AuxTel hologram analysis

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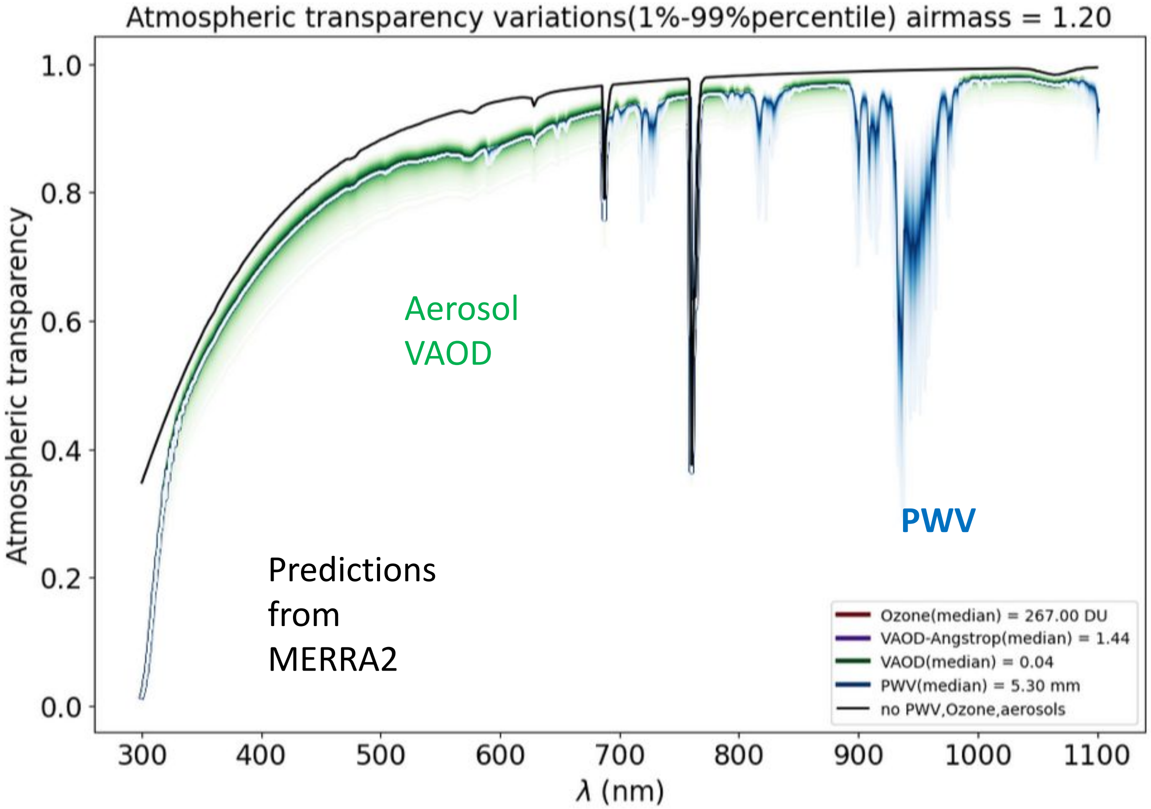
Atmospheric parameters overview



Two main components contribute to atmospheric transparency fluctuations

Important fluctuations:

- **Precipitable water vapor (PWV)**
- **Aerosol VAOD**

Fairly stable:

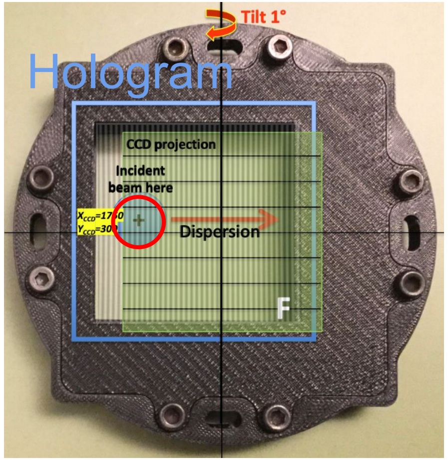
- Ozone
- Aerosol Angstrom parameters

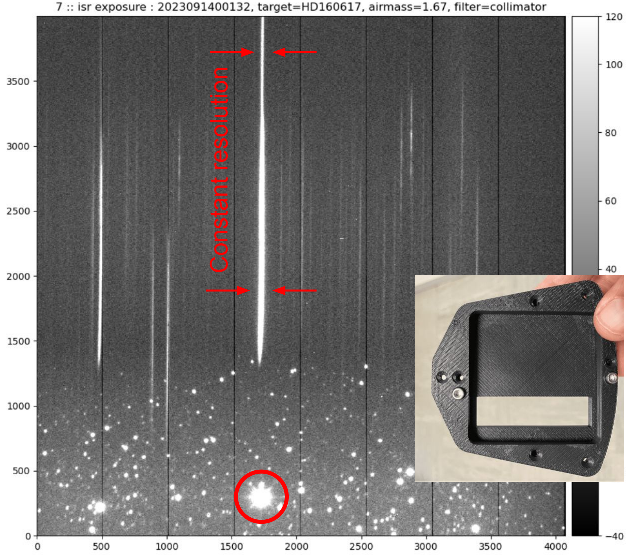
Hologram characteristics

Dispersive element tuned to get a nearly perfectly focused spectrum on the AuxTel plane CCD

- Advantages:
  - spectral separation power is nearly identical from 350 to 1100nm, only limited by seeing
  - 33% maximum transmission (min. 12%)
- Constraints: disperser is not invariant in translation
  - target must be at a specific place (red circle)
  - transmission varies slowly with position
  - superimposition of diffraction orders

Addition of a mask in 2023/10 to eliminate field stars and background





Hologram data analysis

Spectractor: forward model of the spectrogram.

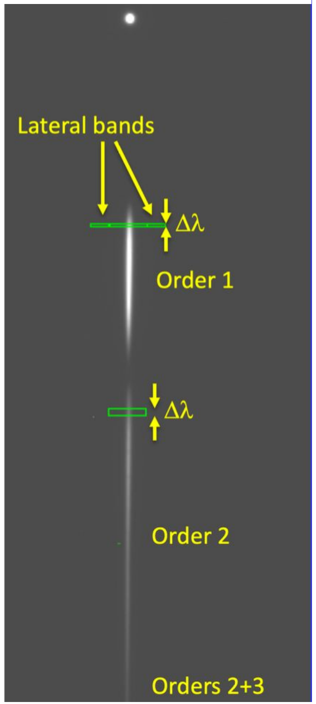
Ingredients for extraction:

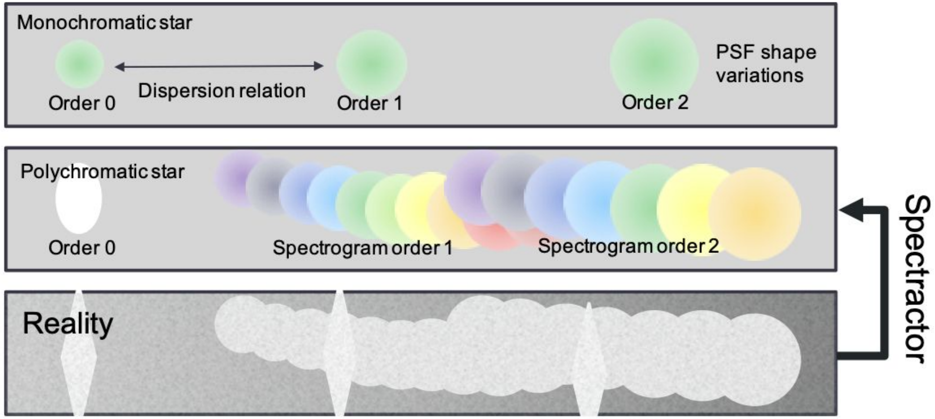
- Dispersion relation: spectrograph and atmospheric refraction model
- PSF(λ): circular Moffat with wavelength dependent parameters (2nd order polynomes) (to be improved)
- Ratio 2/1 extracted from data
- Dedicated spectro flats to avoid steps between amplifiers

Ingredients for atmospheric interpretation

- AuxTel throughput from data using photometric night model
- Use reference star catalogs * throughput * Libradtran to fit atmospheric parameters

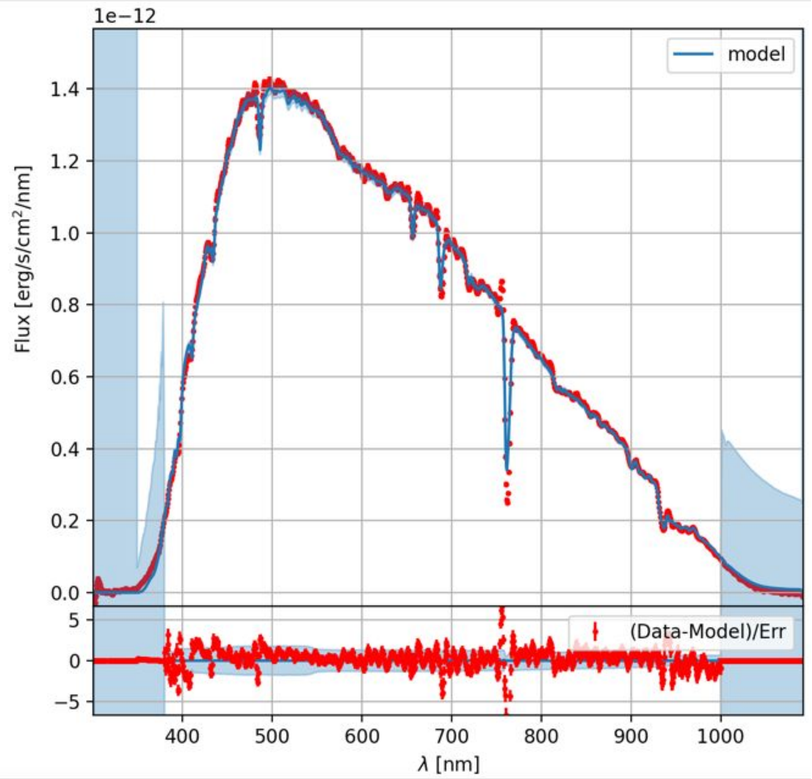
Ratio 2/1 extraction





Spectrum

Polar star HD185975



Overview of the hologram dataset

- Main strategy in 2023-2025: 3 nights every two weeks from sunset to 2am
- Targets: CALSPEC and Gaia stars
- Alternance hologram / quadnotch
- Pairs of exposures (one pair every ~5min)
- Atmospheric refraction orthogonal to spectrograph dispersion to separate diffraction orders
- From 2023/01:
  - #exposures=7758
  - #spectra=6201
  - #good spectra=3240 (depends on the quality cuts)
- Improvement since 2023/10 and then further with dome painting
- Some nights with blocking filters (red or blue)

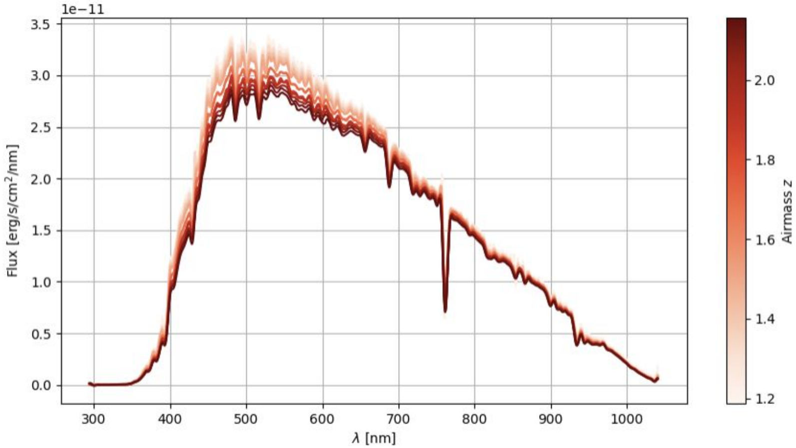
Emphasis on a key ingredient: AuxTel throughput

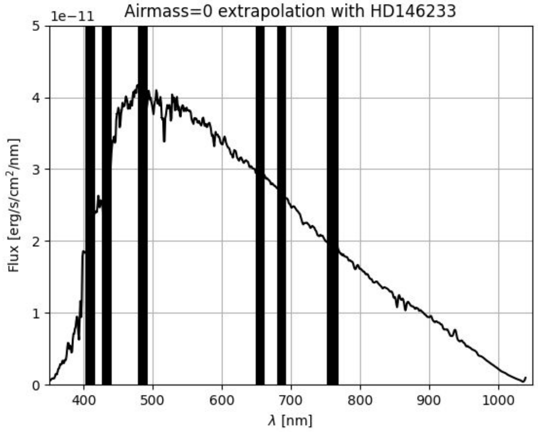
Determined with on-sky data using a photometric night model :

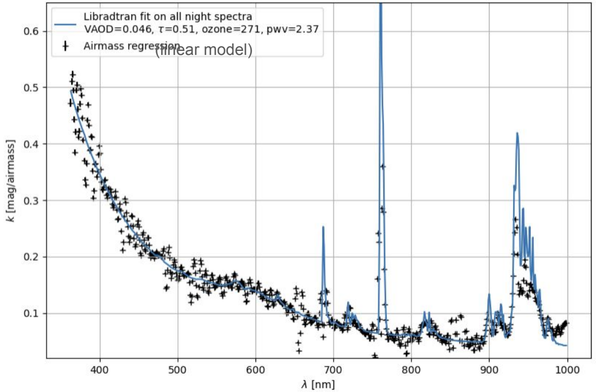
flux(λ) = atm(λ, params, airmass) * ZP(λ, airmass=0)

$ZP(\lambda) = T_{AuxTel}(\lambda) * SED(\lambda)$

Data with HD146233 2023/08/02 (stable)





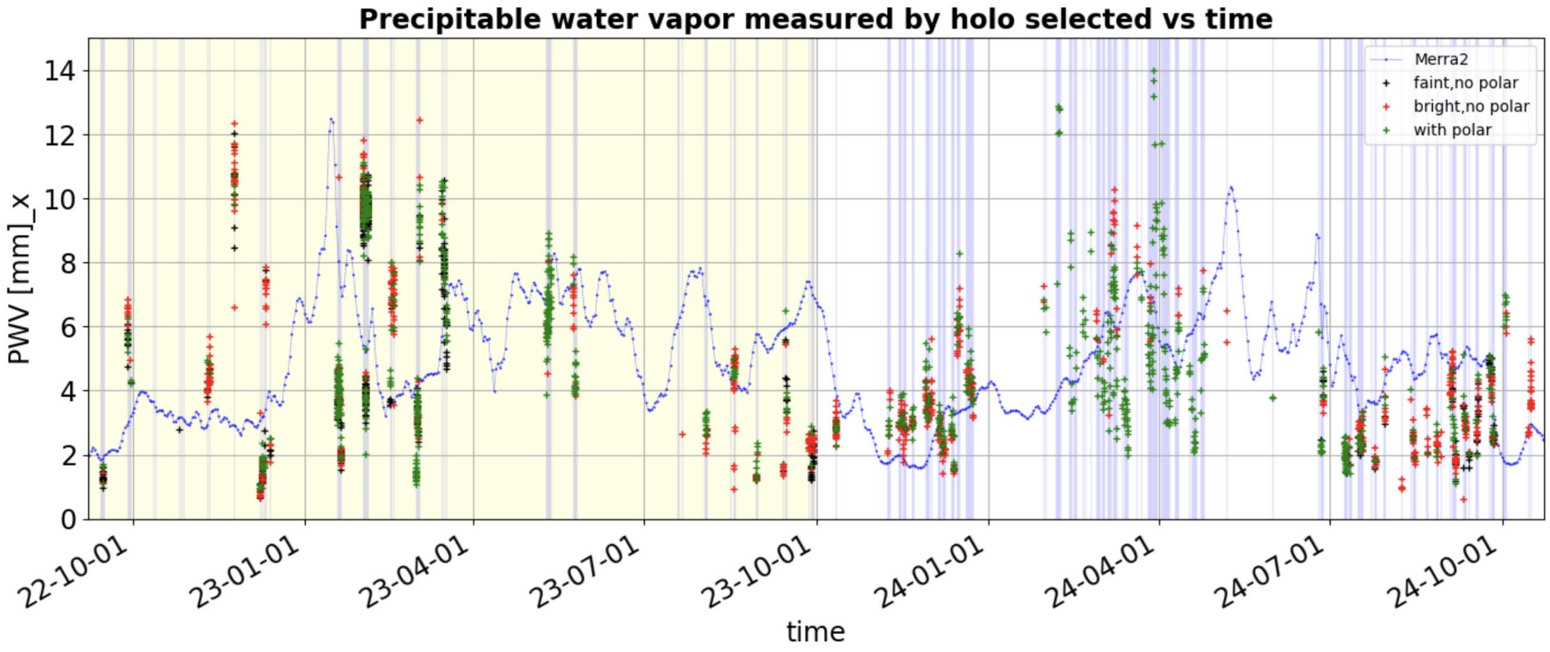


Errors on ZP induce atmospheric parameter offsets

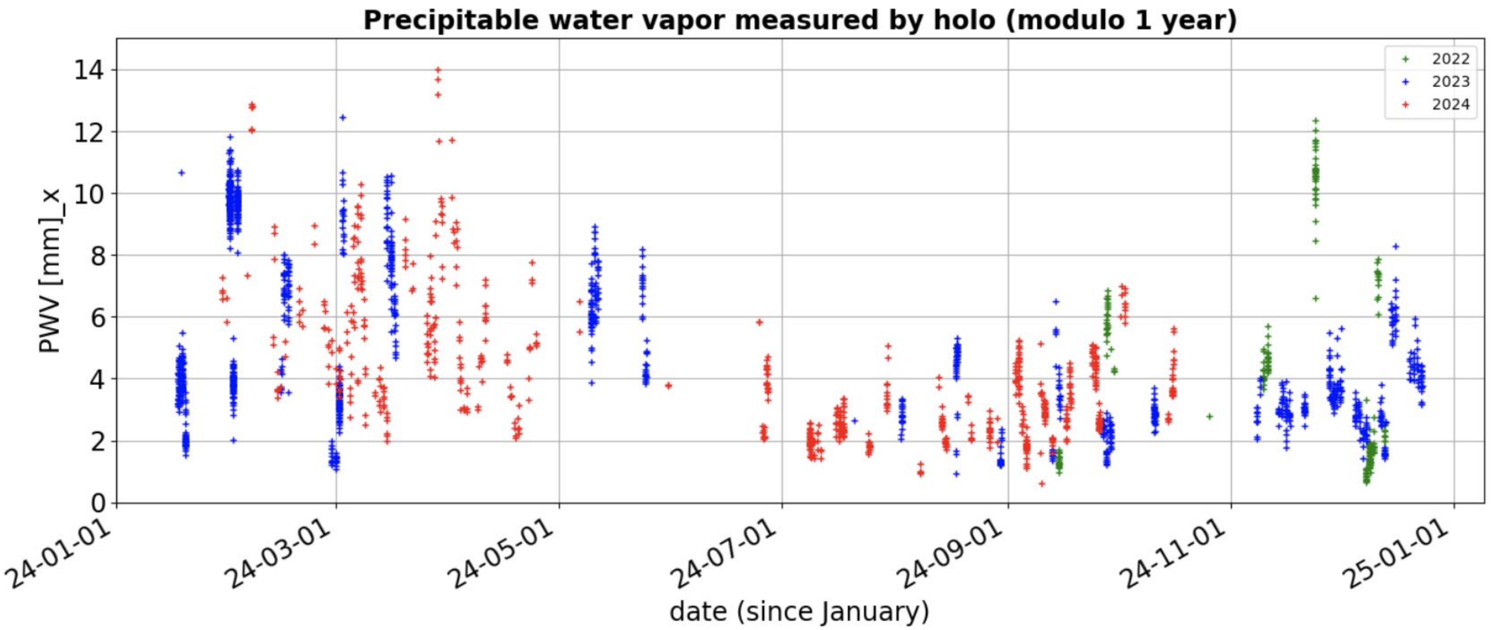
Given T = (ZP / CALSPEC SED) or T = (ZP / Gaia SED), then we can interpret all our spectra in real time

