A.T. Observation strategy:
(Redundant) (Composite) Forward Atmospheric Modeling

\[ T_{\text{atmo}}(\lambda, t, \text{alt}, \text{az}) \]
### Strategies

To deliver a %\text{‰} level monitoring of atmospheric transparency

<table>
<thead>
<tr>
<th>Strategies</th>
<th>AOD+PWV+Mol.Scattering+Ozone Model from</th>
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<td>10-4 electronic</td>
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<td>Steady sources</td>
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<td>MERRA-2</td>
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<td>SED</td>
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<td>Telescope Throughput</td>
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<td>Global fit+priors+nuisance parameters</td>
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<td></td>
<td>Splitted fit</td>
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<td>Hopeless global fit</td>
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- Variability is introduced either by
  - The target
  - The atmosphere
  - The extraction
An holistic approach, that is, exploring all methods:

1) Global fit @ CTIO 0.9m
2) SNFactory @ Mauna Kea
3) Composite solution @ CTIO 0.9m
4) PCWG experts + data challenge
• CALSPEC SED and atmospheric transmission from Libradtran

\[ \Phi(\lambda; \sigma, \text{atm}) = [\text{SED}(\lambda)] \times [T(\lambda, \text{PWV}, \text{VAOD}, \text{OZ})] \times G(\sigma) \]

\[ S(\lambda; \text{params}) = A_1 \left[ \Phi(D_{\text{CCD}}, \alpha_{pix}) + A_2 \left( \frac{1}{2} \lambda(D_{\text{CCD}}, \alpha_{pix}) \right) \right] \]

• 8 parameters to fit (3 atmospheric, 5 instrumental): python EMCEE

**Atmospheric parameters:**
PWV: water; VAOD: aerosols; OZ: ozone

**Instrumental effects:**
- \( A_1 \): general amplitude of the spectrum
- \( A_2 \): level of the order 2 contamination
- \( G(\sigma) \): Gaussian convolution with \( \sigma \) modeling the resolution and the seeing
- \( D_{\text{CCD}} \): the distance between the CCD and the disperser
- \( \alpha_{pix} \): shift in pixels on the order 0 position to calibrate the wavelengths
Test of the fitter on a simulated spectra

From J. Neveu

Global fit + priors + (nuisance parameters)

Target: HD111980

MCMC OK.

A1  A2  ozone  PWV  AOD  reso (pix)  Dccd (mm)  α (pix)
From J. Neveu

Global fit + priors + (nuisance parameters)

Ronchi 400: #130 2017/05/31 02h45 UTC

Target: HD111980

A1 = 1.068, A2 = 0.001, PWV = 2.291, OZ = 333, VAOD = 0.080, reso = 7.25 pix, D = 56.52 mm, shift = -11.33 pix.
Ronchi 400: #130 2017/05/31 02h45 UTC

Target: HD111980

Nuisance parameters
1. Pixel-to-wavelength transformation
2. Resolution
3. Second order light contamination

Atmospheric parameters
4-5. Large uncertainty on PWV and ozone
6. AOD correlates with telescope throughput
Global fit - Lesson learnt from SNFactory

Atmospheric extinction properties above Mauna Kea from the Nearby Supernova Factory spectro-photometric data set


- Snif instrument on the UH telescope at Mauna Kea has been routinely observing standard stars since 2006.
- 4285 spectra from 478 nights.
- Overnight instrument response stability much better than 1%.
- Spectra extraction based on a detailed optical model.
- Wavelength-calibrated using arc lamp exposures acquired immediately after the science exposures.
- Spectro-spatially flatfielded using continuum lamp exposures obtained during the same night.
- Chromatic semi-analytical PSF model (a constrained sum of a Gaussian and a Moffat function) fit over a uniform background.
Global fit - Lesson learn from SNFactory

Residuals of the $\chi^2$ for an individual observation $i$ of the atmospheric extinction in mag/airmass:

$$R_i = \log C(\lambda) - 0.4 \times K_{\text{atm}}(\lambda, \hat{z}) + \log \delta T_i(\hat{z}, t) - \log \frac{S_i(\lambda, \hat{z}, t)}{S^*_i(\lambda)}$$

- Rayleigh scattering is not adjusted, it is determined from the surface pressure.
- Telluric lines are adjusted in a different step.
- There is a degeneracy between $\delta T$ and $\tau \sim \lambda$ 0 on non-photometric nights,
- And between $\delta T$ and $C$.

