Atmospheric Contamination for CMB Ground-Based Observations

4th COSMOS WORKSHOP: Ground-Based CMB experiments

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Unwanted effects from the atmosphere

- Thermal contribution around of 15 K
- Increase of the optical load on each detector, increase of their effective noise;
- Presence of spin synchronous signal for stable enough atmosphere
  - Low wind speed compared to the scan speed

A 3D description of the atmosphere

Atmosphere antenna temperature in $\hat{r}_s$ direction:

$$T_A = \frac{1}{\lambda^2} \int \frac{d\vec{r}}{r^2} B(\hat{r}_s, \vec{r}) \alpha(\vec{r}) T_p(\vec{r})$$

$\alpha(\vec{r})$ describes the whole atmosphere:

- Spatial structures distributions
- Time evolution

Due to its complexity the function $\alpha(\vec{r})$ is unknown!

A time saving approach - Atmosphere correlations

Ok... $\alpha(\vec{r})$ is unknown. I can evaluated the atmospheric correlation

Two points correlation

$$C_{ij}^{tt'} = \left\langle T_A^i(r), T_A^j(r') \right\rangle =$$
$$= \frac{1}{\lambda^4} \int \frac{d\vec{r}}{r^2} \int \frac{d\vec{r'}}{r'^2} B(\hat{r}_s^i(t), \vec{r}) B(\hat{r}_s^j(t'), \vec{r'}) \times$$
$$\times \left\langle \alpha(\vec{r}), \alpha(\vec{r'}) \right\rangle T_p(\vec{r}) T_p(\vec{r'})$$

$C_{ij}^{tt'}$ is defined for two detectors i and j that observe the sky in the directions $\hat{r}_s^i$ e $\hat{r}_s^i$ at the times t e t' [1]

[1] ERRARD, J., et al. Modeling atmospheric emission for CMB ground-based observations. The Astrophysical Journal, 2015, 809.1: 63

A time saving approach - Atmosphere correlations

Evaluation of correlation level between $\alpha(\vec{r})$ and $\alpha(\vec{r'})$

$$\left\langle \alpha(\vec{r}), \alpha(\vec{r'}) \right\rangle = \chi_1(\Delta\vec{r}) \cdot \chi_2(z, z')$$

Spatial distribution of the atmospheric fluctuations

$$\chi_1(\Delta\vec{r}) = \chi_1^0 \exp\left(-\frac{\Delta r^2}{2L_0}\right) \quad L_0 \text{ measurable}$$

Water vapor vertical profile

$$\chi_2(z, z') = \chi_2^0 \exp\left(-\frac{z + z'}{2z_0}\right) \quad z_0 \text{ measurable}$$

The atmosphere dynamic

The atmosphere evolution is due to the wind shear

- Uniform for all altitudes z;
- The atmosphere structures are rigidly moved by wind shear

$$\chi_1(\Delta\vec{r}) \rightarrow \chi_1(\Delta\vec{r} - \vec{W}\Delta t)$$

where

$$\vec{W} = W_x\hat{x} + W_y\hat{y} = W\hat{w}\ \forall z$$

Code check with POLARBEAR data

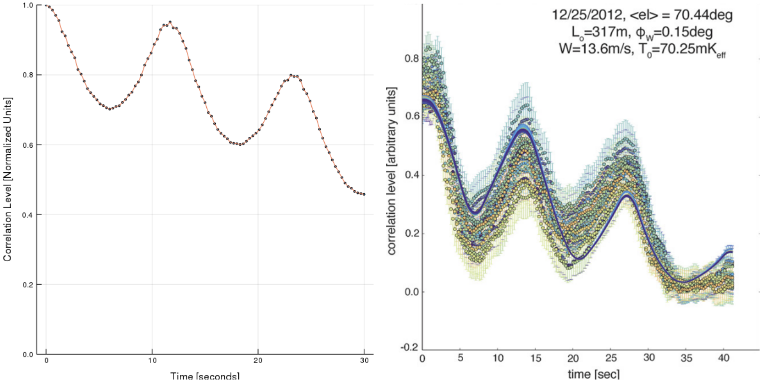
I have checked my code with POLARBEAR data presented in [2]

- Raster Scanning Strategy: $\phi_0 + \frac{\Delta a}{2} \cos(2\pi f_{scan} t + \psi)$ like STRIP-2
- $\Delta a = 5 deg.$
- $ss = 1 deg/sec$
- $f_{scan} = ss/\Delta a$

Evaluation of Auto-Correlation coefficient $C_{ij}^{tt'}$ with $j = i = 0$

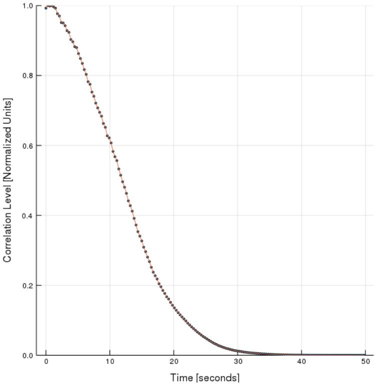
[2] ERRARD, J., et al. Modeling atmospheric emission for CMB ground-based observations. The Astrophysical Journal, 2015, 809.1: 63

