Atmospheric calibration for photometric correction at the Vera Rubin Observatory

The auxiliary telescope

Sylvie Dagoret-Campagne (IJCLab)
Marc Moniez, Jeremy Neveu, Olivier Perdereau (IJCLab)
Laurent Le Guillou (LPNHE)

IJCLAB, IN2P3-CNRS, Universite Paris-Saclay

October 15, 2020

Action Dark Energy, October 13th-15th 2020

Outline

Motivations for magnitude calibration

- Photo-z's
- Supernovae cosmology and others...
- Other non-Dark Energy science (Stellar physics by ex. photometric metallicity)

Review of photometric calibration

The magnitude in filter b to be published in catalog

The standard magnitude at VRO, (extrapolated above the atmosphere)

$$m_b^{std} = -2.5 \times \log_{10}\left(\frac{\int_0^\infty F_\nu(\lambda)\phi_b^{std}(\lambda)d\lambda}{F_{AB}}\right)$$

- $F_\nu(\lambda)$: Spectral energy distribution (SED) of the source in unit of $10^{-23}\mathrm{erg/cm^2/s/Hz}$ or Jansky (Jy),
- $\phi_b^{std}(\lambda)$: Normalised standard passband b (averaged, stable during survey and specific to VRO) to be specified (ex at commissioning),
- $F_{AB} = 3631$ Jy : External Absolute reference calibration, reference flat SED, ($\rightarrow$ StarDice project to calibrate external star reference with a lab source reference.)

The measured magnitude at Rubin Observatory (LSST)

Dependence of standard magnitude on instrumental magnitude and calibration terms

$$m_b^{std} = m_b^{inst}(t) + \Delta m_b^{obs}(t) + Z_b^{obs}(t)$$

- $m_b^{inst}(t) = -2.5 \log_{10} \left(\frac{F_b^{obs}(t)}{F_{AB}} \right)$: the instrumental magnitude which vary at each observation,
- $F_b^{obs}(t) = \int_0^\infty F_\nu(\lambda) \phi_b^{obs}(\lambda, t) d\lambda$: the observed flux

Calibration terms

- $\Delta m_b^{obs}(t) = 2.5 \log_{10} \left(\frac{\int_0^\infty F_\nu(\lambda) \phi_b^{obs}(\lambda, t) d\lambda}{\int_0^\infty F_\nu(\lambda) \phi_b^{std}(\lambda) d\lambda} \right)$: the pure color magnitude correction term evaluated at each observation or each night, used when SED is known.
- $Z_b^{obs}(t)$: the Zero point correcting any grey scale from pixel scale to full CCD scale.

The measured magnitude at Rubin Observatory (LSST)

Dependence of standard magnitude on instrumental magnitude and calibration terms

$$m_b^{std} = -2.5 \log_{10} C_b^{obs}(t) + \Delta m_b^{obs}(t) + Z_b^{obs}(t)$$

instrumental photometry measurement

- $C_b^{obs}(t)$: Number of counts in ADU (or photoelectrons) in passband b measured by aperture photometry,

Zero point

$$\begin{aligned} Z_b^{obs}(t) &= 2.5 \log_{10} F_{AB} \\ &\quad \text{(absolute calibration scale)}, \\ &+ 2.5 \log_{10} \left(\frac{\pi D^2 \Delta t}{4hg} \right), \\ &\quad \text{(conversion term of flux term in photoelectron or ADU)} \\ &+ 2.5 \log_{10} \left(\int_0^\infty T^{atm}(\lambda, alt, az, t) \cdot T_b^{tel}(\lambda, x, y, t) \frac{d\lambda}{\lambda} \right), \\ &\quad \text{atmospheric and telescope zero point.} \end{aligned}$$

The normalized passband

Observation passband and average passband

$$\phi_b^{obs}(\lambda, t) = \frac{T^{atm}(\lambda, alt, az, t) \cdot T_b^{tel}(\lambda, x, y, t) \cdot \frac{1}{\lambda}}{\int_0^\infty T^{atm}(\lambda, alt, az, t) \cdot T_b^{tel}(\lambda, x, y, t) \cdot \frac{d\lambda}{\lambda}}$$

$$\phi_b^{std}(\lambda) = \frac{\overline{T^{atm}}(\lambda) \cdot \overline{T_b^{tel}}(\lambda) \cdot \frac{1}{\lambda}}{\int_0^\infty \overline{T^{atm}}(\lambda) \cdot \overline{T_b^{tel}}(\lambda) \cdot \frac{d\lambda}{\lambda}}$$

- $T^{atm}(\lambda, alt, az, t)$: atmospheric transmission,
- $T_b^{tel}(\lambda, x, y, t)$: telescope transmission : optical throughput, CCD quantum efficiency, electronic gain,...,

When calculated and used

- $\phi_b^{std}(\lambda)$: determined during commissioning (or maybe at each data-release),
- $\phi_b^{obs}(\lambda, t)$: should be evaluated at each observation, to correct magnitudes for some object of known SED. Could be used for later analysis.

