Le telescope auxiliaire (AuxTel)

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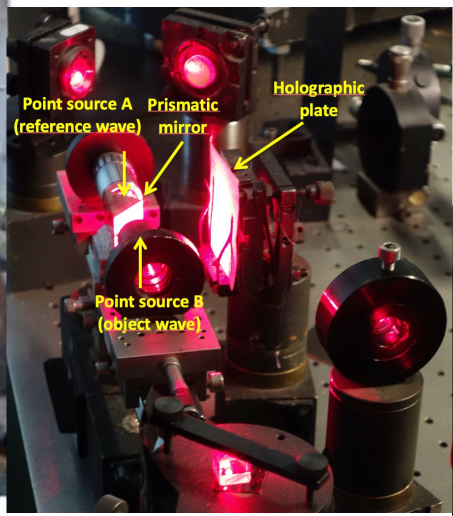
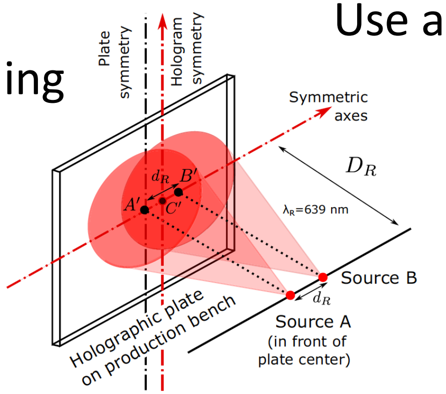
+ Observing team (Patrick, Merlin, Tiago, Craig, Erik, Ioana, Alysha & others)

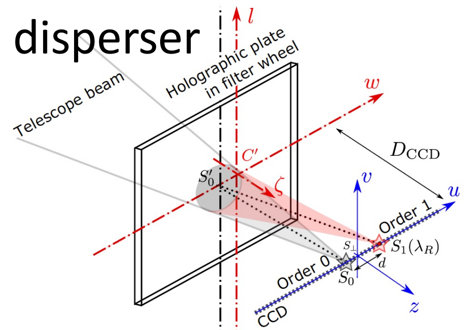
Rubin-LSST France, LPNHE, 30 nov. 2022

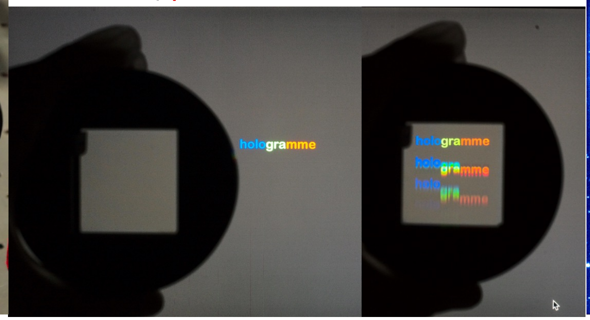


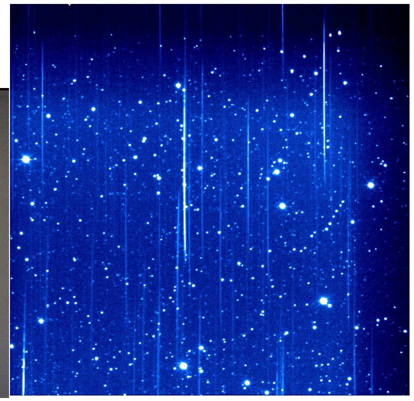
Hologram recording



Use as disperser







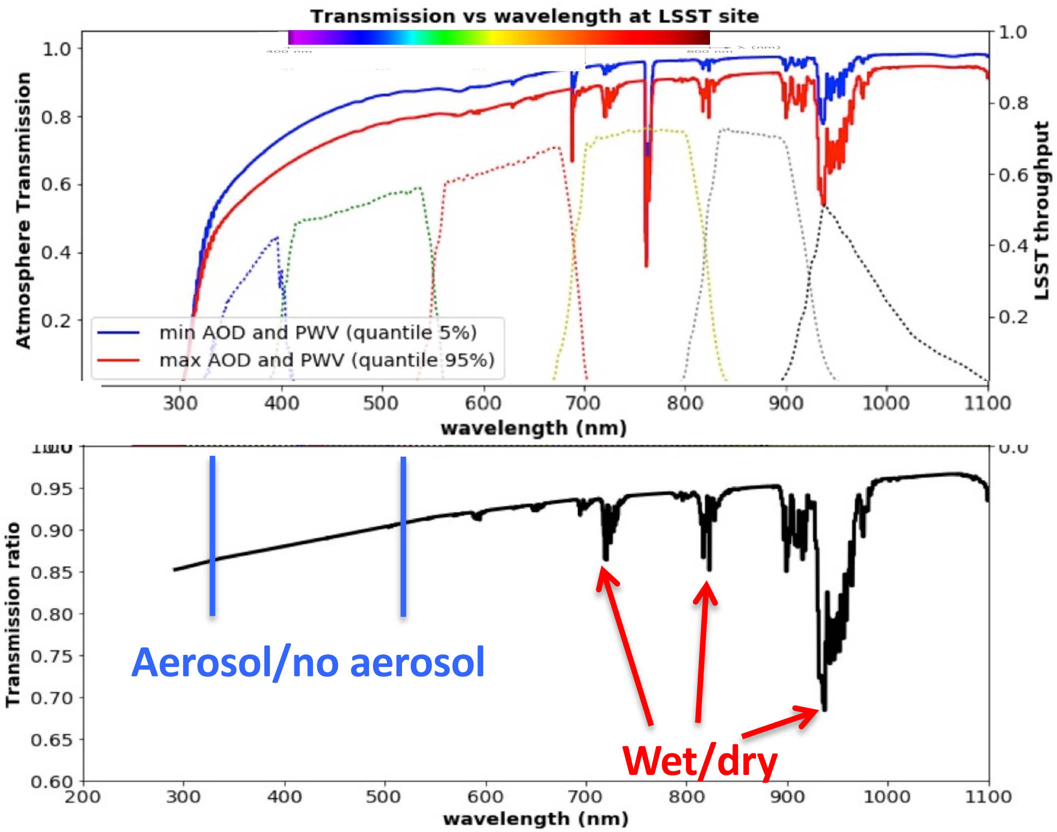
AuxTel spectrograph mission:

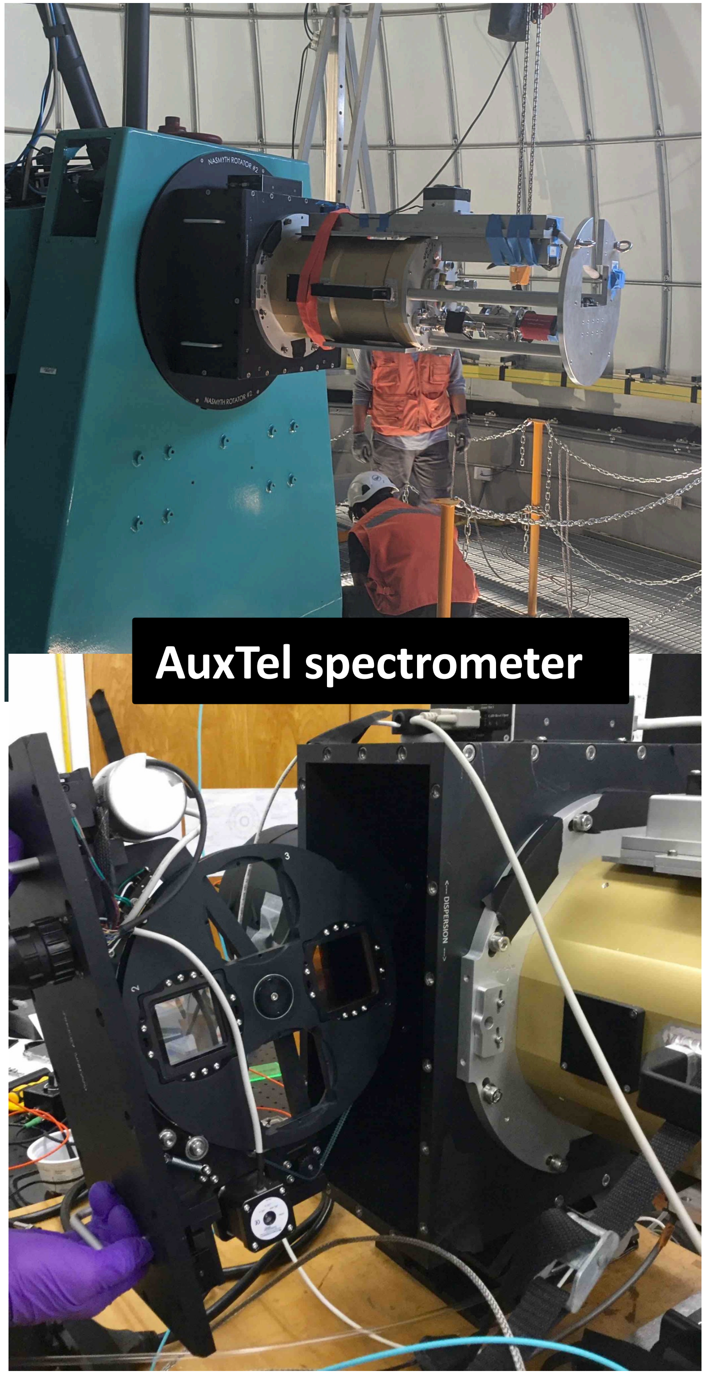
measure the atmospheric transmission to derive the expected fluxes for each object under standard atmospheric conditions

Estimate colour corrections, as functions of the atmospheric conditions and of the object UGRIZY in every LSST field

Example below

- Constant airmass, constant O_2 and O_3. No cloud
- Change only : **H_2O (PWV)**, **Aerosols**





Some facts about AuxTel

- **D = 1.20m**, **f/D = 18**, **f = 21.6m**
- Depth of focus 1 arcsec (10 pixels) for **1.8mm** change in distance (small aperture).

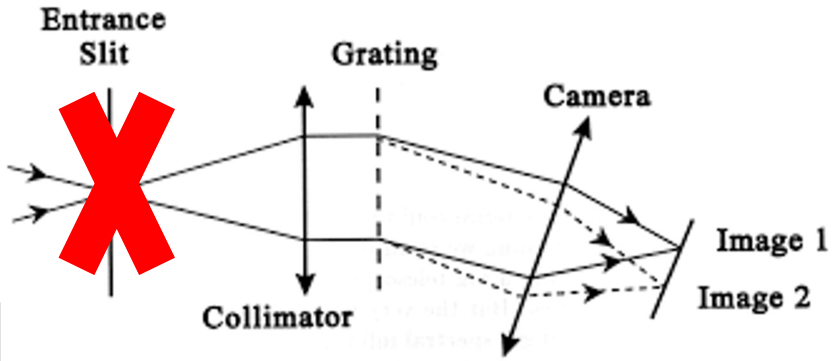
- Secondary mirror (M2) Obturation: **0.3m**
- Total collection area : **S= 1.06 m^2** (taking into account M2 obturation)

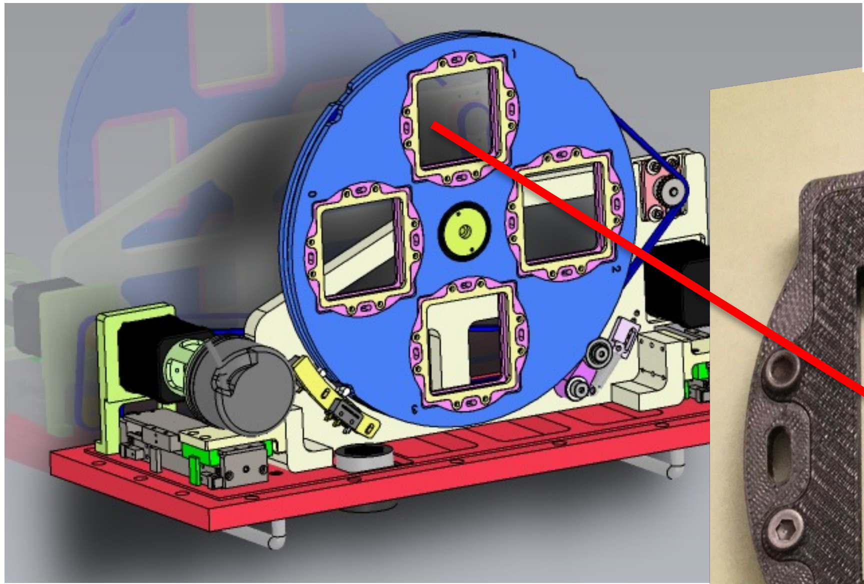
- Plate scale: **105µm/arcsec** -> about **10 pixels/arcsec**.
- Field of view : **6.3 Arcmin**.

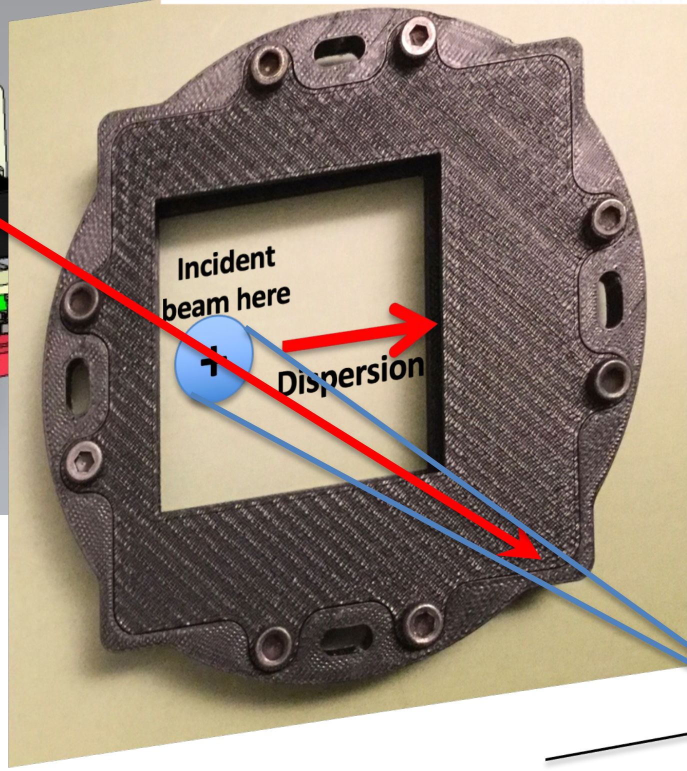
- Distance entrance window-CCD : 63.85mm. Light beam diameter at this distance : 3.55mm
- Distance disperser-CCD: about 191.4mm (tilted). beam diameter at this distance : 10.6mm
- Distance filter-CCD : 229mm (tilted).

