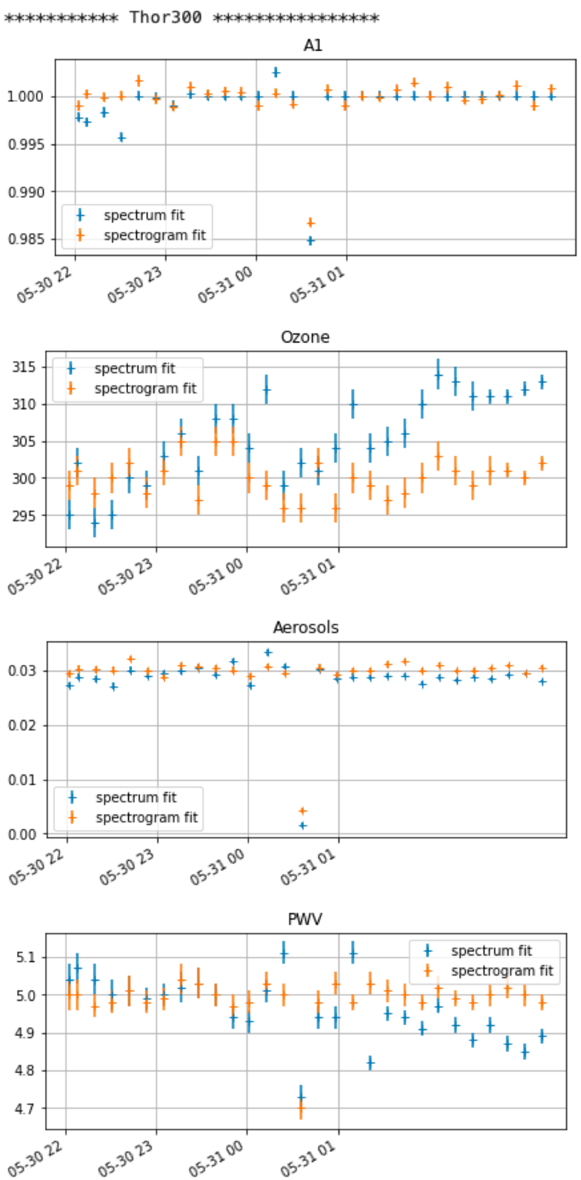
- Fit the spectrogram forward model with the previous instrumental transmissions to get real-time atmospheric parameters

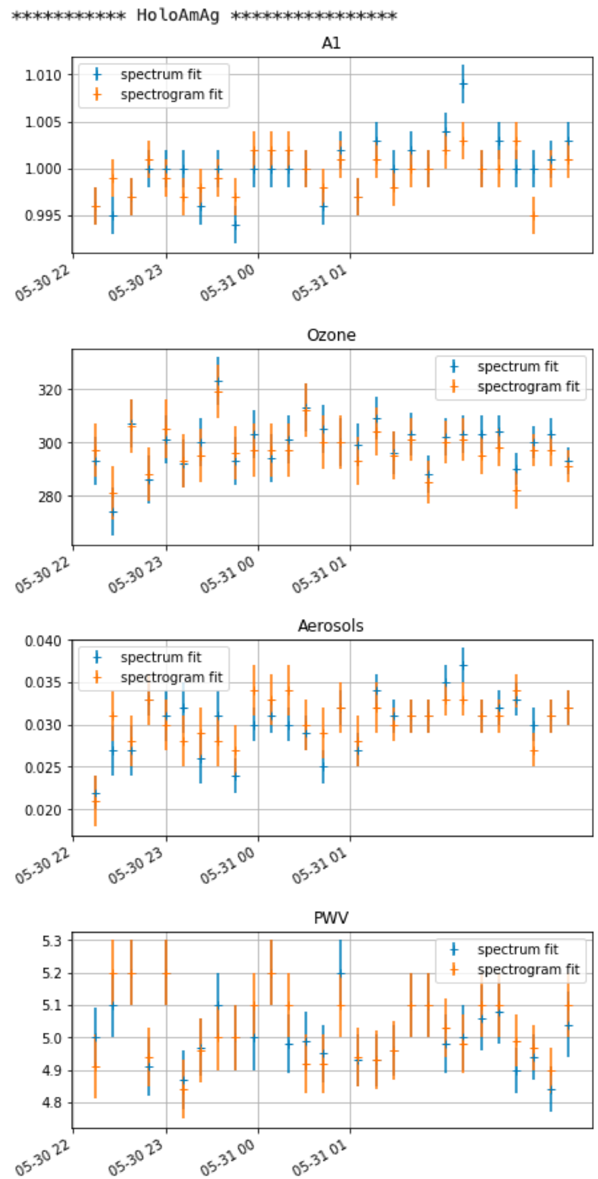


Fit on simulation with truth:
PWV = 5 mm
Ozone = 300 db
VAOD = 0.030



Test on simulations with order 2





- Truth:
  - VAOD=0.03
  - Ozone=300db
  - PWV=5mm
- Thor300 has high SNR compared with amplitude hologram HoloAmAg
- Correlations between atmospheric coefficients

Toward atmospheric transmission with data

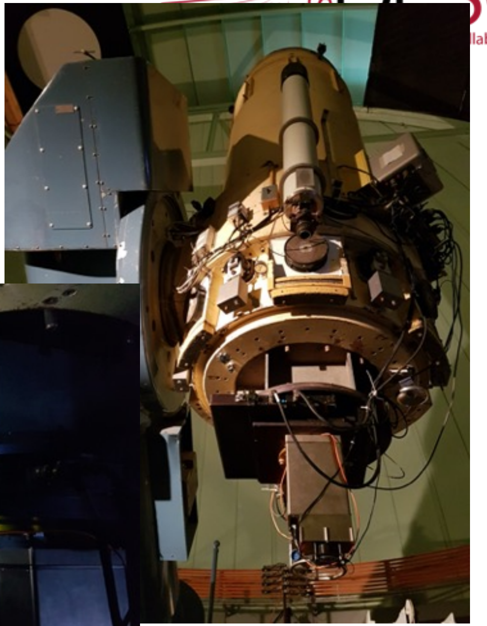
Good ingredients make good crêpes !

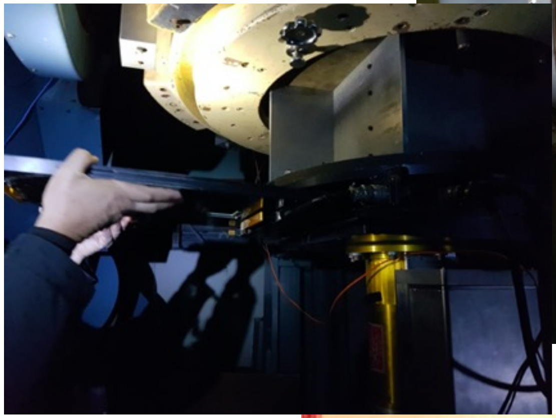
Bad ingredients, even with the best cooking machine, make bad crêpes…

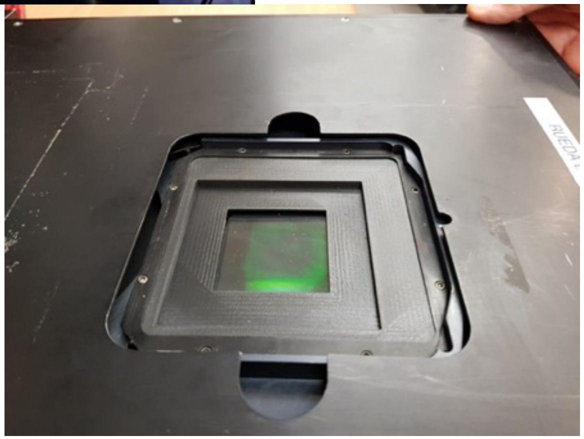
CTIO instrumental transmission

Find the CTIO transmission

- Night of May, 30th 2017 : very stable conditions of seeing and atmosphere parameters
    - Follow HD111980 during 5 hours from airmass 1 to 2
    - Three dispersers in the filter wheel:
        - Ronchi 400 lines/mm
        - Blazed grating Thorlabs 300 lines/mm
        - Amplitude hologram 350 lines/mm

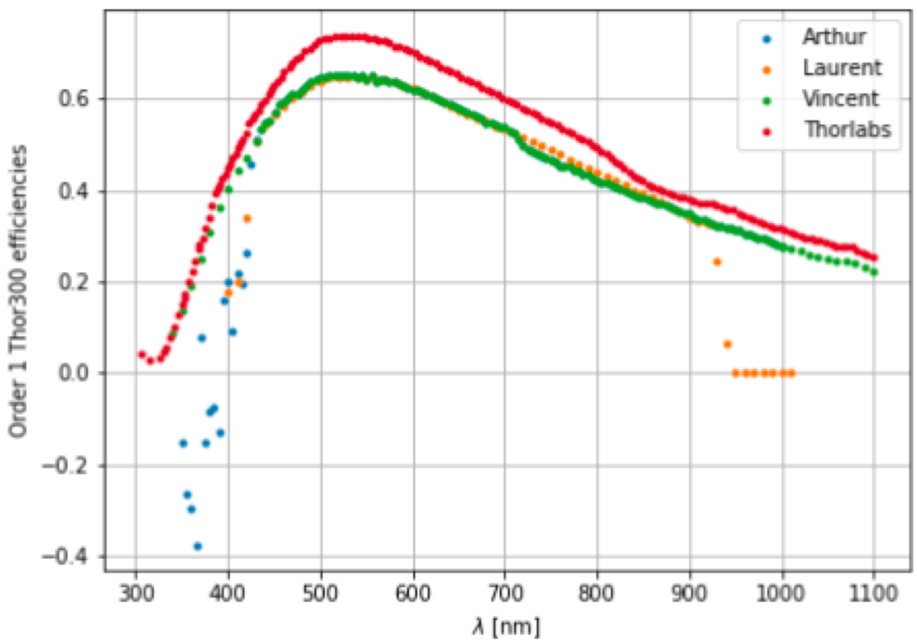






Thorlabs 300 lpmm transmission

- Different sources with different advantages



Arthur: go from 420 to 1000nm and have $r_{2/1}$

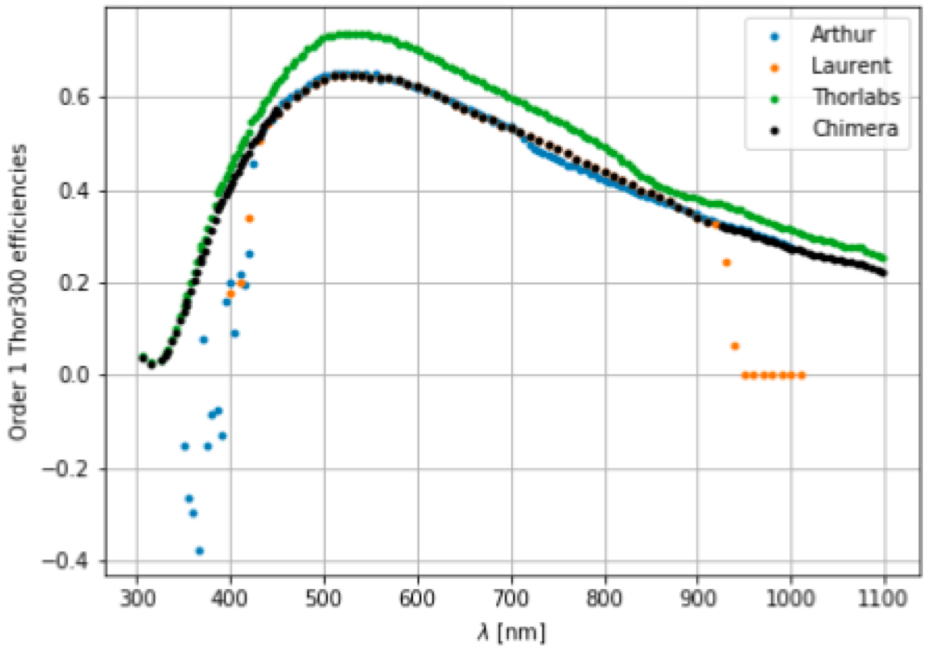
Laurent: go from 420 to 900nm with better amplifier gain calibration but no $r_{2/1}$

Vincent: use Arthur measurement with extrapolation 350 to 1100nm

Thorlabs: generic web data sheet from 300 to 1100nm

Thorlabs 300 lpmm transmission

- Build a chimera !



