Astroclimes - a synthetic transmission spectra code for removing telluric lines and measuring atmospheric CO_2

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Key message

We present Astroclimes, a synthetic transmission fitting algorithm that can be used for measuring the amount of greenhouse gases in the Earth's atmosphere and for removing telluric lines from stellar spectra. Our aims are, respectively, to:

Complement global climate models with CO_2 column measurements taken at night

Provide an improved mechanism to remove telluric lines using a Bayesian approach which could be incorporated into existing models

1 - Compute model spectra

- Calculate molecular cross sections.
- Obtain atmospheric profile.
- Model transmission spectra, including effects:
  - Line-by-line absorption
  - Rayleigh and aerosol scattering
  - Collision-induced absorption (CIA)
  - Instrumental broadening

2 - Test new model against existing models

- Telluric transmission models were generated with the ESO Advanced Sky Model [4] web application, SKYCALC.
- Astroclimes was run on these models to verify that we could reproduce the reported precipitable water vapour (PWV) values from the ESO models (Figure 1).

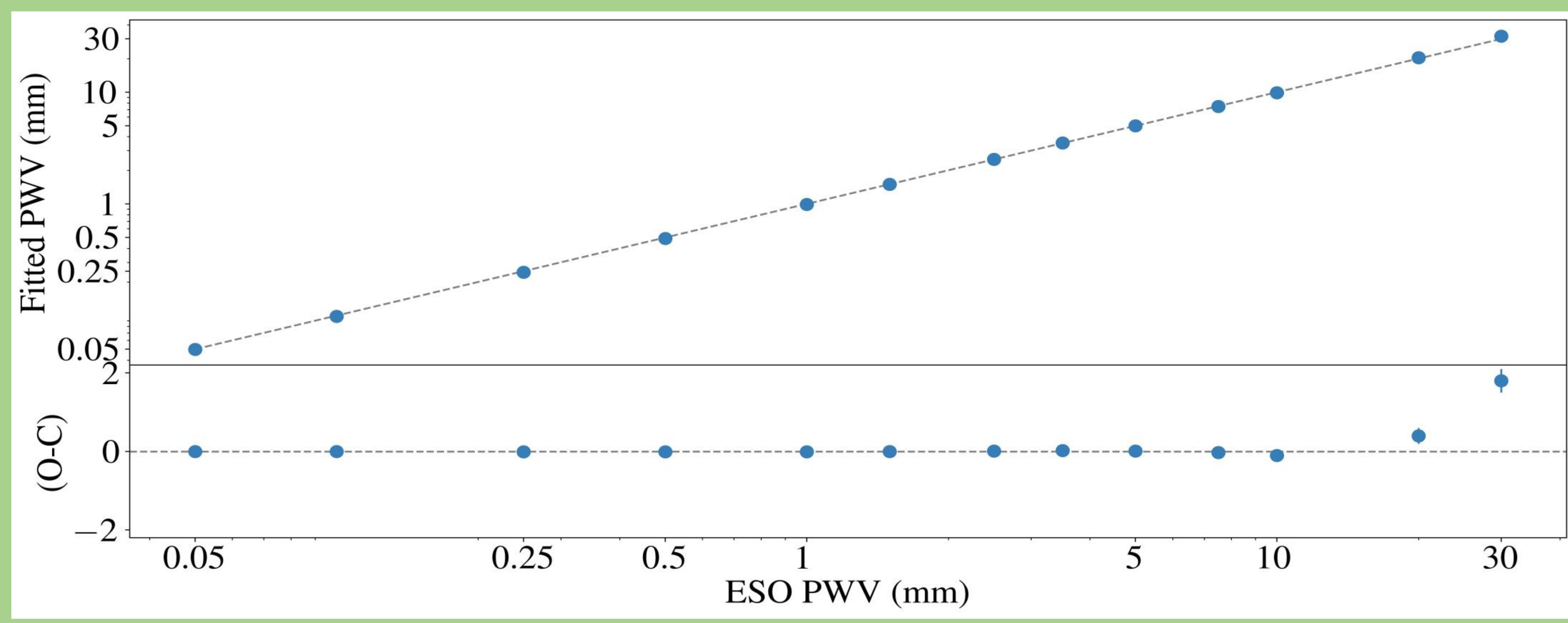

Figure 1: Retrieved PWV values obtained from running Astroclimes on telluric transmission models generated with SKYCALC.