The photometric requirements on m_b^{std}

1) Repeatability during 10 years

- 5 mmag in griz
- 7.5 mmag in uy

2) uniformity in (alt, az), and (x, y)

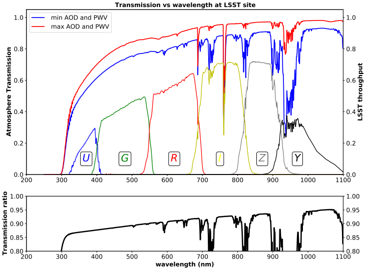
- 10 mmag in griz
- 20 mmag in uy

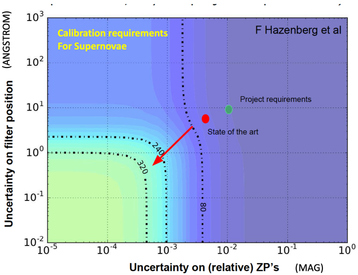
3) band to band photometric calibration

- 10 mmag in griz
- 20 mmag in uy

4) Absolute photometric calibration

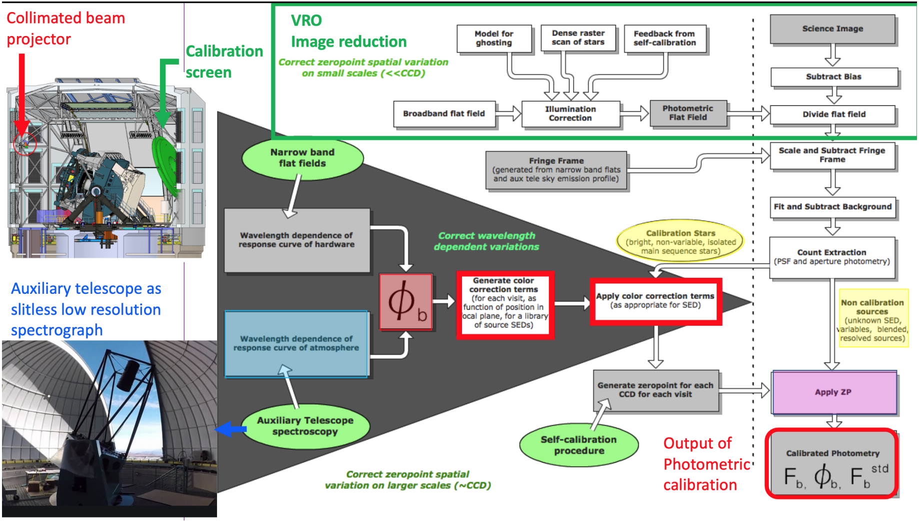
- 10 mmag in griz
- 20 mmag in uy





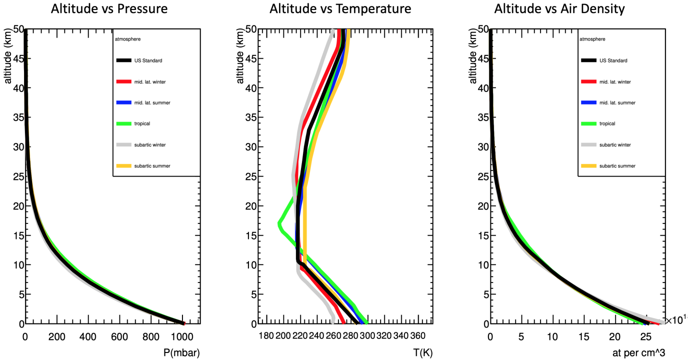
Photometric calibration strategy summary

and piece of hardware used



The atmospheric model (model assumption in LibRadtran)

A) The stable thermodynamic quantities : Pressure, Temperature density vertical profiles