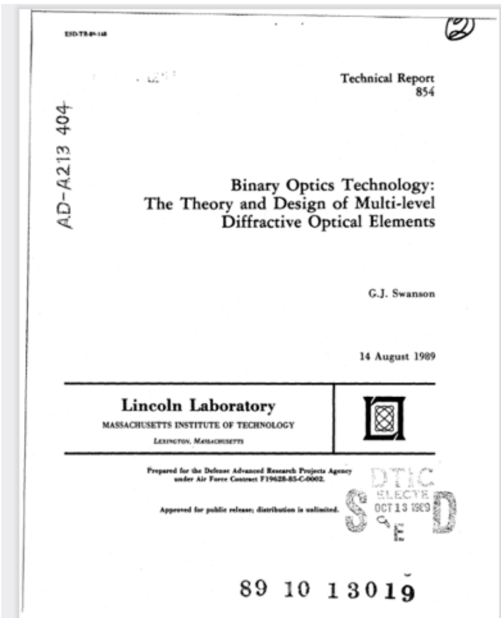
Chimera:
350-450nm: Thorlabs
450-920: Laurent
920-1000: Arthur
1000-100: Thorlabs

- But is it realistic ?

Thorlabs 300 lpmm transmission

- Blazed transmission grating theoretical transmission

Technical Report of 1989



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Technical Report
854

Binary Optics Technology:
The Theory and Design of Multi-level
Diffractive Optical Elements

G.J. Swanson

14 August 1989

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

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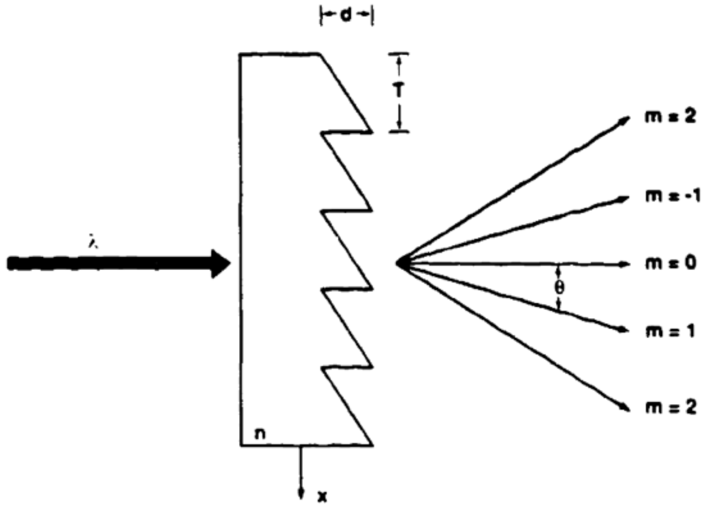


Figure 2-1. Surface relief phase grating.

The diffraction order of interest, in general, is the first diffraction order. Setting m = 1 in Equation (2.4), the diffraction efficiency of the first order is given by

$$\eta_1 = \left[\frac{\sin(\pi(\beta T - 1))}{\pi(\beta T - 1)}\right]^2 \quad \text{where } \beta = (n-1)d/\lambda T \qquad (2.5)$$

Thorlabs 300 lpmm transmission

- Index and transmittance of B270 glass (3mm thickness)

SCHOTT DESAG

SCHOTT

Annex 1.2.1.2

Specification

Physical and chemical properties

PCE - TKT

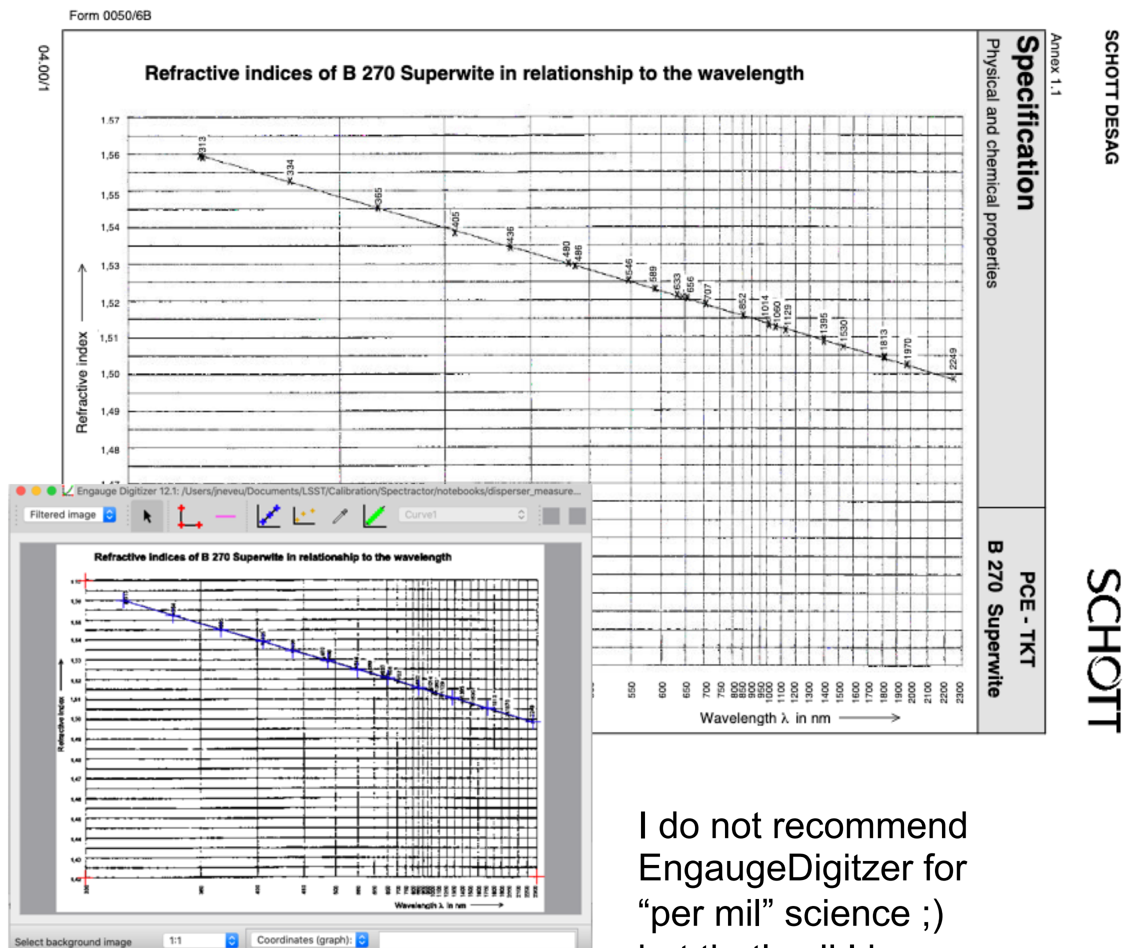
B 270 Superwite

Spectral transmittance τ (λ) in % for the named thickness

λ in nm	thickness in mm 1	2	3	4	5	6	7	8	9	10	15	20	25	30
300	35.1	13.5	5.2	2.0	0.8	0.3	0.1	0.0	0.0	0.0				
310	60.0	39.6	26.1	17.2	11.4	7.5	4.9	3.3	2.2	1.4				
320	76.0	63.4	52.9	44.1	36.8	30.7	25.6	21.4	17.8	14.9	10.9	5.4	2.6	1.3
330	84.2	77.8	71.8	66.3	61.3	56.6	52,3	48.3	44.6	41.2	34.6	25.0	18.1	13.1
340	88.0	84.9	81.9	79.0	76.3	73.6	71.0	68.5	66.1	63.8	59.6	51.8	44.9	39.0
350	89.8	88.4	87.1	85.7	84.4	83.1	81.8	80.6	79.3	78.1	75.1	70.4	65.9	61.8
360	90.6	89.9	89.2	88.5	87.9	87.2	86.5	85.9	85.2	84.6	83.0	80.4	77.8	75.4
370	90.8	90.4	89.9	89.4	89.0	88.5	88.0	87.6	87.1	86.7	85.6	83.8	82.0	80.3
380	90.9	90.4	90.0	89.5	89.1	88.6	88.1	87.7	87.2	86.8	85.4	83.6	81.7	79.9
390	91.2	91.0	90.7	90.5	90.3	90.1	89.9	89.7	89.5	89.2	88.6	87.7	86.8	85.9
400	91.3	91.2	91.0	90.9	90.7	90.6	90.5	90.3	90.2	90.0	89.5	88.9	88.2	87.6
410	91.3	91.2	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.2	89.7	89.1	88.5	87.9
420	91.4	91.2	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.2	89.6	88.9	88.3	87.7
430	91.4	91.2	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.2	89.4	88.8	88.1	87.4
440	91.4	91.3	91.1	91.0	90.8	90.7	90.6	90.4	90.3	90.1	89.5	88.8	88.1	87.4
450	91.4	91.3	91.2	91.1	90.9	90.8	90.7	90.5	90.4	90.3	89.7	89.1	88.5	87.9
460	91.5	91.4	91.3	91.2	91.1	91.0	90.9	90.8	90.7	90.6	90.0	89.5	89.0	88.5
470	91.5	91.4	91.4	91.3	91.2	91.1	91.0	90.9	90.8	90.8	90.3	89.9	89.4	89.0
480	91.6	91.5	91.4	91.3	91.3	91.2	91.1	91.1	91.0	90.9	90.5	90.1	89.8	89.4
490	91.6	91.5	91.5	91.4	91.4	91.3	91.2	91.2	91.1	91.1	90.8	90.5	90.2	89.9
500	91.6	91.6	91.5	91.5	91.4	91.4	91.4	91.3	91.3	91.2	90.9	90.6	90.4	90.1
510	91.6	91.6	91.5	91.5	91.4	91.4	91.4	91.3	91.3	91.2	90.9	90.7	90.4	90.2
520	91.7	91.6	91.6	91.5	91.5	91.4	91.4	91.3	91.3	91.2	91.1	90.9	90.7	90.5
530	91.7	91.6	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.4	91.2	91.0	90.8	90.6
540	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.9	90.7
550	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.9	90.7
560	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.8	90.6
570	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.2	91.0	90.8	90.6
580	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.1	90.9	90.6	90.4
590	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	91.0	90.8	90.5	90.3
600	91.7	91.7	91.6	91.6	91.5	91.5	91.5	91.4	91.4	91.3	90.9	90.7	90.4	90.1
610	91.7	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.9	90.6	90.3	90.0
620	91.7	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.8	90.4	90.0	89.7
630	91.8	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.7	90.3	90.0	89.6
640	91.7	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.0	90.9	90.6	90.2	89.8	89.4
650	91.7	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.0	90.9	90.6	90.2	89.8	89.4
660	91.8	91.7	91.6	91.5	91.5	91.4	91.3	91.3	91.2	91.1	90.7	90.3	89.9	89.5
670	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.7	90.3	90.0	89.6
680	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.7	90.3	90.0	89.6
690	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
700	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
710	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
720	91.8	91.7	91.6	91.6	91.5	91.4	91.3	91.2	91.2	91.1	90.8	90.4	90.1	89.7
730	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
740	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
750	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
760	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.1	89.7
770	91.8	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.8	90.4	90.0	89.6
780	91.8	91.7	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.1	90.7	90.3	89.9	89.5
790	91.9	91.8	91.7	91.6	91.6	91.5	91.4	91.4	91.3	91.2	90.7	90.2	89.8	89.4
800	91.8	91.8	91.7	91.6	91.5	91.4	91.3	91.2	91.1	91.0	90.6	90.2	89.7	89.3

Form 0050/6B

04.00/1 page: 12

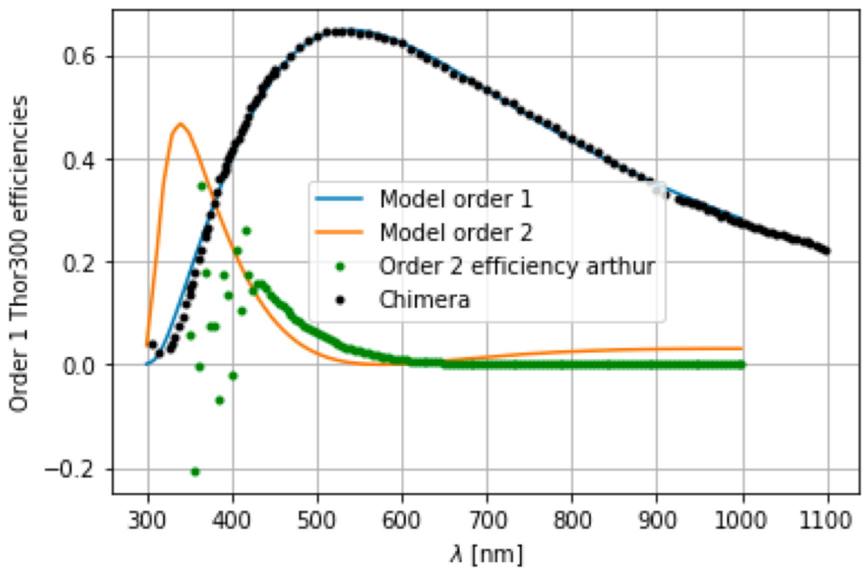


I do not recommend EngaugeDigitzer for “per mil” science ;) but that’s all I have…