PWV overview

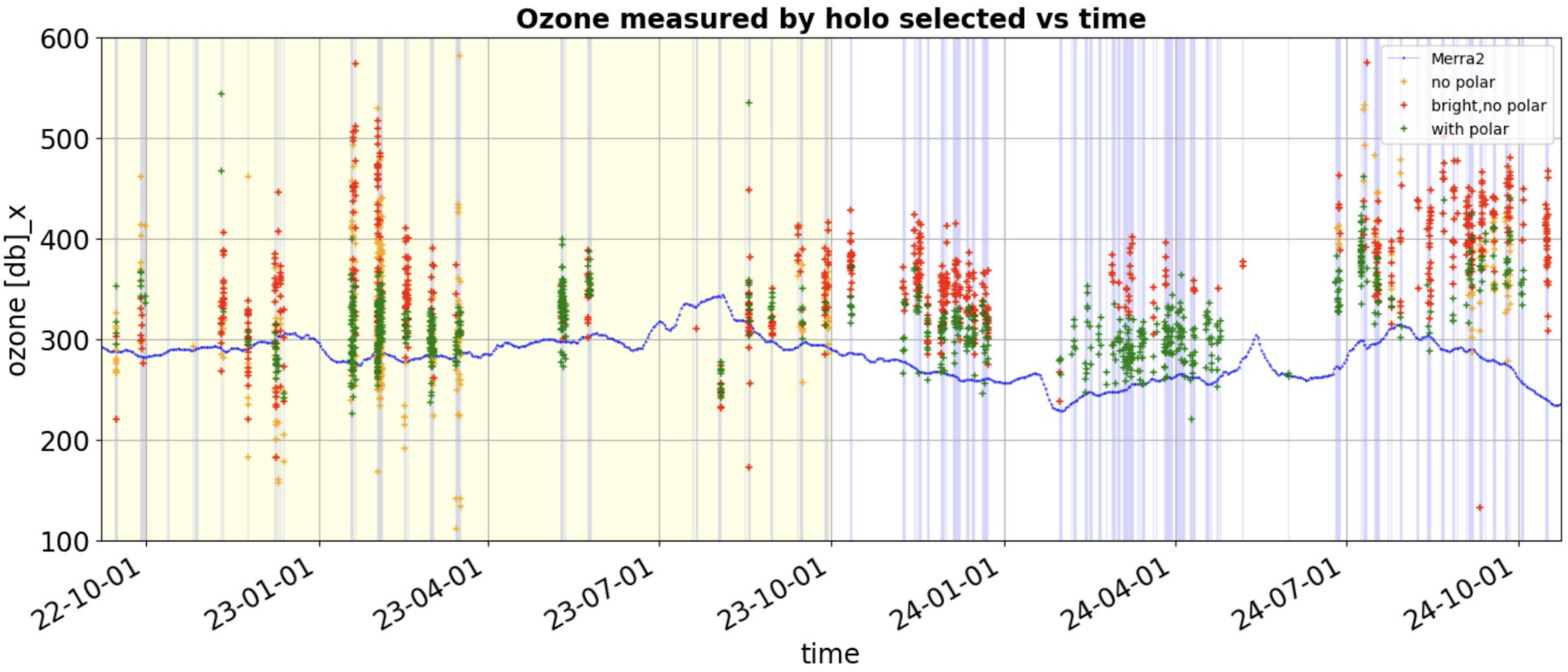
```
Total number of Spectra                :  5919
Number of selected Spectra             :  2180
Number of selected Polars              :  923
Number of selected Non-Polars          :  1257
Number of selected Non-Polars Bright :  820
Number of selected Non-Polars Faint  :  437
```



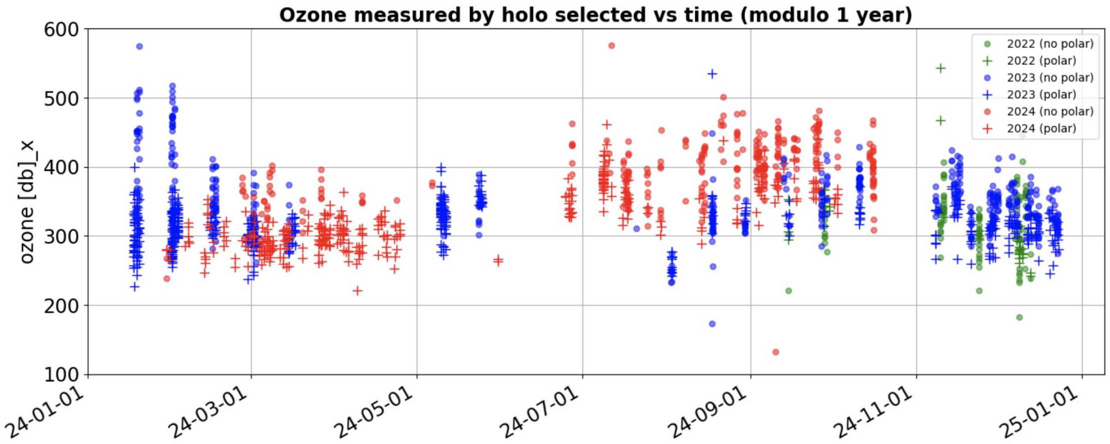
PWV overview

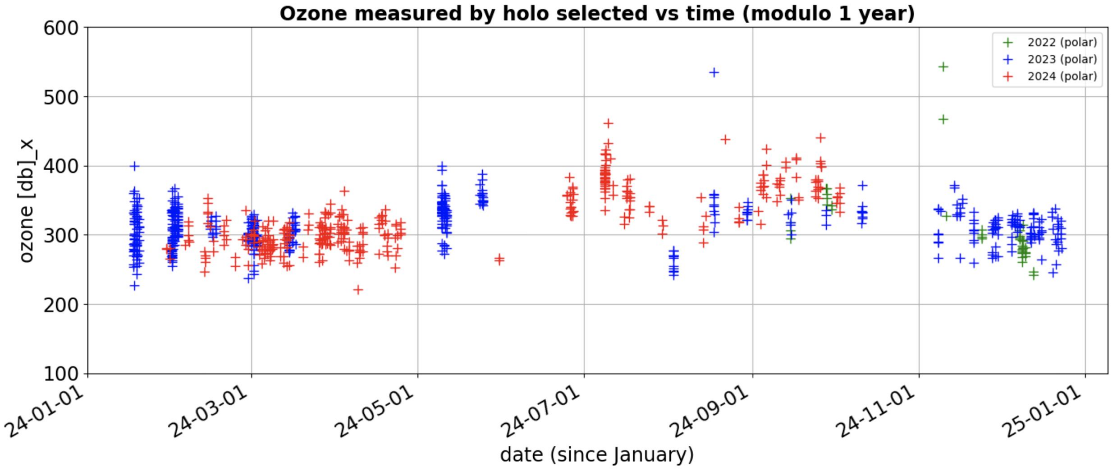


Ozone overview

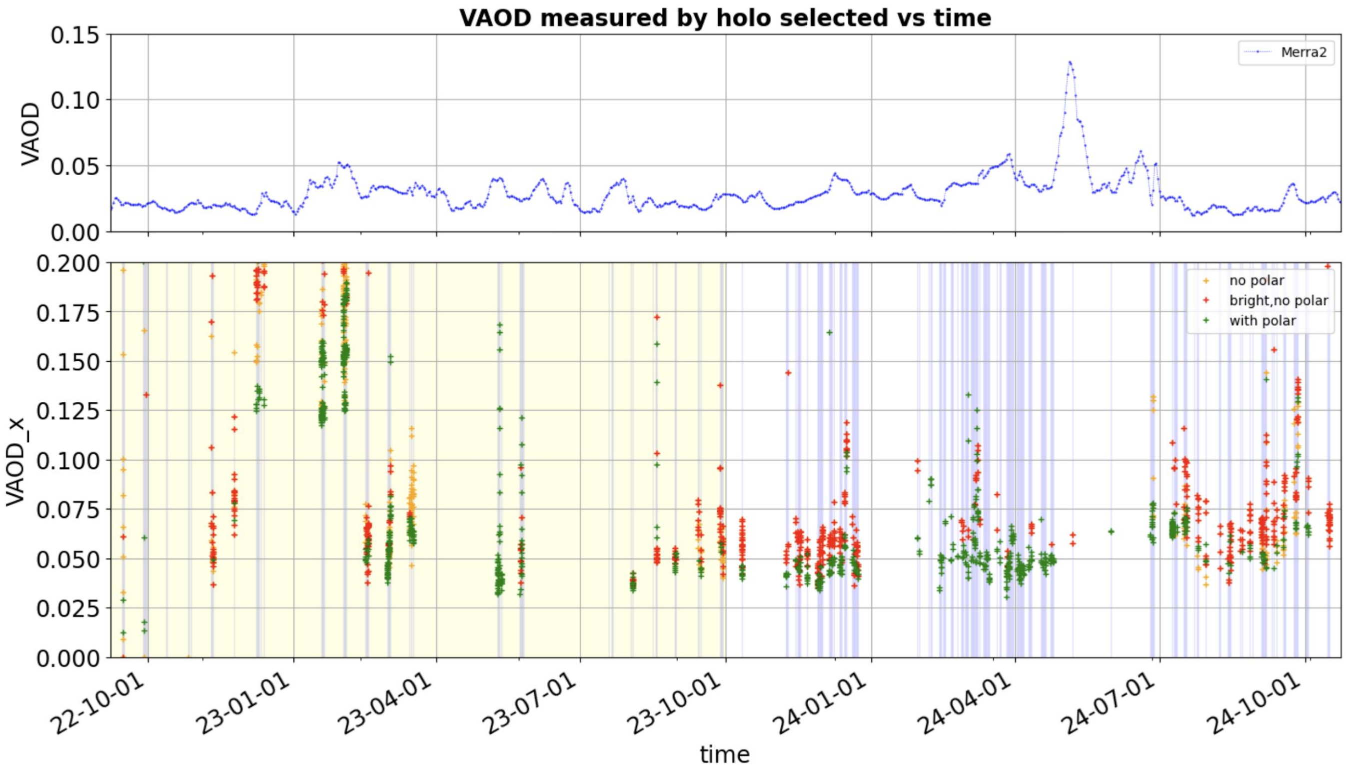


Ozone overview



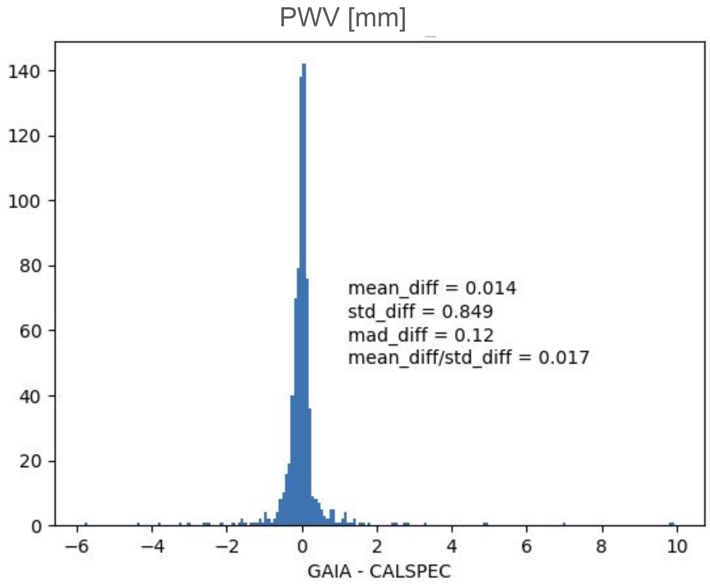


VAOD overview

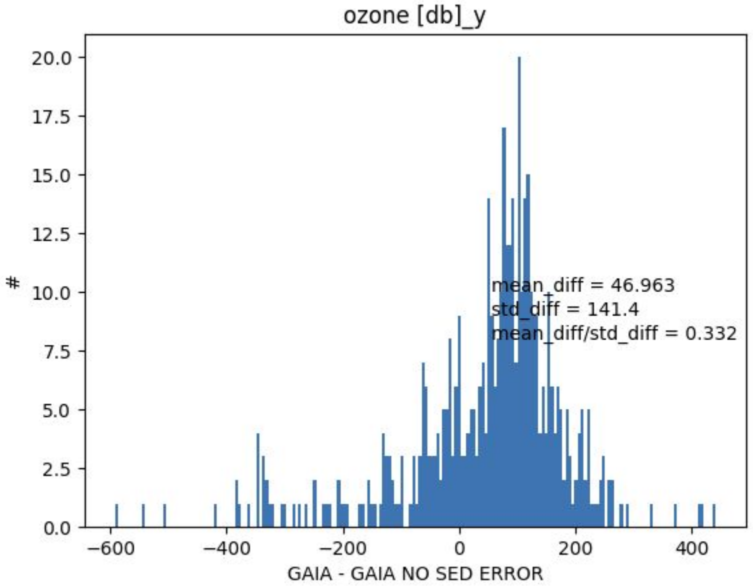


Impact of using CALSPEC of Gaia spectra

Nearly no impact on water measurement



Strong 100DU shift

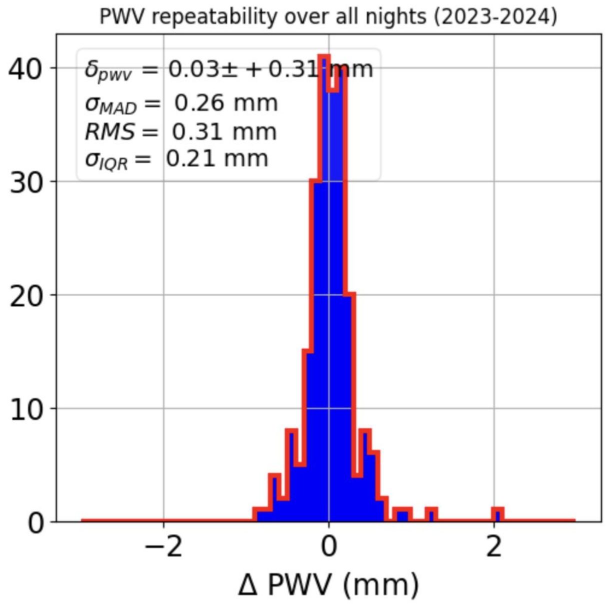


because here we used the AuxTel throughput determined with CALSPEC spectrum instead of Gaia

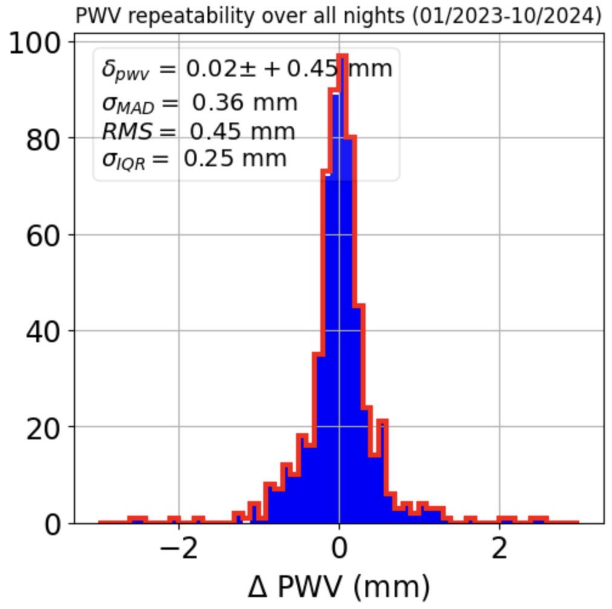
Repeatability test on PWV

PWV difference for pairs of subsequent observations within Δt less than 2 minutes

With mask



Without mask



- Repeatability improved after 2023/10
- Different estimators of spread because of distribution tails

Keep in mind:
- **RMS = 0.31mm**

Minimal accuracy:
- **0.31DU/sqrt(2)=0.22mm**

Blue : same target pairs

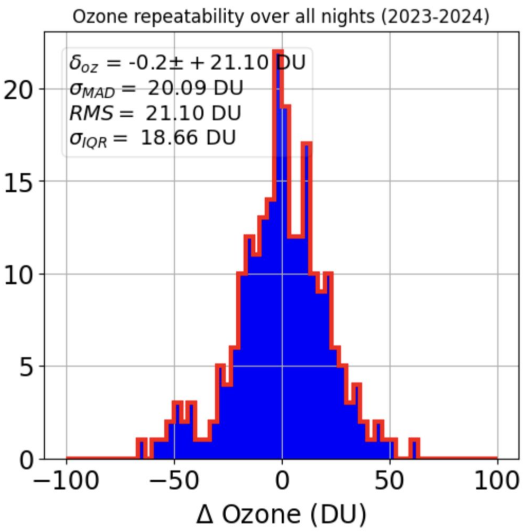
Red : any target pairs

Statistics accumulated over all nights

Repeatability test on ozone

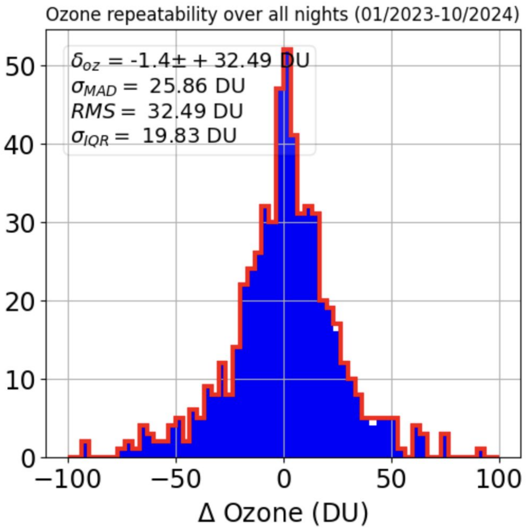
Ozone difference for pairs of subsequent observations within Δt less than 2 minutes