Atmospheric CO_2 fitting

3 - Fit model to observational data

- Observational spectra comes from the CARMENES spectrograph, target HR5676.
- Best fit model is obtained by running an MCMC, with abundances of CO_2, H_2O, CH_4 and O_2 chosen as free parameters. The log likelihood equation comes from Brogi & Line (2019) [1].
- Astroclimes models compared to observational spectra are shown in Figure 2, along with their residuals.

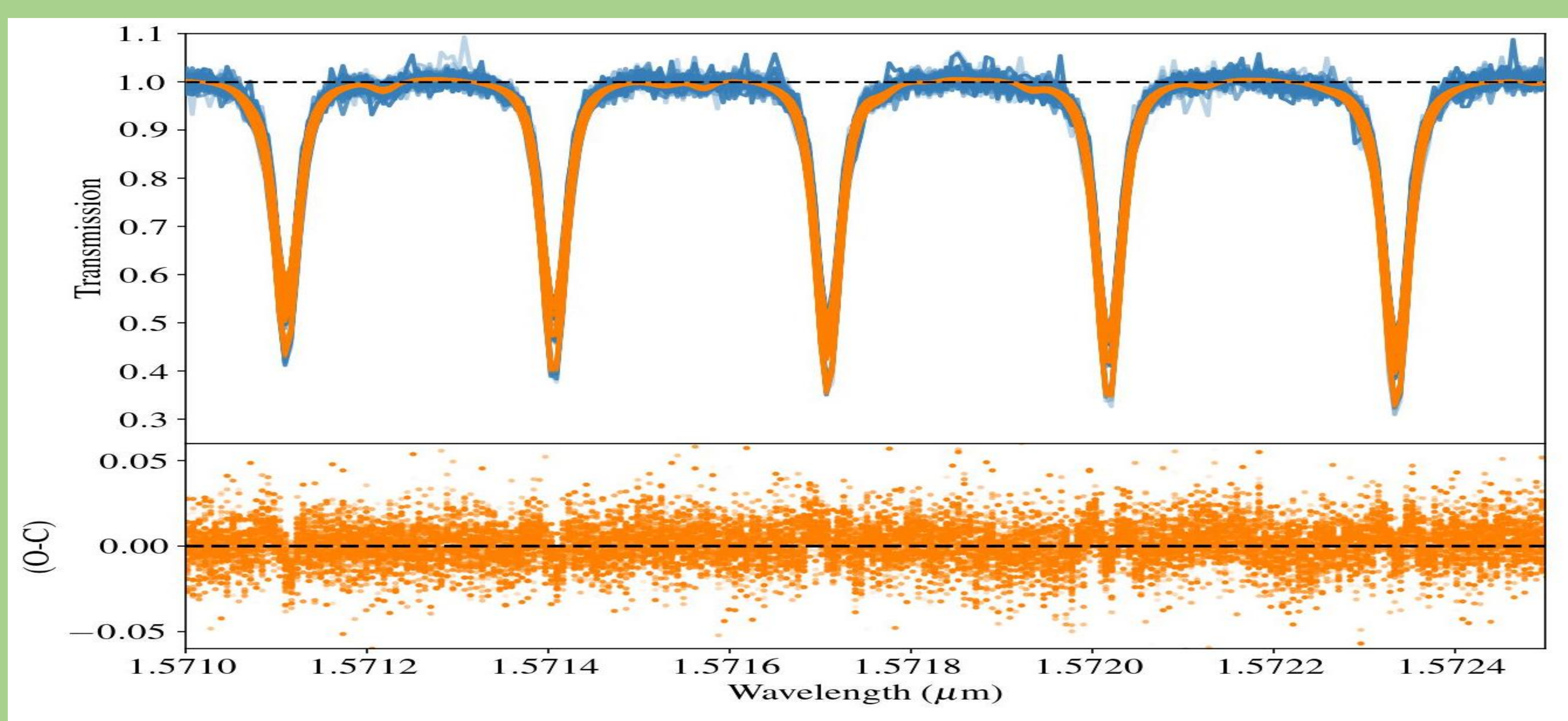

Figure 2: Comparison between the CARMENES observational spectra for HR5676 (blue lines) and the fitted models obtained with Astroclimes (orange lines), zoomed in on CO_2 lines. Bottom plot shows residuals.

4 - Compare results to literature

- Our results are best represented by the column-averaged dry air mole fraction of CO_2, given by [2]:

$$XCO_2 = 0.20935 \frac{CO_2\ column}{O_2\ column}$$

- Satellites such as the OCO-2 and OCO-3 measure this same parameter, albeit using reflected sunlight. Figure 3 shows our measurements compared to theirs.
- Our retrieved values were shifted by a correction factor to account for calibration offsets between the different retrievals.