Thorlabs 300 lpmm transmission

- Fit model on data $\eta_m = A \times t(\lambda)\left[\frac{\sin(\pi T(\beta - m/T))}{\pi T(\beta - m/T))}\right]^2, \quad T = 1/N, \quad \beta = \frac{(n(\lambda)-1)\sin(\phi_{blazed})}{\lambda}$

```
Optimal parameters: phi=17.207deg, A=0.709
```



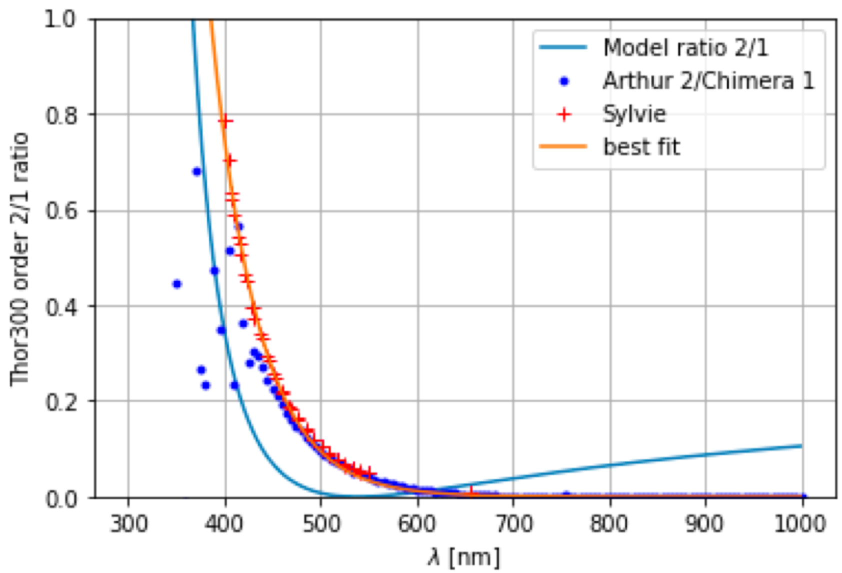
Thorlabs data sheet:
Φ_{blazed} = 17.5 deg

- But bad prediction of order 2/1 ratio ☹

Thorlabs 300 lpmm transmission

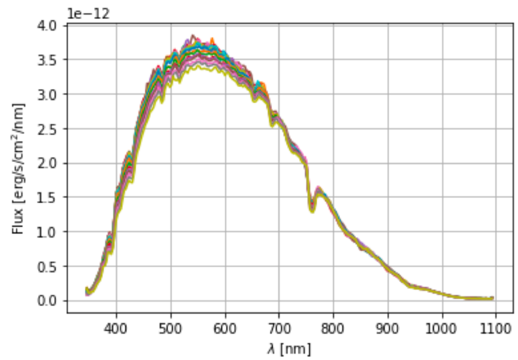
- But bad prediction of order 2/1 ratio ☹
- Instead use Sylvie's estimate on CTIO data (using blue filter)
- Extrapolated with a fit in $A_2 * \exp(-(\lambda - \lambda_0)/\tau)$

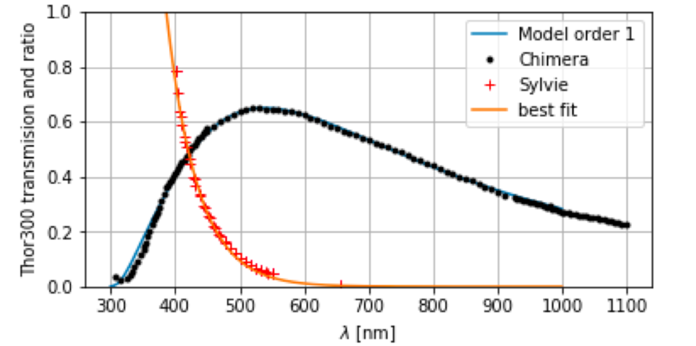
Best fit: [333.88226676 2.94312492 48.44173225]



- Why "it works" ? Because reduced $\chi 2$ decreases when fitting data

Find the CTIO transmission



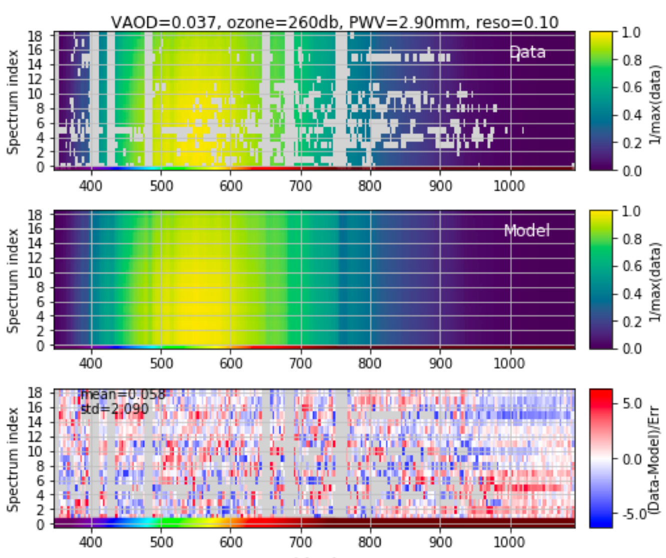


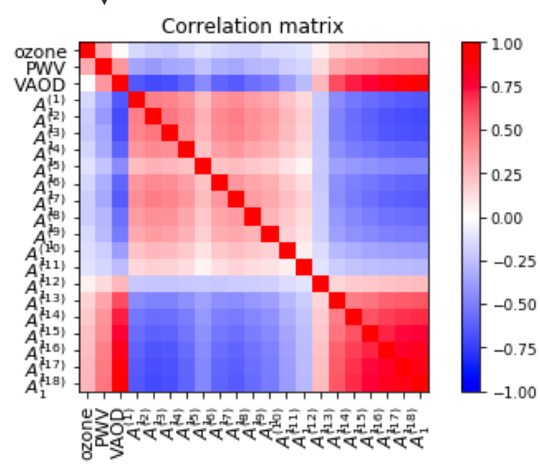
19 good spectra of HD111980 observed with the Thor300 gratings, binning of 3nm

Chimera for the Thor300 order 1 transmission and order 2 / order 1 transmission ratio by Sylvie

Fit 130 $T_{inst,1}(\lambda)$ points,
3 atmospheric parameters,
18 grey factors,
on all Thor300 spectra of
the “photometric night”

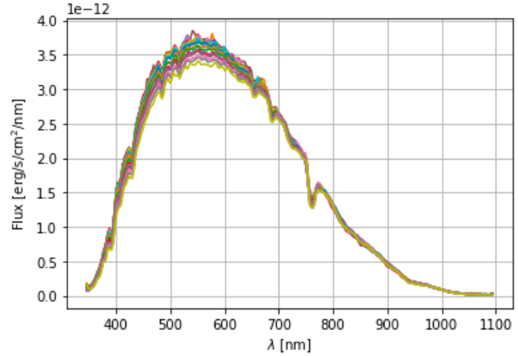
Grey: masking (>5σ)



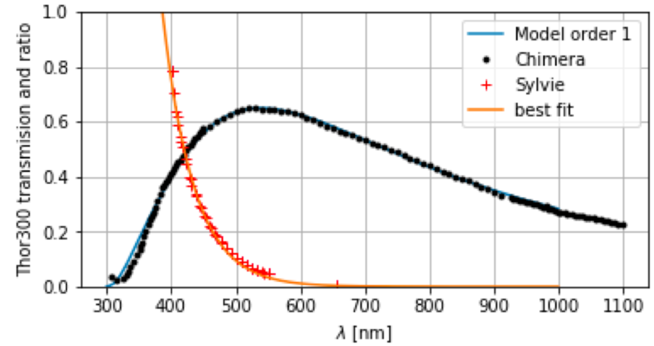



```
ozone: 260 +2 -2
PWV: 2.90 +0.04 -0.04
VAOD: 0.0366 +0.0005 -0.0005
A1_1: 0.9968 +0.0002 -0.0002
A1_2: 0.9949 +0.0002 -0.0002
A1_3: 0.9959 +0.0002 -0.0002
A1_4: 0.9878 +0.0002 -0.0002
A1_5: 1.0016 +0.0002 -0.0002
A1_6: 0.9935 +0.0002 -0.0002
A1_7: 0.9946 +0.0001 -0.0001
A1_8: 0.9986 +0.0001 -0.0001
A1_9: 0.9940 +0.0001 -0.0001
A1_10: 0.9994 +0.0001 -0.0001
A1_11: 0.9931 +0.0001 -0.0001
A1_12: 0.9991 +0.0001 -0.0001
A1_13: 1.0009 +0.0001 -0.0001
A1_14: 1.0073 +0.0001 -0.0001
A1_15: 1.0110 +0.0002 -0.0002
A1_16: 1.0104 +0.0002 -0.0002
A1_17: 1.0150 +0.0003 -0.0003
A1_18: 1.0132 +0.0003 -0.0003
```

Find the CTIO transmission

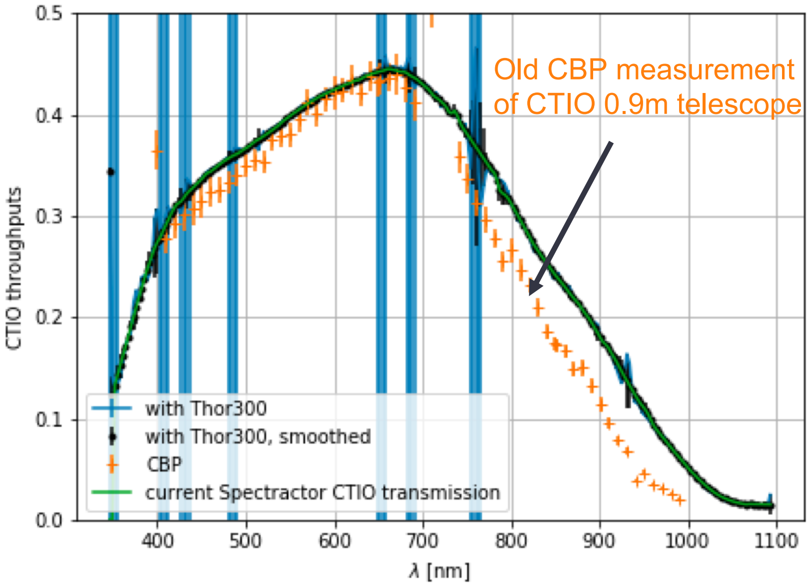


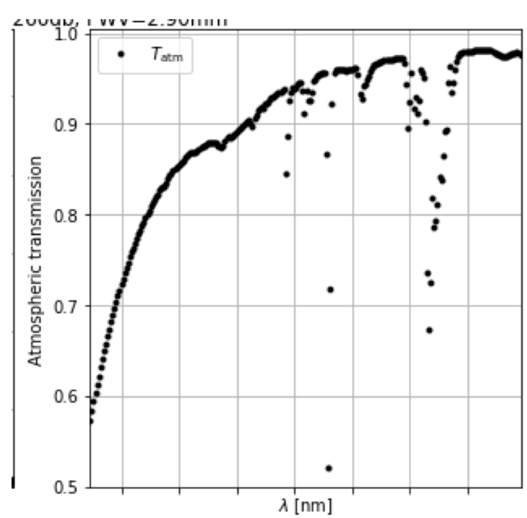
19 good spectra of HD111980 observed with the Thor300 gratings, binning of 3nm

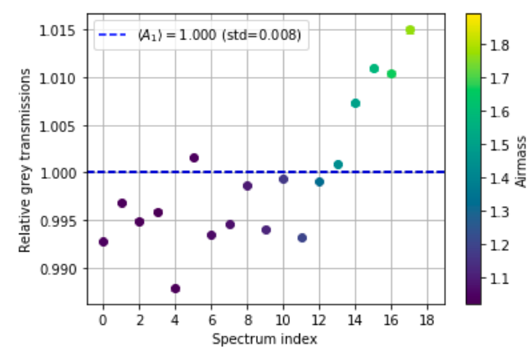


Chimera for the Thor300 order 1 transmission and order 2 / order 1 transmission ratio by Sylvie

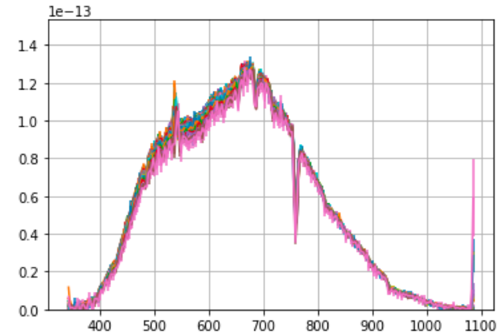
Fit 130 $T_{inst,1}(\lambda)$ points,
3 atmospheric parameters,
18 grey factors,
on all Thor300 spectra of
the "photometric night"