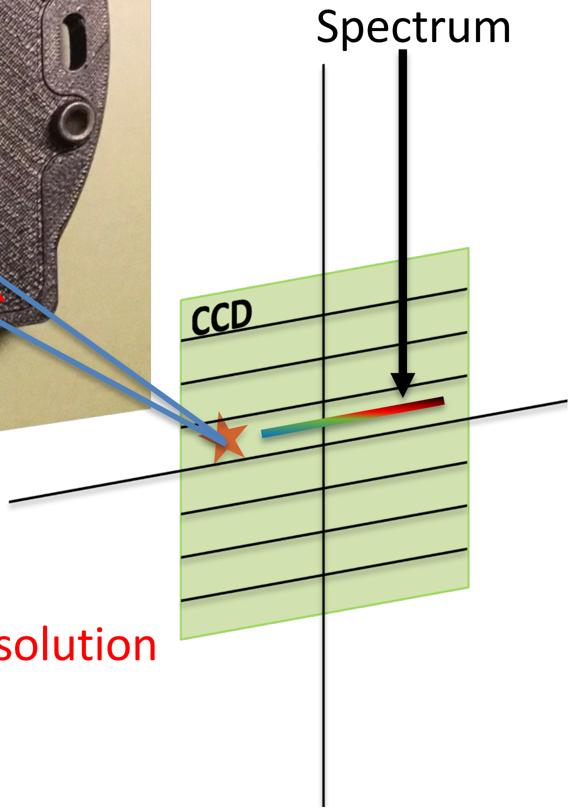
- Saturation (no filter, no disperser, assuming seeing of 1''): $\mathbf{M_{sat}=13.35+2.5Log_{10}(Texp/30s)}$

Our spectrograph is slitless equiped with an Holographic Optical Element









Slitless allows

- fast positioning
- spectrophotometry

Limits: sky+stellar background
low resolution (seeing limited)

Phase hologram (dispersion+focus functionalities)

- Excellent focus for all λ with convergent beam -> nominal resolution
- More light -> better s/n

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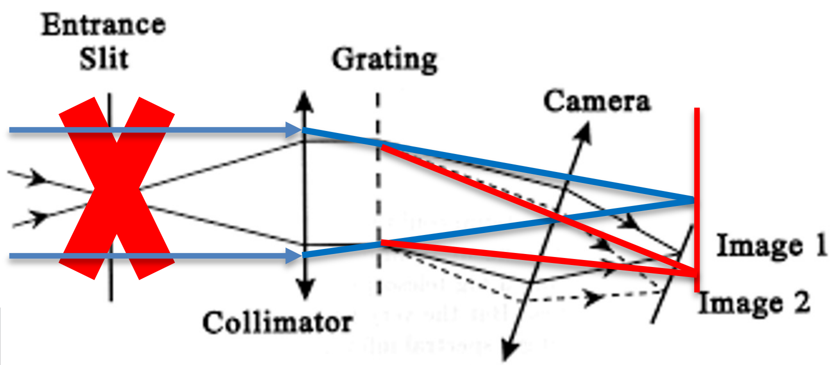

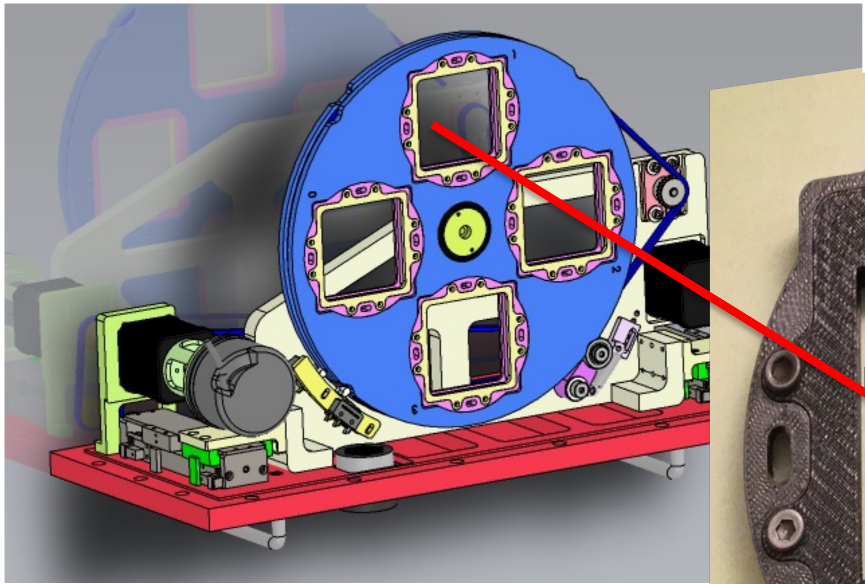

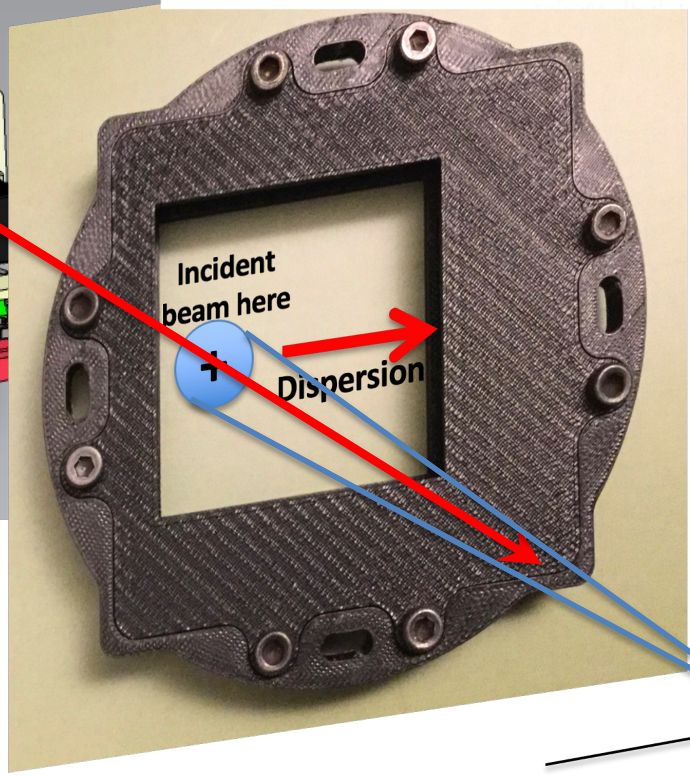

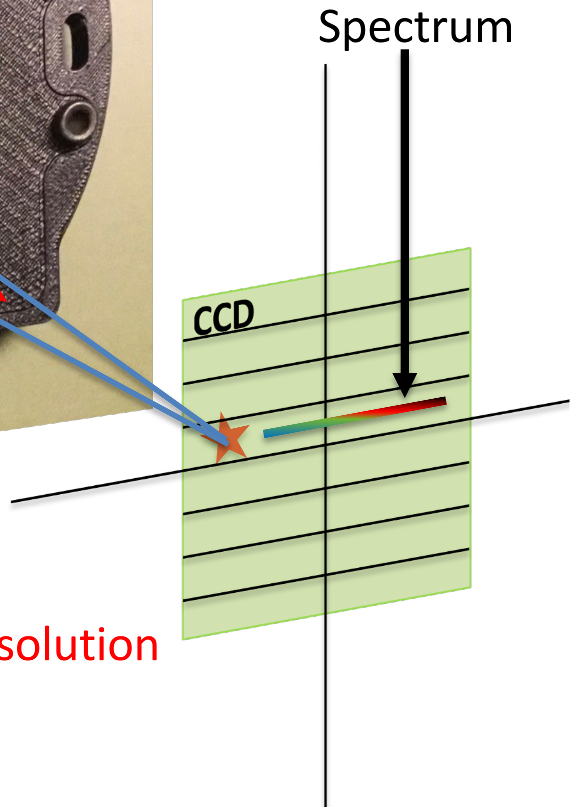

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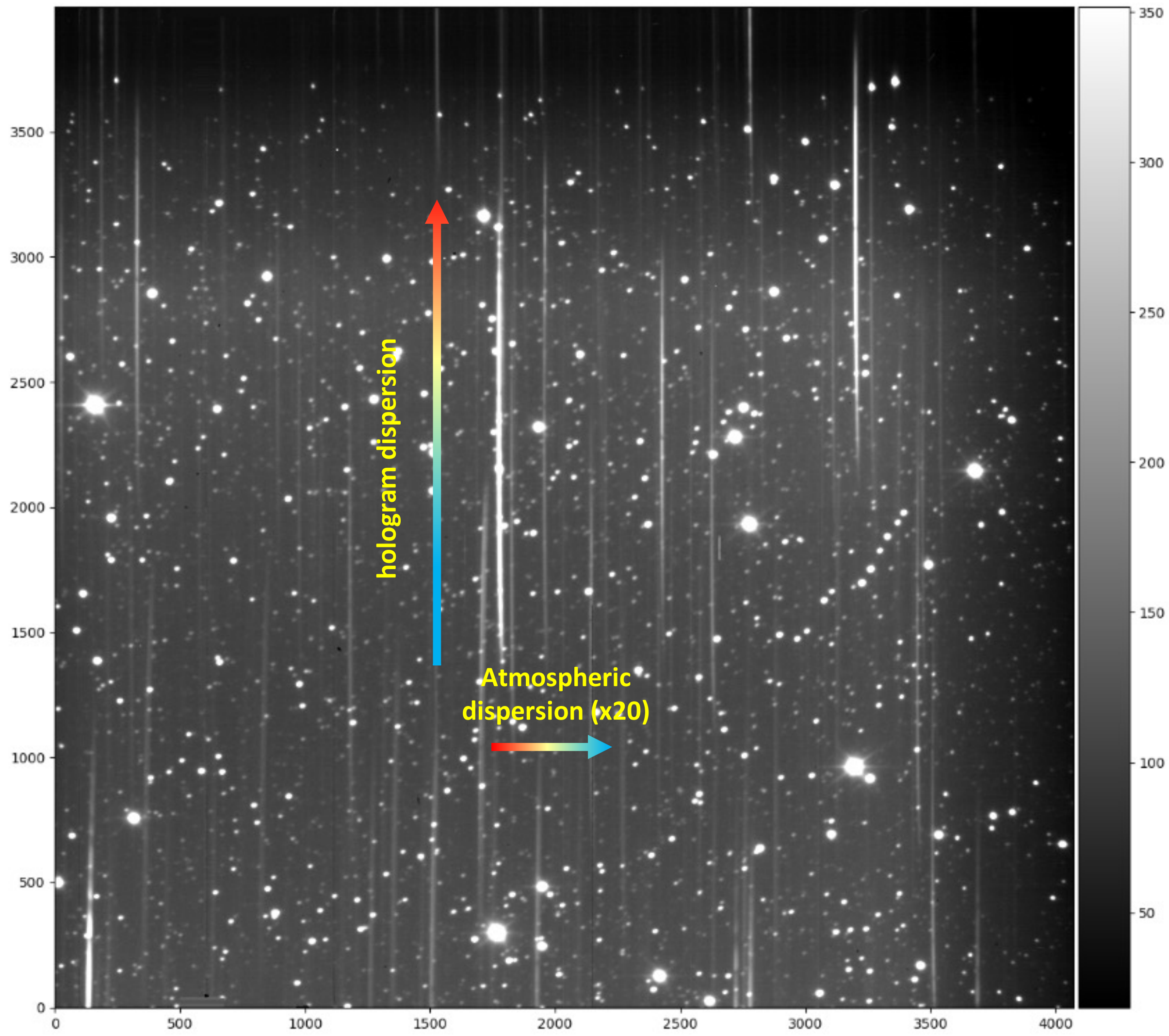
How does it look like?



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Data available (since 16 feb. 21)

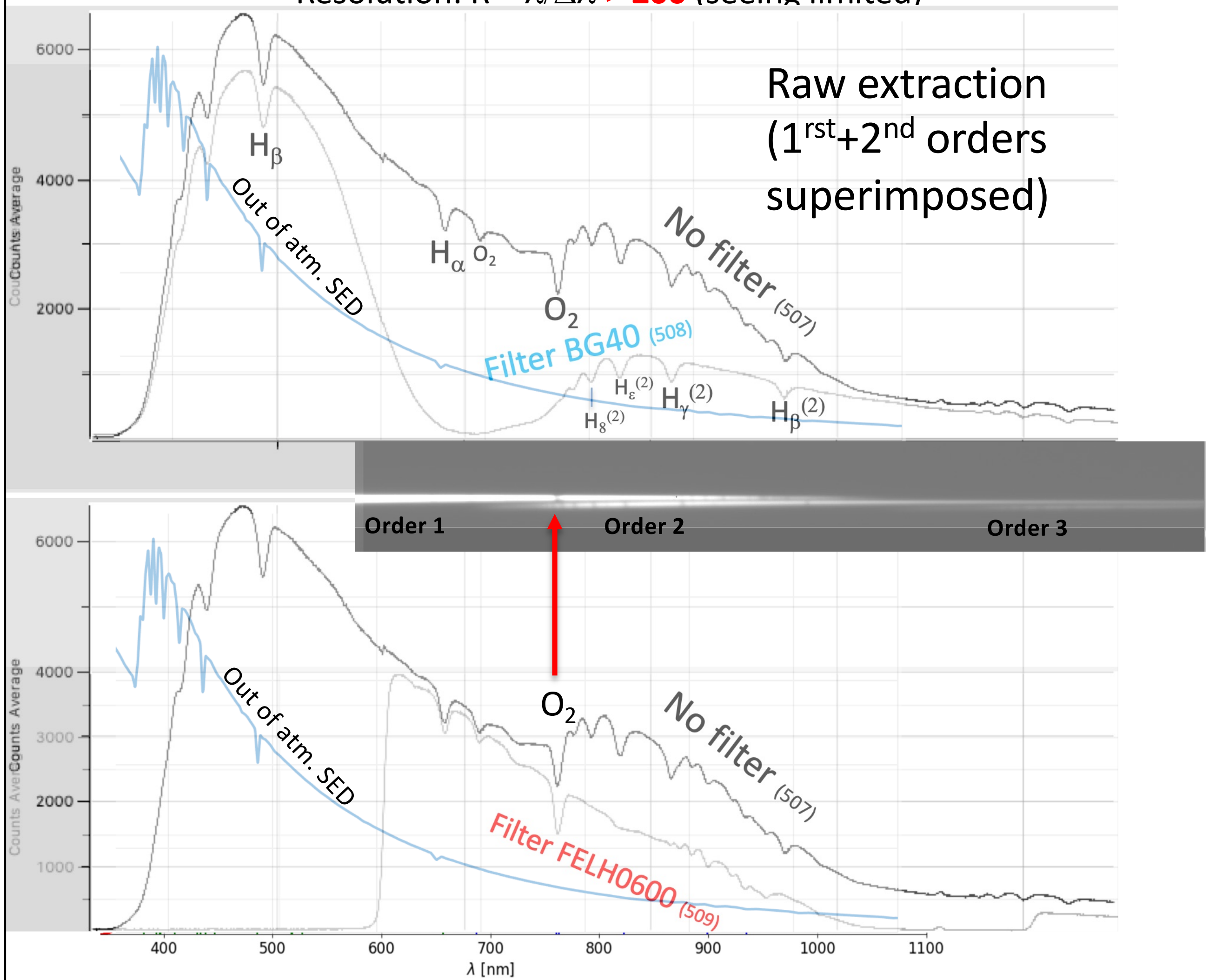
O(1000) spectra for

- Commissioning
  - ~~Geometry~~
  - ~~Resolution study~~
  - ~~Transmission~~
  - 2nd/1rst order : finalization
  - Bouguer lines: finalization for global telescope throughput
- With various
  - CALSPEC standards
  - atmospheric conditions
- with/without blocking filters
- but not that many with good quality

*->The best nights up to now seem to be **30th june and end sept. 2022**.*

- We need to acquire data in the largest domain of atmospheric Conditions.