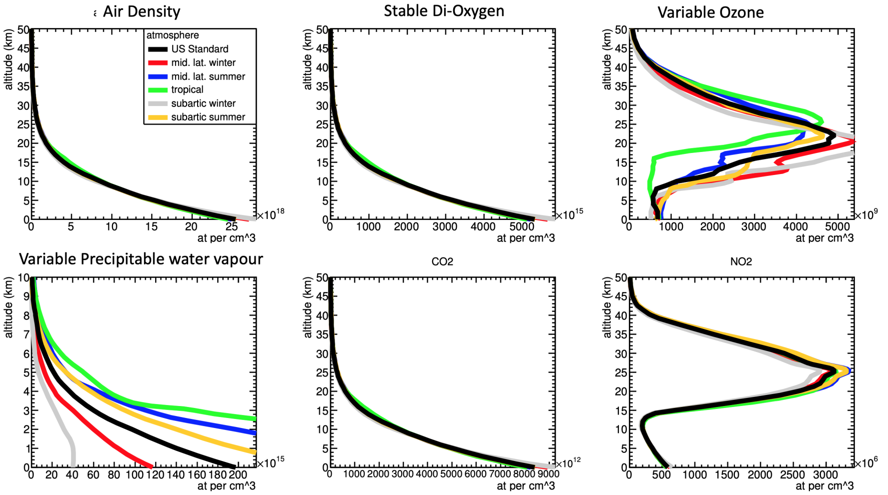
- atmospheric models in LibRadtran,
- choose one model (US standard) to infer its atmospheric parameters with data.

Different base assumption

- US standard atmosphere,
- mid-latitude summer or winter,
- arctic summer or arctic winter,
- tropical atmosphere.

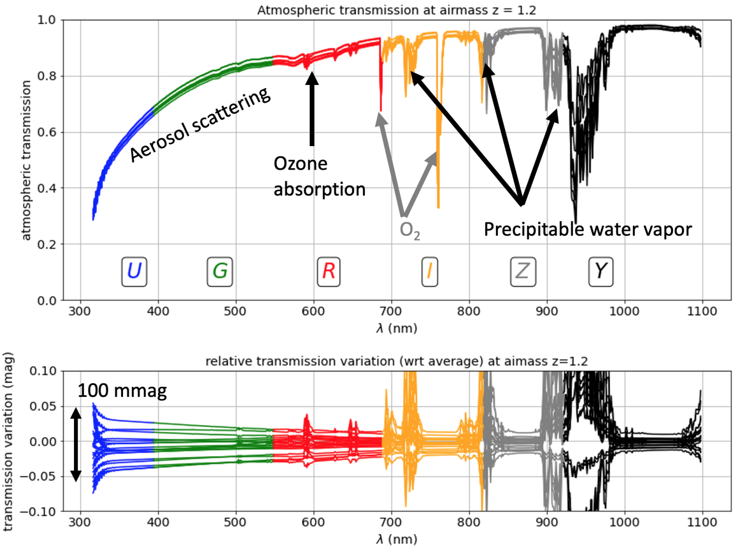
The atmospheric model components (parameters in LibRadtran)

B) The chemical components density vertical profiles: Precipitable water vapor, ozone density vertical profiles (Oxygen not tunable)

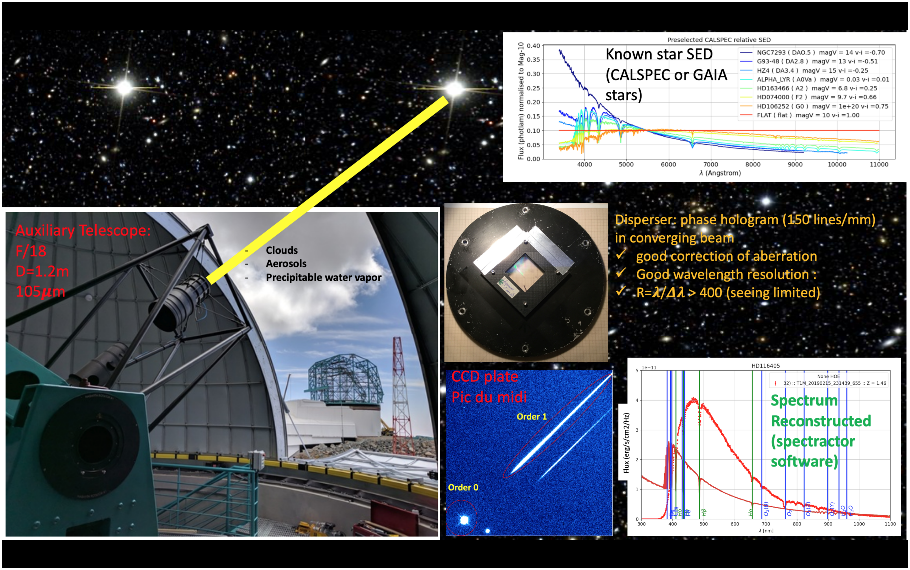


The atmospheric transmission (output of LibRadtran)