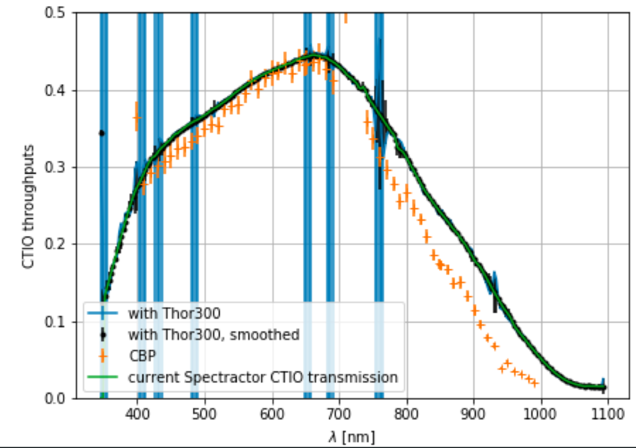




Find the HoloAmAg transmission

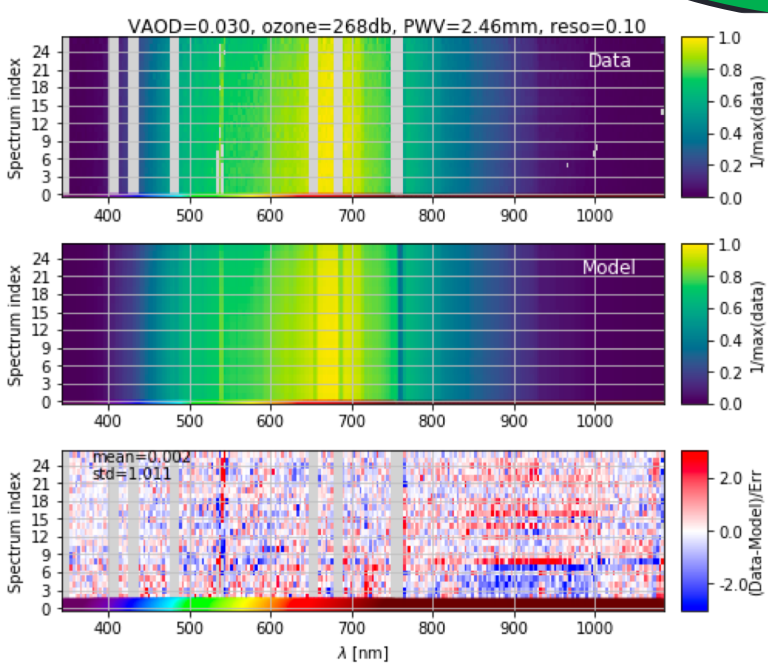


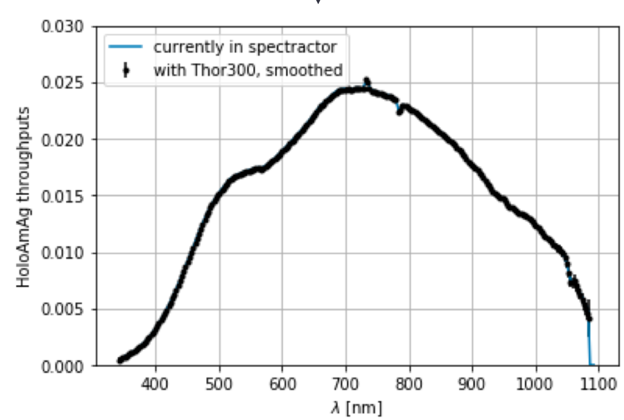
27 good spectra of HD111980 observed with the HoloAmAg grating, binning of 3nm



Smoothed CTIO transmission from the Thorlabs 300 images

Fit 130 $T_{inst,1}(\lambda)$ points,
3 atmospheric parameters,
26 grey factors,
on all Thor300 spectra of
the "photometric night"






```
ozone: 268 +9 -9
PWV: 2.5 +0.1 -0.1
VAOD: 0.030 +0.003 -0.003
A1_1: 0.9908 +0.0005 -0.0005
A1_2: 0.9971 +0.0005 -0.0005
A1_3: 0.9976 +0.0005 -0.0005
A1_4: 1.0028 +0.0005 -0.0005
A1_5: 0.9949 +0.0005 -0.0005
A1_6: 0.9978 +0.0005 -0.0005
A1_7: 0.9916 +0.0005 -0.0005
A1_8: 1.0010 +0.0005 -0.0005
A1_9: 1.0014 +0.0005 -0.0005
A1_10: 0.9950 +0.0005 -0.0005
A1_11: 0.9994 +0.0005 -0.0005
A1_12: 1.0007 +0.0004 -0.0004
A1_13: 1.0008 +0.0004 -0.0004
A1_14: 1.0018 +0.0004 -0.0004
A1_15: 0.9972 +0.0004 -0.0004
A1_16: 0.9971 +0.0004 -0.0004
A1_17: 0.9967 +0.0004 -0.0004
A1_18: 0.9988 +0.0004 -0.0004
A1_19: 1.0011 +0.0004 -0.0004
A1_20: 1.0008 +0.0005 -0.0005
A1_21: 1.0083 +0.0005 -0.0005
A1_22: 1.0072 +0.0006 -0.0006
A1_23: 1.0061 +0.0007 -0.0007
A1_24: 1.0063 +0.0008 -0.0008
A1_25: 1.0031 +0.001 -0.001
A1_26: 1.010 +0.001 -0.001
```

Remarks

- This CTIO transmission and the HoloAmAg transmission strongly depend on the built chimera of the Thor300 disperser.

- The assumption that the night is photometric is strong, but the residuals don’t show evident time-dependent structures except in the infrared.

- This is an example of the Spectractor capabilities on an CTIO night if we feed it as precisely as we can.

CTIO atmospheric transmission

Methodology

- Thor300 is the disperser from which:
  - we have the best knowledge of its transmission
  - but has a complex PSF (we hope that the extraction leaves no chromatic residuals thanks to PSF shape parameters modelled by 4^{th} order polynomials)

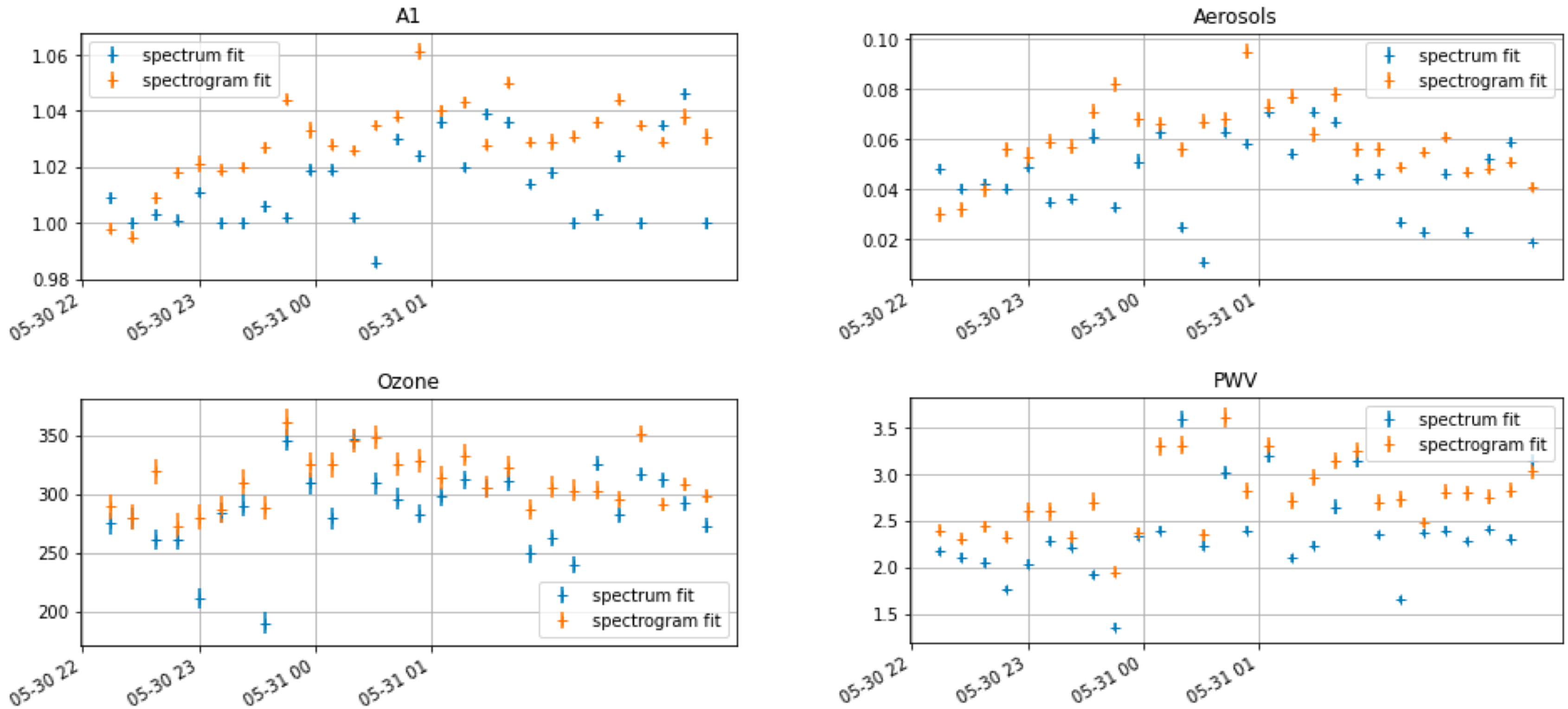
  ⇒ use it to get CTIO and HoloAmAg transmissions (no need of good spectral resolution)

- HoloAmAg is the disperser from which:
  - we have indirect knowledge of its transmission (from CTIO nights)
  - but good narrow PSF (see last hologram's presentation)

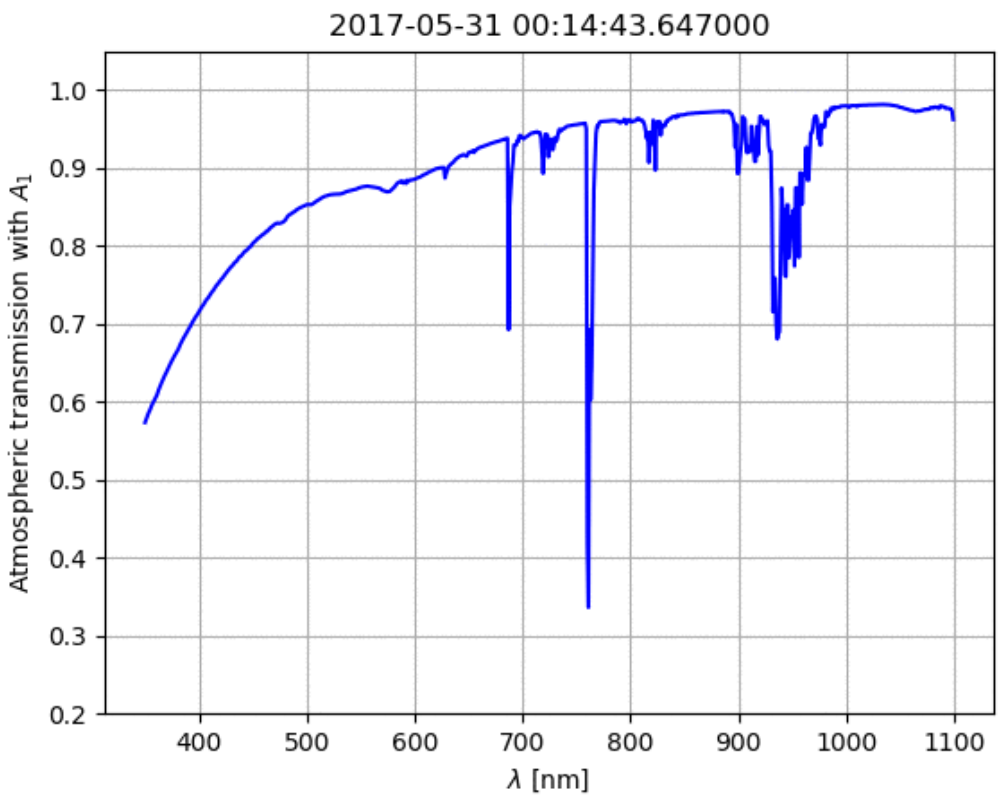
  ⇒ use it to get real time atmospheric transmission

Atmospheric parameters

************ HoloAmAg ****************



Atmospheric parameters

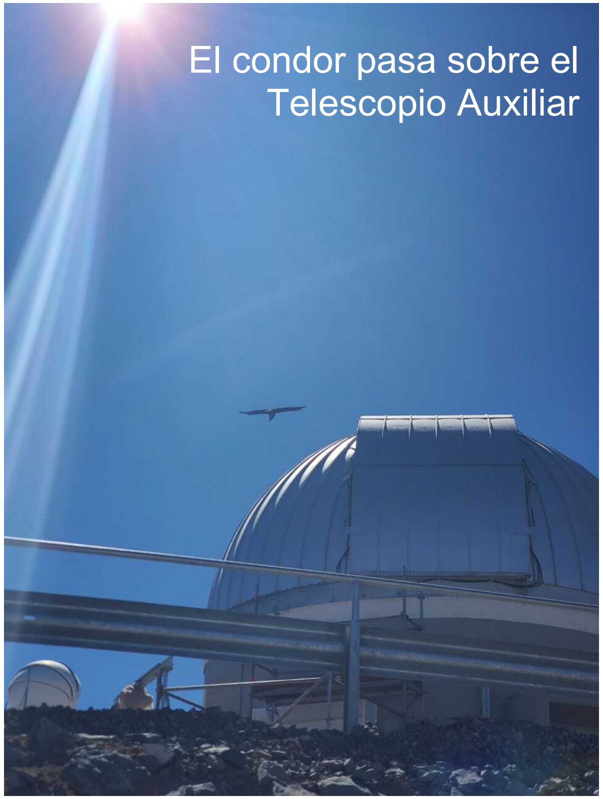


- Good to see this... to go further now we need AuxTel data !