Spectrum extends from ~ **342nm** to **1100nm**
Dispersion: 2.73 pixels/nm
Resolution: R = $\lambda/\Delta\lambda$ **> 200** (seeing limited)

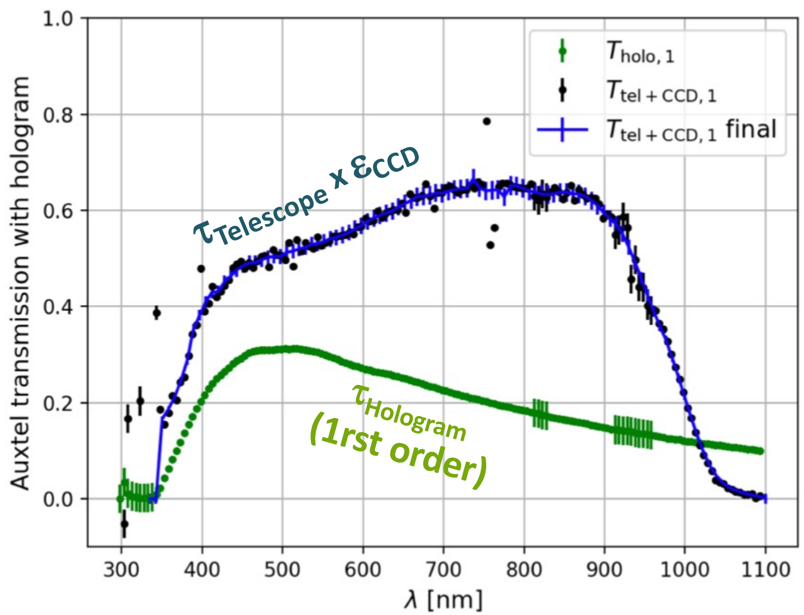


Operations for measuring atmosphere transmission

- Use a spectrophotometric standard measured out of atmosphere (CALSPEC)
- $\tau_{atm}(\lambda,z) = \phi(\lambda,z)_{instrumental} / \phi(\lambda)_{SED\text{-}HST}$

-> in magnitude (for diffraction order p):

- $m_p(\lambda,z)_{instrumental} = m(\lambda)_{SED\text{-}HST} - 2.5\log T_p(\lambda) + A_{atm}(\lambda).z$
- $T_p(\lambda) = \tau(\lambda)_{telescope} \cdot \tau_p(\lambda)_{disperser} \cdot \varepsilon_{CCD}(\lambda)$



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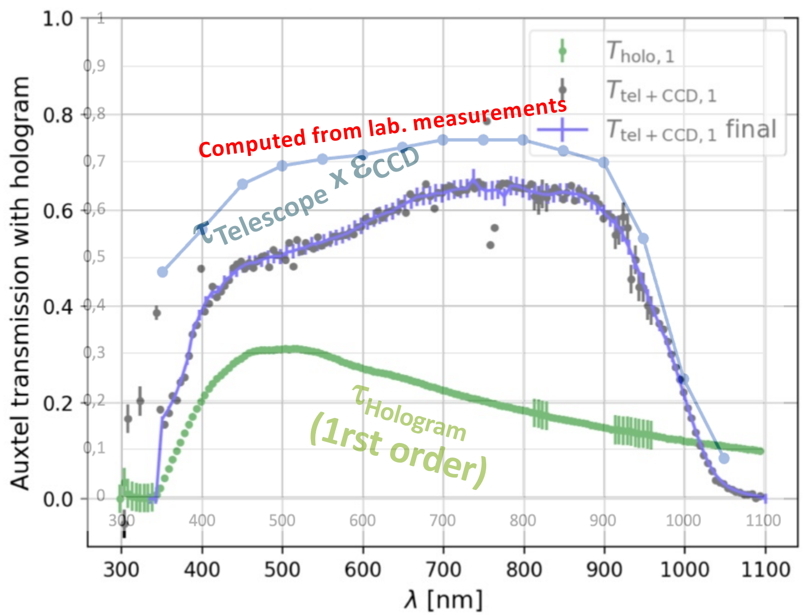
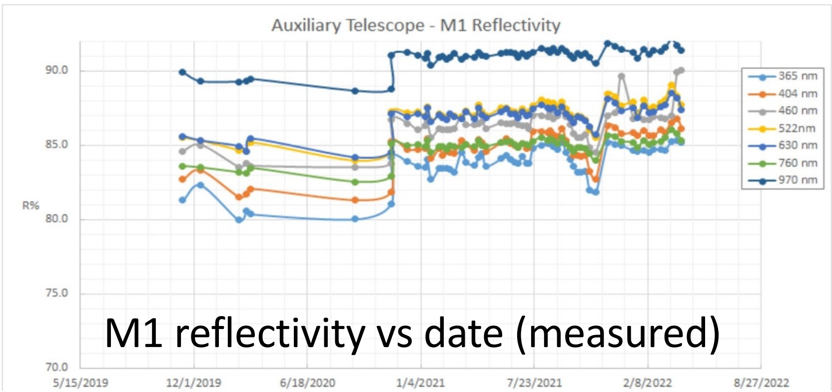
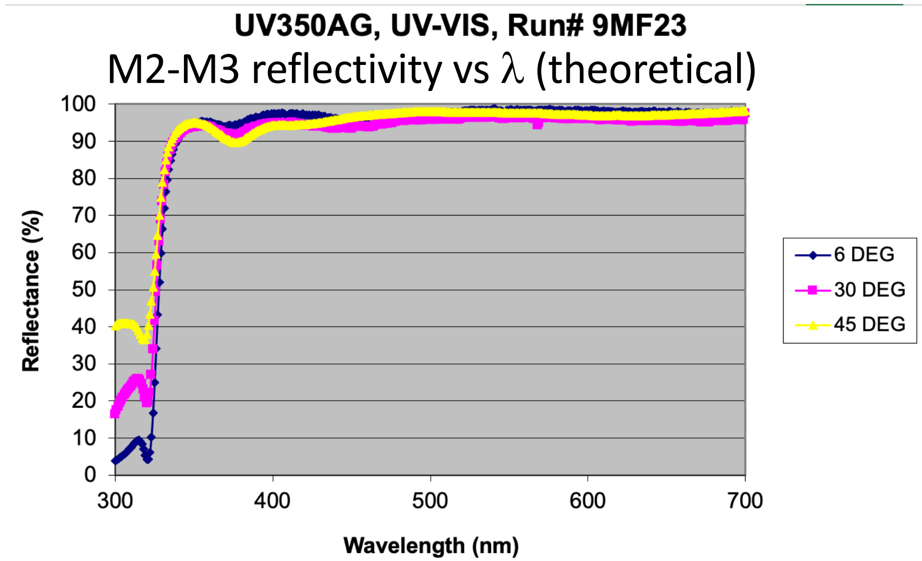
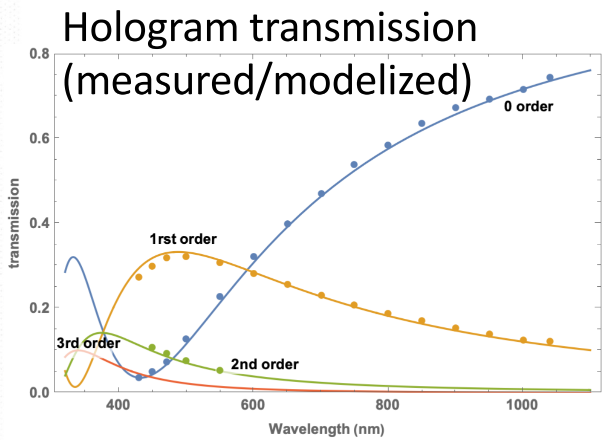
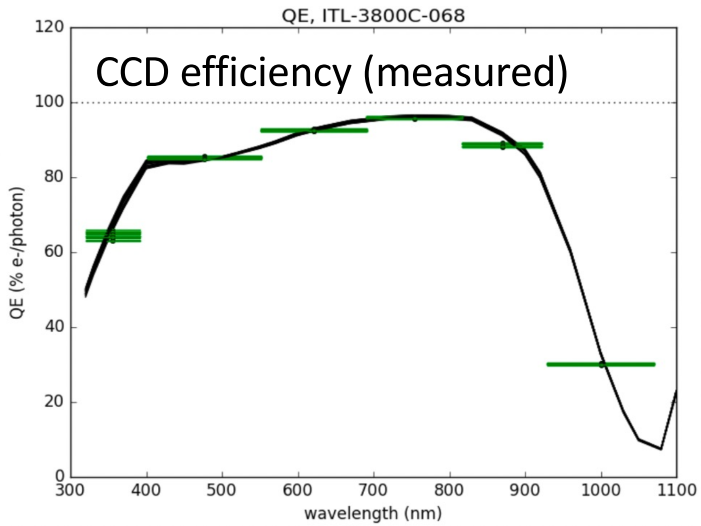


Ingredients of throughput

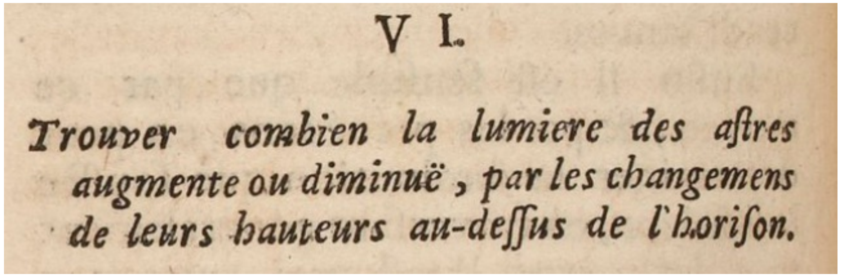








Throughput is estimated with Bouguer lines technique (1729)



V I.

Trouver combien la lumiere des aſtres augmente ou diminuë, par les changemens de leurs hauteurs au-deſſus de l'horiſon.

Example in band [485-515]nm (1rst order)

Series of instrumental magnitudes

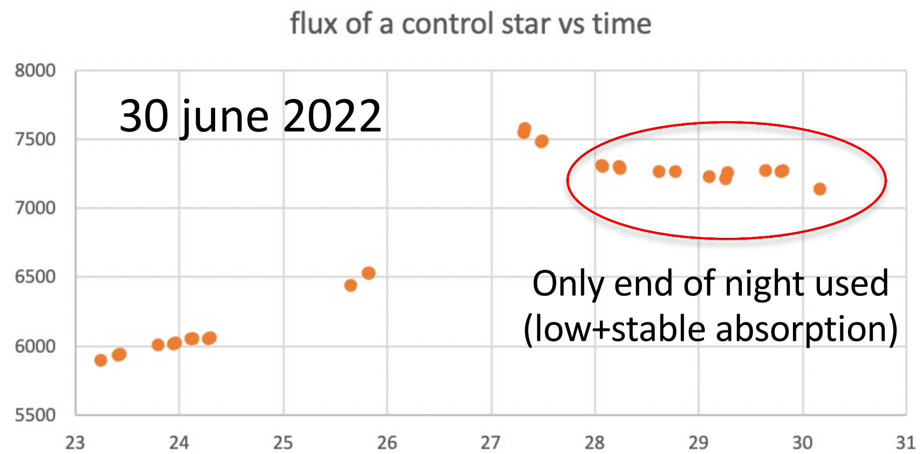
- of the same source
- for various aimasses (here 1.23 - 2.1)
- during a period with stable atmosphere

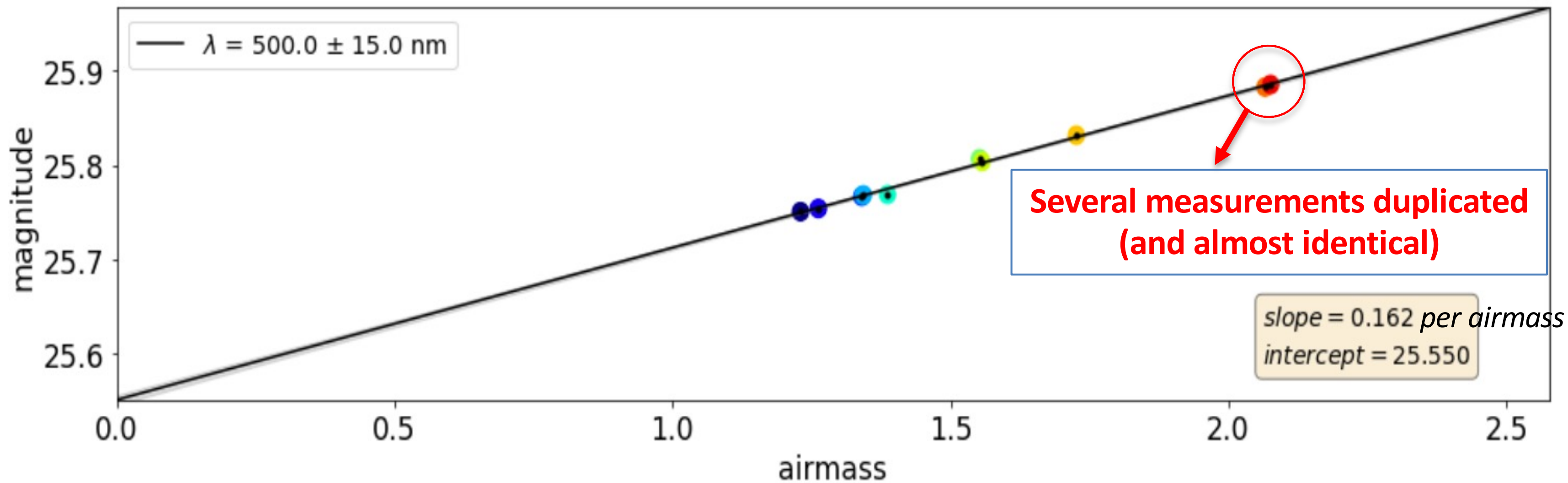
Extrapolation of the line to airmass=0

-> get magnitude OUT OF ATMOSPHERE

-> compare with HST spectrum

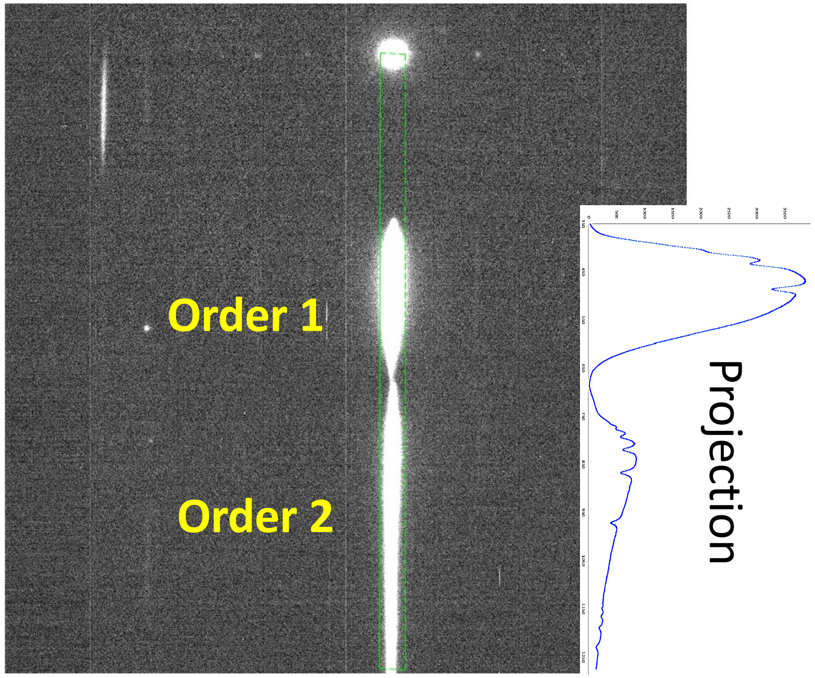
-> **deduce system throughput in the band**