Impact on transmission of varying parameters, at VRO (h=2.7 km)



Atmospheric transmission measurement with Auxiliary Telescope



Mathematical model for atmospheric transmission

Model of spectra at Auxiliary telescope

$$
\begin{aligned}
\delta F(\lambda,t)|_{ADU} &= \frac{S_{coll}}{g_{el}} \cdot T^{atm}(\lambda,t) \cdot T^{opt}(\lambda) \cdot T^{disp}(\lambda) \\
& \times \epsilon_{CCD}(\lambda) \cdot \frac{dN_\gamma}{d\lambda}(\lambda) d\lambda \\
&= Cte(\lambda) \times T^{atm}(\lambda,t) d\lambda \\
T^{atm}(\lambda,t) &= \exp\left(-\tau_{cld}(t)z - \tau_{ray}(\lambda)z - \tau_{aer}(\lambda,t)z \right. \\
& \left. - \sum_{n=O_2,O_3,H_2O} \kappa_n(\lambda,t) f_n(z)\right) \\
\tau_{ray}(\lambda) &\approx \tau_{ray} \cdot g_{ray}(\lambda) \\
\tau_{aer}(\lambda,t) &\approx \tau_{aer}(t) \cdot g_{aer}(\lambda) \\
\kappa_n(\lambda,t) &\approx \kappa_n(t) \cdot g_n(\lambda) \\
g_n(\lambda), \kappa_n(\lambda) & \quad \text{known templates} \\
f_n(z) &\approx z^\gamma \ , \ \frac{1}{2} \leq \gamma \leq 1 \ \text{ z airmass}
\end{aligned}
$$

- Flux at AT
- Atmospheric transmission
- Extinction due to light scattering (Rayleigh and aerosols)
- Extinction due to light absorption (Rayleigh and aerosols)
- Atmospheric depth (airmass $z \approx \frac{1}{\cos\theta_z}$)

Mathematical model linearisation with magnitudes

$$\frac{2.3}{2.5} m(\lambda, t) = Cte(\lambda) + \tau_{ray}(\lambda) \cdot z + \tau_{cld}(t) \cdot z + \tau_{aer}(t) \cdot g_{aer}(\lambda) \cdot z + \sum_{n=O_2,O_3,H_2O} \kappa_n(t) g_n(\lambda) \cdot f_n(z)$$

$$t \rightarrow i \text{ sample number, } 0 \leq i \leq N_{obs}$$

$$\lambda \rightarrow j \text{ wavelength index, } j < 700 \ (400nm \leq \lambda < 1100nm)$$

$$m_j'^i = \tau_{cld}^i + g_{aer\,j} \cdot \tau_{aer}^i + \sum_{n=O_3,H_2O} g_{n\ j} \cdot h_n(z) \cdot \kappa_n^i$$

$$m_j'^{\,i} = \frac{\frac{2.3}{2.5} m_j^i - Cte_j}{z} - \tau_{ray\,j} - g_{O_2\ j} \cdot h_{O_2}(z) \cdot \kappa_{O_2}$$

$$h_n(z) = \frac{f_n(z)}{z} \quad (\mathrm{h}_n(z) \approx 1 \text{ except where absorption saturates})$$

Definition of the parameters

- a priori known constants :
  - Cte_j known from instrument calibration
  - $\tau_{ray\,j}$ known from atmospheric model , ex LibRadtran, (analitic formula known)
  - $g_{aer\,j}$ known from atmospheric model , ex LibRadtran,
  - $g_{O_2\,j}$ known from atmospheric model , ex LibRadtran,
  - $g_{O_3\,j}, g_{H_2O\,j}$ known from atmospheric model , ex LibRadtran,
  - $f_n(z)$ known from atmospheric model , ex LibRadtran
- for each spectrum observation i :
  - $\approx$ 700 j-observations m_j^i (or $m_j'^i$),
  - only 4 unknown variables to estimate: τ_{cld}^i,τ_{aer}^i, $\kappa_{O_3}^i$,κ_{H2O}^i,
  - linear equations between observed variables and variables to estimate.