With collimator



Blue : same target pairs
Red : any target pairs

All data with and without collimator



Statistics accumulated over all nights

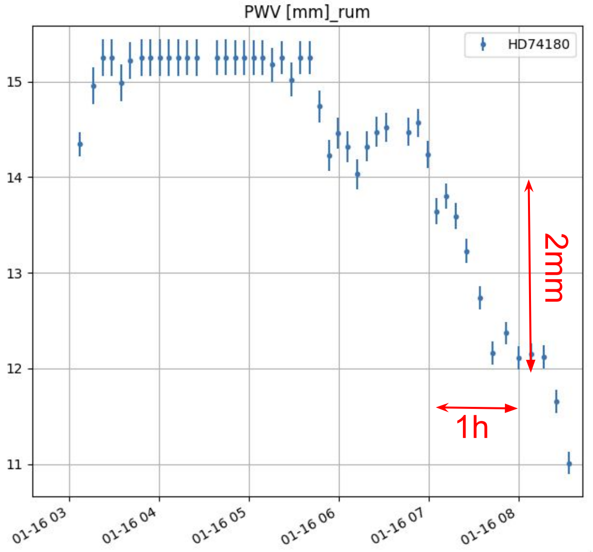
- Repeatability improved after 2023/10

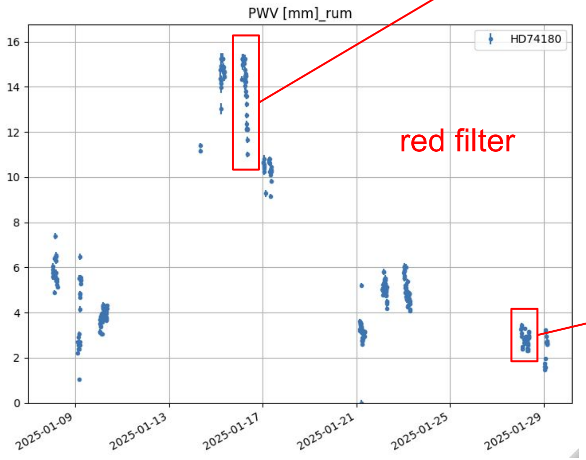
Keep in mind:
- **RMS = 21 DU**

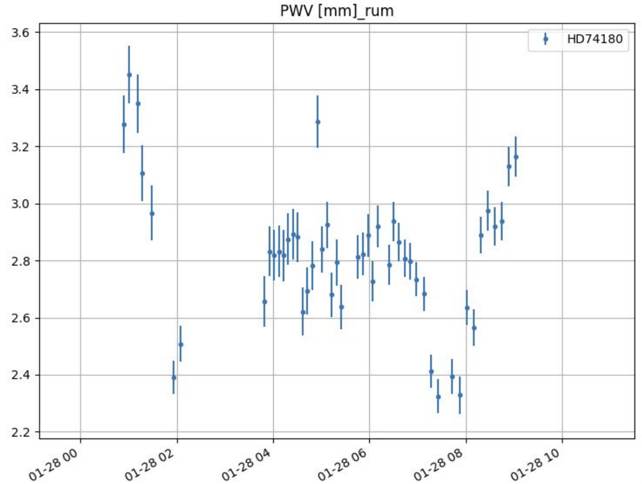
Minimal accuracy:
- **21DU/sqrt(2)=15 DU**

PWV variation time scales

- Month scale: 15mm variations during Chilean summer
- Week scale: ~5mm variations
- Night scale: ~2mm variations (sometimes more, sometimes less), often not polynomial in time
- Hour scale: 0 to 2mm variation per hour
- 5min scale: up to 0.5mm but hard to be affirmative because…
- 30s<dt<5min: not available
- 30sec scale: 0.3mm RMS estimated with exposure pairs

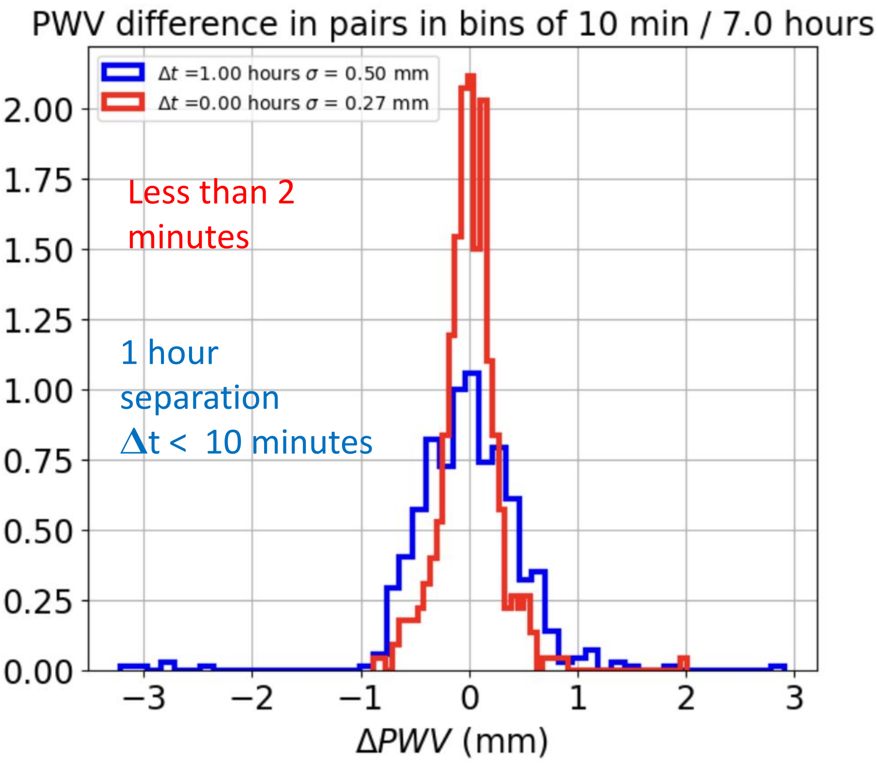






PWV variation distribution for short and larger time separation

- From 2023/10:



How PWV differences broaden as time increases ?

- On average no drift in ΔPWV but for many nights we measure a 0.5mm variation
- The broadening of this distribution indicate the uncertainty

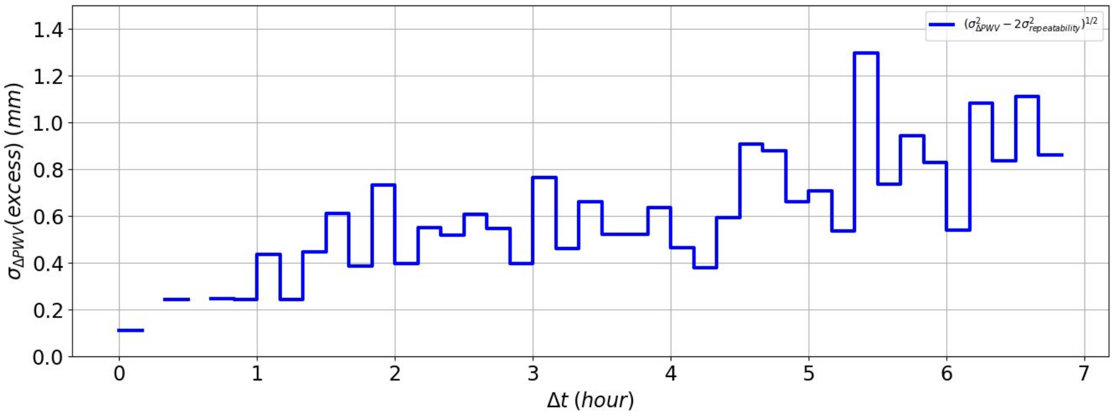
If monitoring with sparse measurements:

- Here 0.2 mm in 1 hour (on average)

Statistics accumulated over all nights

Evolution of RMS with time separation

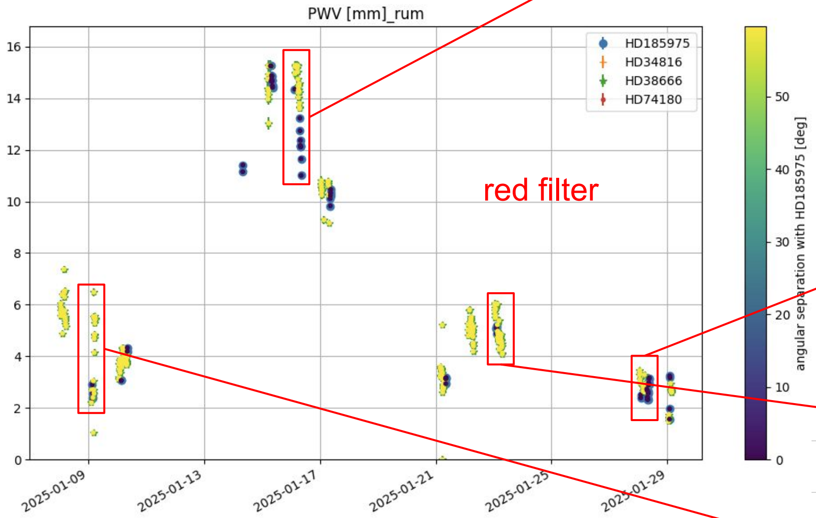
Statistics averaged over all nights from 2023/10

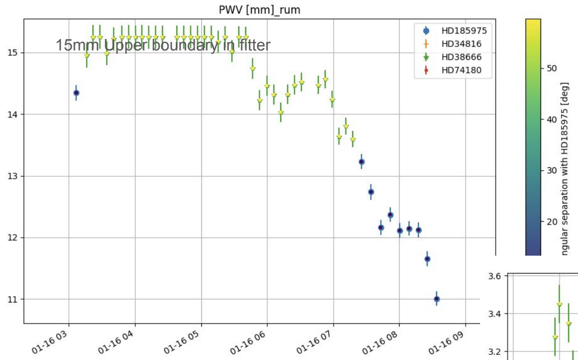


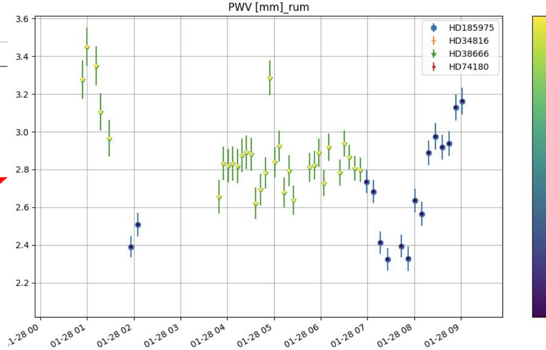
- **Evolution of the distribution RMS with time separation**
  - 1 hour : 0.3 mm
  - 2 hours : 0.5 mm
  - 5 hours : 0.7 mm

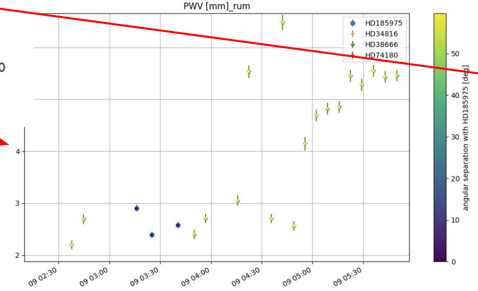
Spatial variations for PWV

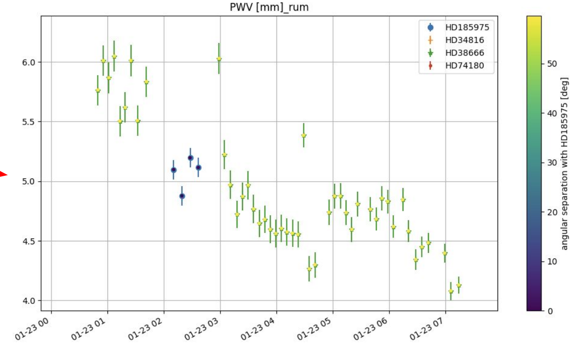
Sometimes we alternated between polar star HD18595 and others