News from AuxTel

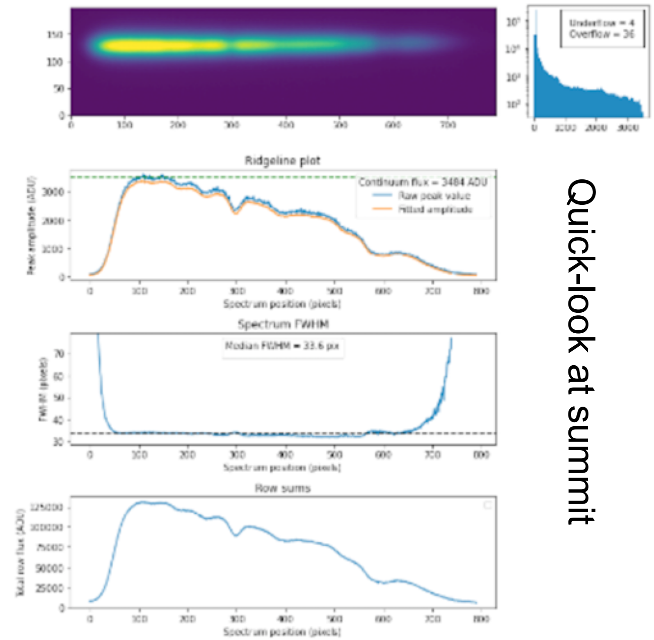
AuxTel runs

- March 2020 : one week before COVID (unpacking of the telescope)
- February 2021 : one good week of technical work with some science nights, and holograms
- March 2021 : only a few nights due to bad weather
- Next run : June 7th !

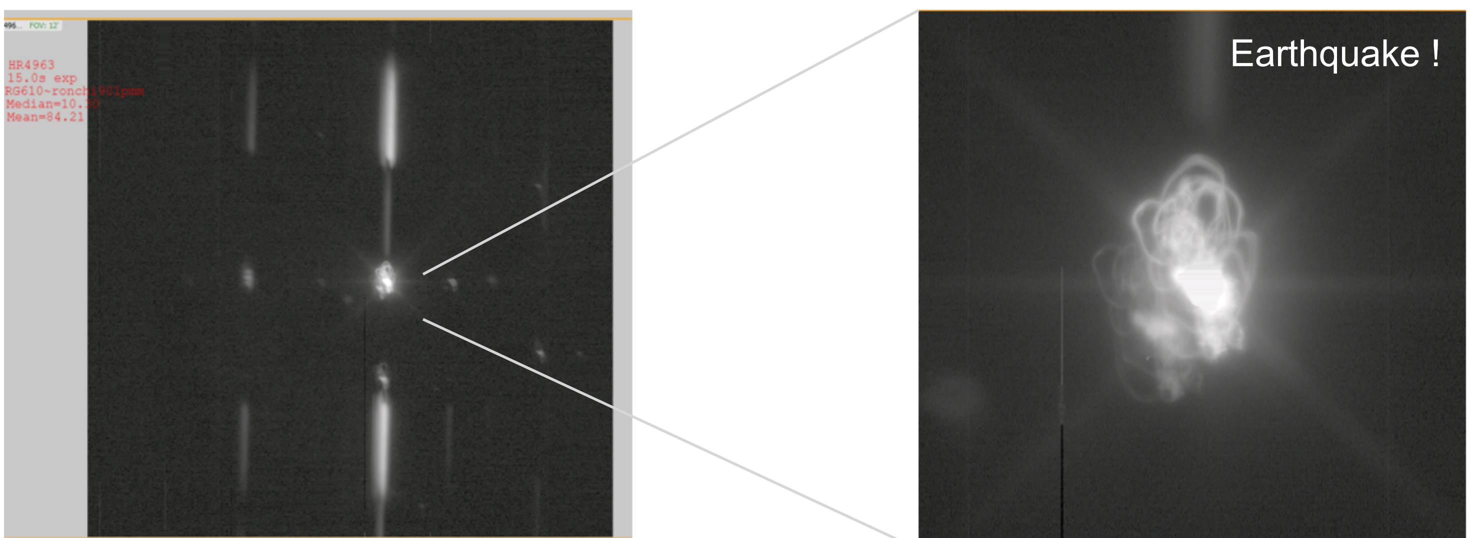


AuxTel

- A lot of progresses since first run :
  - Quick-look utilities at summit to analyse spectra and focus in real time (RubinTV !)
  - Progress with the pointing program
  - Scripted observations, and soon automated reduction
  - First reduction of all AuxTel data using a DM-Stacked Spectractor at NCSA (with rebinning and quick ISR)

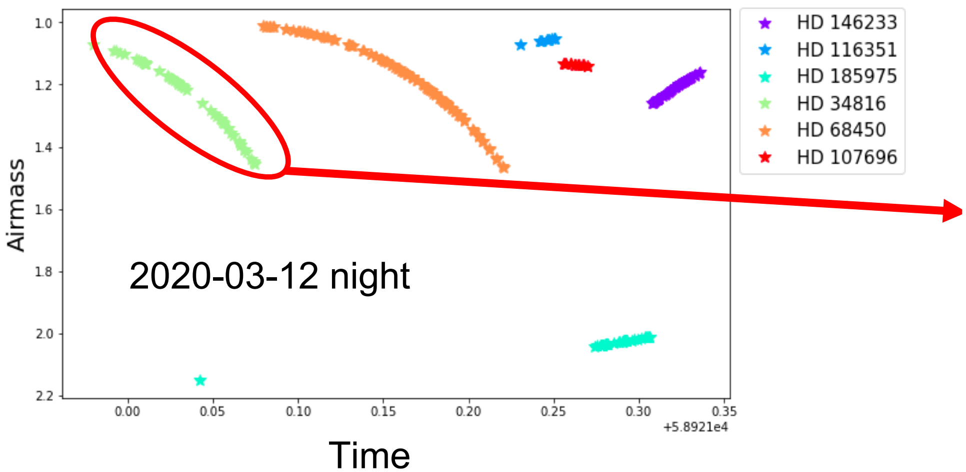


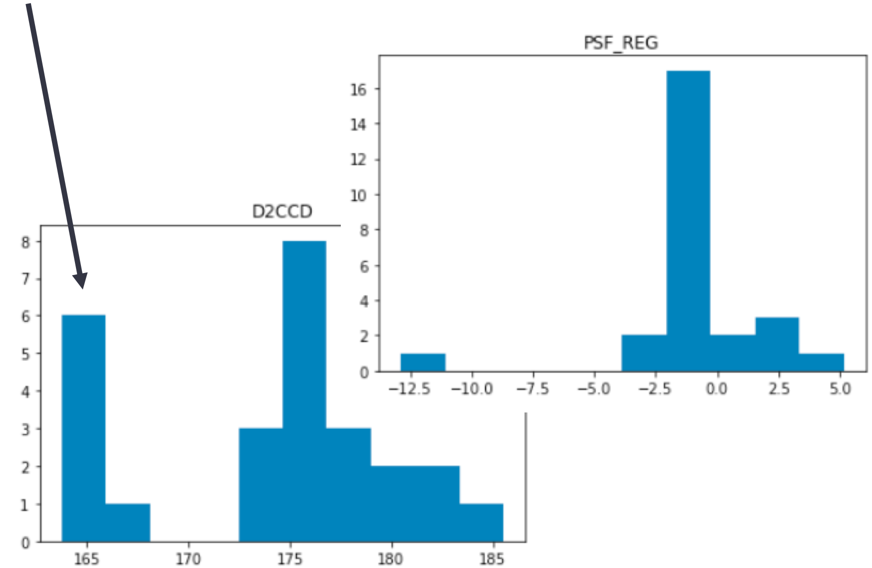
Quick-look at summit



AuxTel

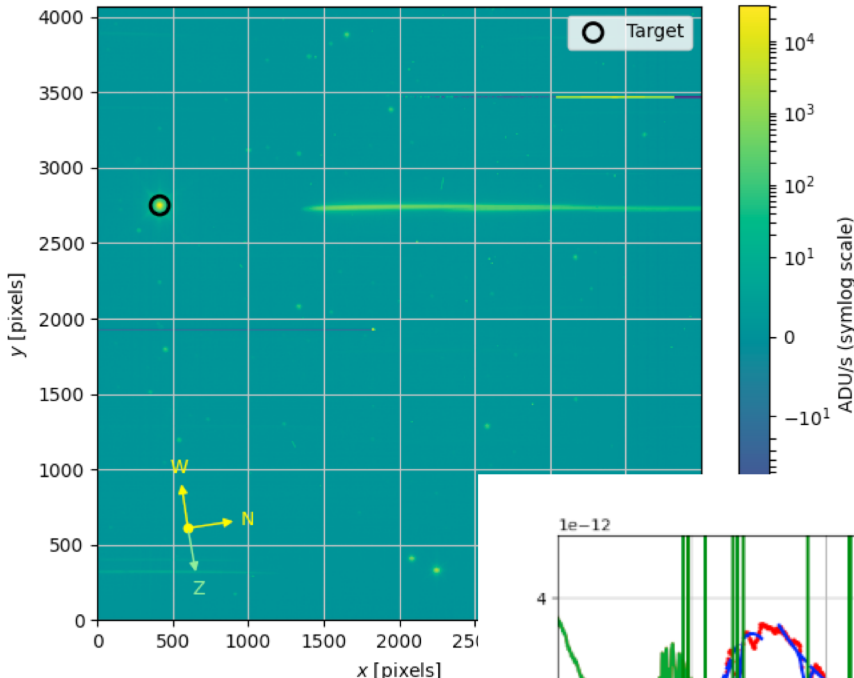
- Still on the technical to-do list :
  - Better control of the focus and pointing/tracking systems
  - Hardware intervention to improve the rotation of the spectrograph
  - Inspect good images and check the failures of Spectractor to improve the code parameters (or the code itself)
  - CCD behavior analysis