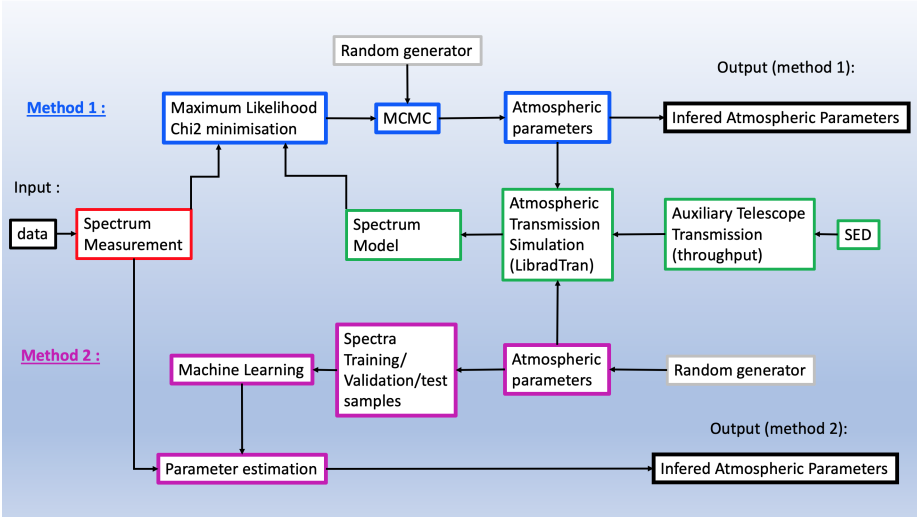
Atmospheric parameters estimation by ML linear regression

Mathematical model for ML (method 2)

$$
\begin{aligned}
\tau^i_{cld} &= \beta_0^{cld} + \sum_{j=1}^{N_j} \beta_j^{cld,1} \cdot m_j^i + \sum_{j=1}^{N_j} \beta_j^{cld,2} \cdot m_j^i / z^i \\
\tau^i_{aer} &= \beta_0^{aer} + \sum_{j=1}^{N_j} \beta_j^{aer,1} \cdot m_j^i + \sum_{j=1}^{N_j} \beta_j^{aer,2} \cdot m_j^i / z^i \\
\kappa^i_{O_3} &= \beta_0^{O_3} + \sum_{j=1}^{N_j} \beta_j^{O_3,1} \cdot m_j^i + \sum_{j=1}^{N_j} \beta_j^{O_3,2} \cdot m_j^i / z^i \\
\kappa^i_{H_2O} &= \beta_0^{H_2O} + \sum_{j=1}^{N_j} \beta_j^{H_2O,1} \cdot m_j^i + \sum_{j=1}^{N_j} \beta_j^{H_2O,2} \cdot m_j^i / z^i
\end{aligned}
$$

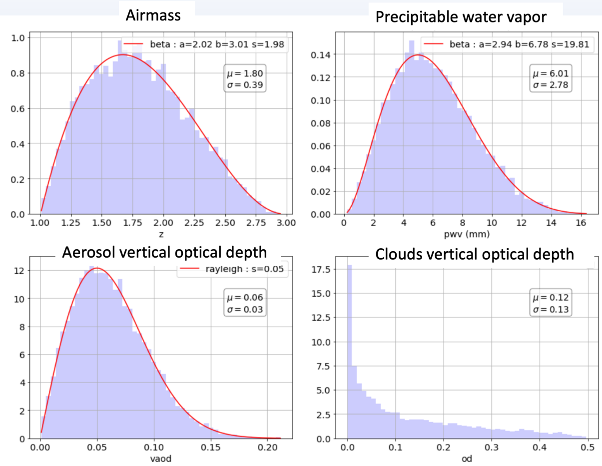
- $i \rightarrow$ index of observation number, $j \rightarrow$ wavelength index
- Features m_j^i / z^i,
- β_j^n : $2 \times 4 \times (N_j + 1)$ parameters to estimate by training on simulated training set and tested on simulated testing set.