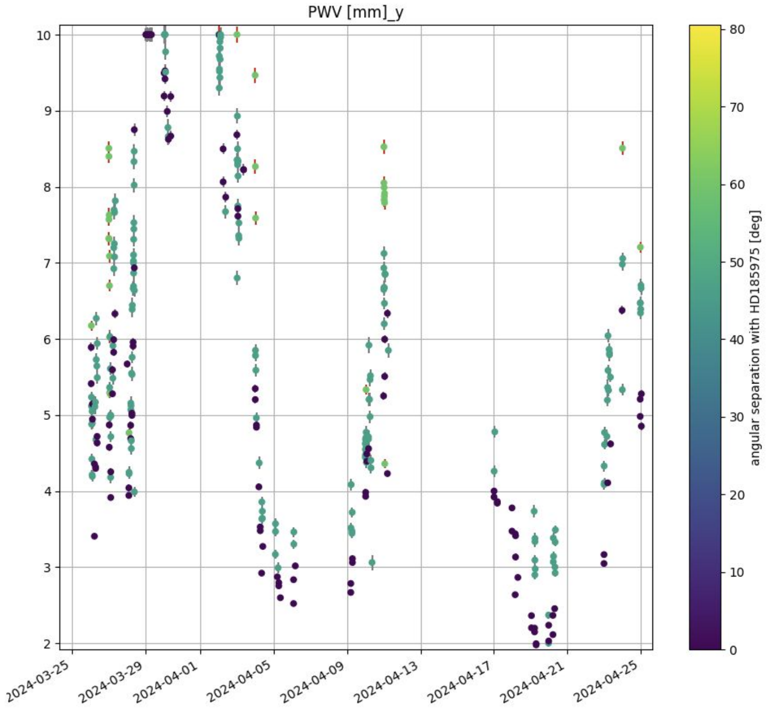




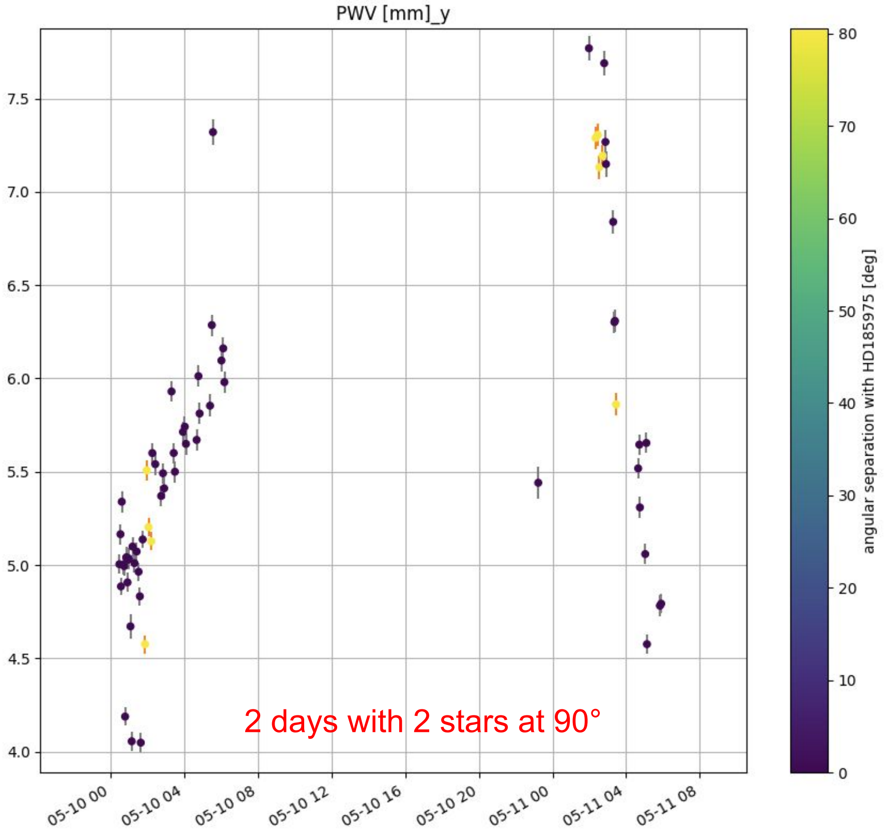


No indication for significant PWV spatial variations at <60° scale and dt~10min

Other examples

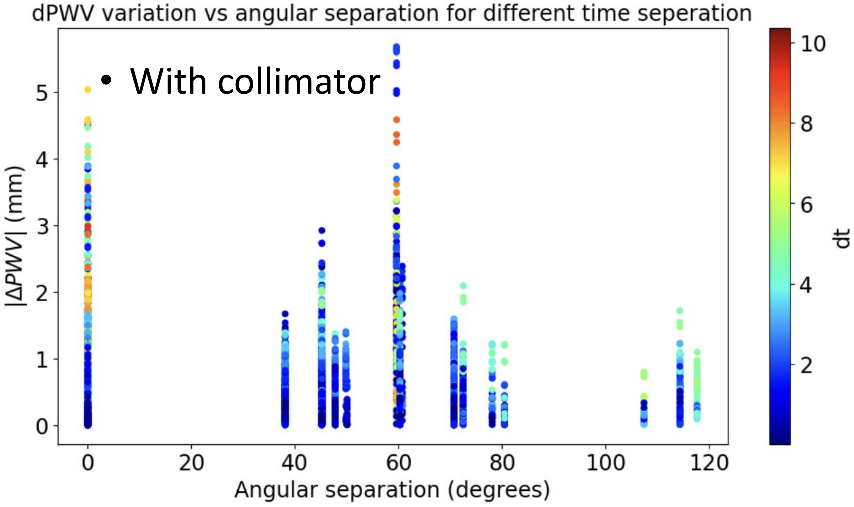


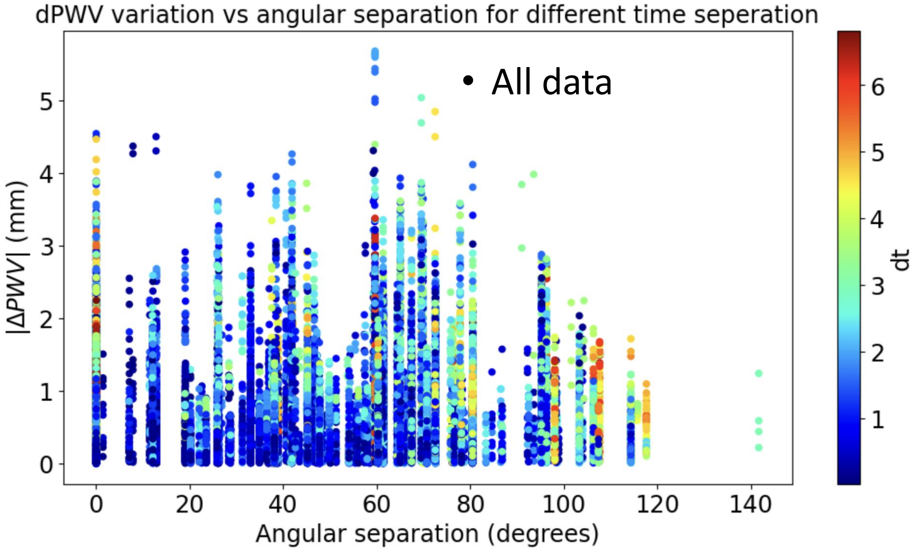
1 month with 3 stars



2 days with 2 stars at 90°

Impact of Angular Separation on ΔPWV

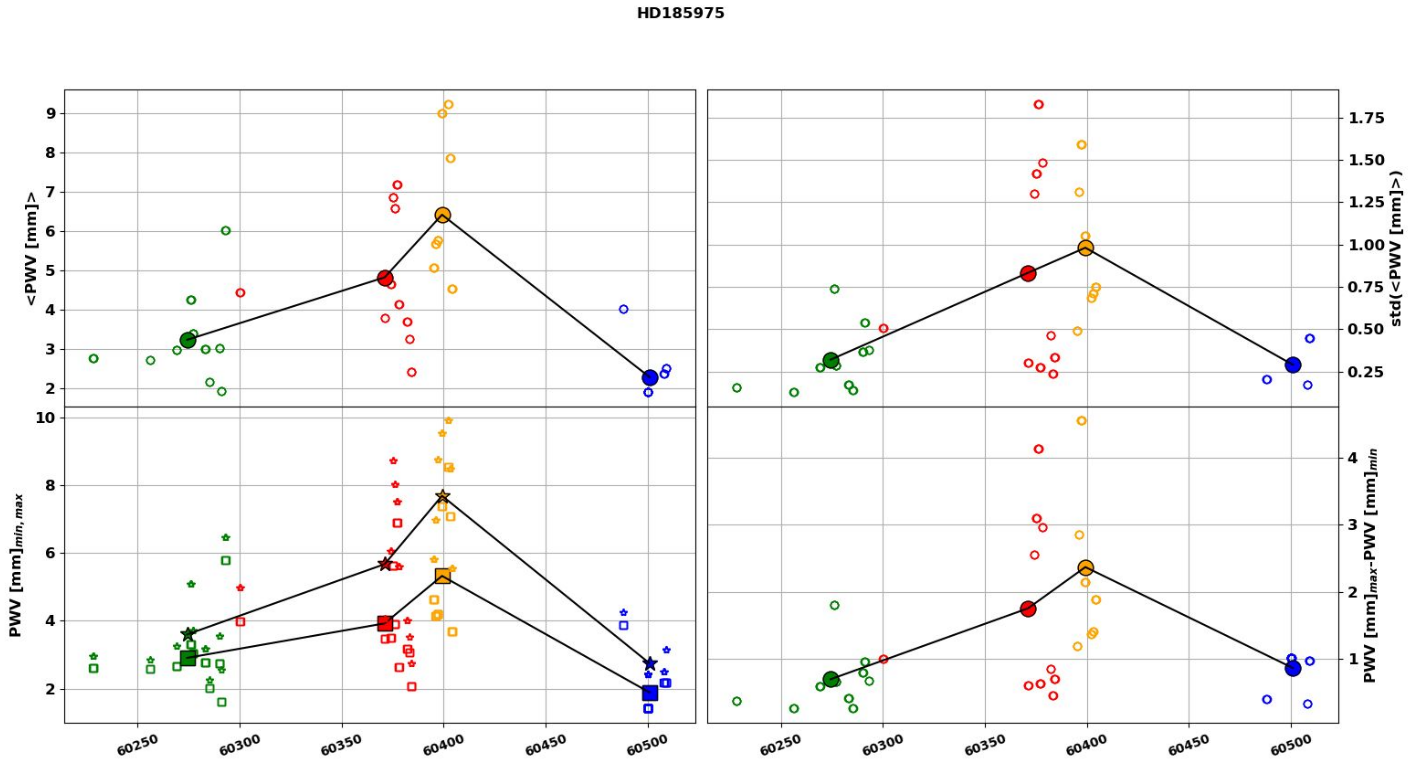




- **No significative effect of angular separation on ΔPWV**
- **Time separation has a stronger impact on ΔPWV**

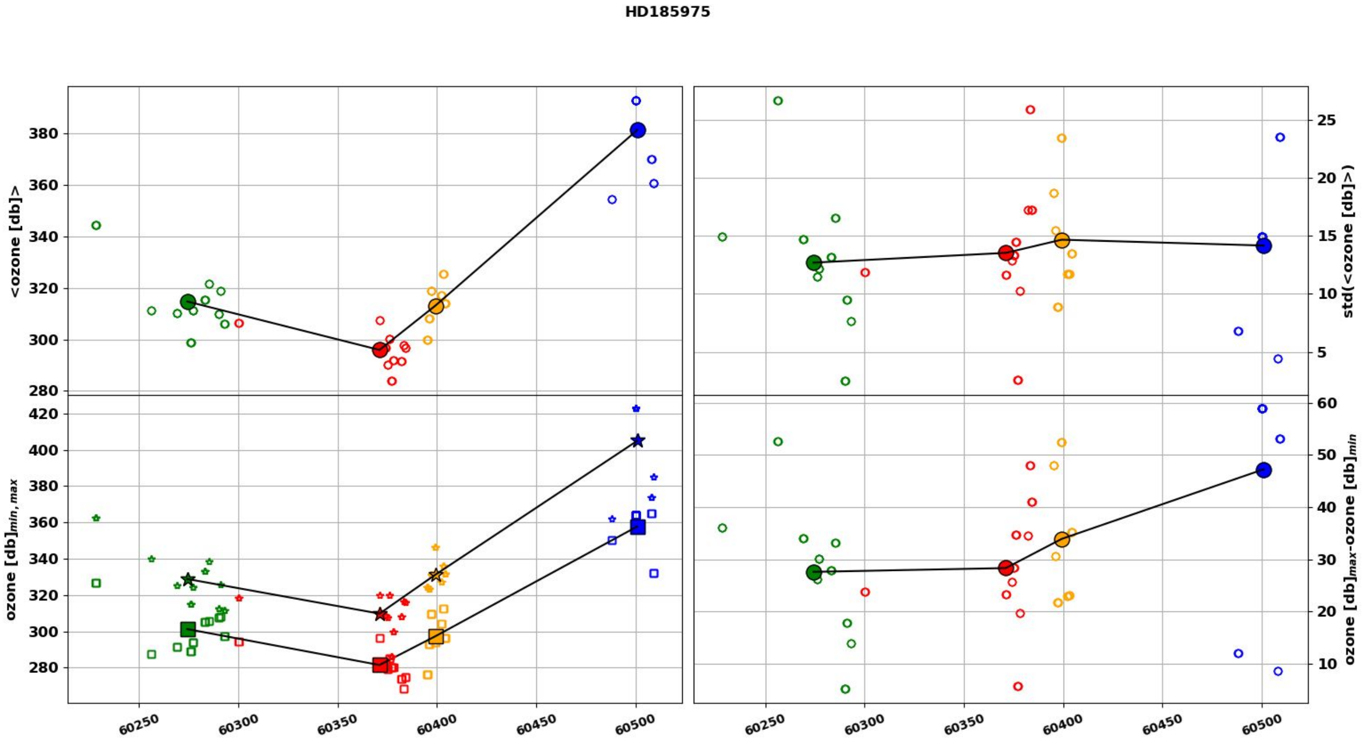
Seasonal effects - PWV (polar star HD185975)

green=spring
red = summer
orange=autumn
blue=winter



Seasonal effects - ozone (polar star HD185975)

green=spring
red = summer
orange=autumn
blue=winter



Seasonal effects

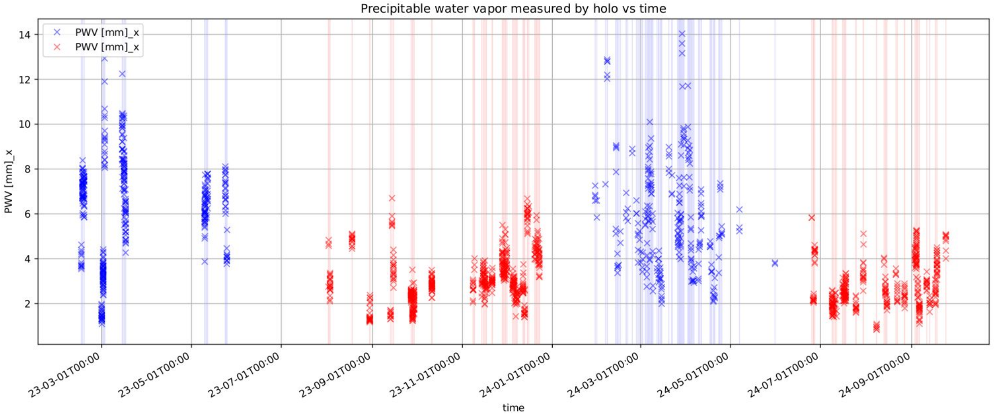
Atmospheric transmission :

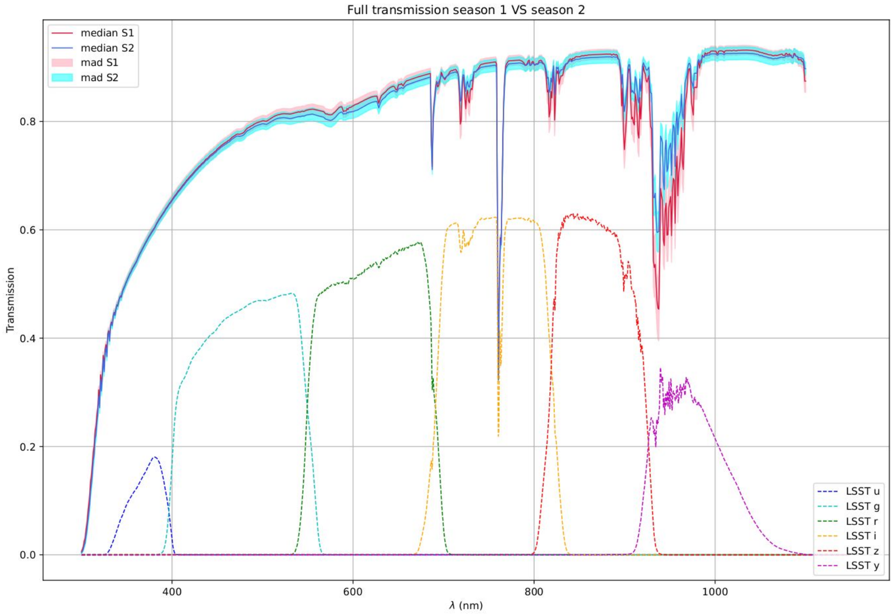
- **2 seasons** :
  S1 : 01/01 - 30/05 (~ summer+autumn)
  S2 : 01/06 - 31/12 (~ winter+spring)

- Transmission down to **~0.45** in **S1** in the y band (**~0.6** in **S2**)

Observed climatic effects :

- **Higher PWV in summer (S1)**, period of maximum rainfall in Chile (linked to the Amazon monsoon)
- **Higher ozone in winter (S2)**





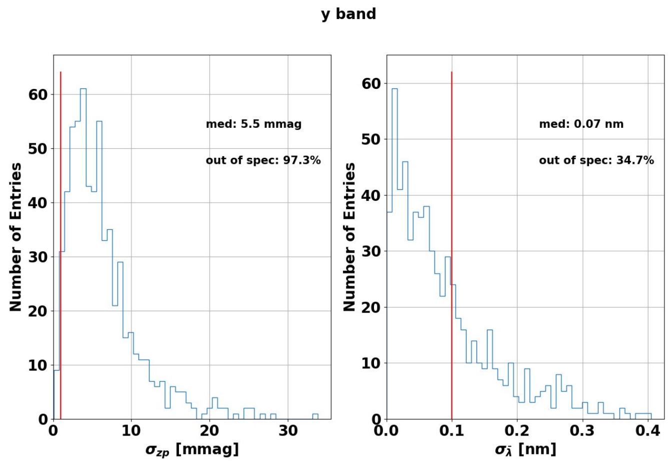
Impact of atmospheric parameters on σ_{zp} and σ_{λ} (LSST throughputs)

- For each observation: (airmass, $\Delta_{airmass}$, pwv, Δ_{pwv}, ozone, Δ_{ozone}, beta, Δ_{beta}, aerosol(VAOD),$\sigma_{aerosol}$ (σ_{VAOD})) -> estimated from pairs

- n random values:
  - param+gauss(0,σ_{param}=$\Delta_{param}/\sqrt{2}$)
  - -> n throughputs (no error on mirrors, lenses and filters)

- For each throughput using LSST throughputs:
  - zero-points estimation (for each band)
  - $$\bar{\lambda}_b = \frac{\int T_b(\lambda)\lambda d\lambda}{\int T_b(\lambda)d\lambda}$$

→ $\sigma^b_{zp}, \sigma^b_{\bar{\lambda}}$

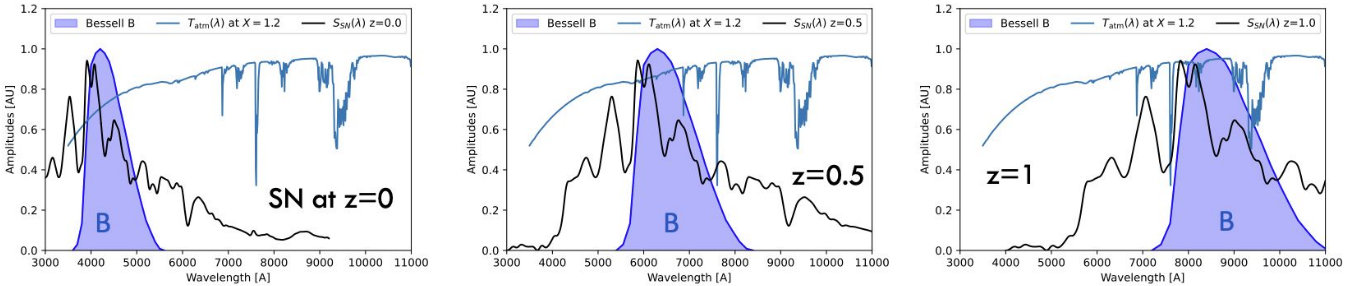


band	σ^{med}_{zp} [mmag]	σ^{med}_{λ} [nm]
u	3.3	0.006
g	2.5	0.024
r	3.3	0.019
i	2.9	0.006
z	3.3	0.012
y	5.4	0.067

Using AuxTel hologram for LSST catalog

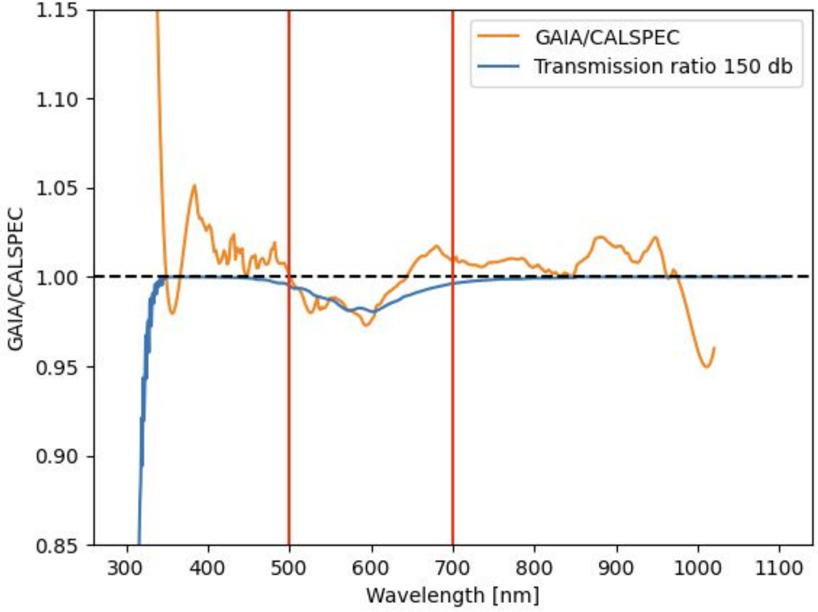
- Summary of atmospheric parameter features:
  - PWV real time measurement under control (up to a litlle offset if throughput is biased)
    - no clear spatial variations with <90° scale with respect to polar star
    - random temporal variations at ~hour scale, up to 2mm/hour
    - seasonal effect: mean and RMS change with season
  - Ozone: seasonal effect visible up to an offset (to be fixed with better throughput determination)
  - Aerosols: “gray” extinction clearly visible in real time but hard to say something about coloured variations
- Needs for a future AuxTel observing strategy after LSSTCam start:
  - known stars (with external or internal catalog)
  - use blocking filters (for now)
  - DDF dedicated target stars for PWV follow-up for SNIa cosmology