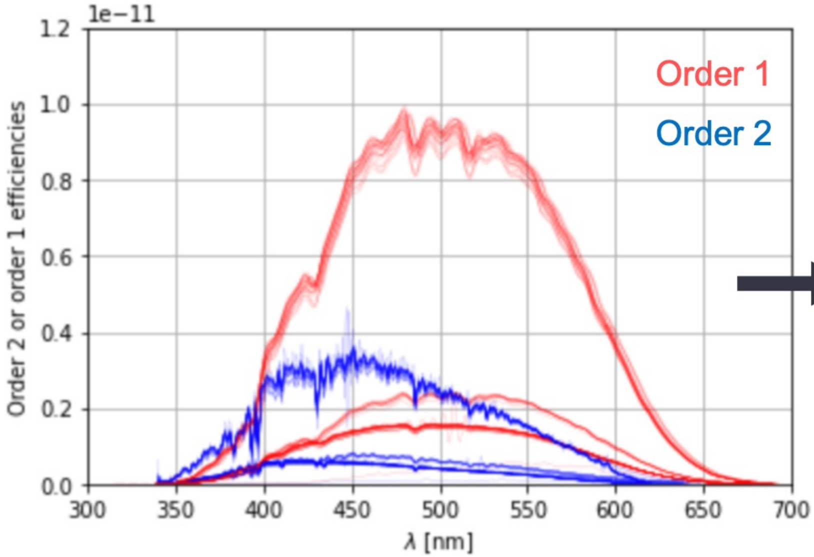


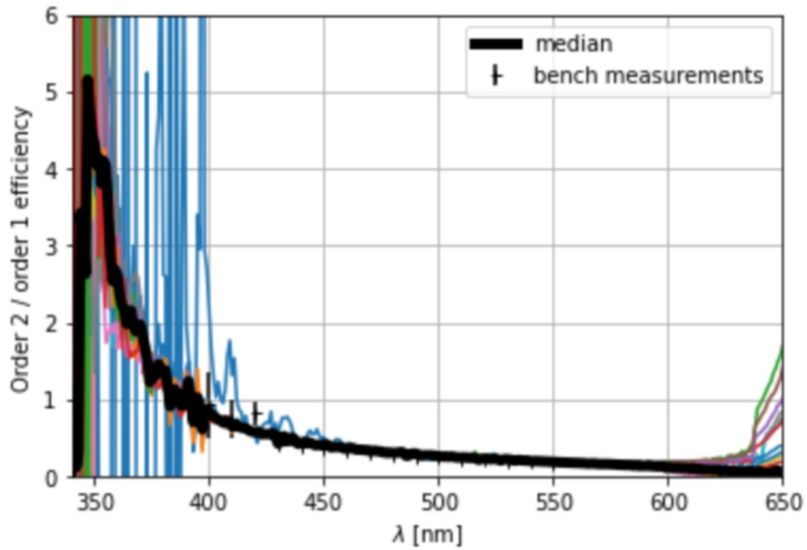


Determination of 2nd order/1rst order

- Use spectra with blue filter (125)
- Extract separately orders 1 and 2
- Compute ratio



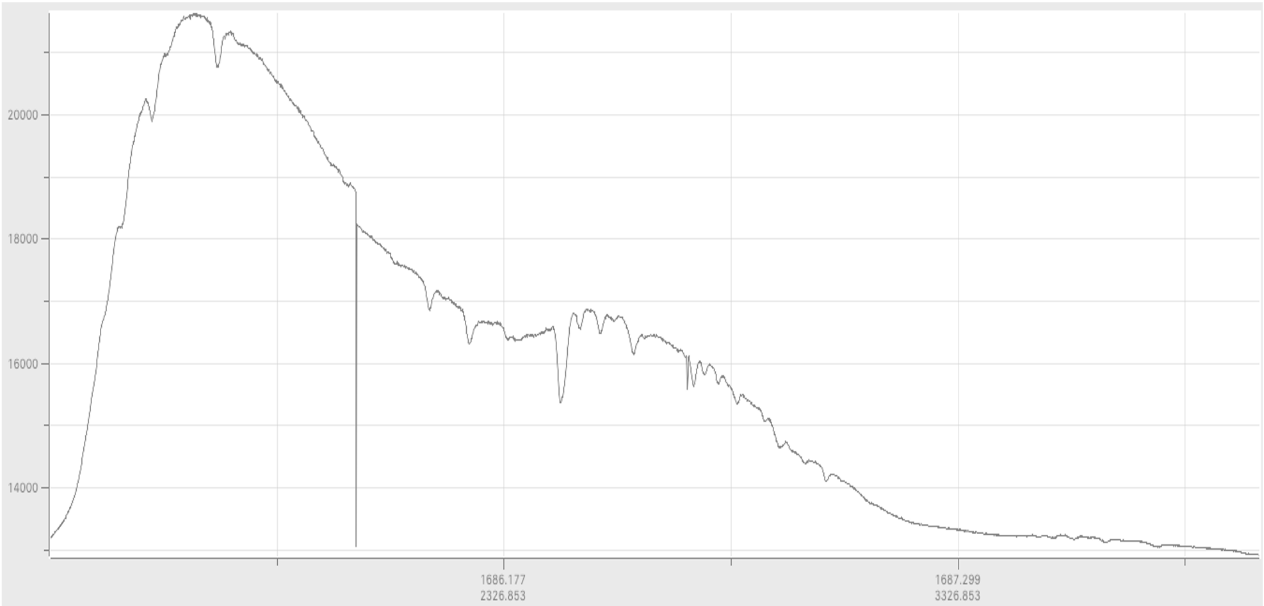




Spectroscopic reduction: état de l’art

- **SpecTractor** operational tool for spectrum extraction
  - Forward modelling, taking into account every instrumental effect:
    - dispersion law, PSF(λ), focus, 1rst+2nd orders, atmospheric dispersion…
  - Separation of 1^{rst} and 2nd diffraction orders now satisfactory

From RAW



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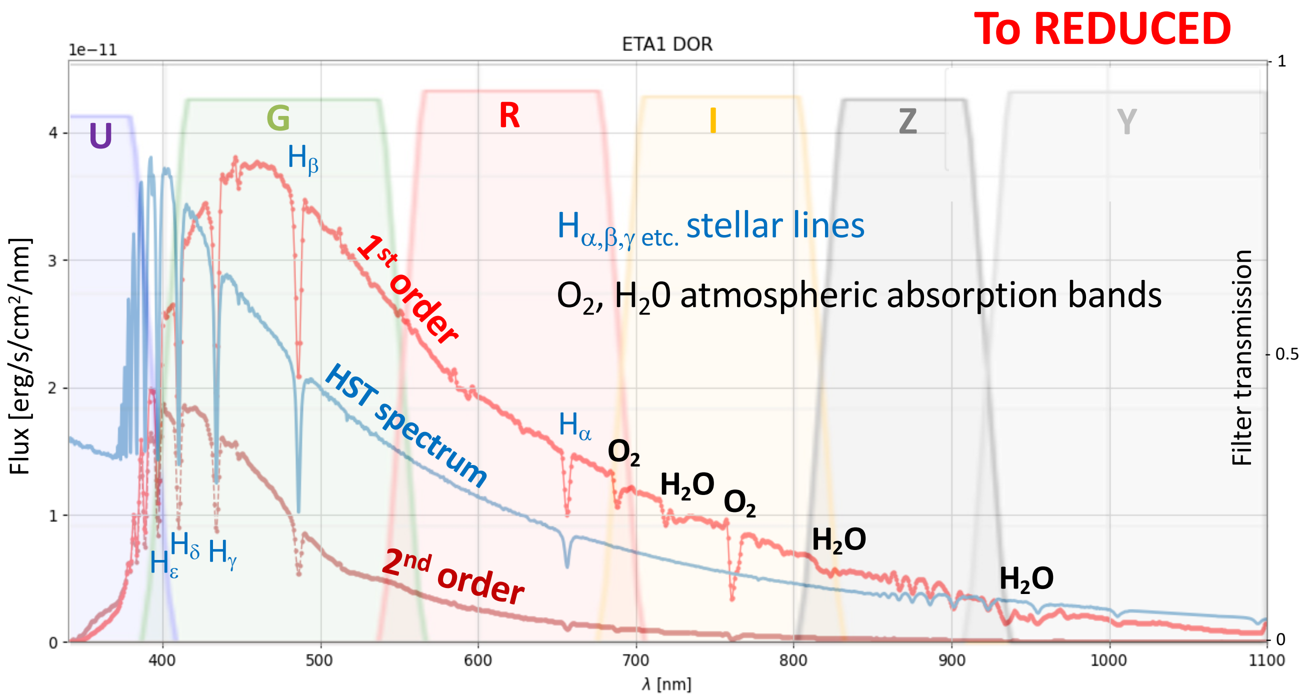
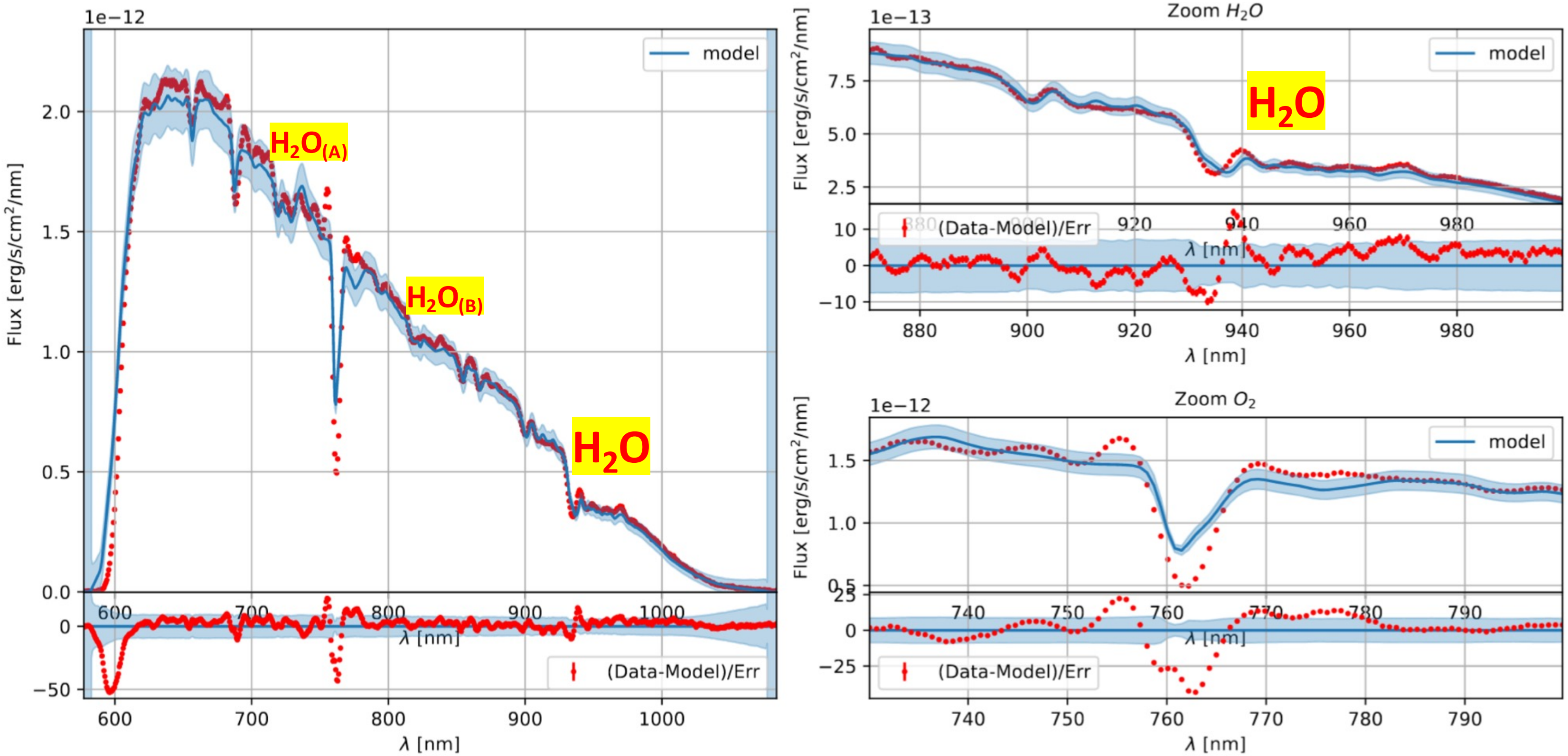


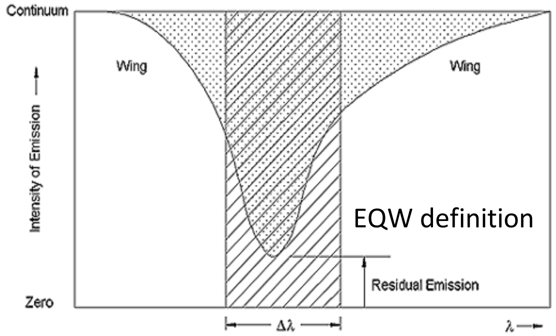
Extraction of atmospheric parameters

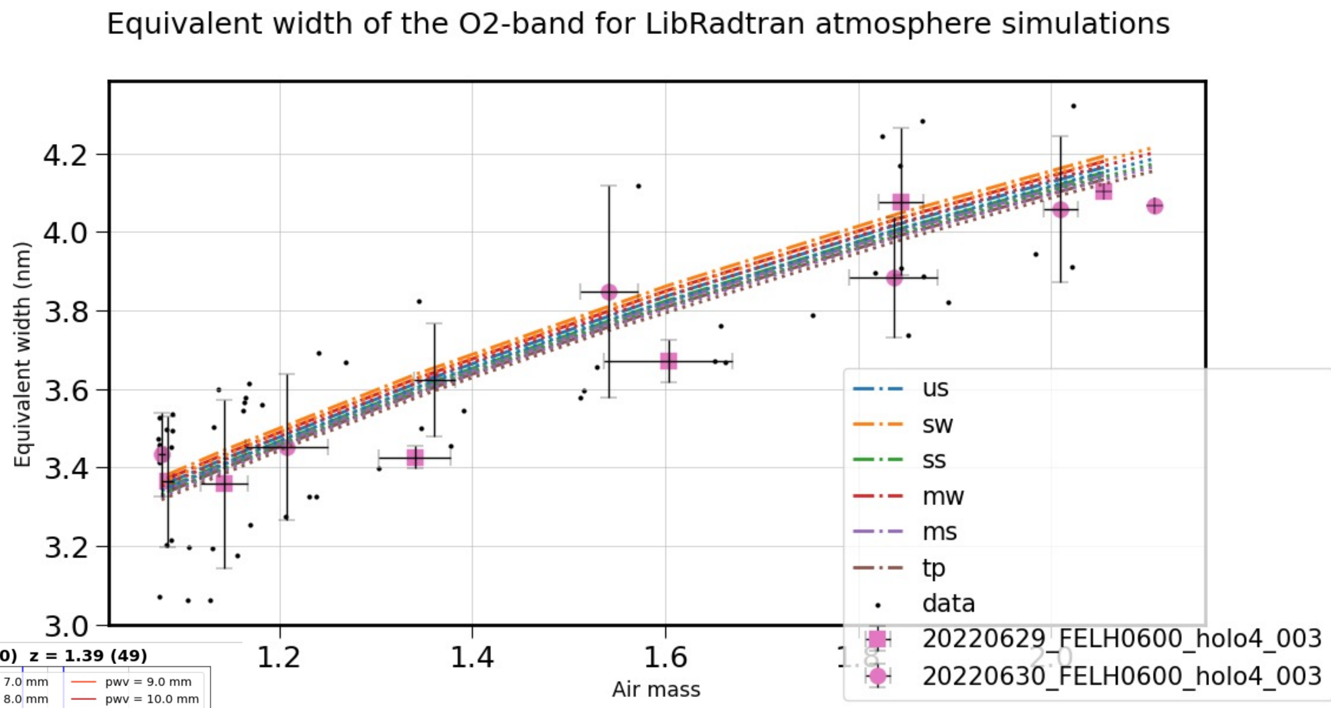
After knowing the telescope/hologram/(filter) throughput:

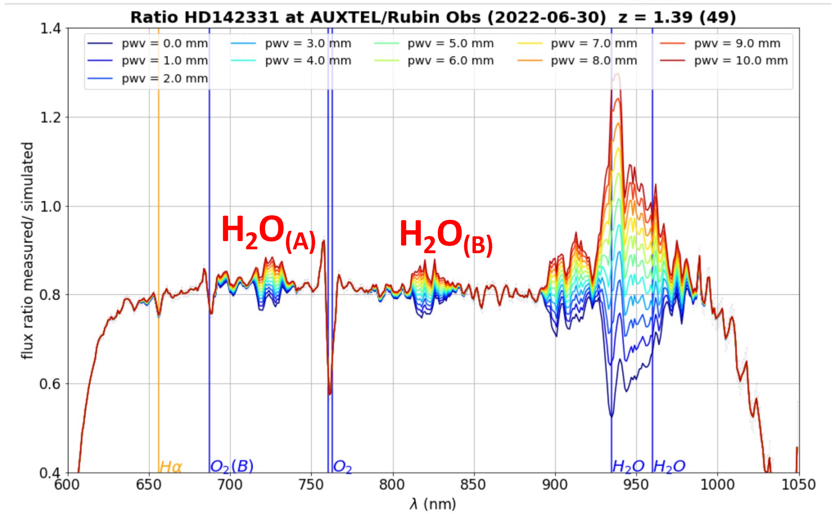
- Find atmospheric parameters (LibRadTran) from fit of data with model
  - Ozone, aerosols, and PWV=4.55+/-0.03 (Precipitable Water Vapor)



Control tool : EQW(O_2) should depend only on airmass x pressure







After checking EQW(O_2), we will measure EQW($H_2O_{(A)}$) and EQW($H_2O_{(B)}$)

Next steps / work in progress

We have now a kind of hygrometer

- Ultimate check by comparing dispersion of measurements after/before correction

We also need to measure aerosols

- Difficulty: no sharp feature
- We have sensitivity (comparison before/after culmination, same airmass shows variations)
- Test using multiband filters with spectro

Special flat-fielding

- derived from standard flat-field
- Obtained through special telescope operations

From atmospheric parameters to color corrections

Color changes induced by water vapor
Color changes induced by aerosols

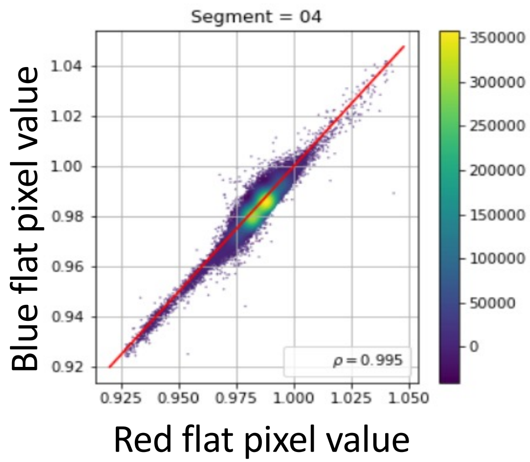
Flat-fielding in spectroscopy

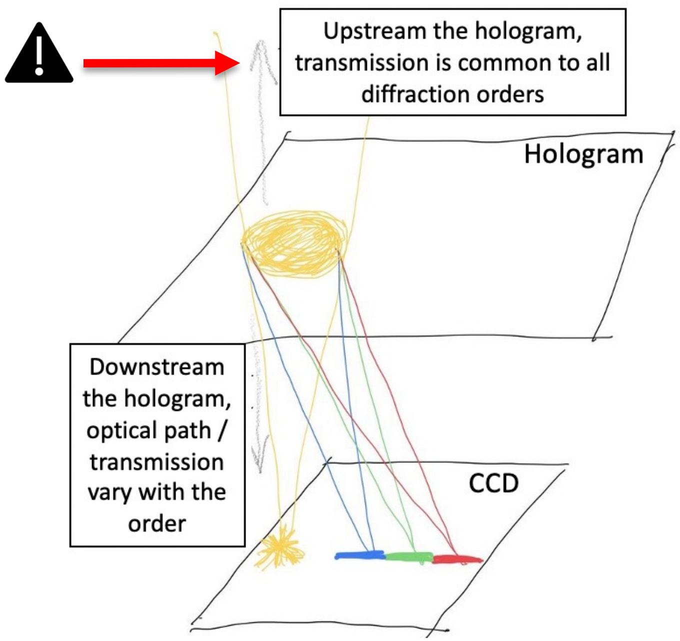
Flat-fielding is not standard for spectroscopy

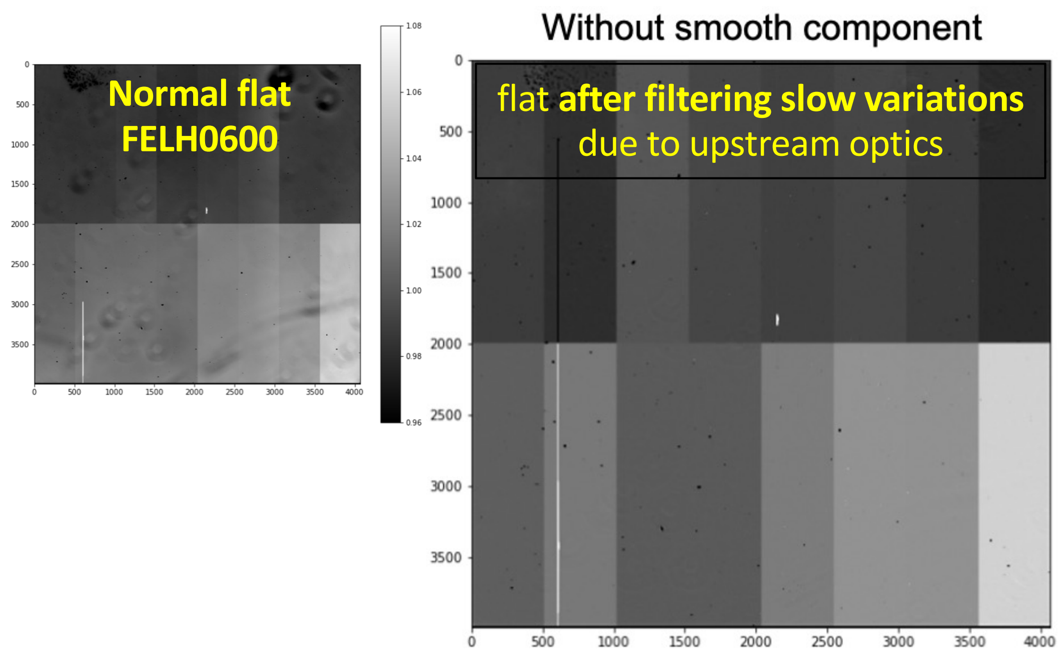
- Ultimately, the CBP will be the best tool
- In the meanwhile,we use approximations :
  - Keep only fluctuations due to camera window + CCD (dust & pixel-to-pixel gain variations)
  - **spatial** and **wavelength** efficiencies factorize

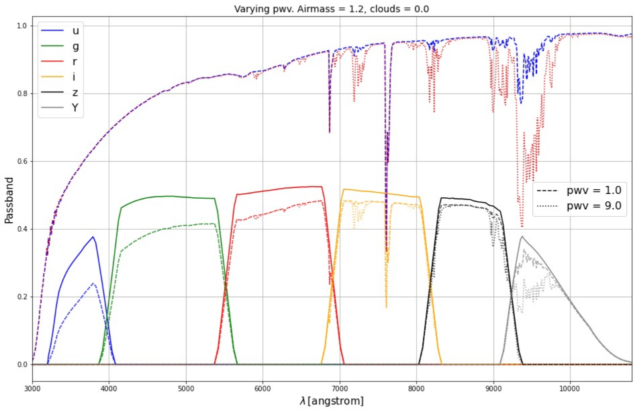
$$F_{CCD}(i,j,\lambda) = G_{CCD}(i,j) \times \varepsilon_{CCD}(\lambda)$$

- drifting star to produce a special flat-field to be tested

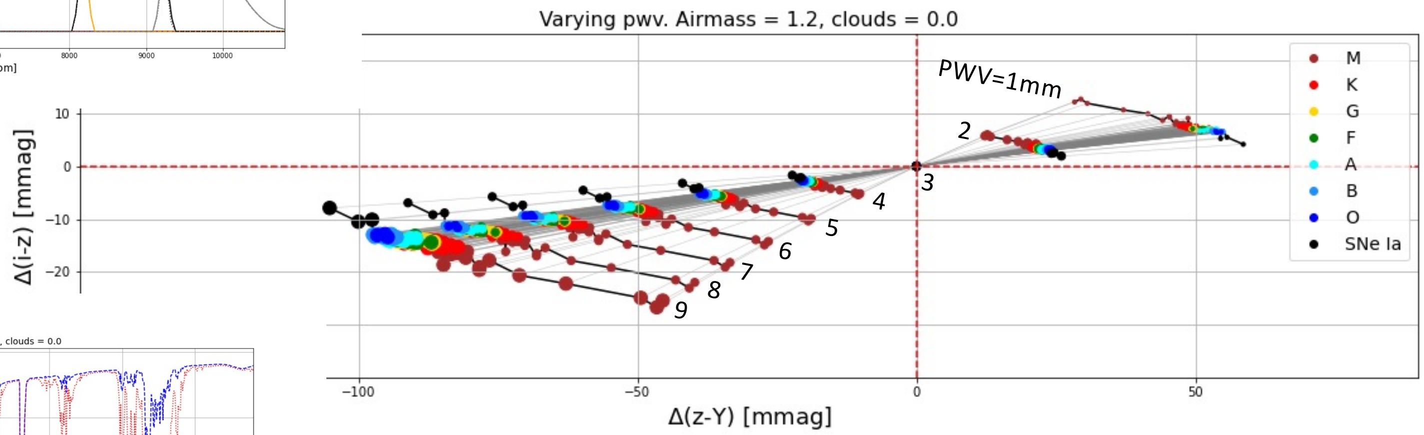


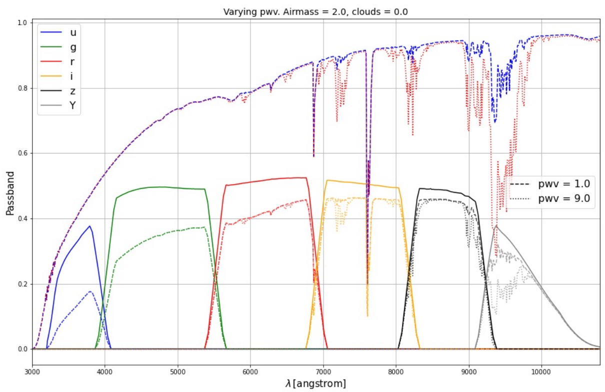




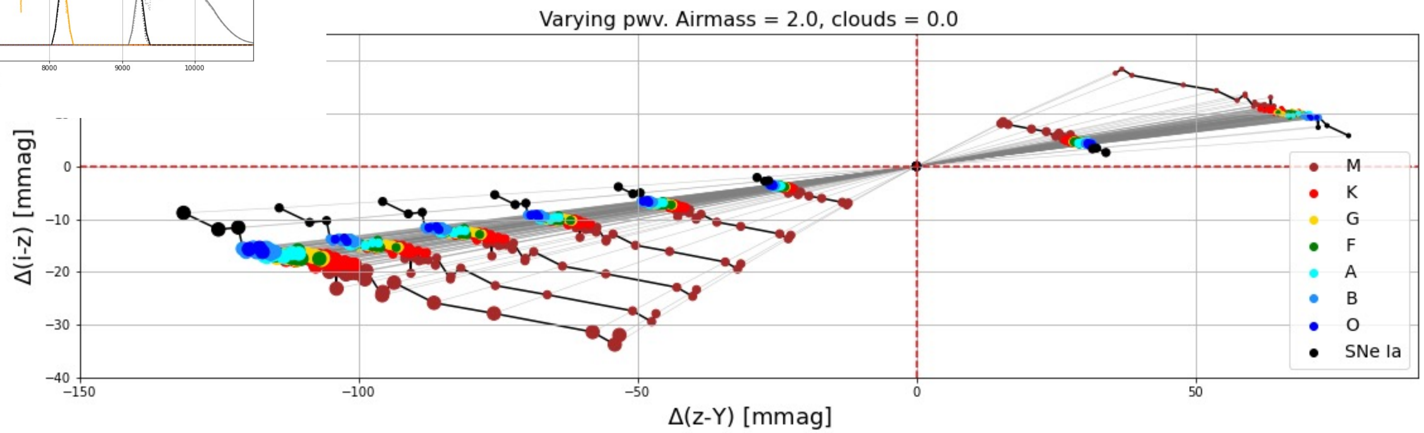


Color changes due to water vapor





Color variations follow: Scalar(PWV)x**Vector**(type)



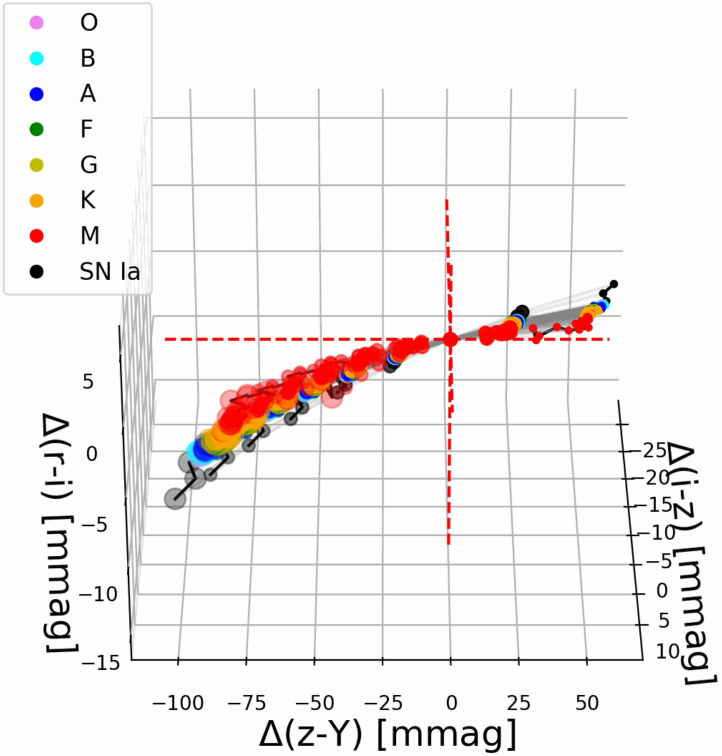
Color changes due to water vapor

Impact of PWV on colors

- mainly (i-z) and (z-y)
- described by Scalar(PWV)x**Vector**(type)
- with type linked to (ugrizY)

Impact of aerosol on colors

- mainly (u-g) and (g-r)
- work in progress



COMPLEMENTS

Spectrograph commissioning results

Objectives of the spectrograph commissioning:

Short term: characterize the spectrograph

- Geometry -> **done**

- Spectrograph resolution **R > 200** within **[342, 1100]nm** : limited by the seeing (as expected); 2x better for the second order -> ex. H9 absorption line (@383nm) clearly visible. -> **OK**

- Software: SpecTractor[1] operational, constantly improving -> **work in progress**

- Checked the equivalent width (EQW) properties -> **OK**

- Telescope throughputs of 1rst and 2nd orders holographic disperser[2] with Bouguer lines -> **work in progress**, near to end (needs one « ideal » photometric night to consolidate).