Methods for atmospheric parameters inference



Generation of atmospheric parameters

simulation of atmosphere



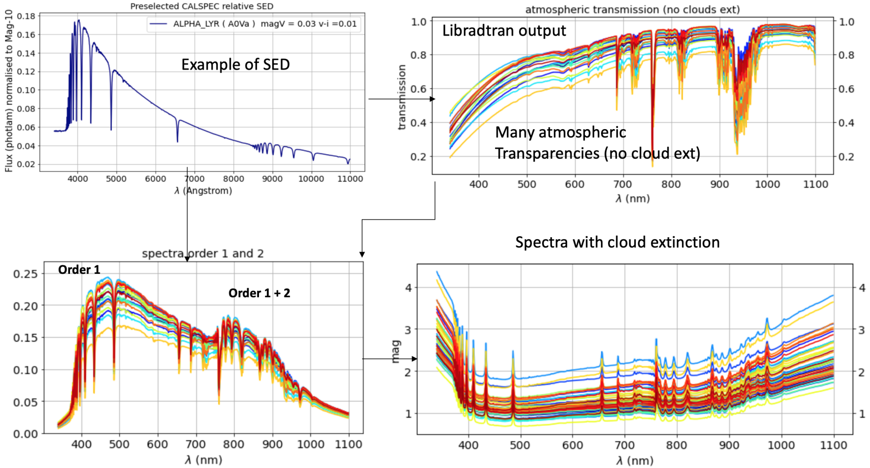
Clouds:

- 53% nights : od < 1-2 %
- 85% nights :
  - ✓ m_{cld} < 1.5 mag
  - ✓ od < 0.14

(od : optical depth)

Simulation of observed spectra

simulation for VRO observation site (h=2.7 km)

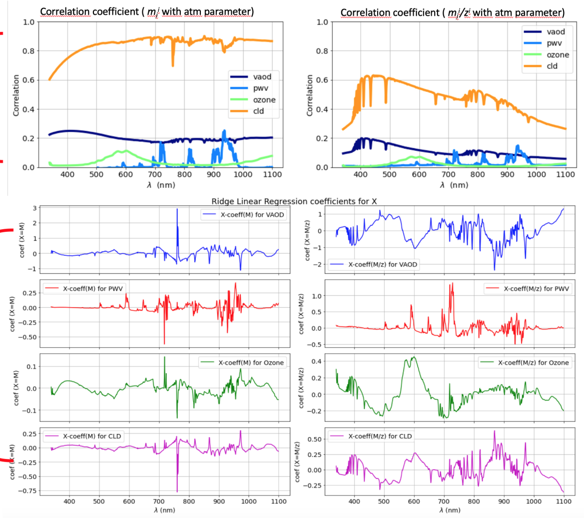


Correlation between atmospheric parameters and features m_j and m_j/z

simulation at VRO (h=2.7 km) + ML Linear Regression with Ridge (L2) regularisation of coefficients

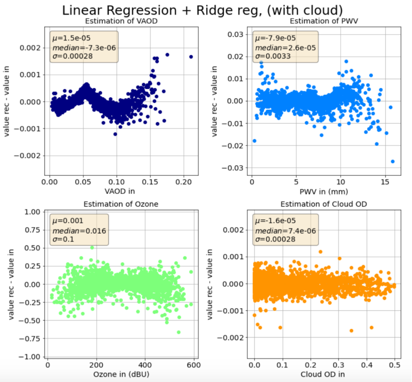
Correlation coefficients

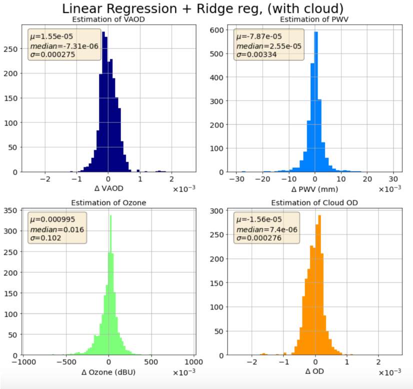
Linear Regression parameters (Ridge reg)



Resolution on inferred atmospheric parameters

simulation at VRO (h=2.7 km) + ML Linear Regression with Ridge (L2) regularisation of coefficients



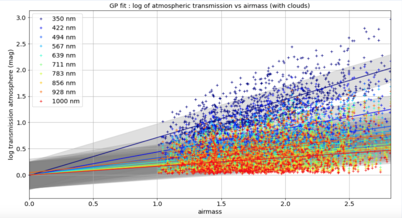


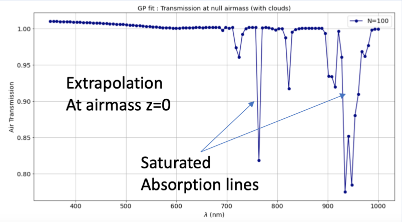
- The linear regression model fits with Ridge regularisation $\alpha = 10^{-3}$ very well the simulated data.
- The accuracy limitation will come mainly from photoelectron statistics and sky background (for moderate star brightness),
- But is assumes the instrument throughput is well known.