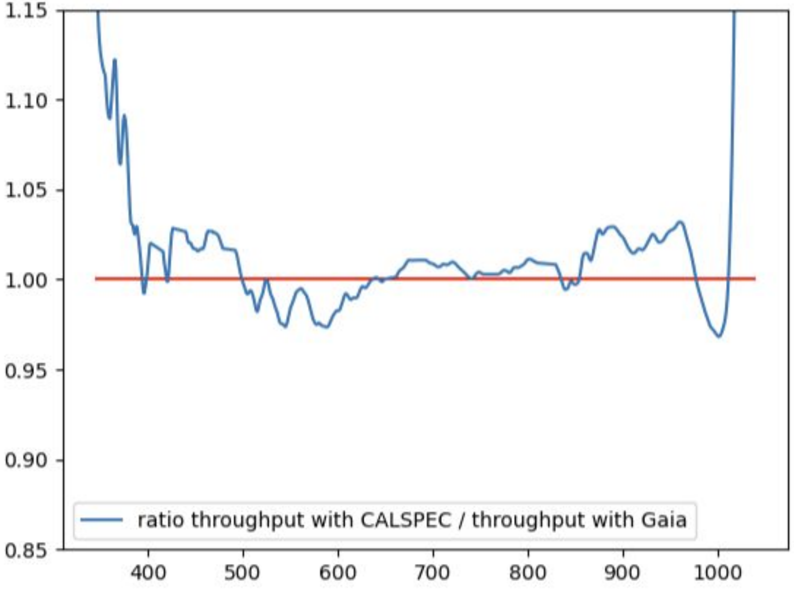
Distance moduli μ are estimated using the B-band rest-frame magnitude of the SNIa… which shifts with redshift in Earth frame



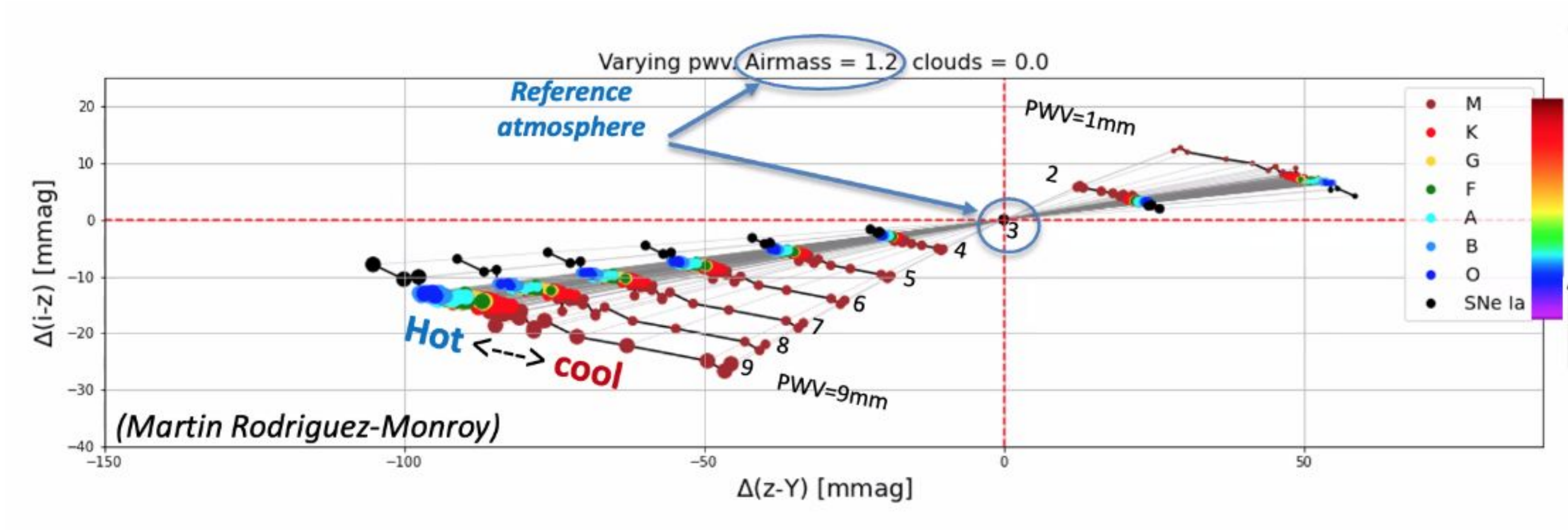
Backups

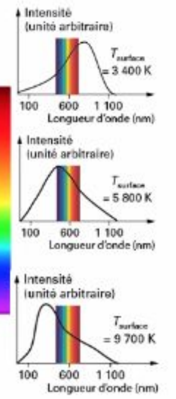
CASLPEC vs Gaia





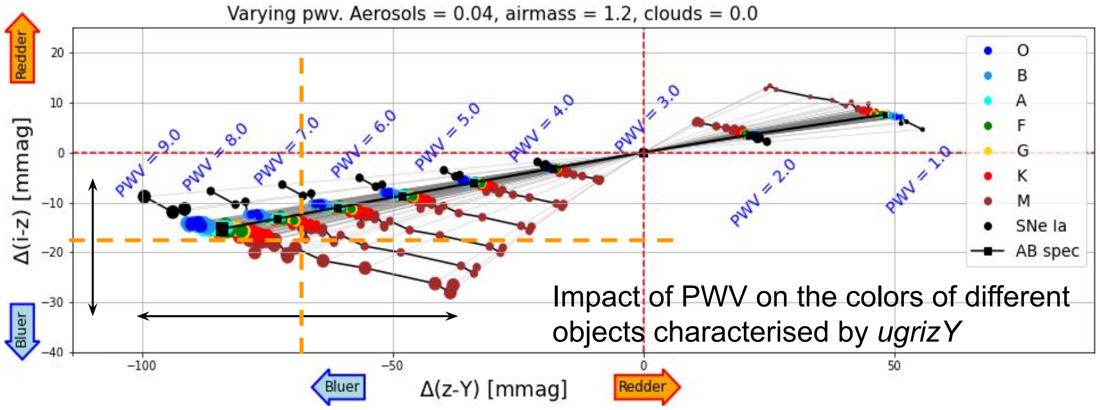
Colour compensations





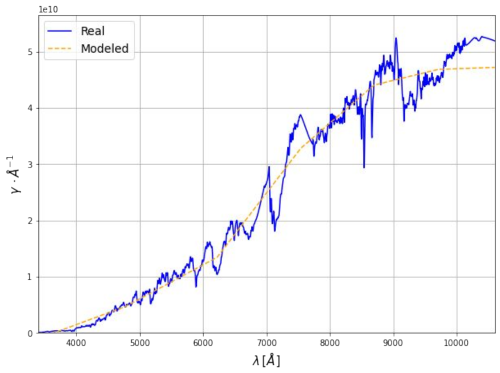
- Colour shift between PWV=3 and 9mm is between ~50-100mmag depending on stellar type
- Ignoring this dependence means using average colour shift -> object per object shift uncertainty ~20mmag
- If the stellar type is known and PWV is measured with <0.5mm of precision => we can return to reference atmospheric conditions with 1mmag precision

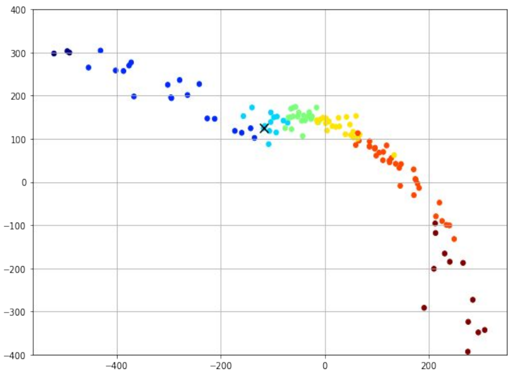
Dependence on object's SED



- Impact on colour depends on
  - Atmosphere (PWV, aerosols, ozone,....)
  - Object's SED (spectral types, galaxies, SNe)
- Mean colour correction → biased colors (several mmag depending on atmospheric components)

- SED modeling needs to account for object's nature, i.e. **SED shape**
- Currently working on different approaches:
  - Analytical modeling → improving fitting method
  - k nearest colour neighbours (kNN) → need to expand training catalogue



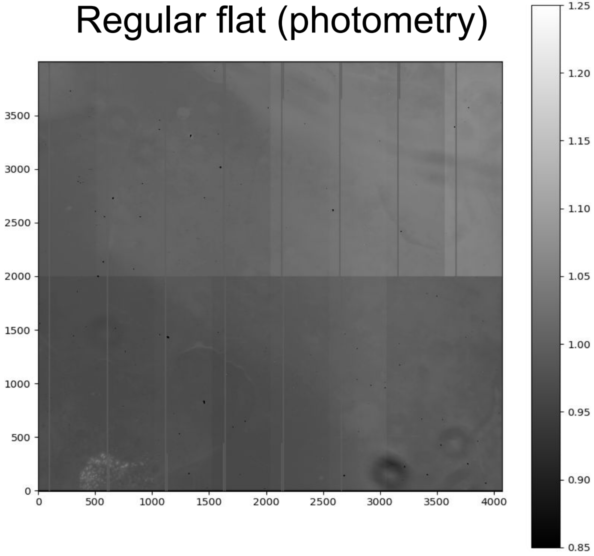


Special-flats for spectroscopy

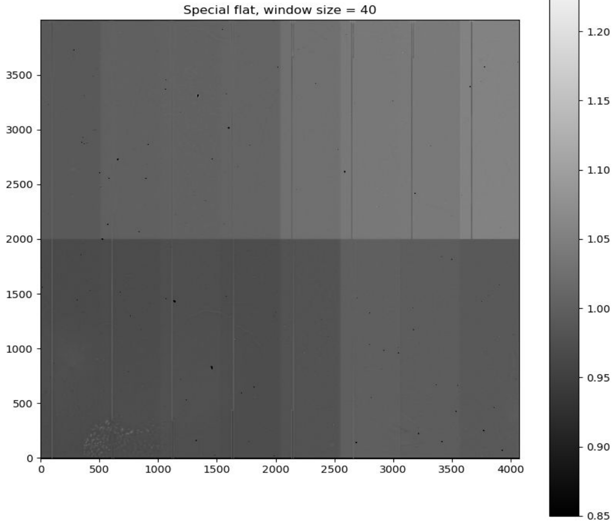
Why special? Because the final path of the light is modified by the dispersor

- Obtain special flats for spectroscopy → **Sensor-flats**
  - We want to **keep pixel-to-pixel variations** (high frequency) while **removing large-scale variations** (low frequency) due to upstream optics, common to all wavelengths
  - Develop methodology to achieve this → **Smooth component removal by filtering**

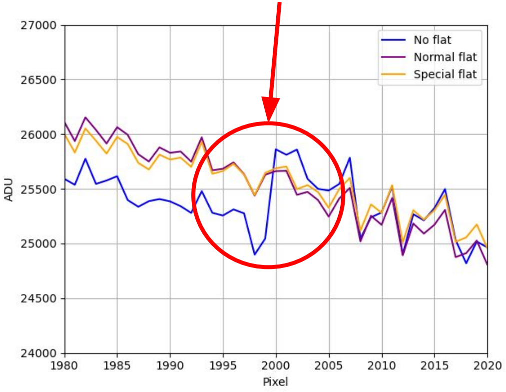
Regular flat (photometry)



High-frequency pixel flat



Effect of flat-fielding on amplifier transition

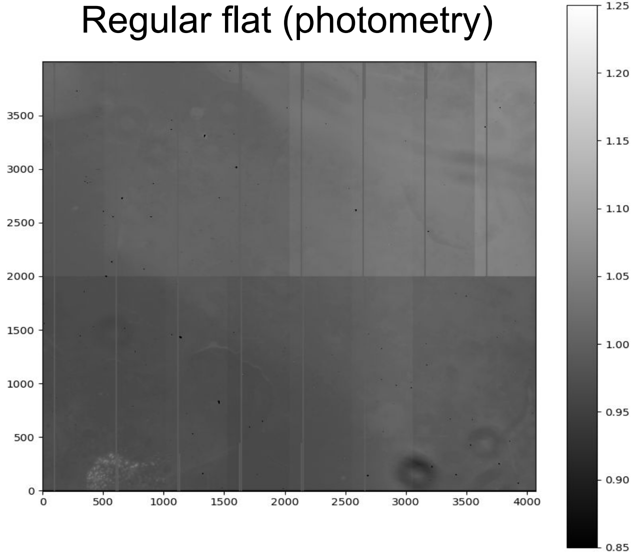


Special-flats for spectroscopy

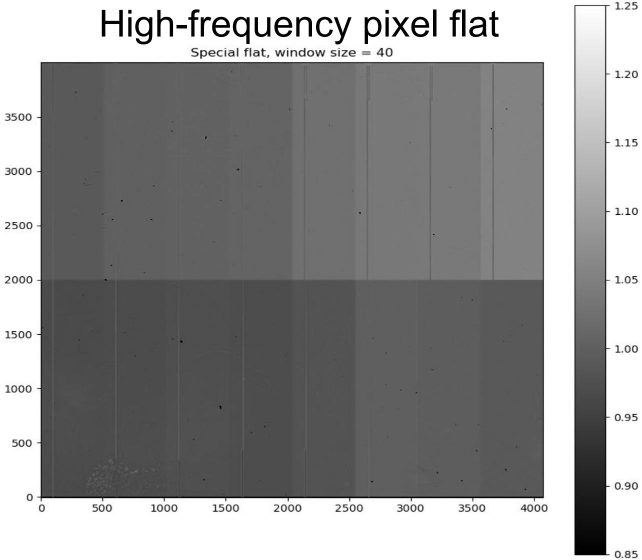
Studying different methods to produce **“flat-fields” for spectroscopy:**

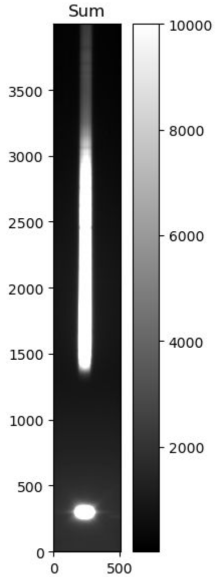
- Low frequency component removal → **Sensor-flats**
- Spectral exposures with horizontal shifting star → **Dither-flats**

Regular flat (photometry)



High-frequency pixel flat

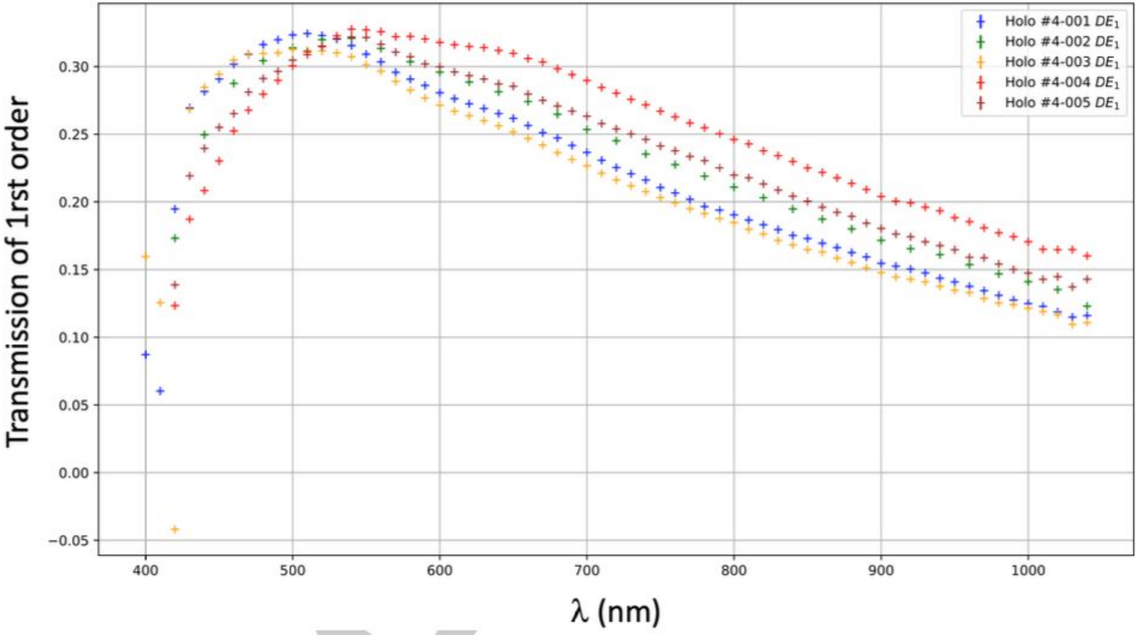




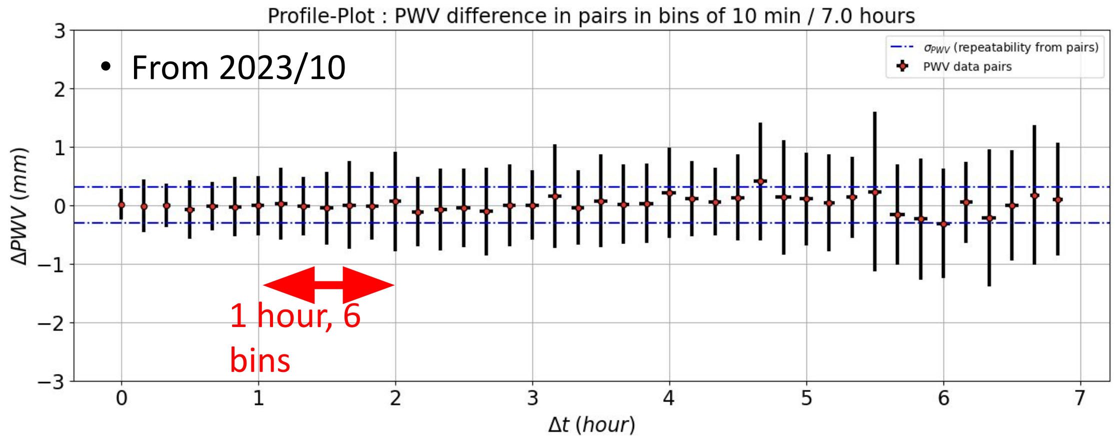
Hologram transmission

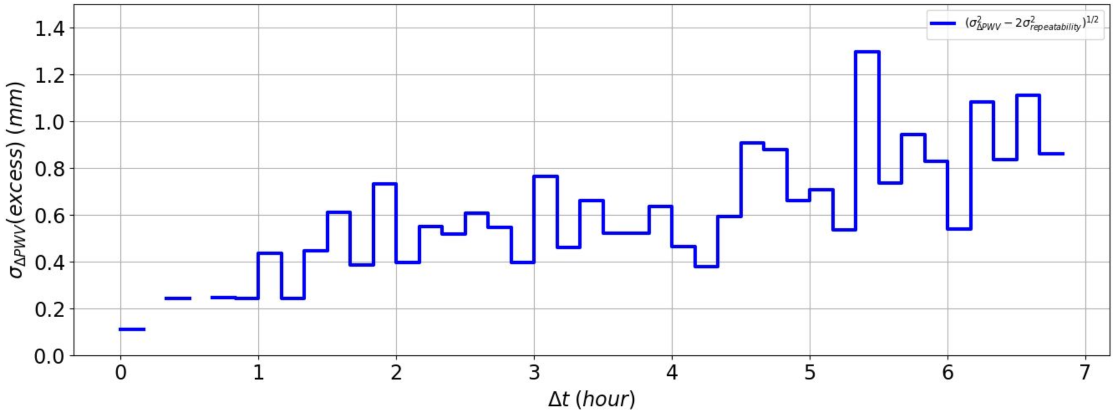
Measured on optical test bench:

- holo4_003: currently installed on AuxTel
- holo4_001: spare



Evolution of RMS with time separation





- ΔPWV broadening
- over 10 hours of 10 minutes slices

- **Evolution of the distribution RMS with time separation**
  - 1 hour : 0.3 mm
  - 2 hours : 0.5 mm
  - 5 hours : 0.7 mm

Statistics averaged over all nights

Quality cuts

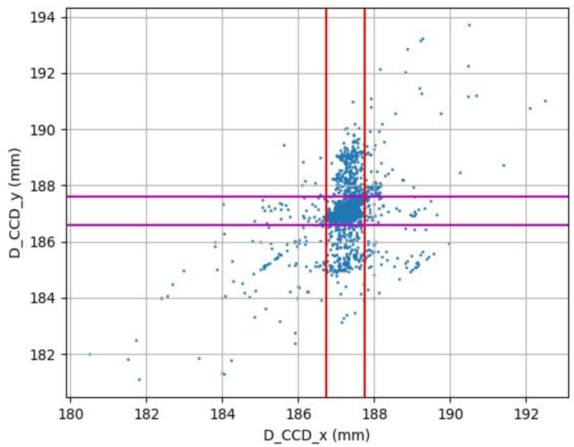
$\chi^2 < 20$

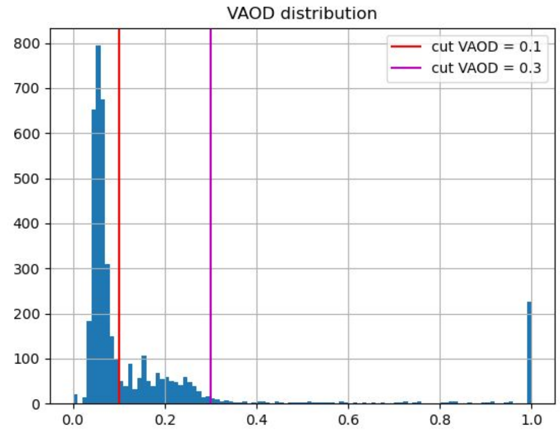
186.75 mm < D_CCD_x < 187.75 mm

186.6 mm < D_CCD_y < 187.6 mm

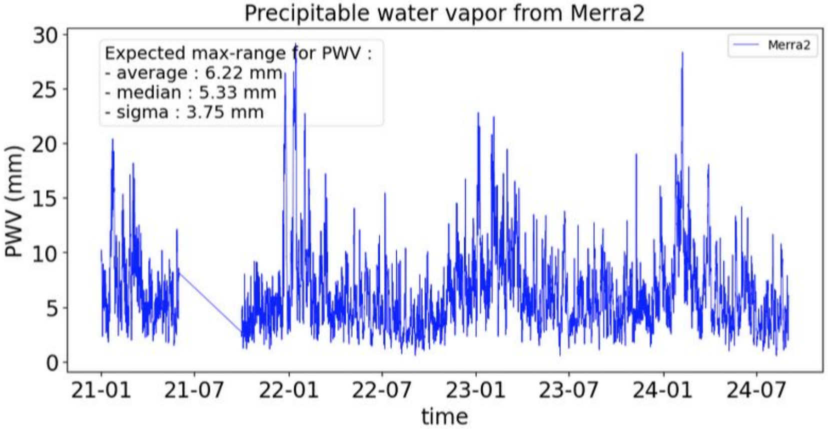
VAOD < 0.1

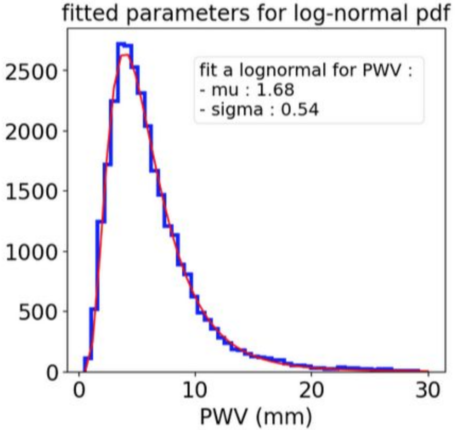
Ozone < 620 db

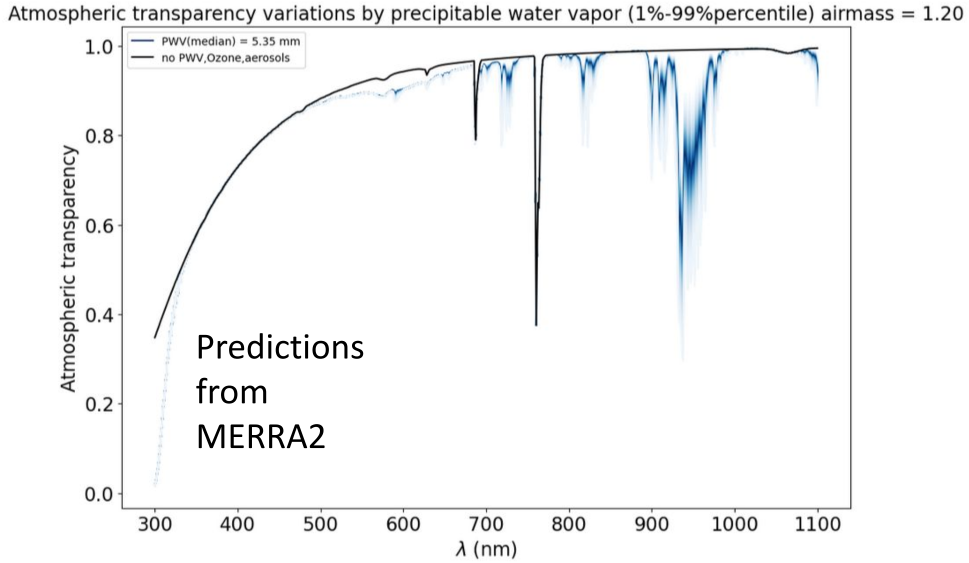




Atmospheric Transparency variations with Precipitable water vapor

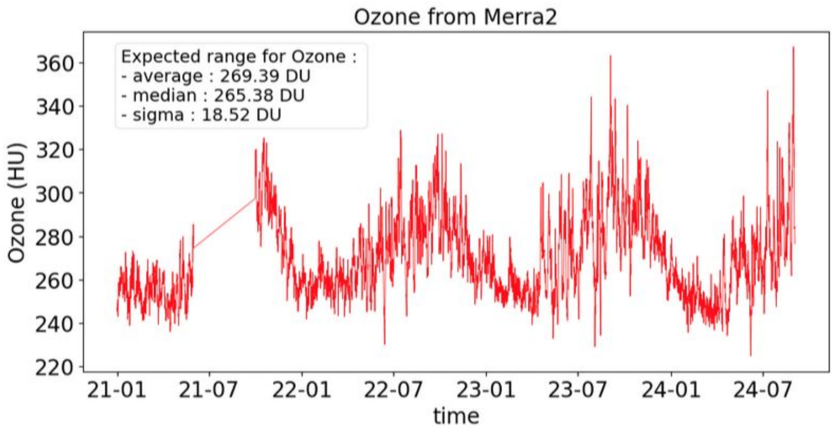


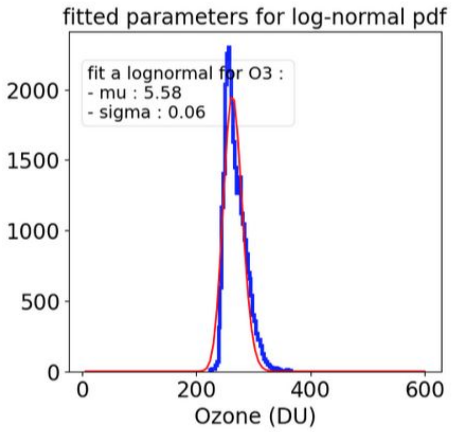


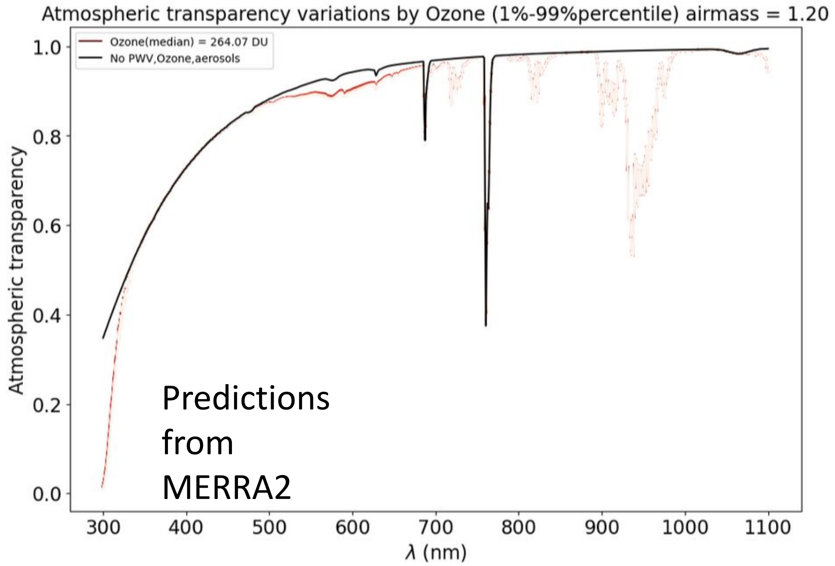


- Expect seasonal fluctuations
- Significant variations

Atmospheric Transparency variations with Ozone

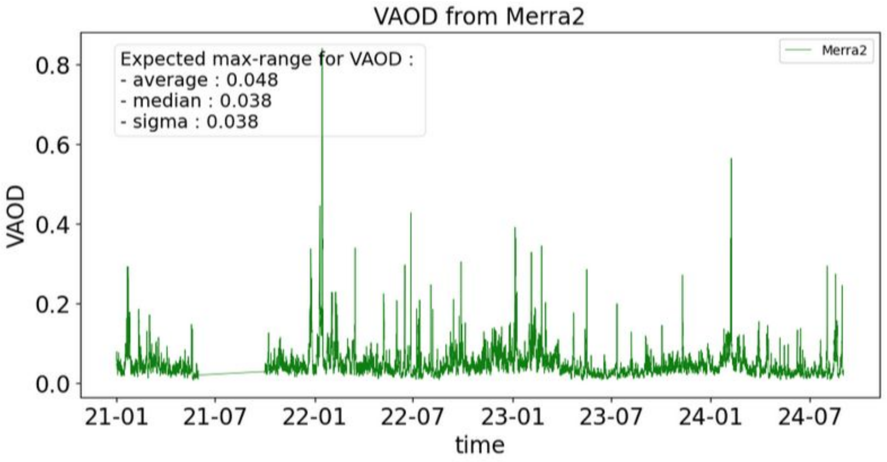


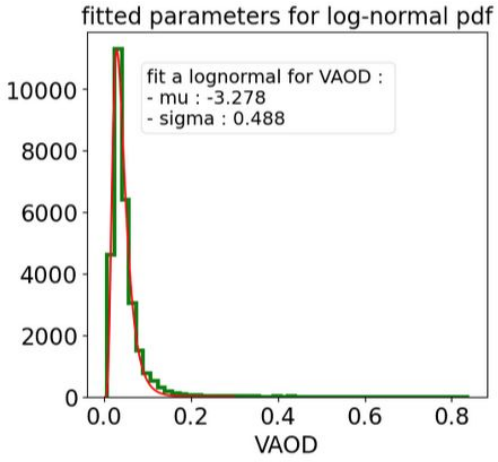


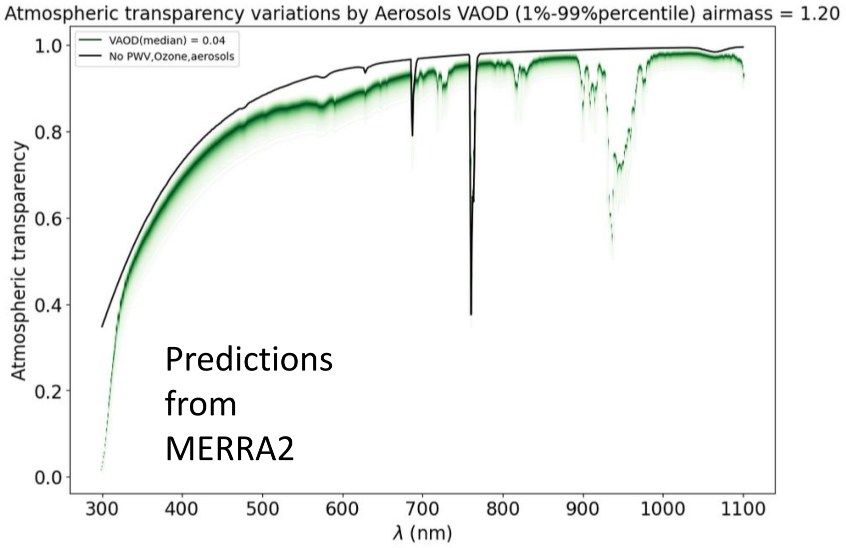


- Expect seasonal fluctuations
- Restricted range.
- Limited impact on transparency variations

Atmospheric Transparency variations with Aerosol Vertical Depth



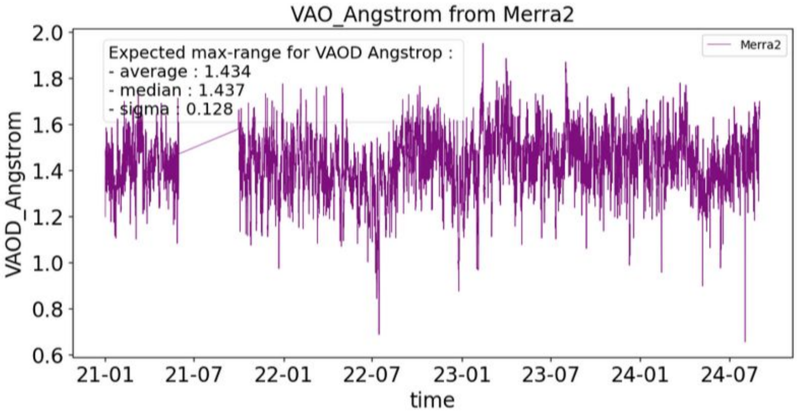


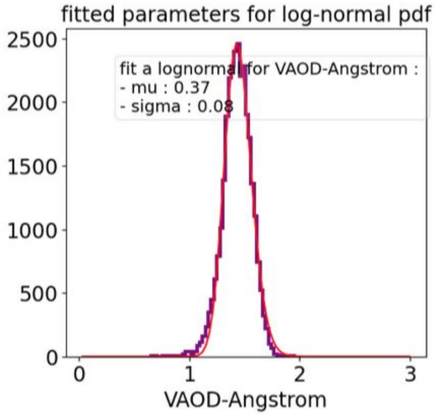


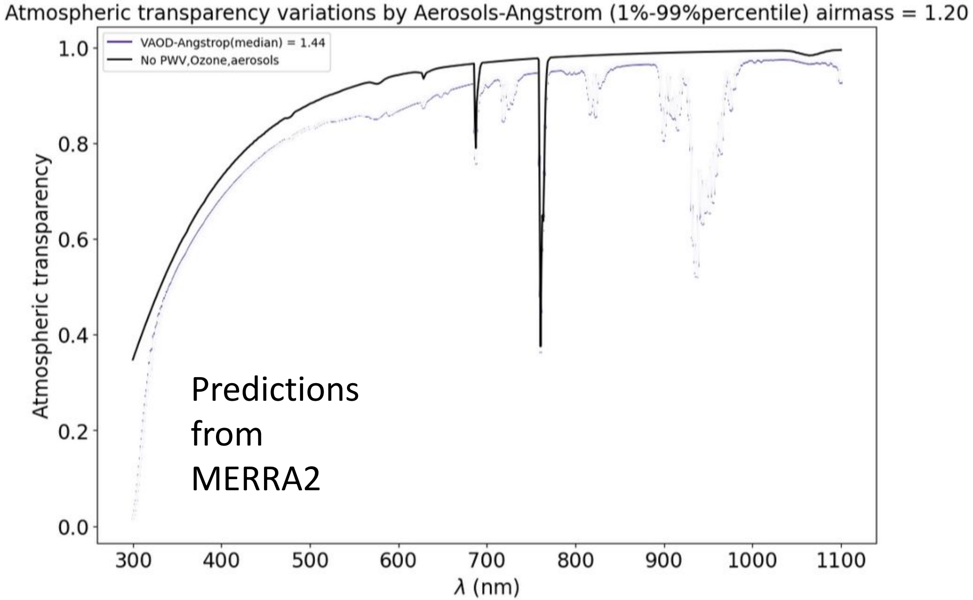
- Vertical aerosol depth
- Very significant variations

$$T_{aerosols} = \exp(-\tau(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\beta})$$