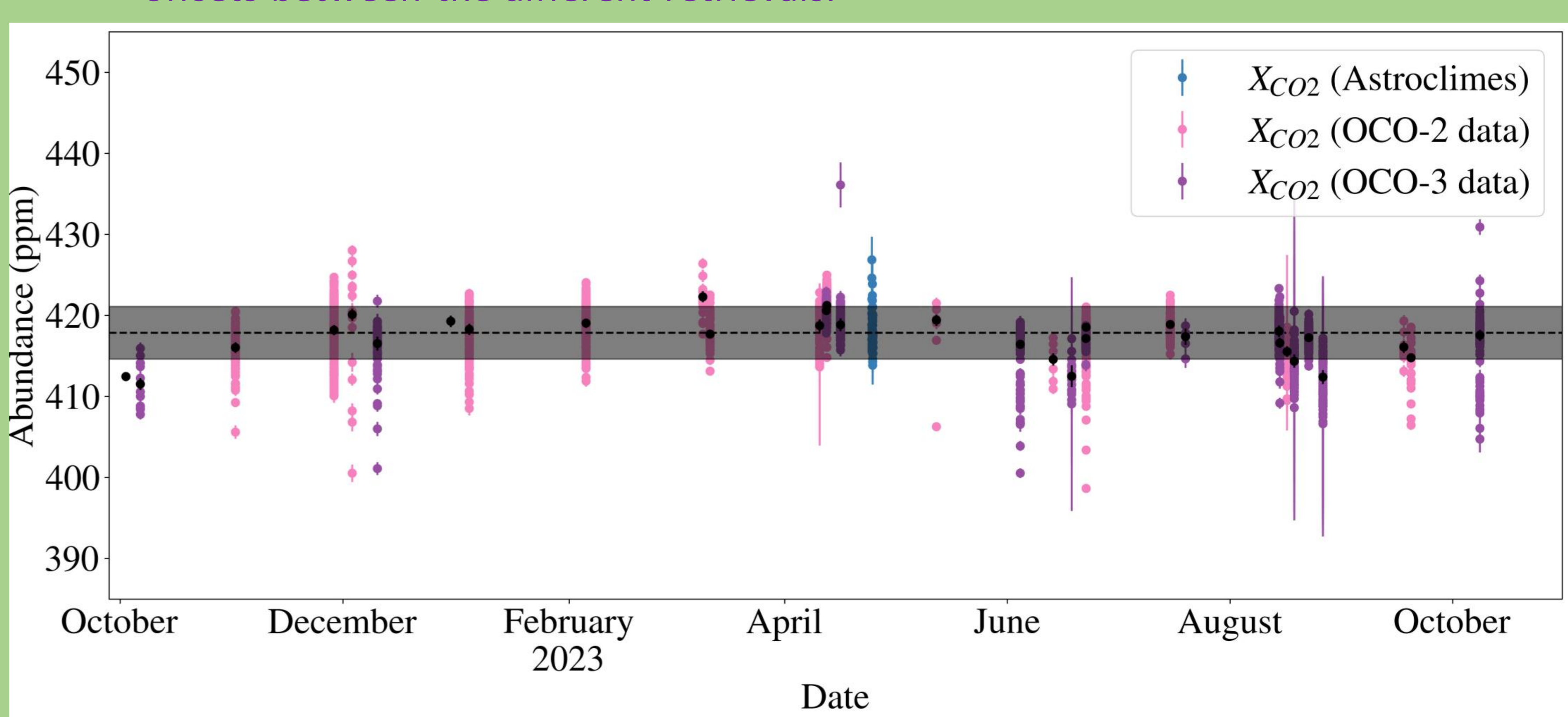

Figure 3: Retrieved XCO_2 from Astroclimes (blue points), OCO-2 (pink points) and OCO-3 (purple points). Black points are the daily medians of OCO-2 and OCO-3, black dashed line is the median of both distributions and black shaded area is the 1σ confidence intervals. The Astroclimes values were multiplied by a correction factor of 0.963 to align them with the OCO2 and OCO-3 values.

References

[1] Brogi, M., & Line, M. R. 2019, AJ, 157, 114.
[2] Crisp, D., et al. 2015, SPIE Conference Series Vol. 9607, p. 960702.
[3] Giacobbe, P., et al. 2021, Nature, 592, 7853, 205-208.
[4] Noll, S., et al. 2012, A&A, 543, A92.
[5] Webb, R., et al. 2022, MNRAS, 514, 4160-4172.

Telluric line removal – Tau Bootis

3 - Organise data in "cubes"

- Data is stacked in "cubes" of shape (n_{orders}, $n_{observations}$, $n_{wavelength}$), as shown in Figure 4.