- + a faint V=11.3 standard gives « enough » signal in 30s for spectroscopy

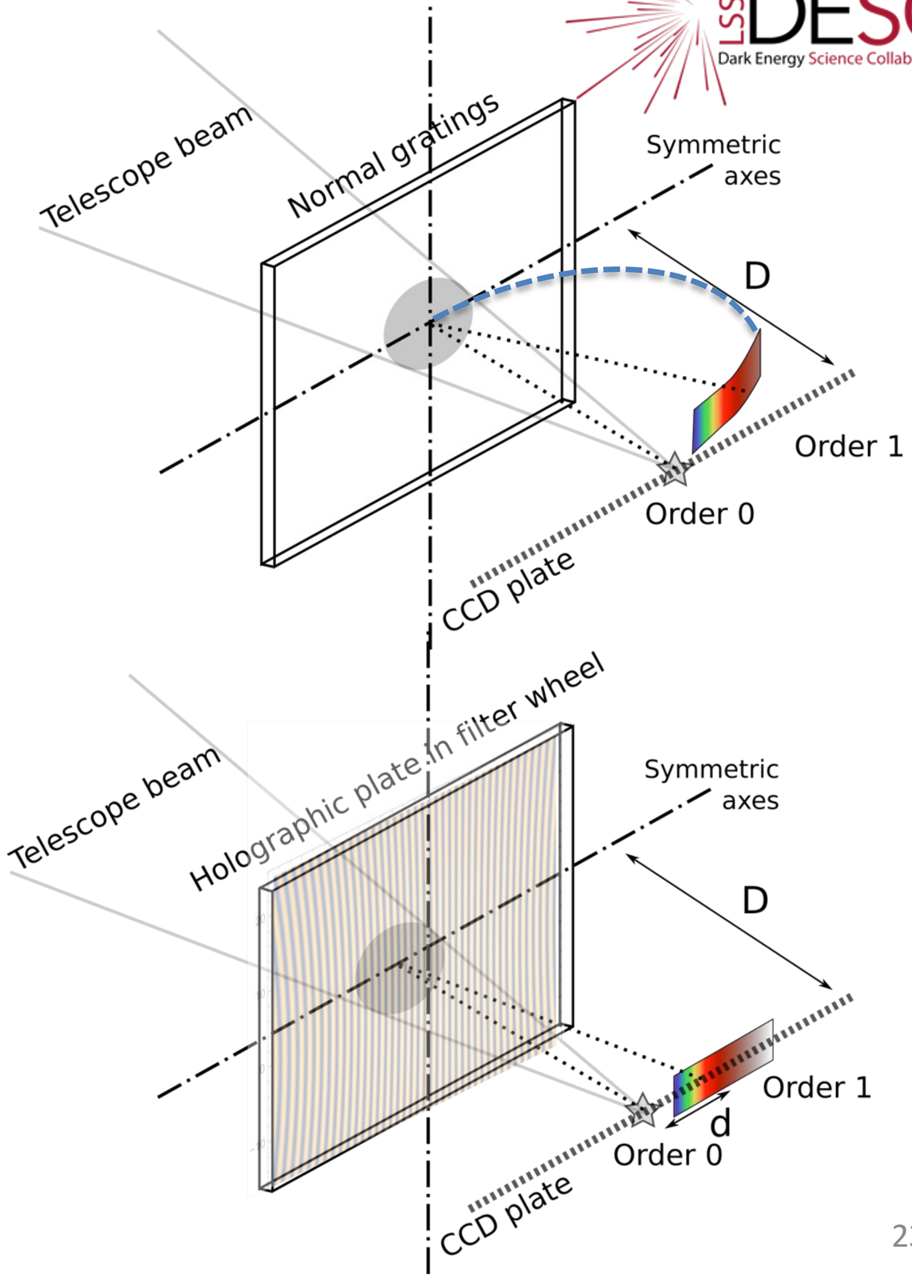
Long term: **Estimate colour corrections, as functions of the airmass, atmospheric conditions and the object UGRIZY in every LSST field** -> work in progress (Martin Rodriguez-Monroy)

- Either with an atmospheric model established from the follow-up of standards throughout the night
    - -> Check the predictivity of the model versus airmass AND versus azimuth
- And / or with simultaneous measurements near the LSST field (needs secondary standards and observation strategy to « follow » LSST)
    - -> Rely on GAIA DR of spectra

(1) Paper in preparation (2) MNRAS **506,** 5589–5605 (2021). 2nd paper in preparation.

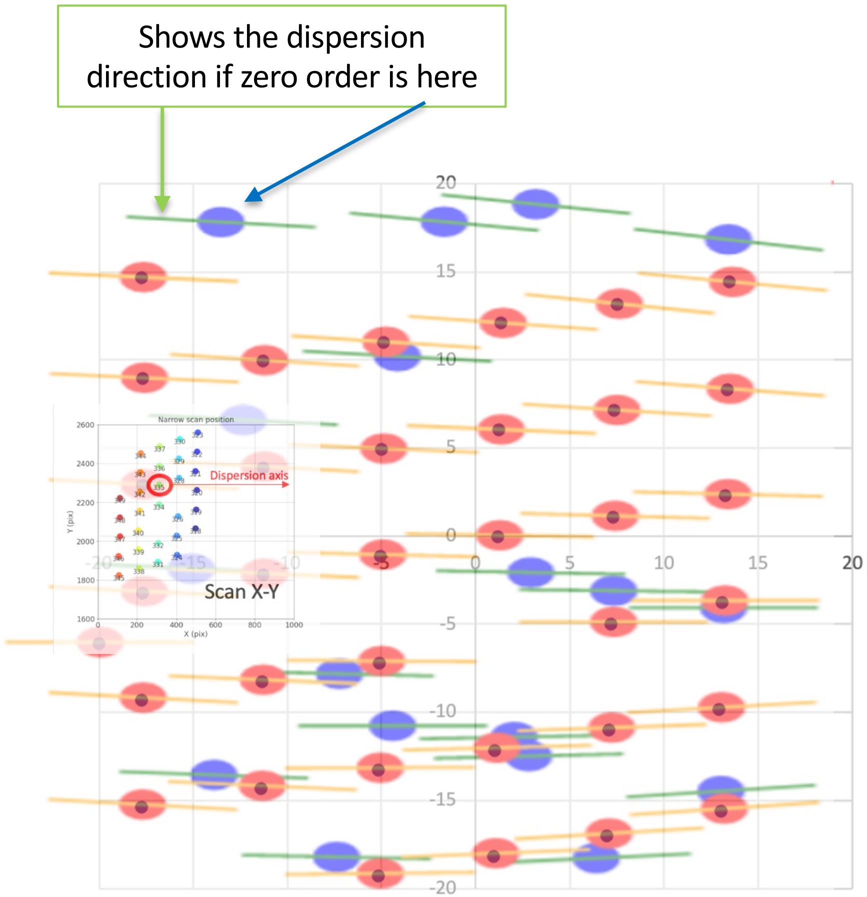
Hologram for AuxTel

- **Goal :** measure atmospheric parameters by extracting spectrum of standards
- **Constraints**
  - Easily switch imager / spectro.
  - Incident beam perpendicular to CCD-plane
  - Converging beam (not parallel)
- **Usual gratings:**
  - **Strong defocus** due to optical path variations with the diffraction angle
  - **Distorsion** when used with a converging beam
- **Holographic grating:**
  - forced focus on the focal plane at all wavelengths: **0th and 1rst order at same focus**
  - No distorsion by design of hologram

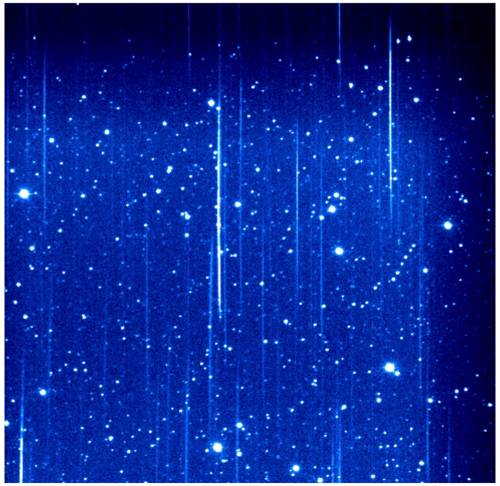


Holographic element characterization

- **Geometry**: 2 scans (wide and fine meshes); changing position of the 0 order star
- Determination of the **nominal zero order position (1750, 300)** -> determined with < 0.5 mm precision
- **Transmission is found constant** within >1mm from nominal position
- **Good focus** along the full λ [342-1100]nm scale -> one of the main improvements w/r Ronchi grating
- **Transmission efficiency** -> up to 3x more than Ronchi (depending on λ)



Estimating a lower limit of resolution, using narrow emission lines of Planetary nebula *Hen 2-113*



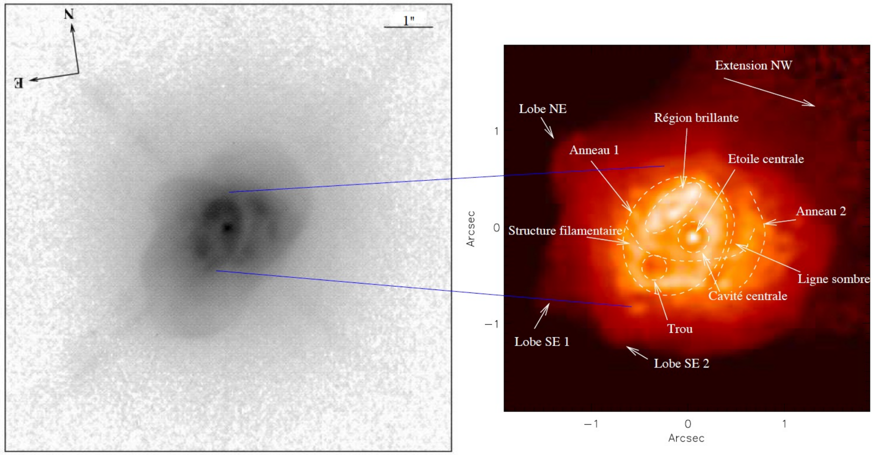
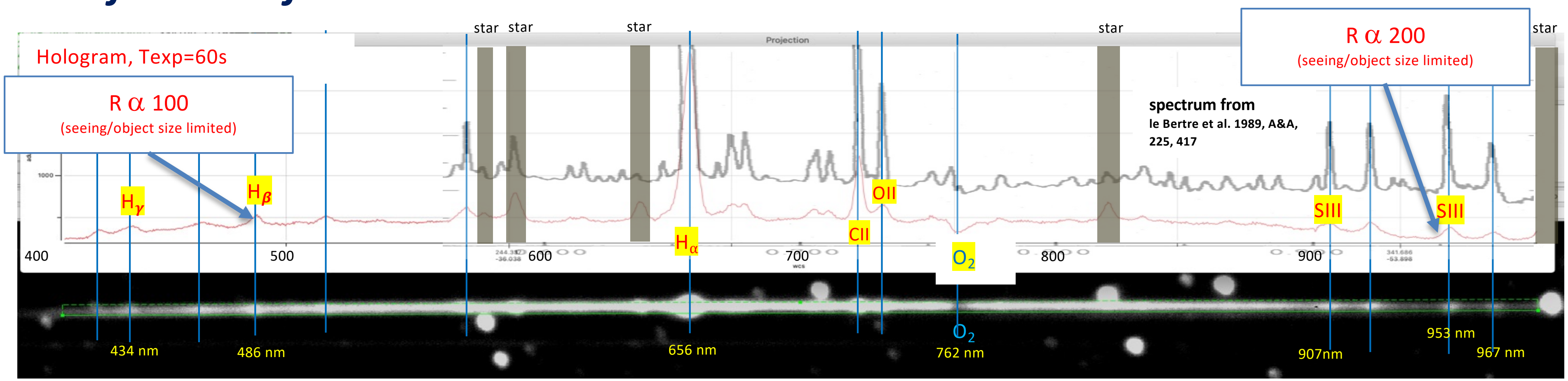


Fig. 1. Left: optical HST image of Hen 2-113 (Sahai et al. 2000). Right: NACO image of Hen 2-113 at 3.74μm (Lagadec et al. 2006).