Atmospheric Transparency variations with Aerosol Angstrom exponent



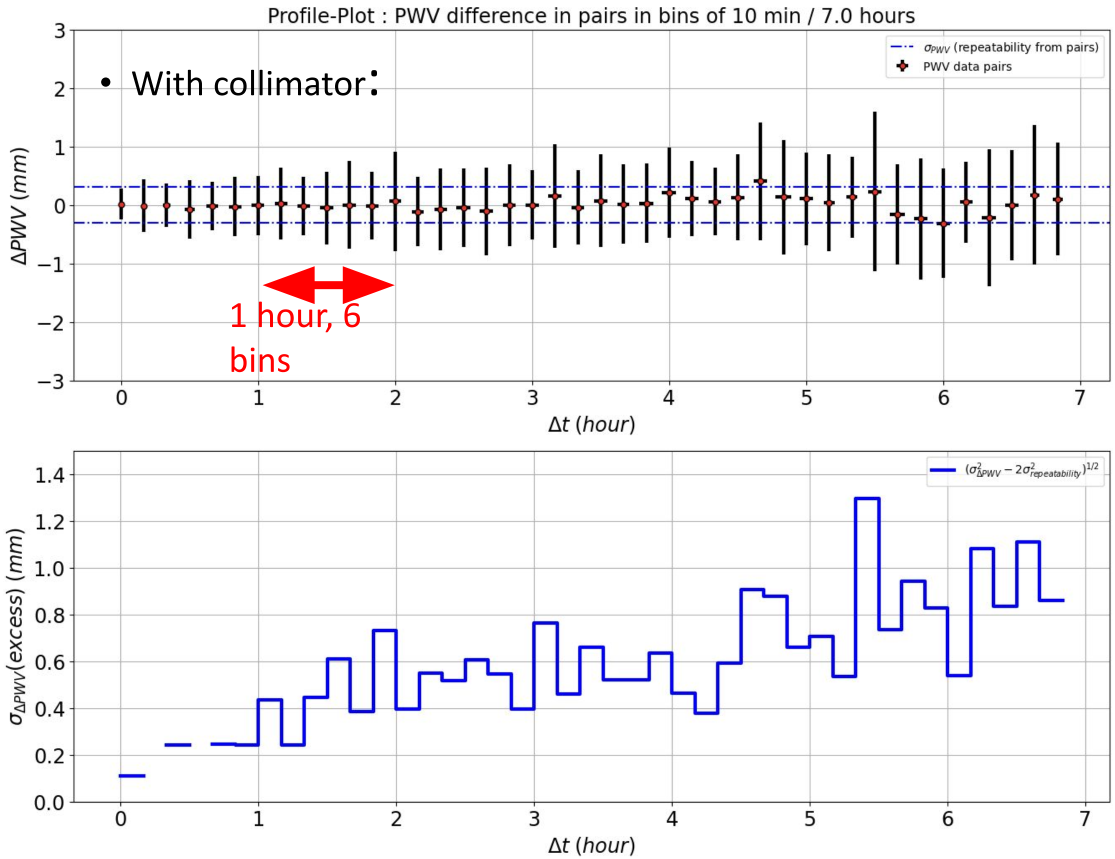




- Vertical aerosol depth exponent parameter
- Does not induce large variations in transparency
- (unless mixed with grey attenuation)

$$T_{aerosols} = \exp(-\tau(\lambda_0)\left(\frac{\lambda}{\lambda_0}\right)^{-\beta})$$

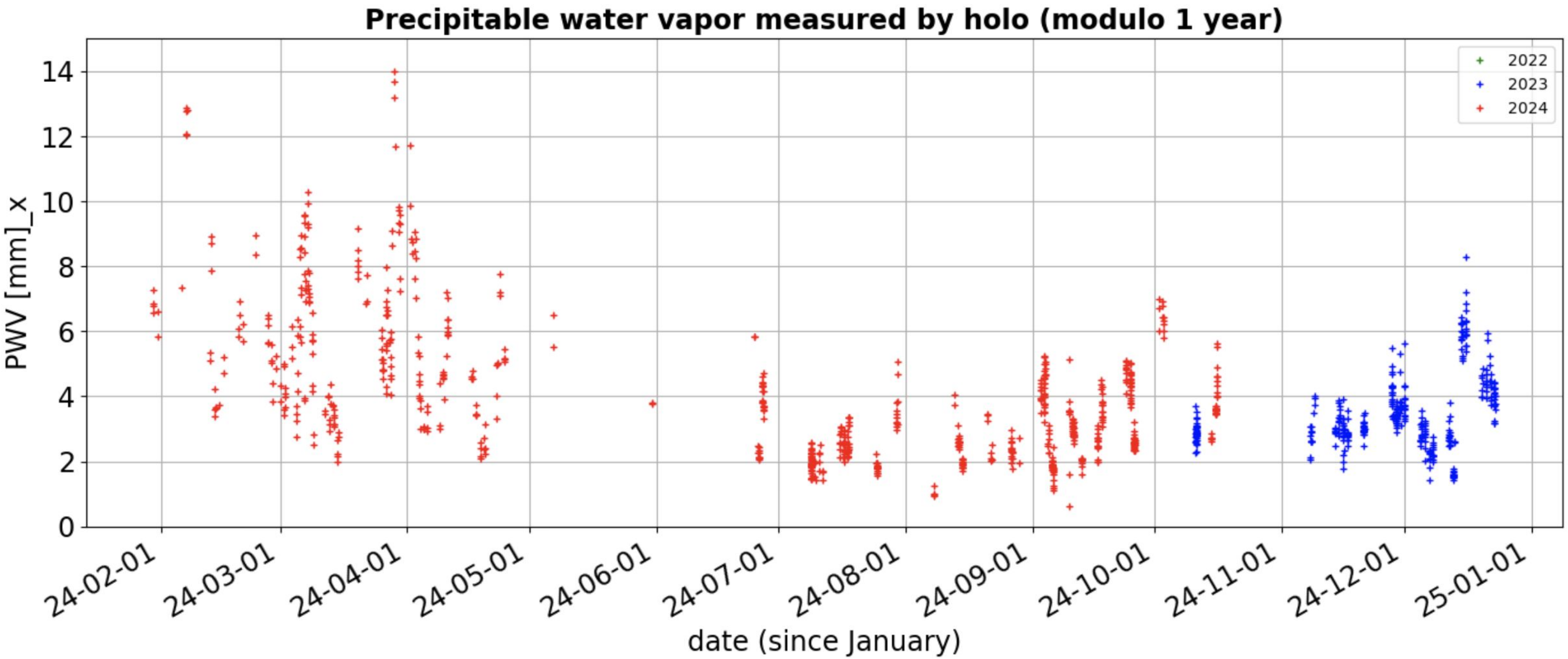
Excess uncertainty with time separation



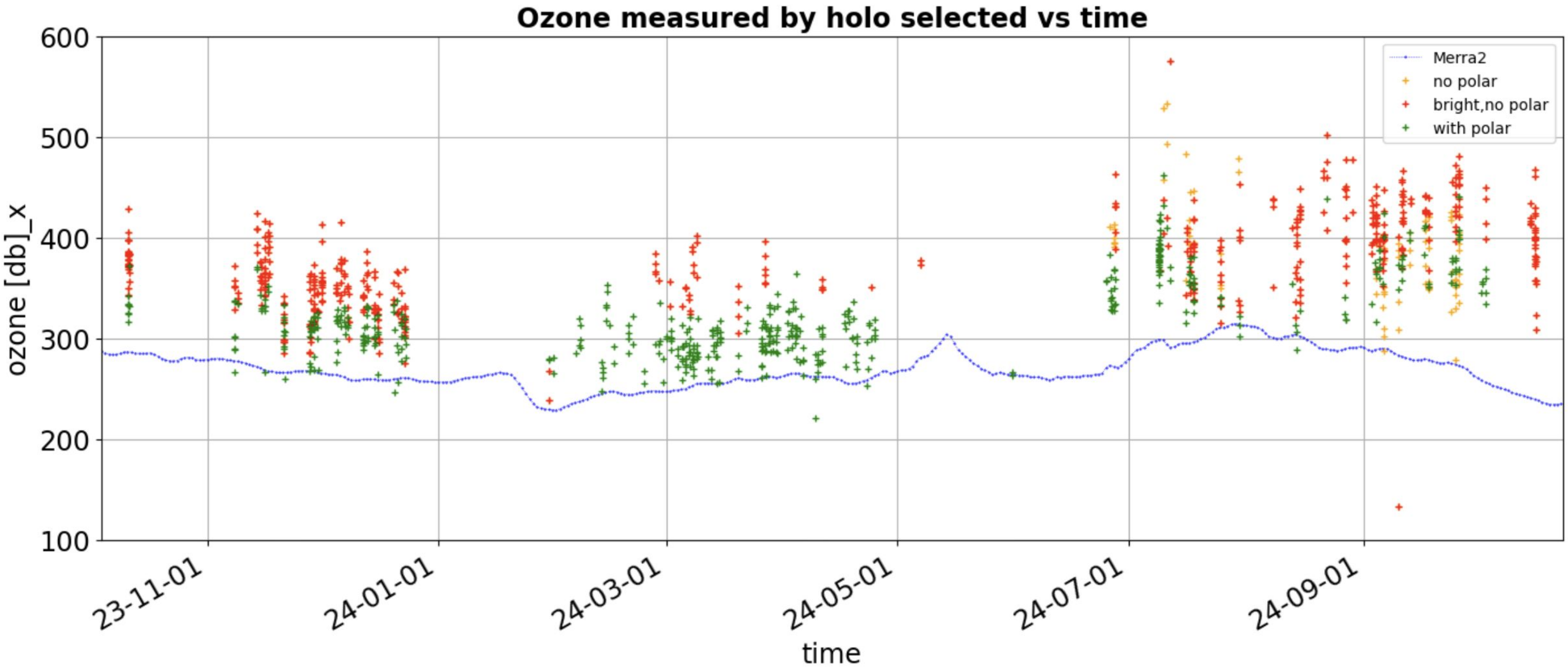
- ΔPWV broadening
- over 10 hours of 10 minutes slices
- **Excess in spread** over the photometric repeatability
  - 1 hour : 0.3 mm
  - 2 hours : 0.5 mm
  - 5 hours : 0.7 mm

Statistics averaged over all nights

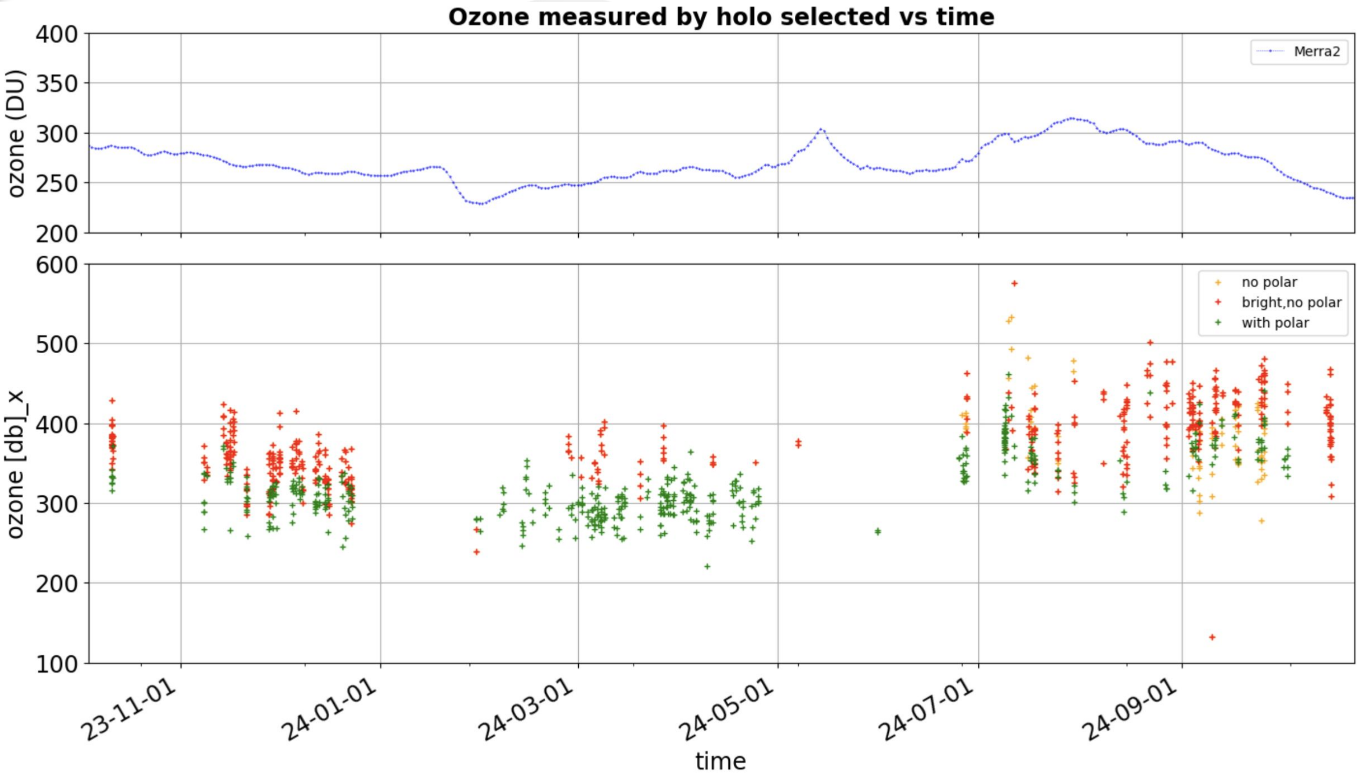
Precipitable water vapor/1 year after collimator in place



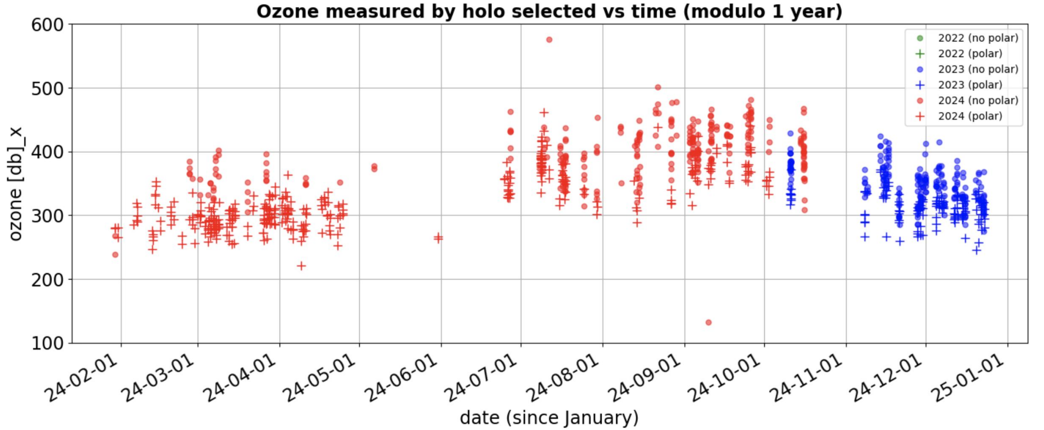
Ozone variation after collimator in place