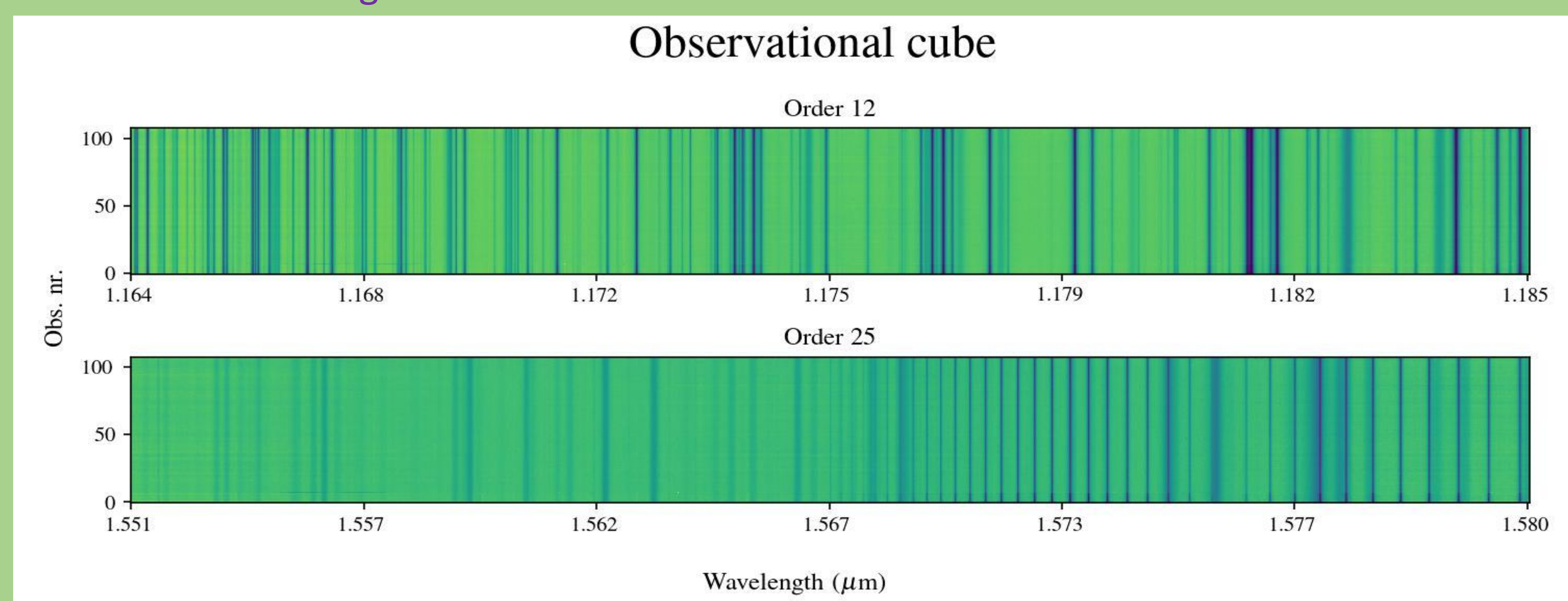

Figure 4: CARMENES observations of Tau Bootis stacked over the y-axis, with wavelength on the x-axis, for two selected CARMENES orders with H_2O (order 12) and CO_2 (order 25) lines.

4 - Remove telluric and stellar lines

- Data is divided by the telluric line model, and stellar lines are removed by dividing each observation by the time average telluric line removed spectra (Figure 5).
- This is done to uncover possible planetary signals, which Tau Bootis is known to have [5].
- For comparison, removal of telluric and stellar lines by Principal Component Analysis (PCA) [3] is shown in Figure 6.