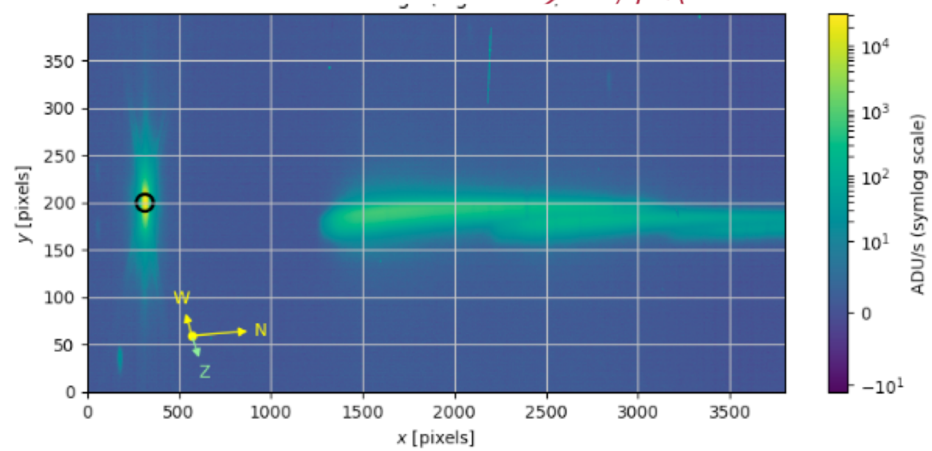


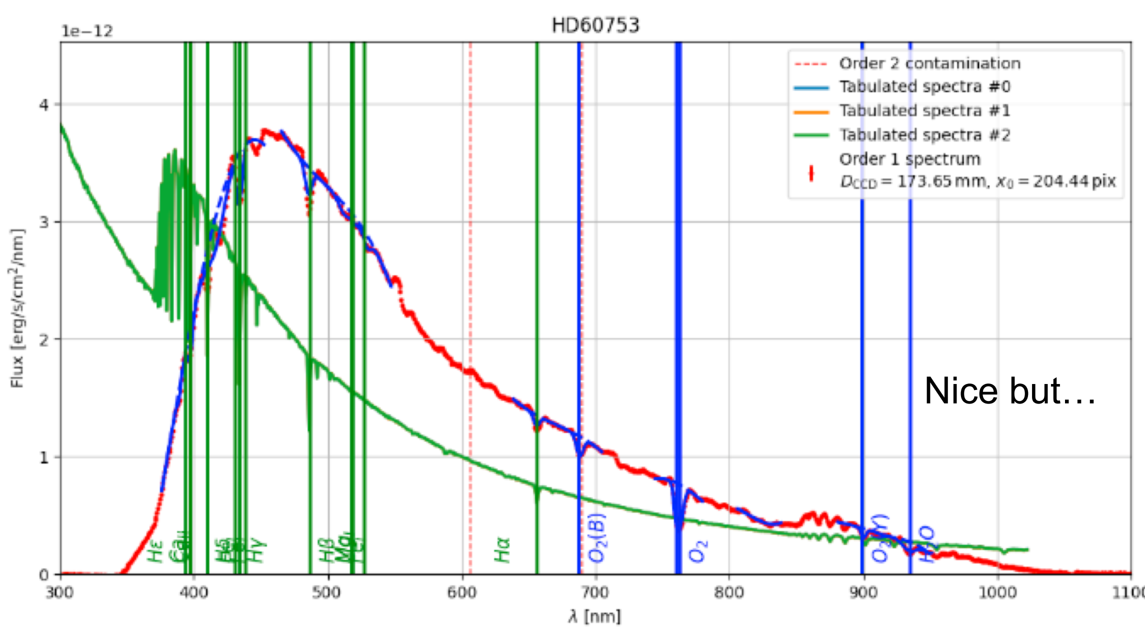


- Science to-do list with good images/spectra :
  - Build an instrument model : PSF and instrumental transmission
  - Measure atmospheres !
  - Elaborate a strategy to calibrate VRO photometry

AuxTel image and spectrum example





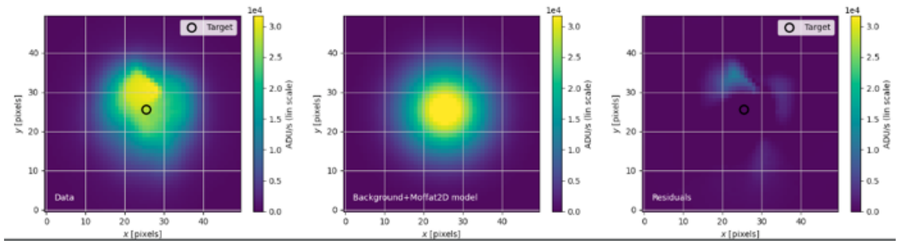


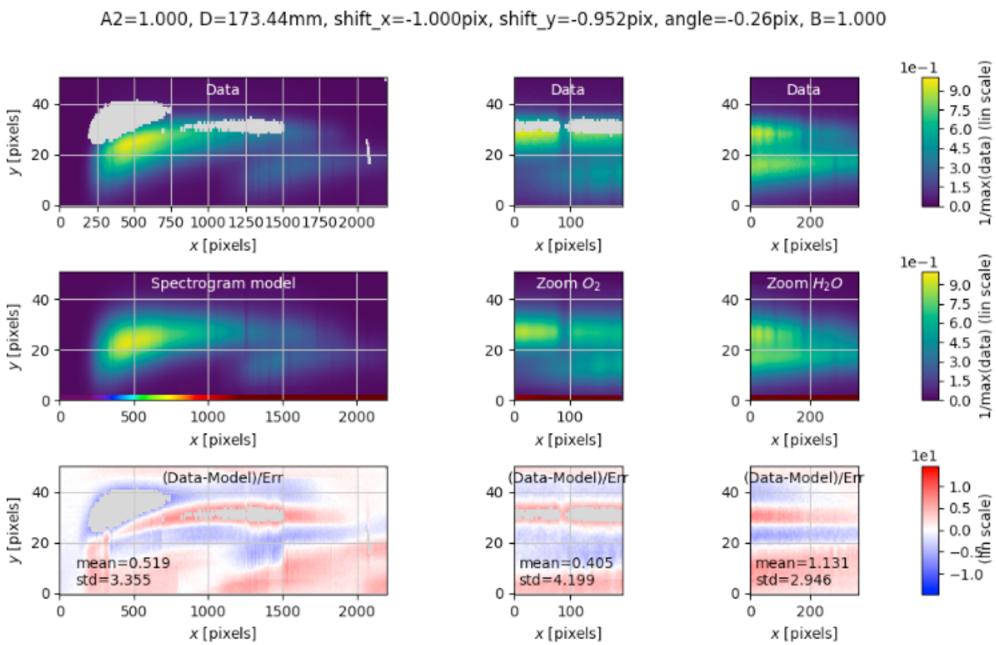
Nice but…

AuxTel image and spectrum example

LSST DESC Dark Energy Science Collaboration

Order 0





Motion during the exposure ☹

⇒ Bad PSF model

⇒ Strong residuals

⇒ Even with a good looking spectrum !

⇒ Not goof for science

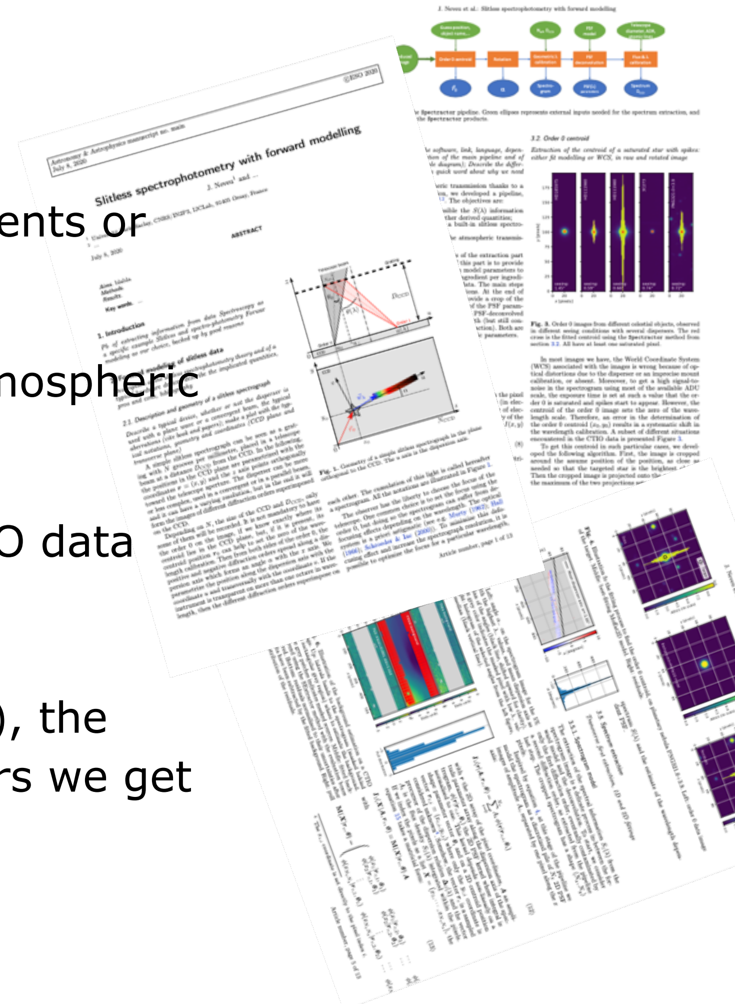
Summary

Summary

- Spectractor has the capability to un-pile the colors of a spectrogram
- For the CTIO data analysis:
  - I had to pick up points on scanned documents or build a chimera
  - But the code returns smooth curves of atmospheric parameters

  ⇒ I think this is the most I can get from CTIO data

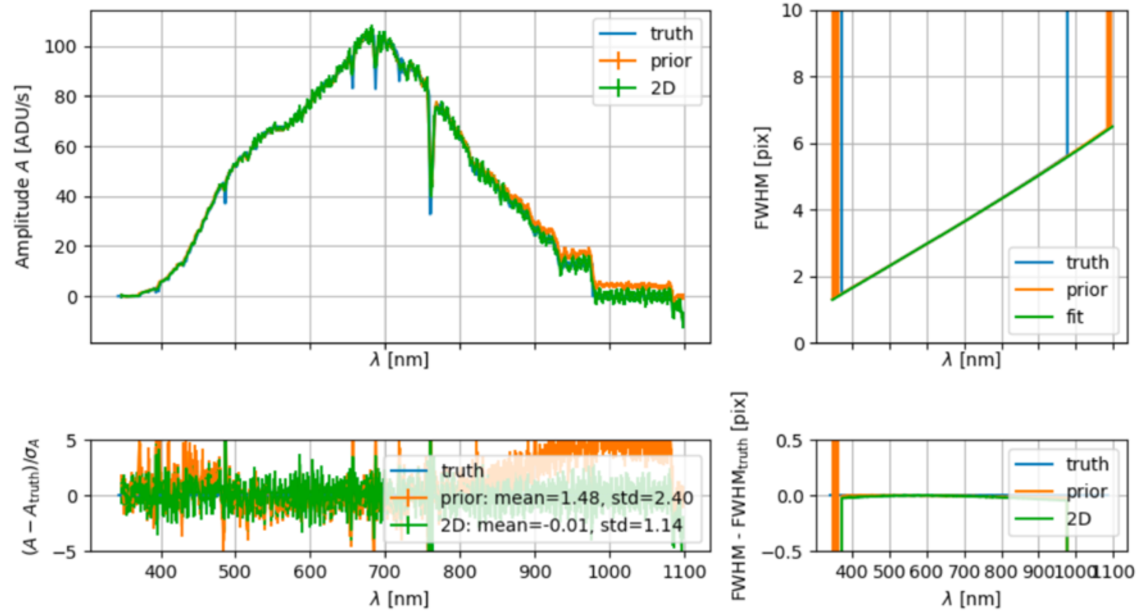
  ⇒ Finish my paper
- The weaker prior information we have (T_{inst}, …), the larger potential bias on atmospheric parameters we get => build CBP !
- Ready for AuxTel !