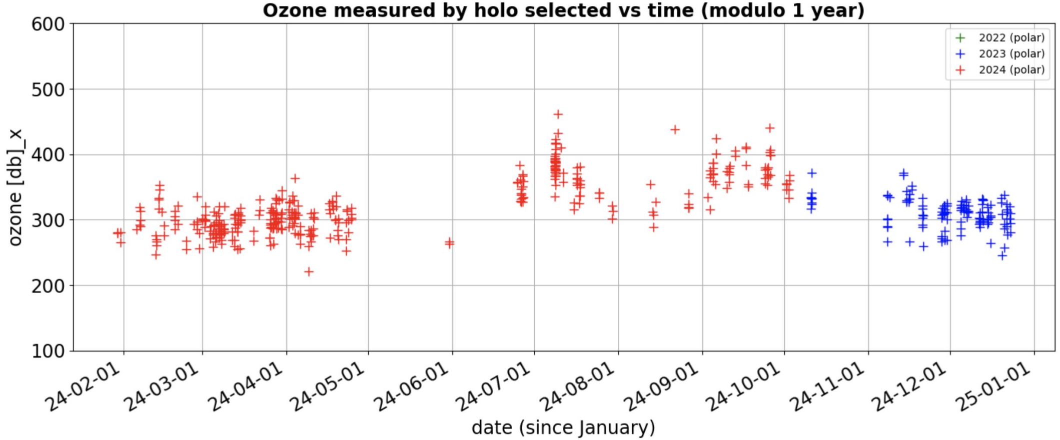


Ozone variation after collimator in place

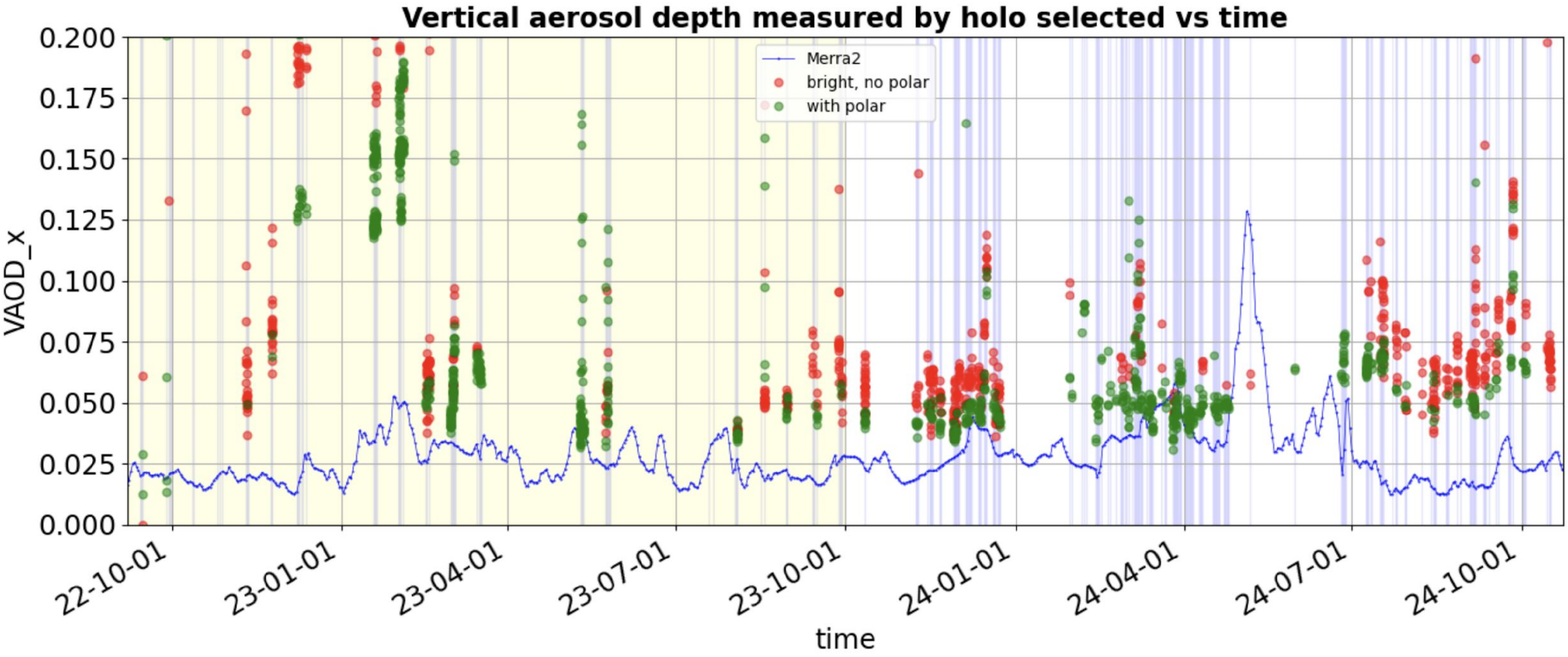


Per night ozone median after collimator

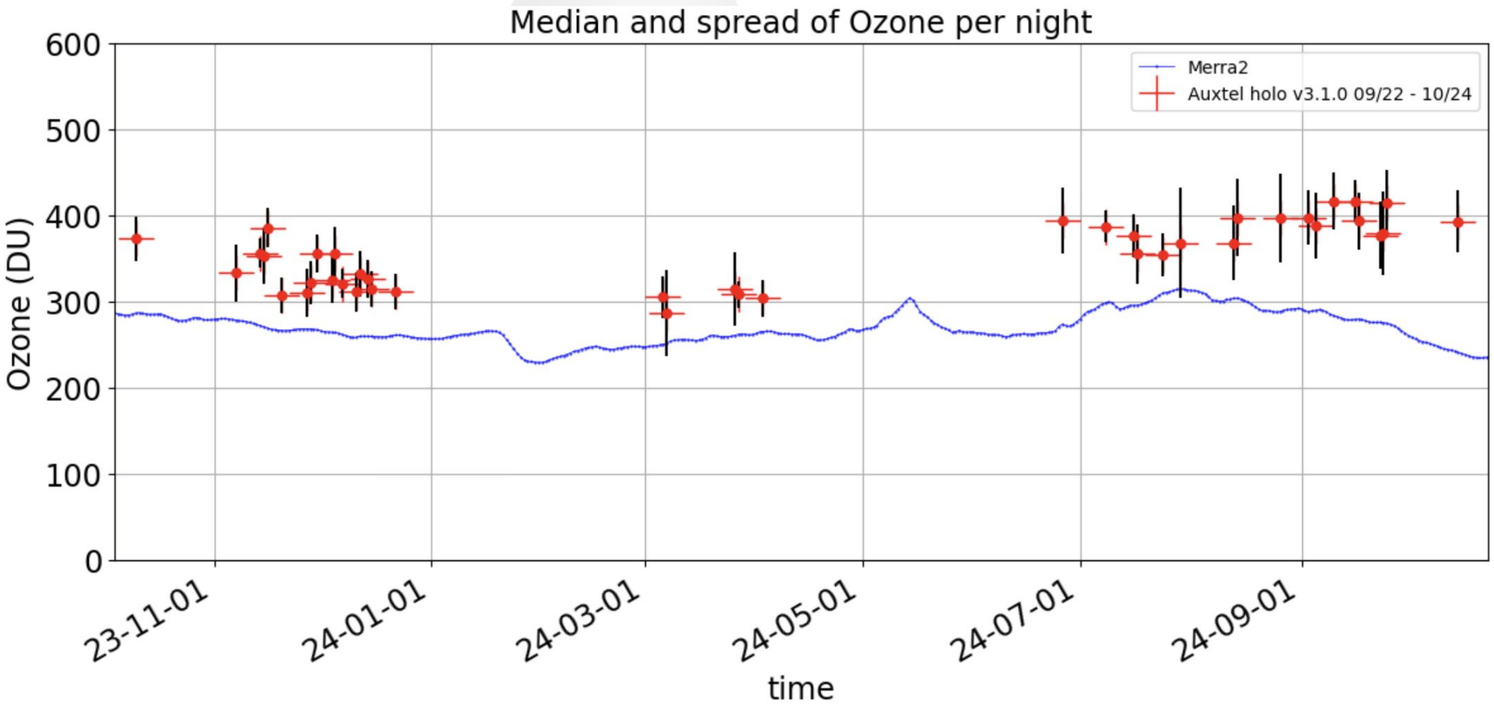




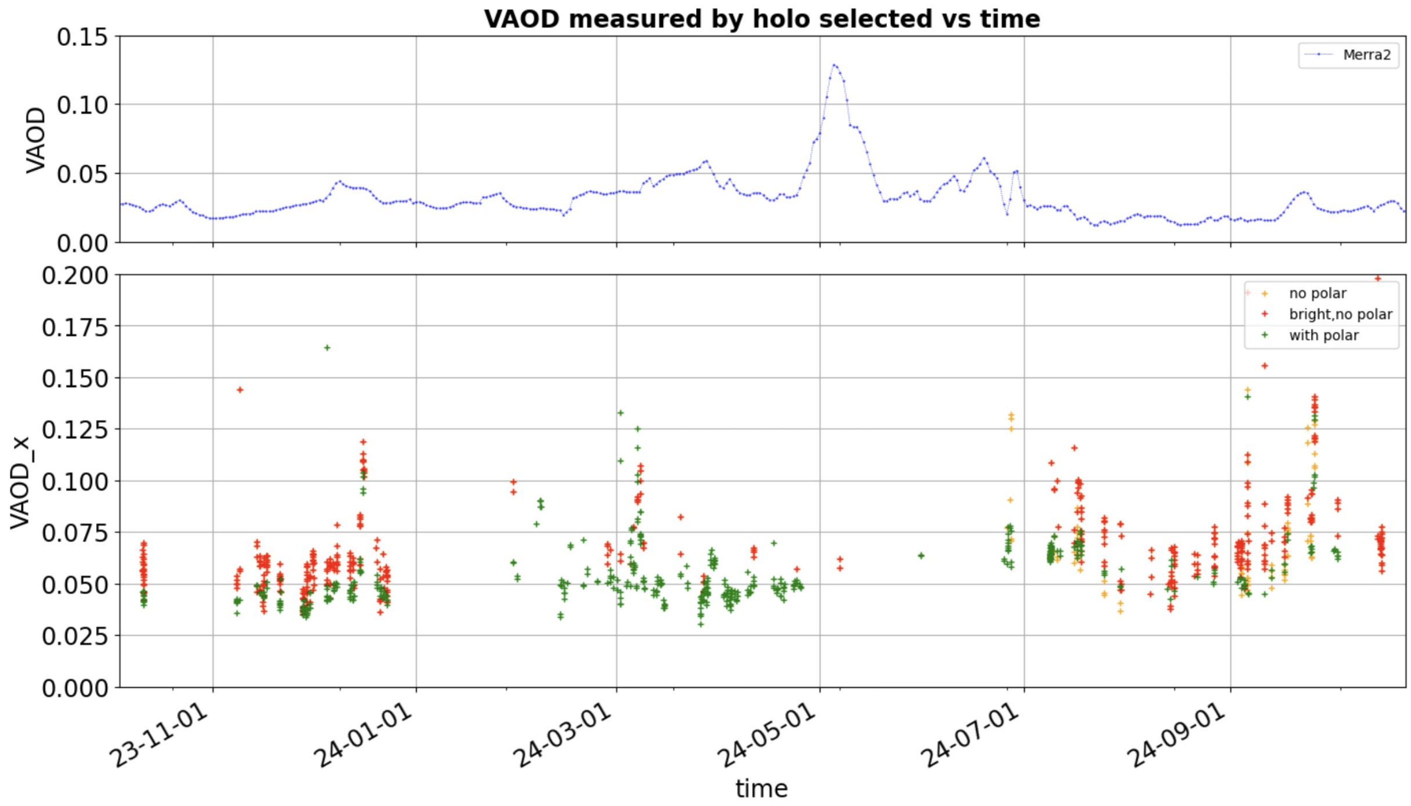
Vertical aerosols depth



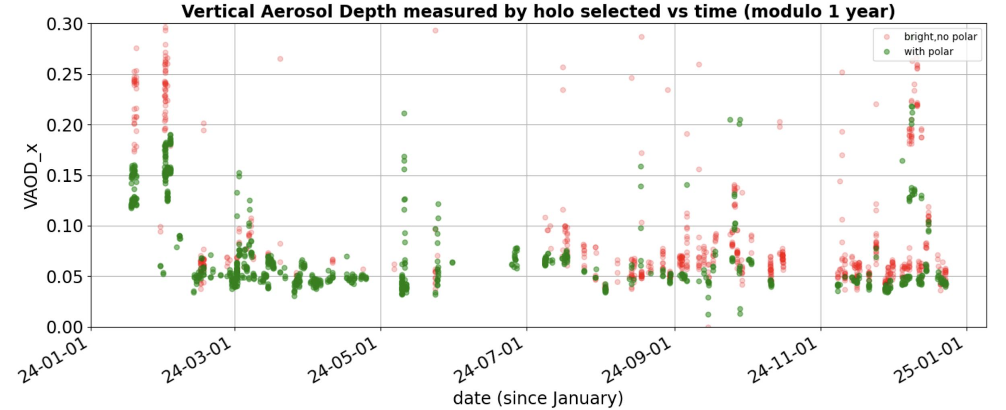
Vertical aerosols depth after collimator

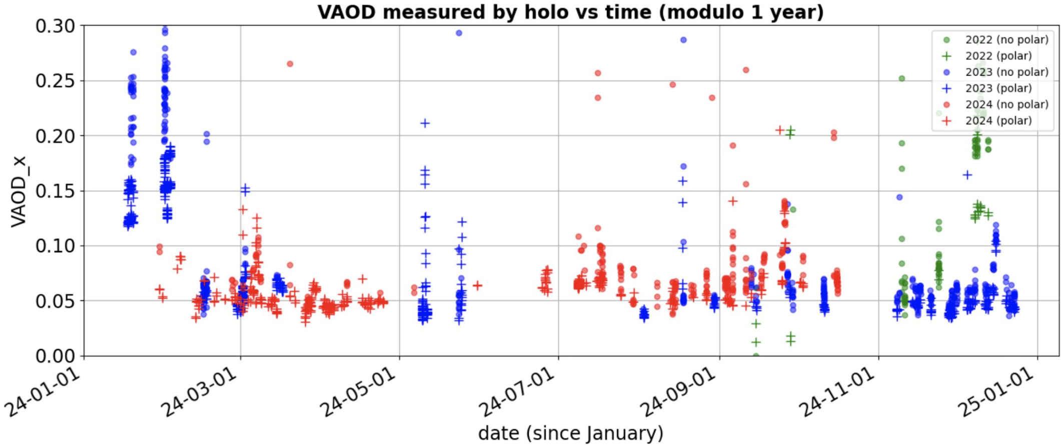


Vertical aerosols depth after collimator

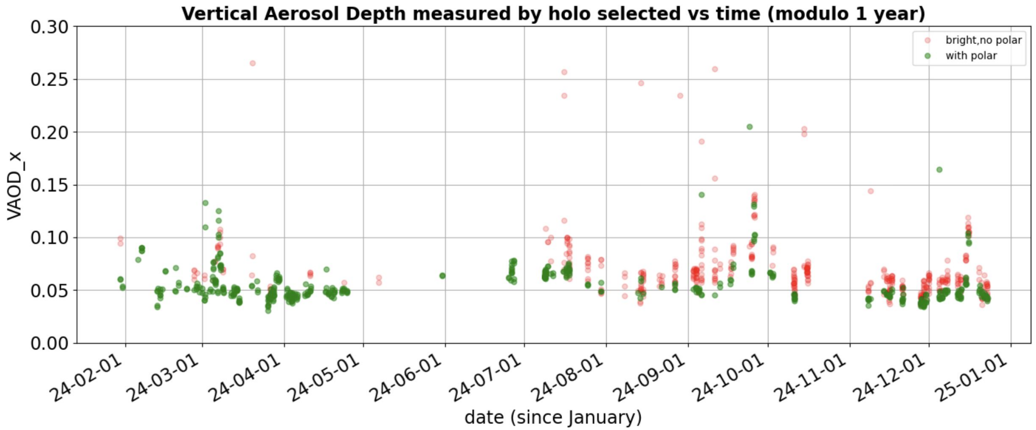


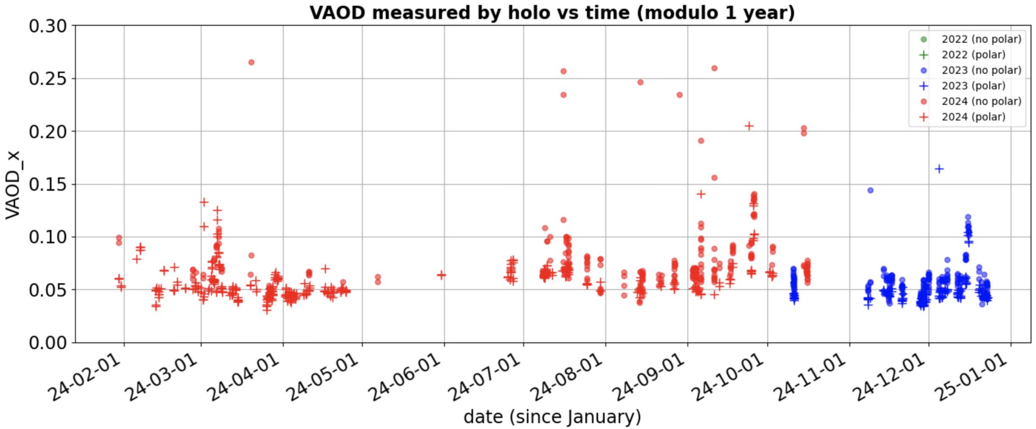
Seasonal effect (Modulo 1 year)





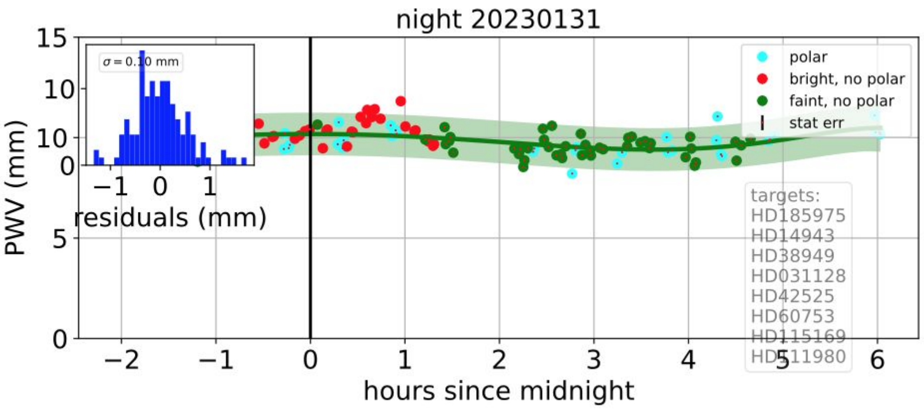
Seasonal effect (Modulo 1 year) after collimator

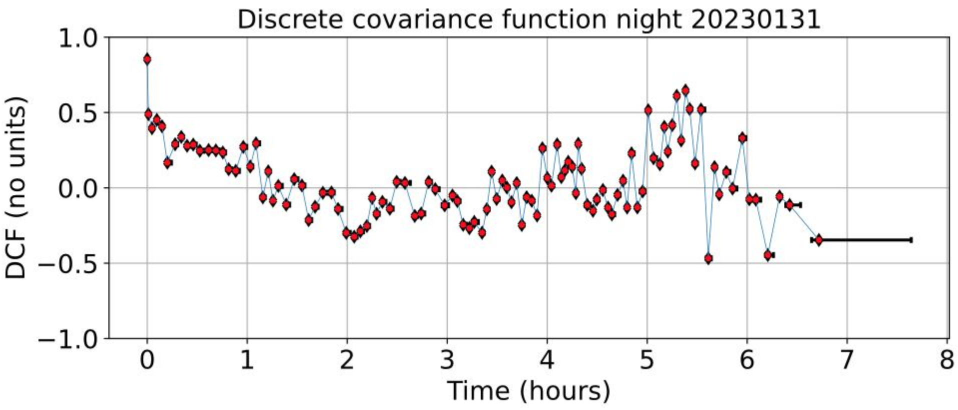




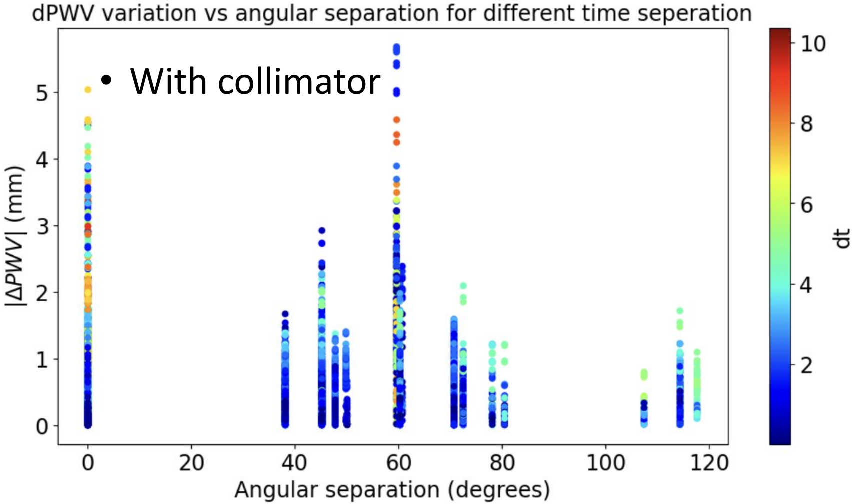
Precipitable water vapor time variation

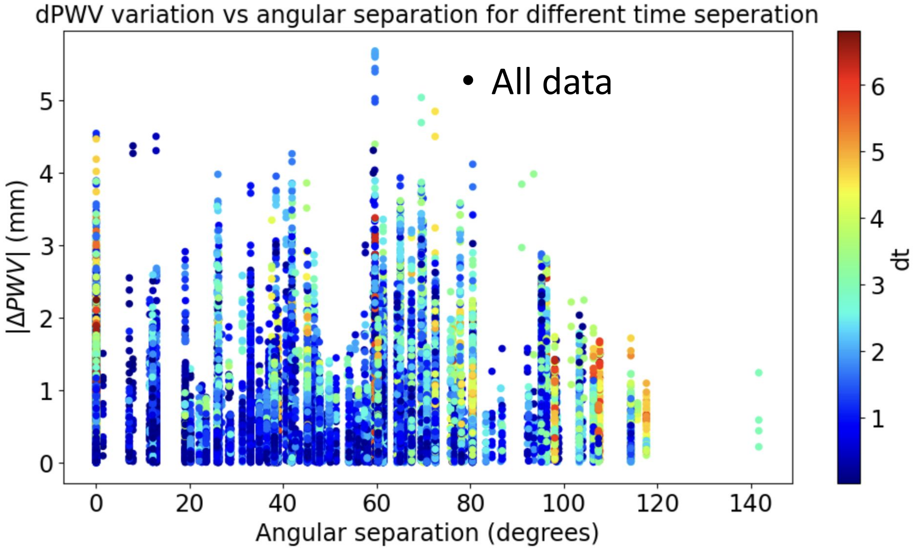
- Slow variation per night





Impact of Angular Separation on ΔPWV





- No obvious effect of significative effect on ΔPWV due to angular separation
- Time separation account more to on ΔPWV dispersion