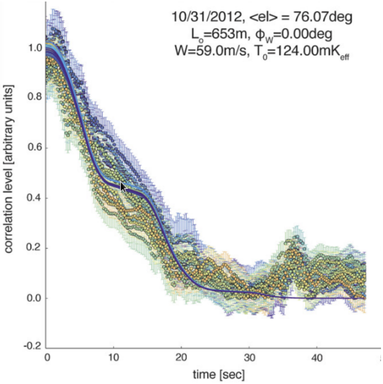
Code check with POLARBEAR data



Low wind speed: $W = 13.6$ m/s, and $\phi_w = 0.15$ deg

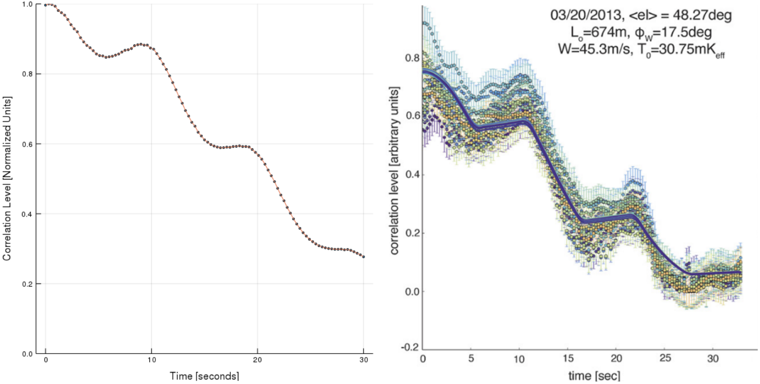
Code check with POLARBEAR data





High wind speed: $W = 59.0$ m/s, and $\phi_w = 0$ deg

Code check with POLARBEAR data



Halfway condition: $W = 45.3$ m/s, and $\phi_w = 17.5$ deg

Summary and on-going work

SUMMARY

- The atmosphere is not a constant optical load!
- Our code reproduces the main correlation features observed in the POLARBEAR data
- This tool will help optimise the scanning strategy for STRIP-2

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NEXT STEPS

- Extract from the auto-correlation pattern the information about the spurious signal of different atmospheres (wind speed/direction)
- Simulate a complete TOD (all noise sources + atmosphere): incidence on the scientific case
- Go over the code to reach best performance and make it usable on the department HPC cluster with docker or singularity

Thank you for the attention!

BS1: effective noise

Let s the CMB signal, n the total noise signal, the observed signal x is given by:

$$x = s + n \tag{1}$$

the S/N is given by

$$SNR = \frac{s + n}{\sqrt{s + n}} \tag{2}$$

so I have a better S/N on x, but it is got worse on s

BS2: Importance sampling integration

$$I = \int_{\Omega} d\vec{x}\, f(\vec{x}) \tag{3}$$

1. First integral evaluation $I = S = \frac{1}{N}\sum_{i=1}^{N} \frac{f(\vec{x}}{p(\vec{x})}$. With uniform random samples.
2. If I have M evaluations of the integral I: $\{S_\alpha\}_{\alpha=1}^{M}$:
   $I = \bar{\sigma}\sum_\alpha \frac{S_\alpha}{\sigma_\alpha^2}$
3. $\sigma_\alpha^2 = \frac{1}{N-1}\frac{1}{N}\sum_{i=1}^{N}\frac{f^2(\vec{x}_i)}{p(\vec{x}_i)} - S_\alpha^2$
4. The error is minimal iff $p(\vec{x}) = \frac{|f(\vec{x})|}{\int_\Omega d\vec{x}|f(\vec{x})|}$
5. Transformation 1: $\int_a^b f(x)dx = \int_0^1 f(y(b-a)+a)(b-a)\,dy$
6. Transformation 2: $\int_0^1 f(x)dx = \int_0^1 dy\, \frac{f(x)}{\beta x^{\beta-1}}\Big|_{y=x^\beta}$ per $\beta > 1$

BS3: The alpha function

Let τ the optical depth so

$$\Gamma = \exp(-\tau) = \exp\left[-m(\theta)\tau_0\right] \tag{4}$$

where $m(\theta)$ is the airmass as function of latitude elevation angle. Transmission $\Gamma(\lambda)$ and absorption $\alpha(\vec{r}, \lambda)$ are related by

$$\Gamma(\lambda) = \exp(-\tau(\lambda)) = \exp\left[-\int_0^r \alpha(r', \lambda) dr'\right] \tag{5}$$

and the term

$$\left[-\int_0^r \alpha(r', \lambda) dr'\right] \tag{6}$$

is not constant for $\theta = const.$ but it is in relation with spatial distribution of atmosphere structures.

BS4: Coordinate System