Estimation of the telescope throughput: Bouguer lines : Mag vs airmass

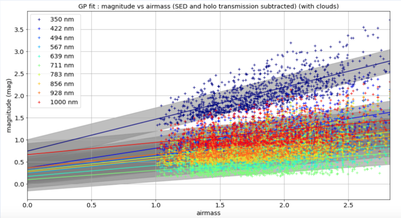
simulation at VRO (h=2.7 km)

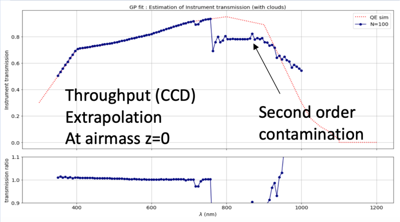
Fit only atmosphere





Fit only $M_{obs} - M_{source}$ - $M_{disperser}$

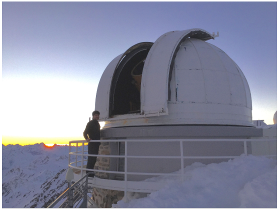




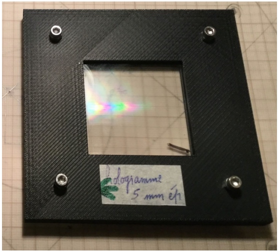
Observational data at Pic du Midi observatory (h=2.9 km)

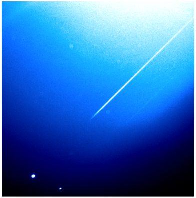
Observation of calibration star CALSPEC HD116405 at night 2020-02-15

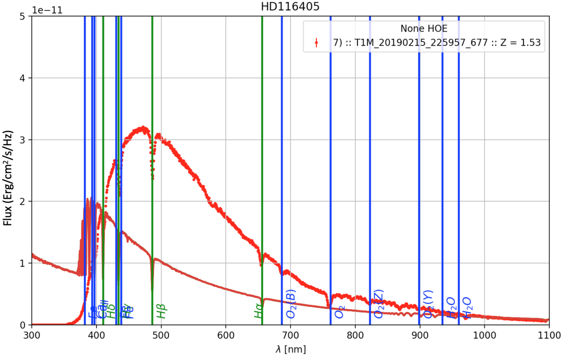
Pic du midi coupole



Phase Hologram

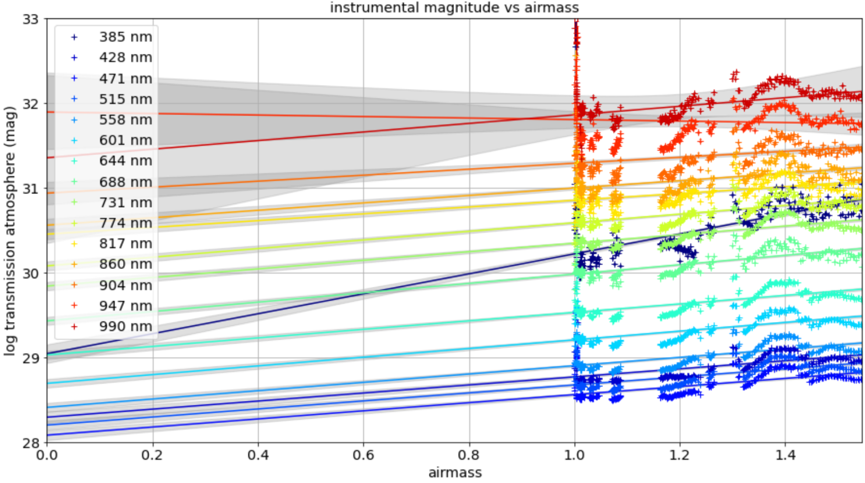






Bouguer lines fit on data

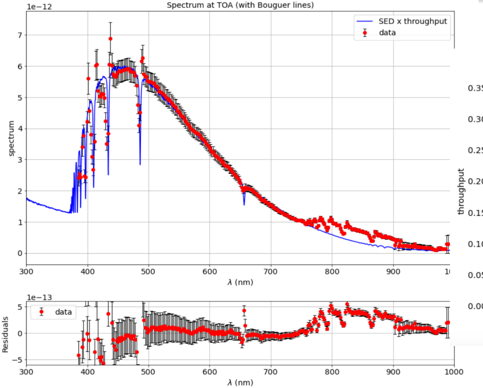
Observation of calibration star CALSPEC HD116405 at PDM VRO (h=2.7 km) during night 2020-02-15