(Gaussian) Bayesian priors

<table>
<thead>
<tr>
<th>Prior</th>
<th>Value</th>
<th>Scaling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I^*_O3$</td>
<td>260 ± 50 DU</td>
<td>linear</td>
</tr>
<tr>
<td>$\tau^*$</td>
<td>0.007 ± 80%</td>
<td>logarithmic</td>
</tr>
<tr>
<td>$\alpha^*$</td>
<td>1 ± 3</td>
<td>linear</td>
</tr>
</tbody>
</table>

Instrument calibration, Gray extinction, SED, O3, aerosols
Global fit - Lesson learn from SNFactory

O₂ lines fluctuations are remarkably small.

**Rayleigh extinction**
Peak-to-peak variation of 6 mbar around 616 mbar.
Dispersion of 2 mbar which translate into $2 \text{ mmag/airmass}$ at the blue edge.

**Ozone** Varying mostly on seasonal timescales.
60 DU uncertainty with no prior.
Difficult to detect 20 DU variation ($4 \text{ mmag/airmass}$ at 6000 Å.)
$\rightarrow$ Better to use a dedicated probe.

**H₂O** Has large fluctuations.

**Aerosol** Largest contributor to the variability of the extinction continuum from one night to another.
$\sim10-40 \text{ mmag/airmass}$ overnight $\rightarrow$ the primary concern for extinction variations.
δT is degenerated with an aerosol extinction having an Ångstrom exponent of zero.

limited temporal sampling during each night $\rightarrow$ difficult to detect extinction variability of less than 1%

**Overall relative error of 2-3%**
Going beyond the current limitations with a composite solution
Using MERRA-2 global modeling system:

**Ozone**  MERRA-2 tables provides an accurate estimate.

**Molecular scattering**

MERRA-2 tables and weather balloons are in excellent agreement.

—> Impact LibRadTran transmission by < %.

**PWV**  Smooth variation and axis-symmetry approximations are not valid.

—> H2O EW [880 - 990] nm from single order blocking filter exposure.

**AOD**  Degenerated both with telescope throughput and SED uncertainties

—> Pair of exposures method.
MERRA-2 ozone

< Oct. 1st. 2004

From Solar Backscatter Ultra Violet Radiometers (SBUV)
Assimilates partial column ozone on 21 layers, each ~3km deep.

> Oct. 1st. 2004

Stratospheric profiles from the Microwave Limb Sounder (MLS, Waters et al. 2006) instrument and total ozone column observations from the Ozone Monitoring Instrument (OMI), Onboard NASA’s Earth Observing System Aura (EOS Aura) satellite.

Comparing OMI with ground-based measurements and with aircraft for four campaign missions. (McPeters et al. 2008):

+ 0.4 % offset with respect to ground-based measurements,
- 0.2 % offset with aircraft measurements and an RMS difference of 3%.

—> For 300 DU, these numbers indicate an offset of ~1 DU and RMS difference of 9 DU.
Chile, 8 years of ozone data above Cerro Pachon

1 Dobson E-W gradient

https://confluence.lsstcorp.org/display/DM/Atmospheric+parameters+horizontal+gradients+above+CTIO

Ozone above Cerro Pachon resides predominantly in the upper troposphere and lower stratosphere, and driven by jet stream winds, can vary 5%-10% day-to-day around average values that exhibit season variations of 25% or so.
The ozone layer is well above the mountains, it is not much affected by local condition. —> 2-D interpolation of MERRA-2 table probably ok
Weather Balloons Vs. MERRA-2
Temperature and barometric profile

Daily launch of weather balloons

![Map showing location of LSST and Antofagasta, Chile with a 200km scale marker.](image-url)
Weather Balloons Vs. MERRA-2
Temperature and barometric profile

Daily launch of weather balloons

excellent agreement…
Weather Balloons Vs. MERRA-2
Temperature and barometric profile

Daily launch of weather balloons

![Map of Chili with cities marked: Antofagasta, Mejillones, Taltal, Copiapó, Vallenar, La Serena, LSST.]

Weather Balloons

Pressure (Pa)

Temperature (K)

Excellent agreement…

Weather balloons above Cerro Pachon?
Steady non axis-symmetry of H2O component

- large east-west PWV gradient.