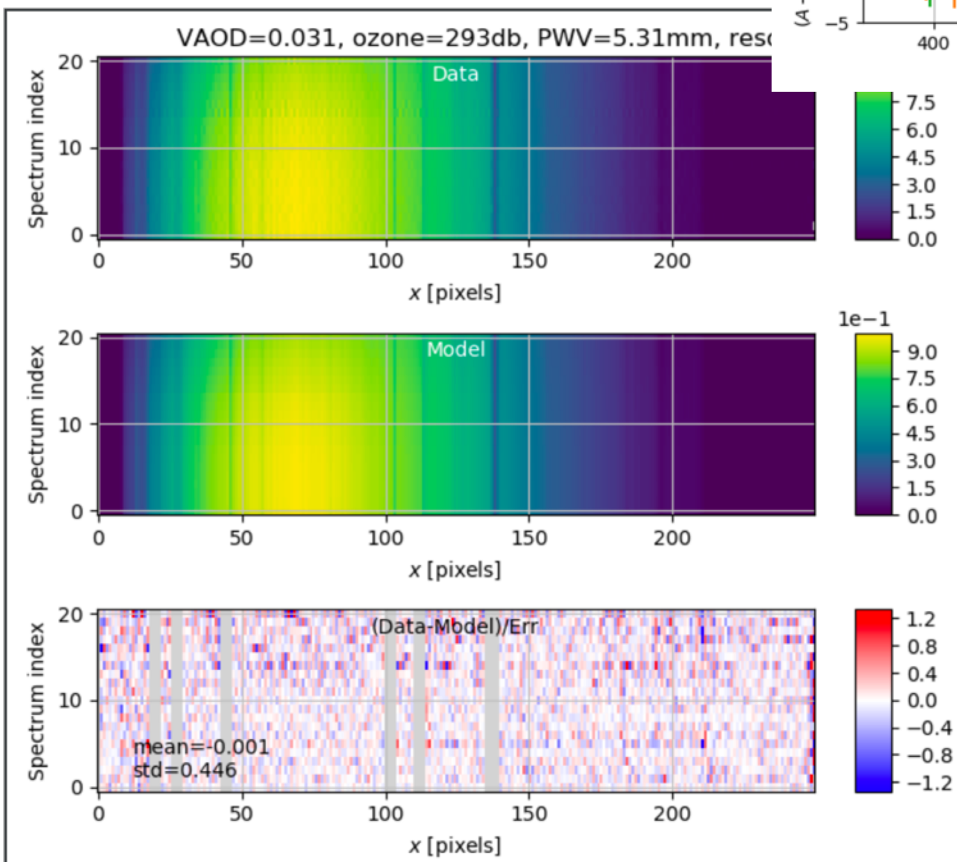


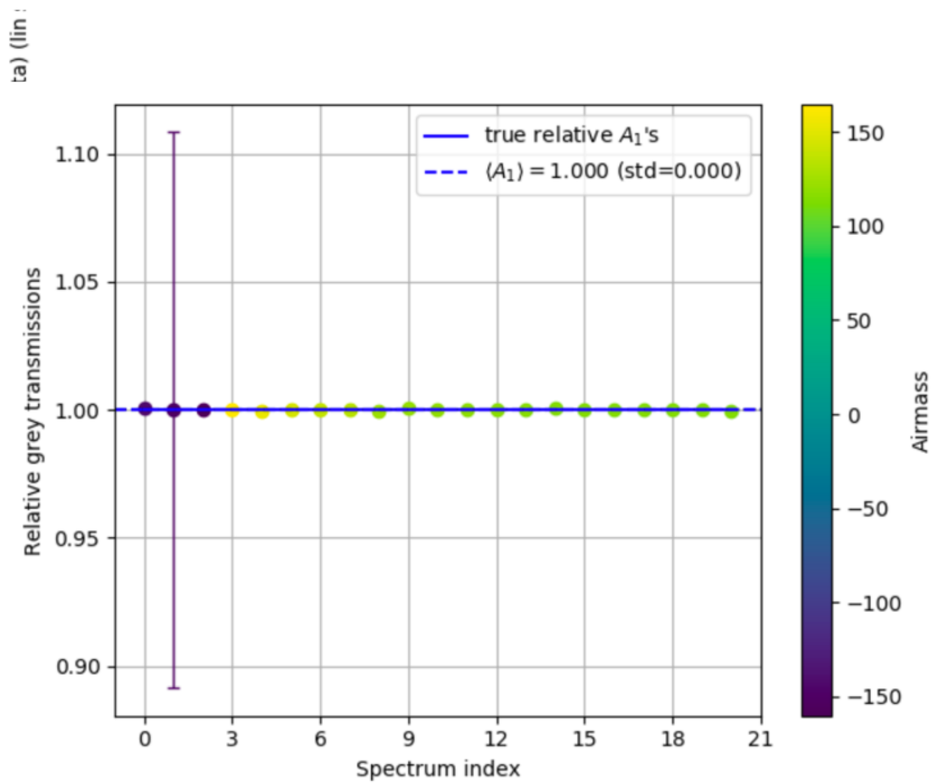
BACKUP

Simulations

- Parfait !
- Paramètres atmos ok
- Termes gris ok







PSF deconvolution: how to choose r_{opt}?

- Use of the resolution matrix **R**:

$$\mathbf{R} = \mathbf{I} - r\mathbf{CQ}$$

$$\mathrm{Tr}\,\mathbf{I} = \mathrm{Tr}\,\mathbf{R} + \mathrm{Tr}\,(r\mathbf{CQ})$$

$$N_x = [\text{Parameters resolved by data}] + [\text{Parameters resolved by prior}]$$

- Build a "kind-of reduced $\chi 2$":

$$G(r) = \frac{\chi^2(\vec{A}|\vec{\theta})}{(N_x N_y - \mathrm{Tr}\,\mathbf{R})^2}$$

~ N^2_{dof}

- Mathematically, this method is known as Generalized Cross-Validation (GCV). The minimum of G(r) corresponds to the minimum of $\|\mathbf{M}\,\hat{\vec{A}} - \mathbf{M}\,\vec{A}_{\text{truth}}\|^2$

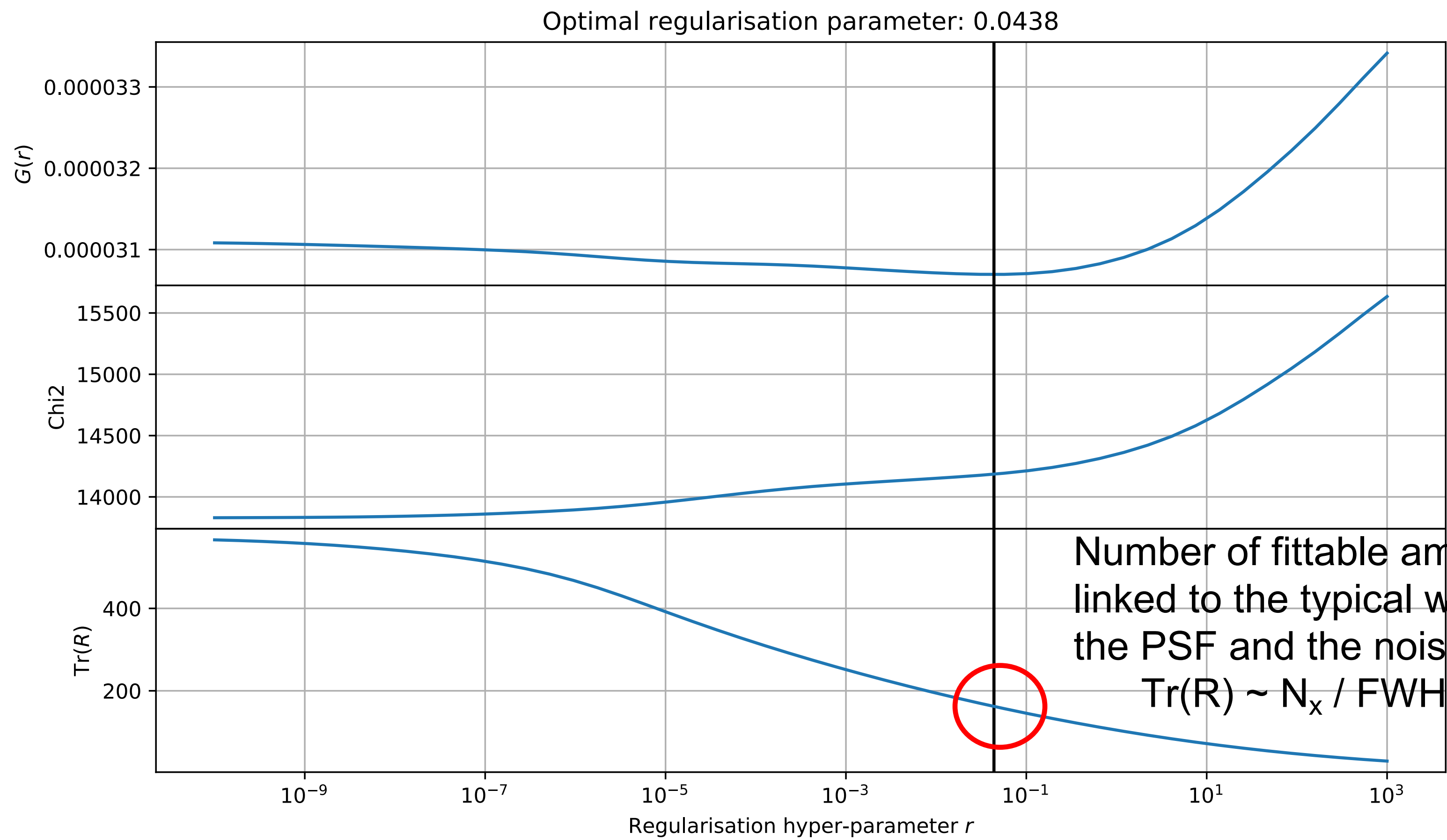
Best fit

Data wo noise

[Golub, Gene H., et al. "Generalized Cross-Validation as a Method for Choosing a Good Ridge Parameter." Technometrics, vol. 21, no. 2, 1979, pp. 215–223]

PSF deconvolution: results

- $r_{opt} \sim 0.04$



Number of fittable amplitudes linked to the typical width of the PSF and the noise

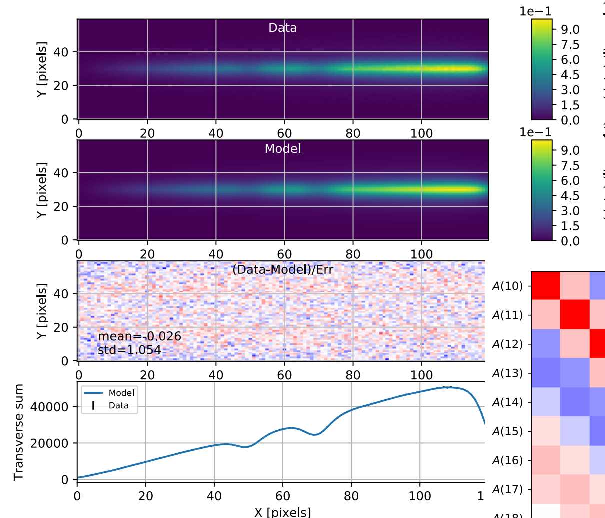
$Tr(R) \sim N_x / FWHM$

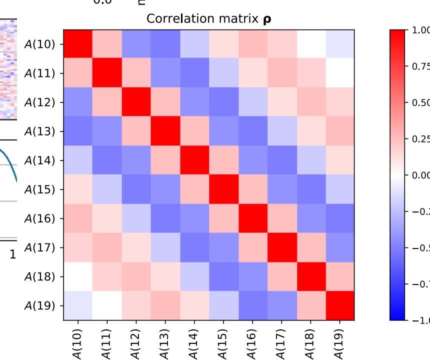
Example on simple toy model

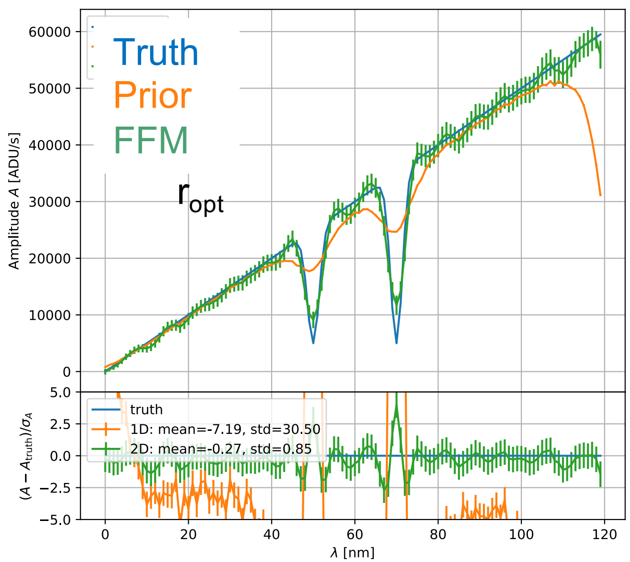
- Test of the Laplacian operator:

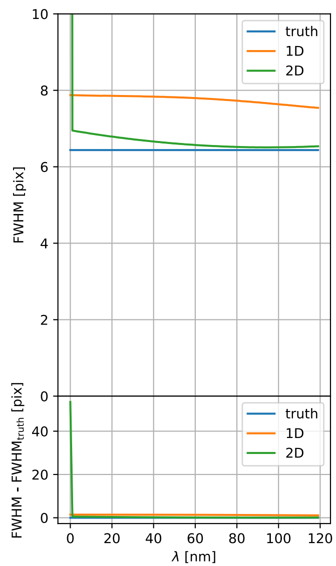
$$\mathbf{L} = \begin{pmatrix} -1 & 1 & 0 & 0 & \cdots & 0 & 0 \\ 1 & -2 & 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & -2 & 1 & \cdots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots & \vdots & \\ 0 & 0 & 0 & 0 & \cdots & -2 & 1 \\ 0 & 0 & 0 & 0 & \cdots & 1 & -1 \end{pmatrix}$$

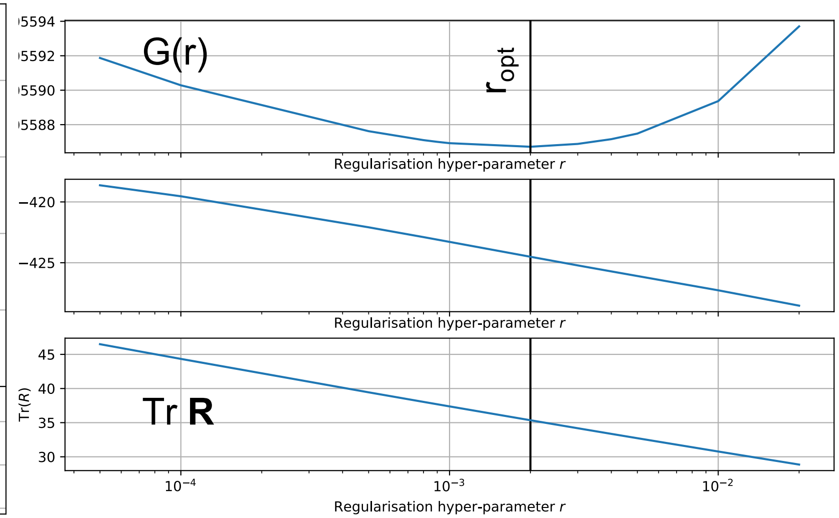
$$\mathbf{Q}(r) = \mathbf{L}^T \mathbf{U}^T \mathbf{U} \mathbf{L}, \qquad \vec{A}_0 = \hat{\vec{A}}_{1D}$$











Why the Laplacian operator works?