-> lower limits on R=$\lambda/\Delta\lambda$ (because extended object)

-> focus OK for all λ

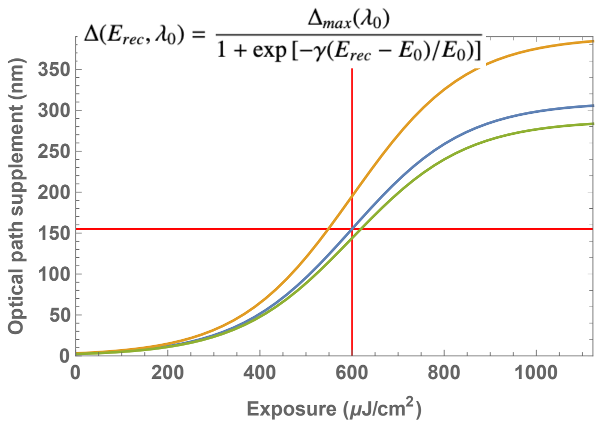


486 nm

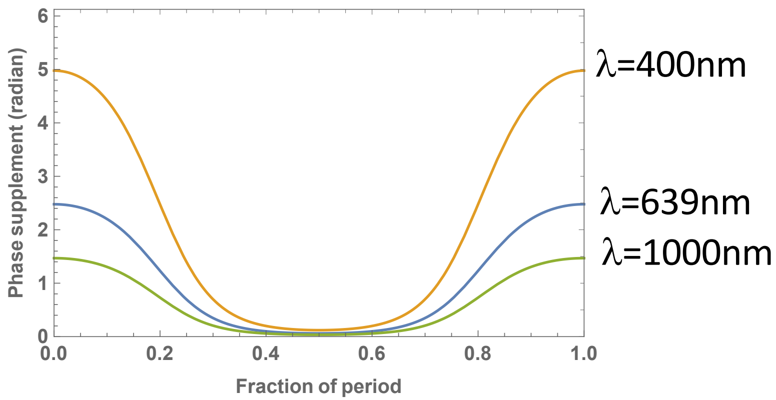
656 nm

762 nm

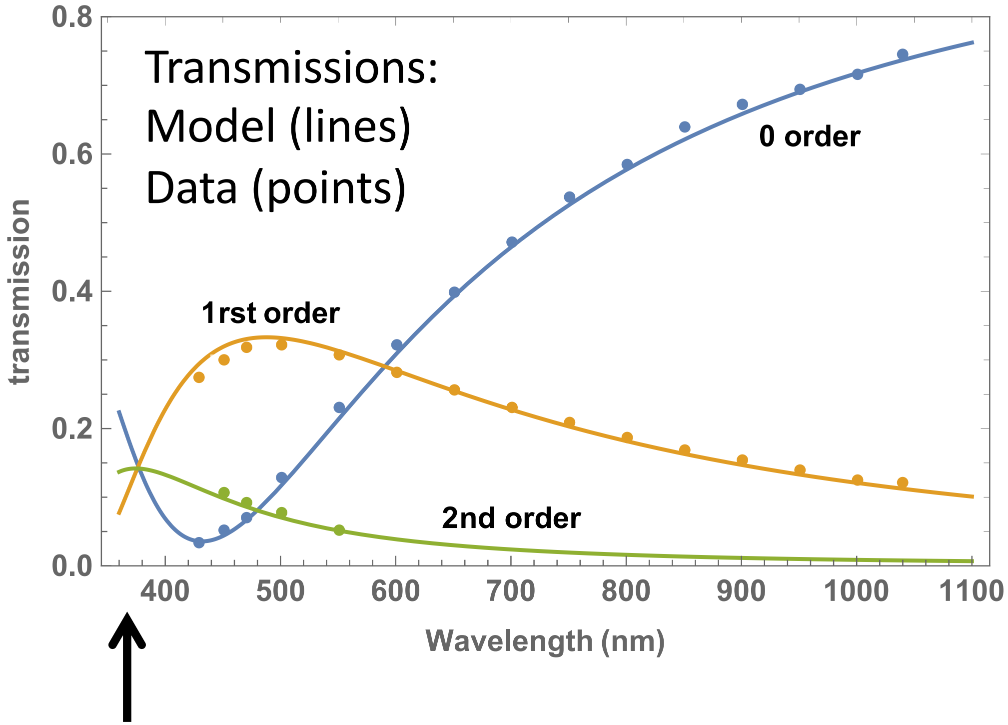
Transmission efficiency model vs test-bench measurements



Caracteristic curve of holographic emulsion



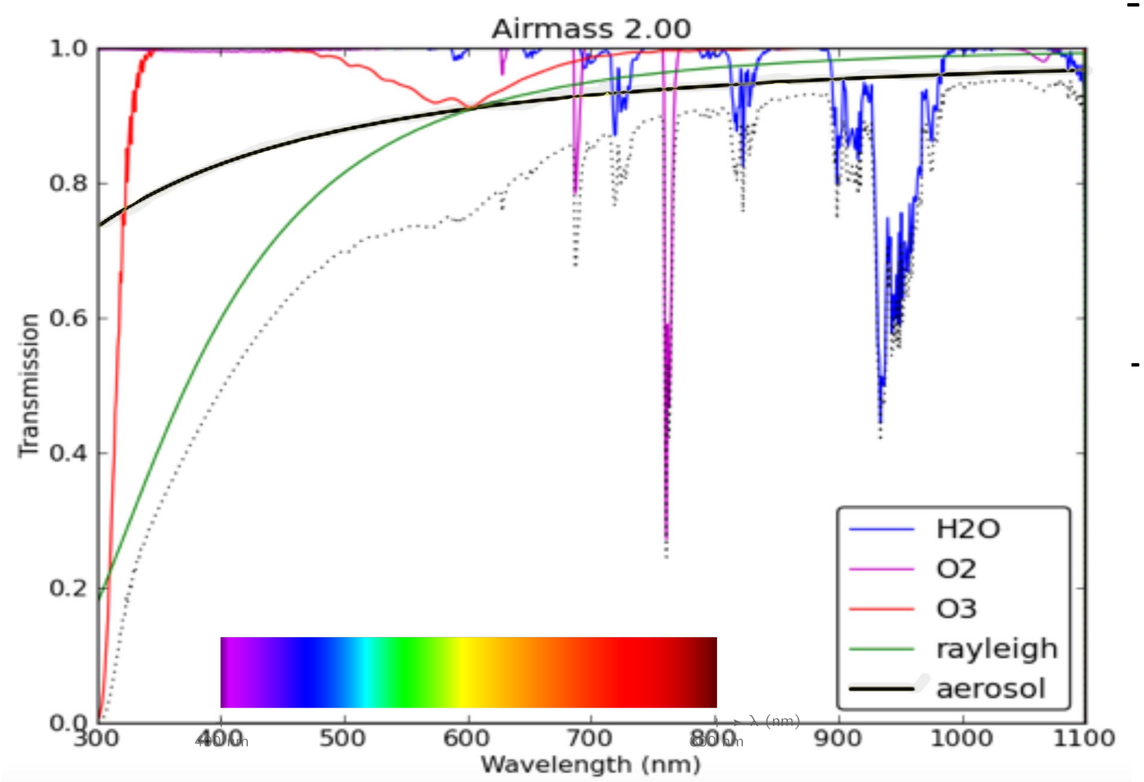
Phase delay profile of holographic grating



UV transmissions measured on sky (Bouguer lines): in progress

Variability of the atmospheric transmission

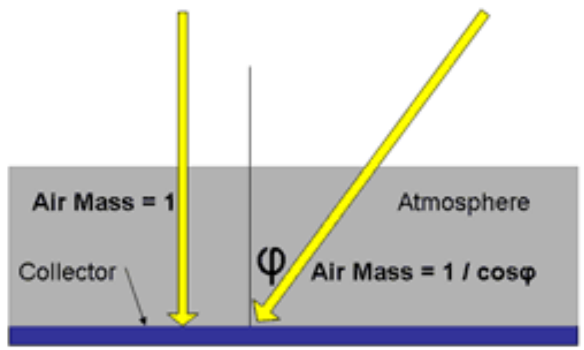
(Stubbs et al. PASP, 119: 1163–1178, 2007)



- **Photometrists** use photometric quality nights and narrow band filters
  - *No cloud*
  - *Low humidity*
  - *Low aerosols*
- **LSST** wants to **use all nights** with **wide band** filters
  - *Few clouds (grey absorption)*
  - *Humidity (affects I & Z)*
  - *Aerosol (affects U & G)*

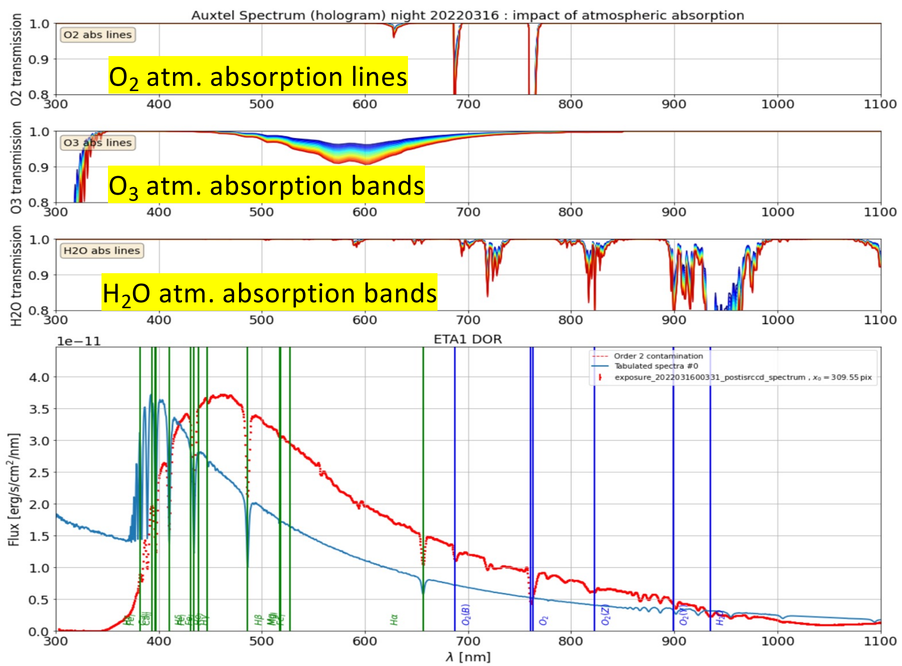
After correcting for Airmass:

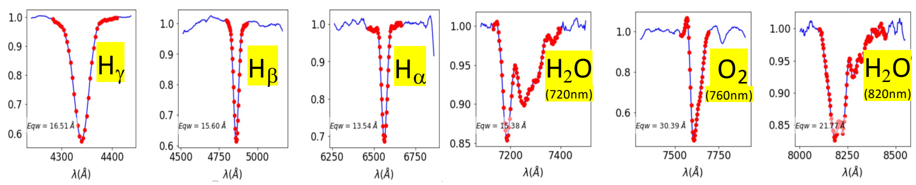
- O_2, O_3, rayleigh can be extracted
- Then determine H_2O and aerosol

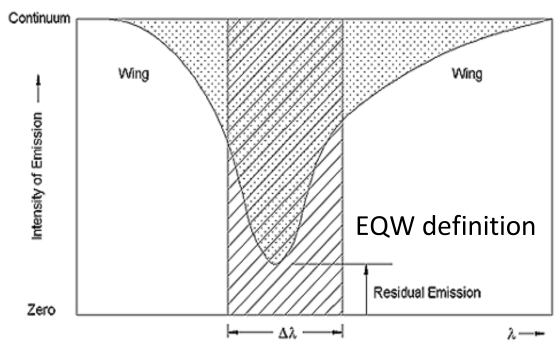


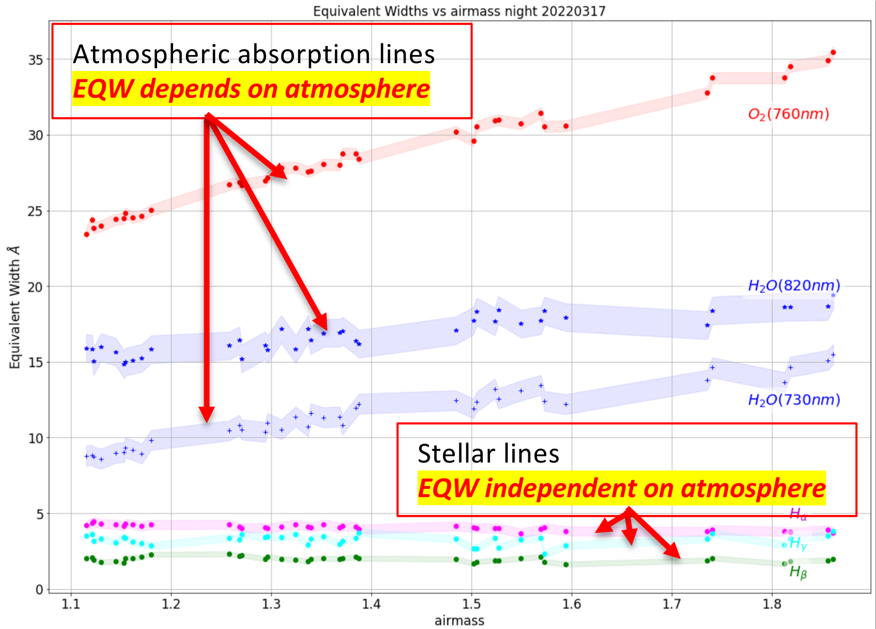
Energy Absorption by the Atmosphere

Auxtel : First estimates of atmospheric parameters

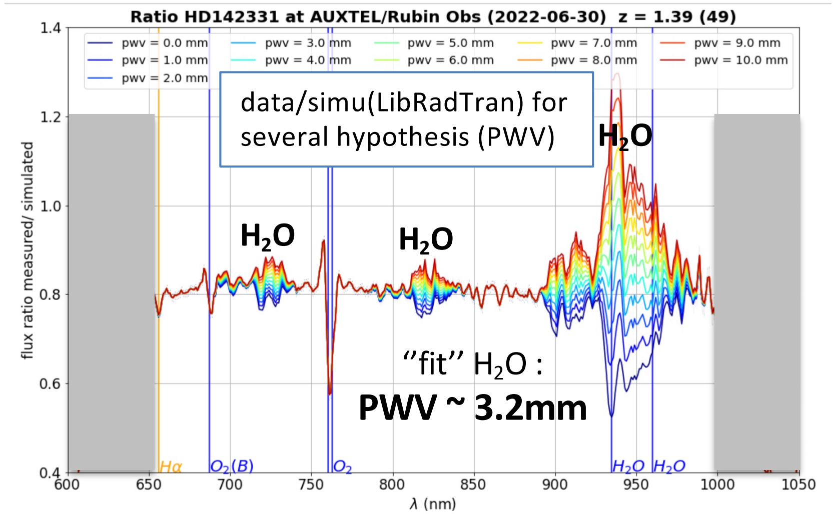








Variation of EQW for atmospheric lines illustrates sensitivity to atmospheric parameters (EQW)



Atmospheric studies

Objective of the AuxTel calibration:

Estimate colour corrections to vector $(\mathbf{UGRIZY})_{LSST}$ for each object, as a function of

- the atmospheric parameters **(airmass, PWV, τ_{VAOD})** -> the baseline
- or the directly measured atmospheric transmission function **$T_{atm}(\lambda$, RA, Dec)** synchroneously within the LSST field

What are the orders of magnitude of the corrections ?