Extrapolation of Bouguer lines at airmass $z = 0$

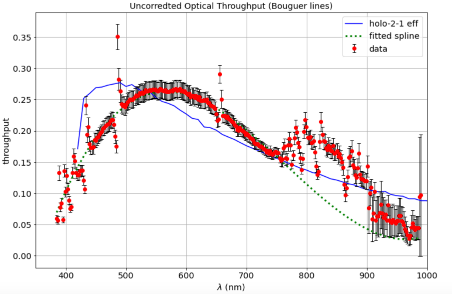
Observation of calibration star CALSPEC HD116405 at PDM VRO (h=2.7 km) during night 2020-02-15

Extrapolated Spectrum above the atmosphere



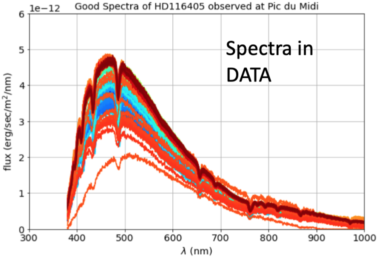
Estimation of the throughput at Pic du Midi

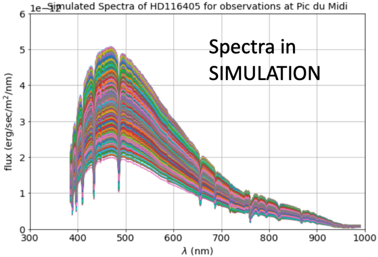
including hologram efficiency



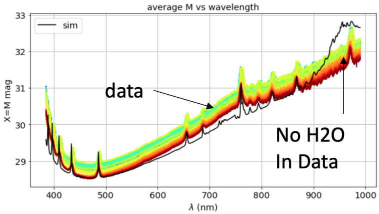
Comparison of experimental spectra with simulated spectra

Observation of calibration star CALSPEC HD116405 at PDM VRO (h=2.7 km) during night 2020-02-15

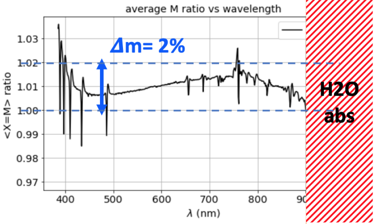




Magnitudes vs airmass



Magnitudes ratio data/sim : thrp. error



Summary, Lesson learned and Take home message (1)

- Ground cosmological survey requires Photometric corrections (1-5 mmag) and implies accurate measuring the atmospheric transparency :
  - $T^{atm}(\lambda, t) \rightarrow \Delta m_b^{obs}(t)$ for each object $\rightarrow m_b^{std}$,
  - $\overline{T^{atm}}(\lambda) \rightarrow \phi_b^{std}(\lambda)$ at a average airmass.
- Need an atmospheric model (ex LibRadtran) + atmospheric parameters (clouds, aerosols, precipitable water vapour, Ozone) to be estimated by some method,
  - Data on Bouguer lines indicate exponential attenuation is relevant, (get telescope throughput at percent level),
  - Data may suggest aerosol template profile in LibRadtran may be not relevant,
- Which is the accuracy required on telescope throughput, including CCD Quantum Efficiency, optical throughput, disperser efficiency ?
  - Method of fitting Bouguer lines interesting but must be improved on bias and statistical errors,
  - Phase holograms have good wavelength resolution, small aberration, good efficiency,
  - Second order correction for holograms.

Summary, Lesson learned and Take home message (2)

- Method of inference, model used in ML (In Progress by now !):
  - ML : Linear Regression + Regularisation (L2 = Ridge) evaluated on observation at Pic du Midi
  - improve aerosol model,
  - check impact of telescope throughput accuracy,
  - improve ML model (more robust):
    - features : group wavelength bins - spectra smearing, wavelet decomposition, $\cdots$
    - extension of ML to non linear model $\cdots$,
- Need more data to tune atmospheric model (at VRO site) $\rightarrow$ commissioning should start soon.