- Because of Cauchy-Schwartz inequality, controlling the norm 2 of the second derivatives is controlling the norm 1 of the first derivative (in the function space)

- Equivalent to the norm-1 total variation regularization:
  - With an analytical solution
  - But only for functions at least C^2, so for a physical spectrum it is ok

- Note written by my roommate…

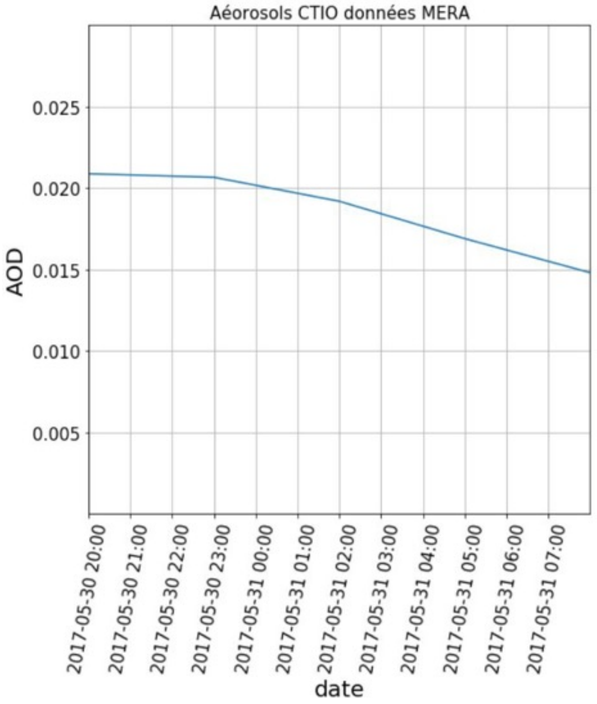
How to correctly remove order 2?

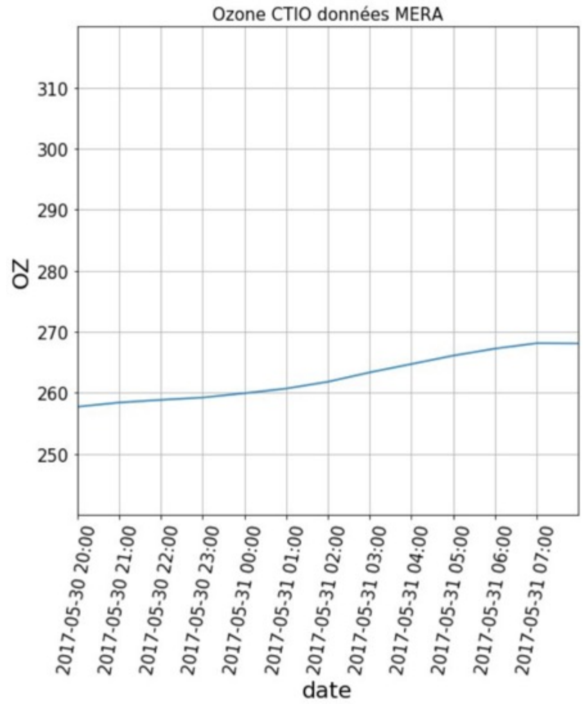
- Solution: forward-model it !
- New ingredients:
  - knowledge of order 2/1 disperser transmission ratio $r_{2/1}$
  - ADR prediction to model the respective traces $r_c^{(1)}$ and $r_c^{(2)}$ of order 1 and order 2 spectrograms on the CCD
- Algorithm: deconvolution with core matrix M being

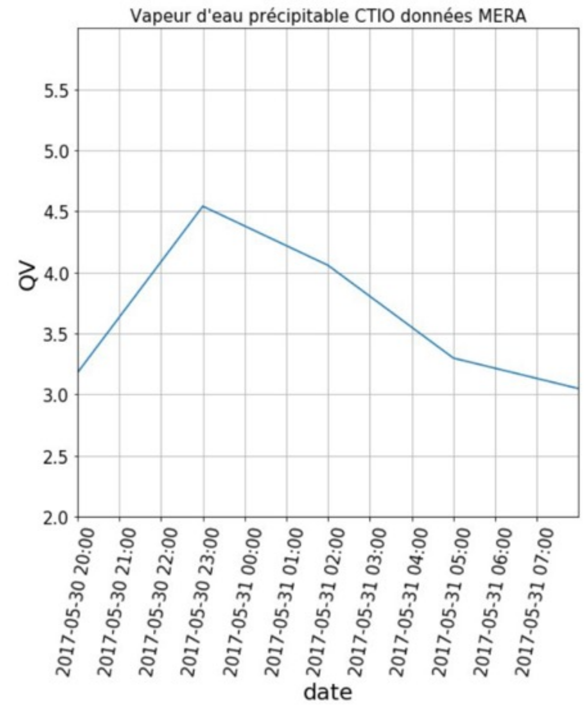
$$\mathbf{M} = \mathbf{M}(\phi^{(1)}, \vec{r}_c^{(1)}) + r_{2/1}\mathbf{M}(\phi^{(2)}, \vec{r}_c^{(2)})$$

- Hypothesis:
  - $\phi^{(2)}$ is the copy of $\phi^{(1)}$ at same distance from order 0 (PSF shape evolves only with geometrical distance to order 0, no wavelength dependence)
  - $r_c^{(1)}$ and $r_c^{(2)}$ are predicted with ADR model (given pressure, airmass, temperature, humidity) and grating dispersion properties
  - Spectrum prior: the spectrum at previous Spectractor step

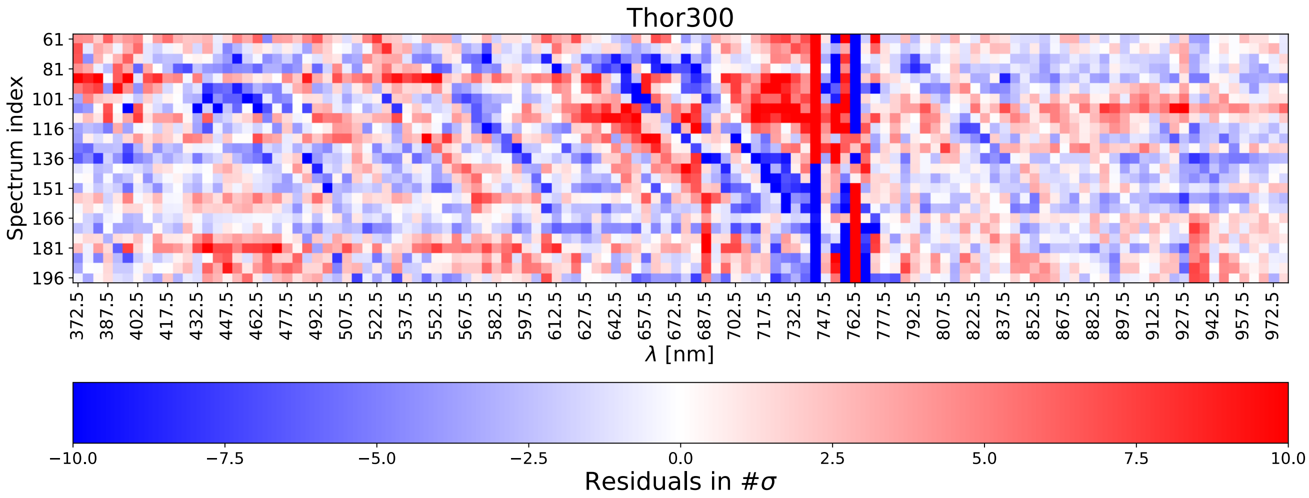
Find the atmospheric transmission

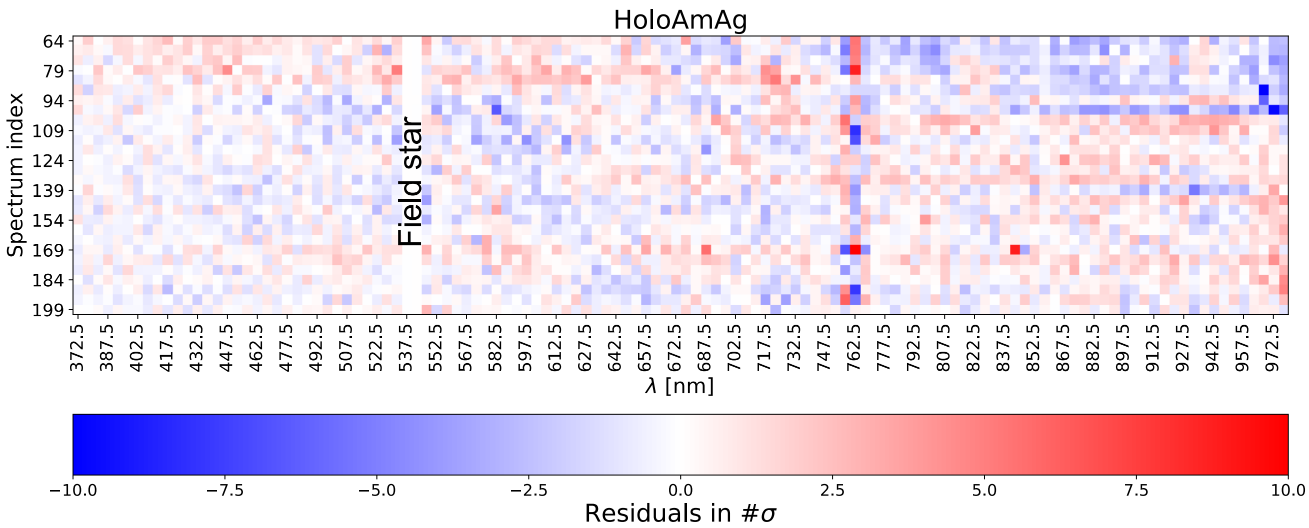






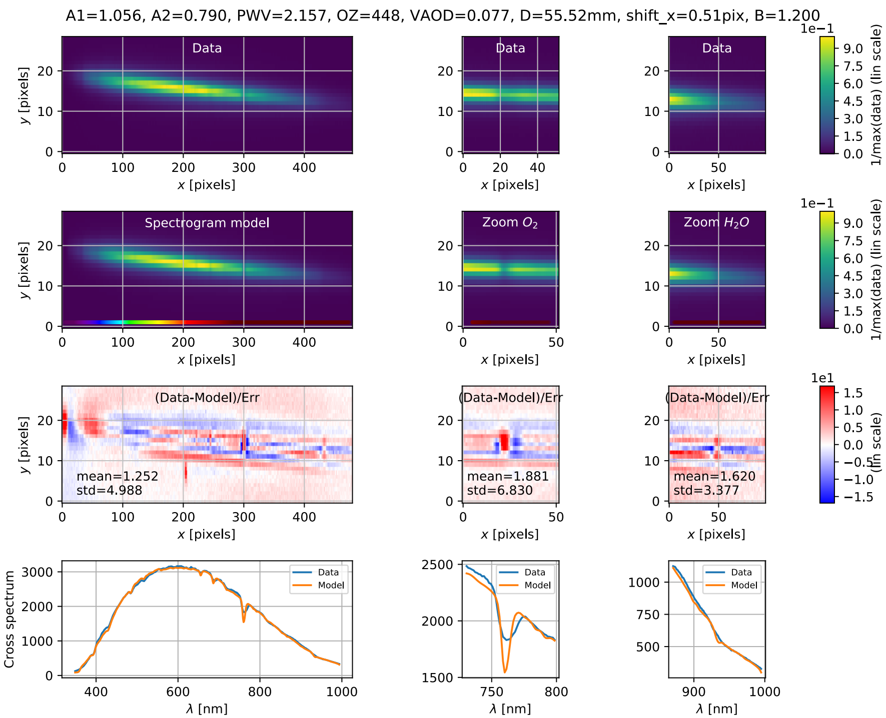
Find the atmospheric transmission





Forward model of spectrograms

- Fit the spectrogram forward model with the previous instrumental transmissions to get real-time atmospheric parameters



Thor300 data

HoloAmAg data