![Graph showing PWV gradient over days (2017) with distinct lines for SN and WE gradients.](image-url)
Strong variability near the ground layer

MERRA-2 PWV profiles may not represent the local atmospheric conditions of the geographical position and height of the observing site.
Measurement along the line-of-sight

$$EW = \int \frac{(\phi_{continuum} - \phi_{line})}{\phi_{continuum}} d\lambda$$
Measurement along the line-of-sight

CTIO 01/10/17

![Graph showing EW H2O (nm) vs Airmass with various lines and markers indicating simulated and observed PWV.](image-url)
AOD determination

\[ S(\lambda, z, t) = SED(\lambda) \times T_{tel}(\lambda, t) \times T_{atmo}(\lambda, z, t) \quad (1) \]

Examining the same target at two different airmasses \( z_1, z_2 \):

\[ \frac{S_{z1}(\lambda)}{S_{z2}(\lambda)} = \frac{T_{z1}^{\text{atmo}}(\lambda)}{T_{z2}^{\text{atmo}}(\lambda)} \]

Using an inverse power law for the chromaticity of the aerosol scattering:

\[ k_A(\lambda) = \tau \lambda^{-\alpha} \]

Rewriting Equation (1):

\[ \frac{S_{z1}(\lambda)}{S_{z2}(\lambda)} = \frac{10^{-0.4z_1(k_r(\lambda)+k_o(\lambda))}}{10^{-0.4z_2(k_r(\lambda)+k_o(\lambda))}} \cdot 10^{-0.4z_1\tau\lambda^{-\alpha}} \]

Using radiative transfer simulation of the observations without aerosols:

\[ \left( \frac{S_{z1}(\lambda)}{S_{z2}(\lambda)} \right) \left( \frac{T_{z1}^{\text{atmosim}}(\lambda) / (T_{z2}^{\text{atmosim}}(\lambda))}{T_{z1}^{\text{noA}}(\lambda) / (T_{z2}^{\text{noA}}(\lambda))} \right) = 10^{-0.4(z_2-z_1)\tau\lambda^{-\alpha}} \]
AOD Fitting interval

Wght solution Unreliable below 400nm

H2O lines

Fitting Range
Practical test

LamLep in a time series - October 9th, 2017

Aerosol Fitting Range
AOD pair of exposures method

$\Delta \text{AOD } 0.01 \rightarrow \Delta \text{Tatmo} \sim 1\% \ @ \ 500\text{nm}$
PCWG experts + data challenge

- What can we learn from LSST measurements themselves:
  
  ~ $10^4$ i < 19 stars / exposure
  
  most often with good color diversity
  
  uniformized mags sensitive to Tatmo at the level of a few mmag

How can calibration residuals help constrain the variations of Tatmo?
We will discuss tomorrow

How ancillary data could be further assimilated to improve our measurement
Discussion

Observation cadence?
— Do we want a telescope throughput determination from airmass regression?
— Cadence for order blocking exposure in LSST field ($\Delta$PWV~1mm/hour)?
— Broadband exposure in LSST field to align telescopes photometry and Checks against synthetic photometry?

What else?
Atmospheric transparency at LSST: What we can expect

<table>
<thead>
<tr>
<th>Parameter Variability</th>
<th>Impact on transmission</th>
<th>Achievable precision</th>
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<tr>
<td>$\Delta$ O3 $\sim$ 20 Dobsons overnight</td>
<td>8% variation</td>
<td>$\sigma_{\text{O3}} \sim$ 6 Dobsons</td>
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<tr>
<td></td>
<td>4 mmag/airmass</td>
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<tr>
<td></td>
<td>@ 6000 Å O3 peak</td>
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<tr>
<td></td>
<td>Buton et al. 2012</td>
<td>From MERRA-2</td>
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<tr>
<td>$\Delta$ PWV $\sim$ 1 mm hourly</td>
<td>$\Delta T_{\text{trans}} \sim$ 3% @ 900 nm</td>
<td>$\sigma_{\text{pwv}} \sim$ 0.3 mm</td>
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<tr>
<td>$\Delta$ AOD $\sim$ 0.05 overnight</td>
<td>$\Delta$ AOD $0.01$→ $\Delta T_{\text{atmo}} \sim$ 1% @ 500nm</td>
<td>$\sigma_{\text{AOD}} \sim$ 0.02</td>
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<td></td>
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