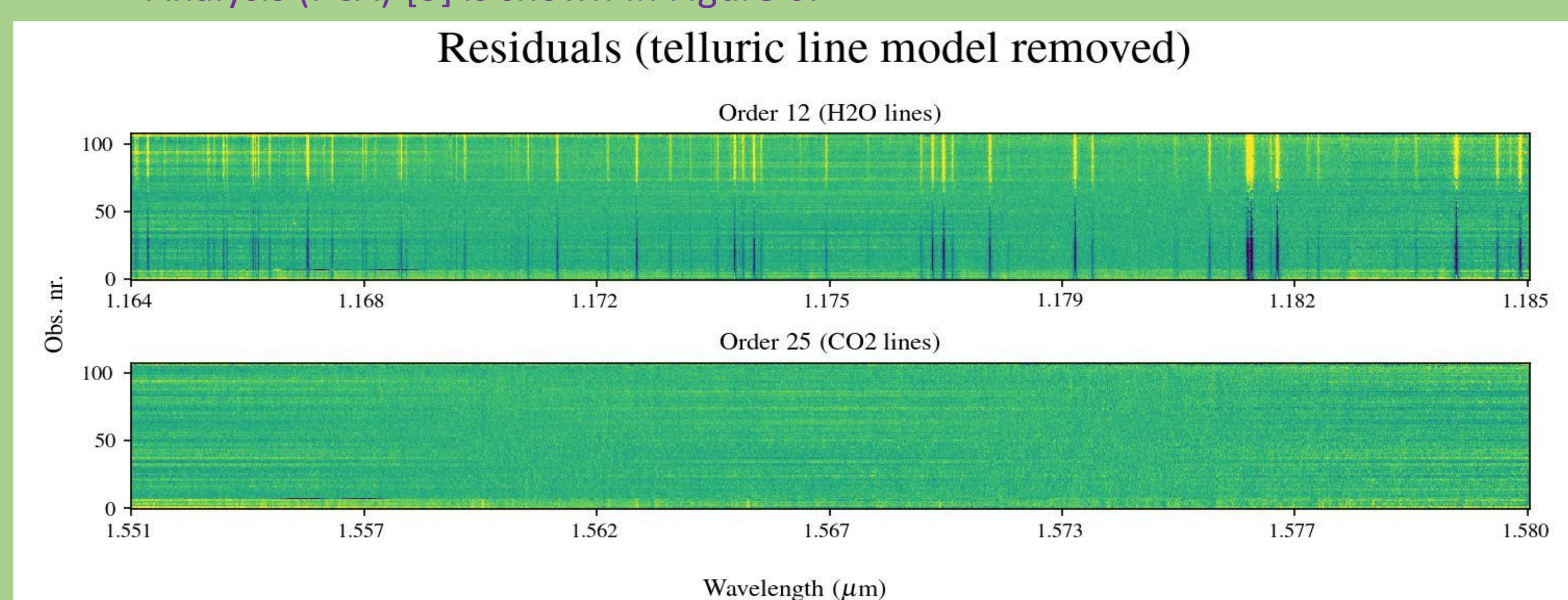

Figure 5: Data shown in Figure 5 divided by the telluric line model and further divided by the time average telluric line removed spectra.

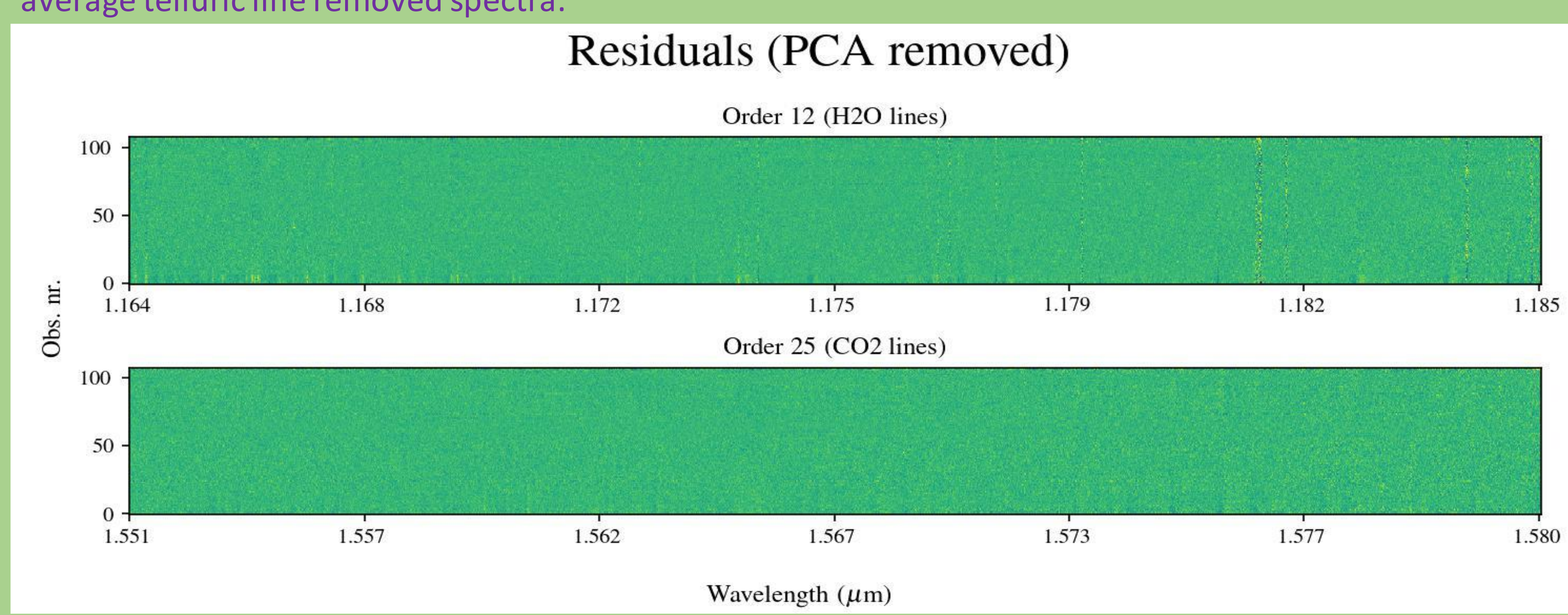

Figure 6: Data shown in Figure 5 divided by the PCA model.

5 - Future work

- Inject and recover planetary signals to determine the quality of our telluric line removal compared to PCA and Molecfit.
- Apply correction to different stellar types and different spectrographs.

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