From simulation: atmospheric fluctuations induce typically less than **10mmag** (max. ~30mmag @ airmass=2 for cold stars) residual colour variations per airmass after removing grey common absorption

-> Correction precision $\boldsymbol{\delta}$**C** needs to be such that:

0.010 x δC < wanted resolution

i.e. **δC=50%** for 5mmag / **10%** for 1mmag

Characterizing the AuxTel throughput with Bouguer lines

to measure separately order1 and order 2 transmissions versus λ

Spectrum extraction software (SpecTractor) needs the **global throughput** of the system **for each diffraction order** p:

$$T_p(\lambda) = \tau(\lambda)_{telescope} \cdot \tau_p(\lambda)_{disperser} \cdot \varepsilon_{CCD}(\lambda)$$

-> Obtained by the ratio of instrumental out-of-atmosphere flux to HST reference flux (as a function of λ)

If constant atmospheric conditions, instrumental magnitude@λ follows a Bouguer line in airmass z:

$$m_p(\lambda,z)_{instrumental} = m(\lambda)_{SED\text{-}HST} + A_{atm}(\lambda) \cdot z + 2.5.\mathrm{Log}[T_p(\lambda)]$$

At a given λ, extrapolating the line from the series of $m_p(\lambda,z)_{instrumental}$ to z=0 airmass gives out-of-atmosphere instrumental magnitude and allows to deduce the throughput from:

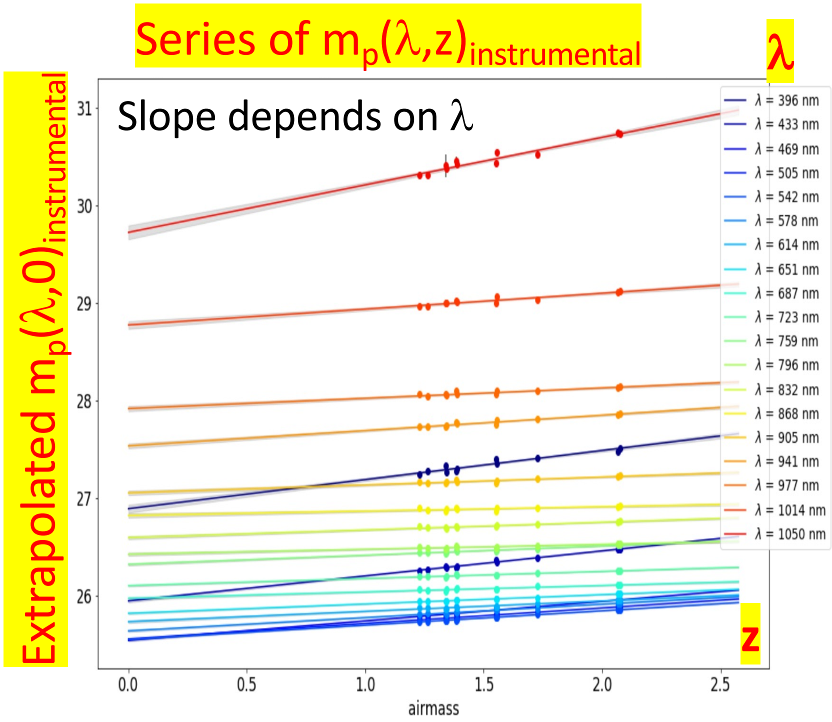
$$m_p(\lambda,0)_{instrumental} = m(\lambda)_{SED\text{-}HST} + 2.5.\mathrm{Log}[T_p(\lambda)]$$

Requirements

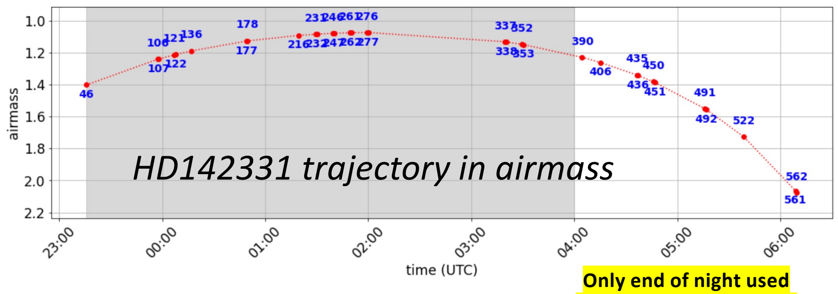
-> (at least) one photometric night (*i.e.* stable atmosphere) to obtain long series of spectra.

-> The **same star** needs to be measured during the **same night** in the widest airmass domain.

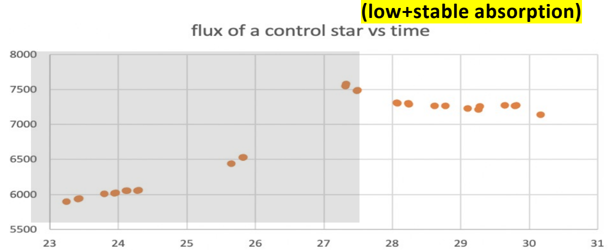
-> large # of measurements allows better determination of the slopes and of z=0 extrapolation.



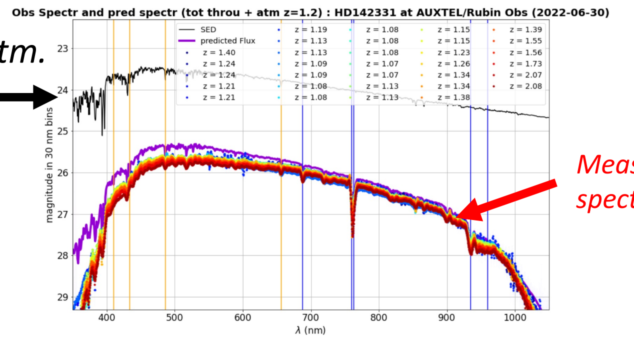
Measurement of Bouguer lines



Only end of night used (low+stable absorption)

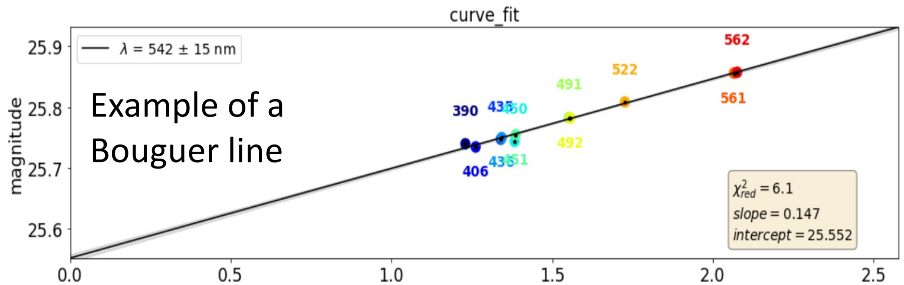


Out of atm. SED

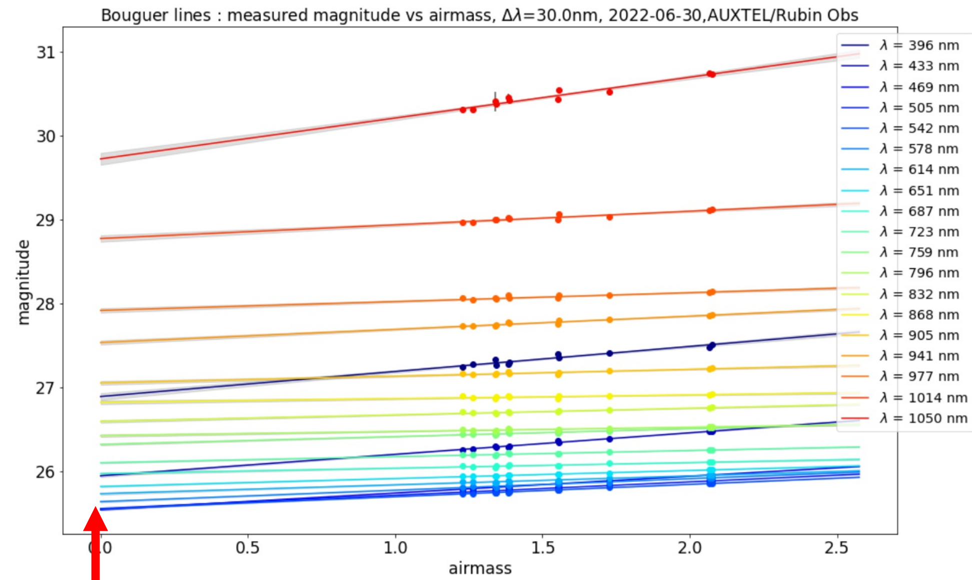


Measured spectra

Spectra integrated in bins of 30 nm width

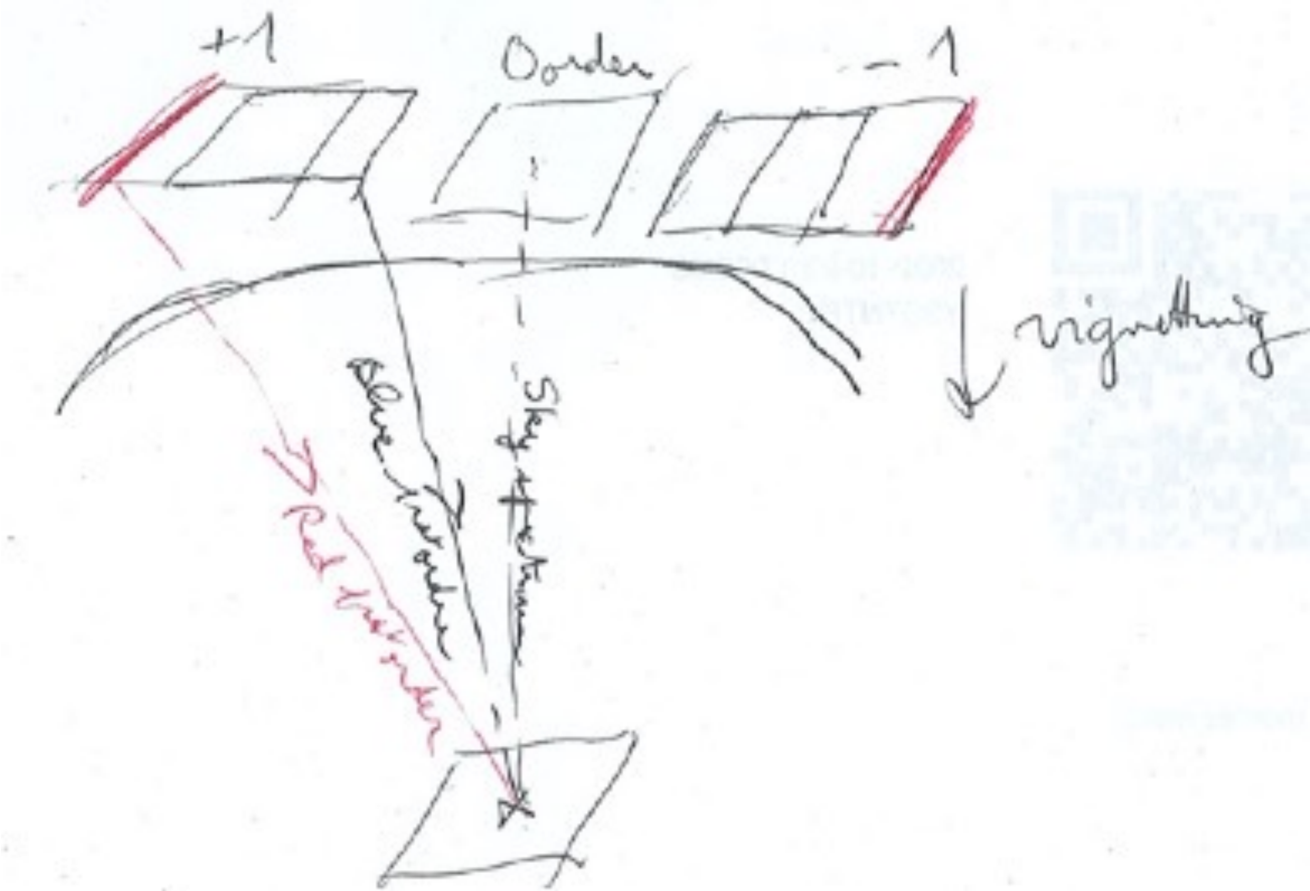


Instrumental magnitude vs airmass



Extrapolated out of atmosphere instrumental magnitudes in narrow [30nm] bandwidth

Sky background has spectrum depending on the position on CCD



Factorization of the wavelength dependence

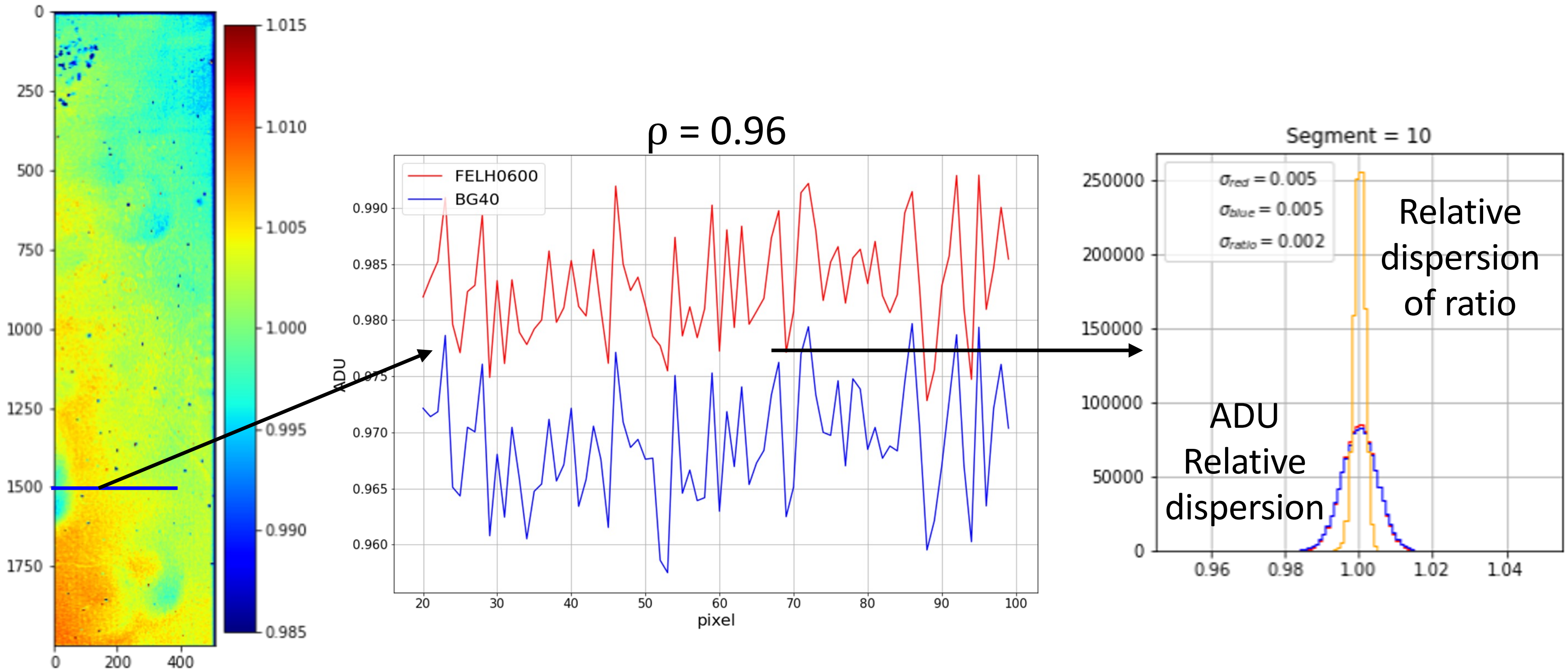
Idea:

- Evaluate spatial correlation between flats with different filters

$$ADU(i,j,\lambda) = F_{o.f.}(i,j) \times F_{CCD}(i,j,\lambda) = F_{o.f.}(i,j) \times G_{CCD}(i,j) \times \varepsilon_{CCD}(\lambda)$$

- See if can factorize out the wavelength dependency on the flats:
  - $F_{o.f.}(i,j)$ = **out of focus artifacts** (vignetting, dust on optical components) = **slow** pixel to pixel variation (real space) or **low** spatial frequency (Fourier space)
  - $F_{CCD}(i,j,\lambda)$ = **focused artifacts** (dust on the CCD, pixel surface variations) = **fast** pixel to pixel variation or **high** spatial frequency
  - We examine the **hypothesis** of $F_{CCD}(i,j,\lambda) = G_{CCD}(i,j) \times \varepsilon_{CCD}(\lambda)$
- If ~ true, then we could preliminary use a single flat for spectra reduction
- How can we test this?
  - By examining the **ratio** of flat images **at different wavelengths (with different filters)**

Factorization of the wavelength dependence: pixel correlation



Establishing correction procedures

- *We did predictions from simulations, based on parametrization with (z, PWV, VAOD). But O_3 , O_2 and cloud absorption (grey) can also be parameters.*
- The methods have to be systematically checked for every atmospheric situation:
  - Predictability of the correction in (airmass, azimuth)
  - Needs observation of CALSPEC standards through entire nights (to estimate atm. parameters) AND various fields in (airmass, azimuth) containing standards to test the prediction. « ronde des standards ».
- **Alternative**: directly measure atm. transmission in the same direction than LSST, using secondary spectrophotometric standards measured out of atmosphere by GAIA.
  We checked that spectra of stars as faint as **M=10** are measurable in 30s with s/b>100