Synthetic and measured atmospheric spectra at mm and sub-mm wavelengths from Dome C

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Outline

Dome C atmospheric performance monitoring to support future sub&mm sky observations

1) A semi-empirical approach to perform analysis of atmospheric transmission and emission at Dome C:
   • Radiosoundings data + ATM spectra
   • Transmission & Emission statistics @ sub&mm bands
   • Atmosphere quality characterization
   • Noise constraints

2) A MP spectrometer to explore the 90–450 GHz (3–15 cm⁻¹) spectral region: CASPER 2
   • The instrument: telescope + MPI + altaz mount
   • Spectra acquisition: modus operandi & timescales
Semi-empirical approach: data + code

469 radiosounding measurements taken routinely at Dome C at 12:00 UTC from May 2005 to Jan 2007

Data Correction (Tomasi et al. 2006)

(i) the not correct calibration of the Barocap sensors;
(ii) the effects caused by solar and infrared radiation heating, heat conduction and ventilation on the Thermocap sensors;
(iii) lag errors, ground-check errors and dry biases of the Humicap sensors due to basic calibration model, chemical contamination, temperature dependence and sensor aging, corrected according to Wang et al. (2002).

Selected 7 observational bands

<table>
<thead>
<tr>
<th>Table 1. Characteristic spectral bands assumed in this work.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_0 ) (GHz)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>220</td>
</tr>
<tr>
<td>270</td>
</tr>
<tr>
<td>350</td>
</tr>
<tr>
<td>660</td>
</tr>
<tr>
<td>870</td>
</tr>
<tr>
<td>1500</td>
</tr>
</tbody>
</table>

Note. References: 1 – SPT, Schaffer et al. (2011); 2 – MITO, De Petris et al. (2002); 3 – ACT, Swetz et al. (2011); 4 – BRAIN, Battistelli et al. (2012); 5 – SCUBA, Holland et al. (1999); 6 – SCUBA-2, Dempsey et al. (2010); 7 – THUMPER, Ward-Thompson et al. (2005).

Millimetre and submillimetre atmospheric performance at Dome C combining radiosoundings and ATM synthetic spectra

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ATM
Atmospheric Transmission at Microwaves
Opacity
100 GHz – 2 THz

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Transmission cumulatives

Transmission quartiles

<table>
<thead>
<tr>
<th>$\nu_0$ (GHz)</th>
<th>$\lambda_0$ (μm)</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>2000</td>
<td>0.97</td>
<td>0.97</td>
<td>0.96</td>
</tr>
<tr>
<td>220</td>
<td>1400</td>
<td>0.95</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>270</td>
<td>1100</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
</tr>
<tr>
<td>350</td>
<td>860</td>
<td>0.91</td>
<td>0.89</td>
<td>0.87</td>
</tr>
<tr>
<td>660</td>
<td>450</td>
<td>0.64</td>
<td>0.56</td>
<td>0.46</td>
</tr>
<tr>
<td>870</td>
<td>350</td>
<td>0.58</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>1500</td>
<td>200</td>
<td>0.15</td>
<td>0.08</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Comparison with other available estimates for different periods & different sample durations

150 GHz: 95% median value by Battistelli et al. (2012) during the summer campaign in 2009 December/2010 January; 350 GHz: 95% median value by Battistelli et al. (2012) during the summer campaign in 2009 December/2010 January;

220 GHz: 95% median value by Valenziano & Dall’Oglio (1999) in 1997 January;

450 μm: 70% median transmission by Minier et al. (2008) in 2003-2008. 60% median winter value by Yang et al. (2010);

350 μm: 50% median value by Tremblin et al. (2011);

200 μm: 10% for 25th percentile by Tremblin et al. (2011); 13% for 25th percentile by Yang et al. (2010).

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pwv fluctuations

Daily values of pwv estimated from the 12:00 UTC radiosounding measurements performed at Dome C over the period from 2005 May to 2007 January. PWV seasonal variation with values lower than 0.3 mm and a mean dispersion of about 150 μm (on daily data)

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pwv fluctuations

The same amount of PWV variation contributes, with a different weight, to the total optical depth variations.

Optical depth fluctuations corresponding to a 150 μm PWV variation around 3 different average PWV values:

- 150 μm
- 500 μm
- 1 mm

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pwv fluctuations

comparison with other PWV Dome C estimates

Table 3. Pwv quartiles comparison.

<table>
<thead>
<tr>
<th>Period</th>
<th>25 per cent</th>
<th>50 per cent</th>
<th>75 per cent</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997 January</td>
<td>0.38</td>
<td>0.52</td>
<td>0.68</td>
<td>1</td>
</tr>
<tr>
<td>2005 May–2007 January</td>
<td>0.20</td>
<td>0.30</td>
<td>0.45</td>
<td>2</td>
</tr>
<tr>
<td>2008</td>
<td>0.15</td>
<td>0.24</td>
<td>...</td>
<td>3</td>
</tr>
<tr>
<td>2008–2010</td>
<td>0.21</td>
<td>0.27</td>
<td>0.35</td>
<td>4</td>
</tr>
<tr>
<td>2009 December–2010 January</td>
<td>0.49</td>
<td>0.75</td>
<td>1.1</td>
<td>5</td>
</tr>
</tbody>
</table>

Notes. References: 1 – Valenziano & Dall’Oglio (1999); 2 – this work; 3 – Yang et al. (2010); 4 – Tremblin et al. (2011); 5 – Battistelli et al. (2012).
In-band Transmission fluctuations

Monthly average values of transmission

Monthly transmission fluctuations

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To quantify the real capability of the observational site we need to study the atmospheric performance, mainly stability and high transmission.

A new specific quality indicator: the Site Photometric Quality Ratio for each band monthly averaged transmission monthly transmission fluctuations

It is difficult to identify a desired SPQR threshold but this proxy could represent a useful tool to compare band performance or ...sites
Comparisons of atmo performance @200μm

Fixed the band, SPQR has been used as indicator to quantify and compare the best sub/mm worldwide observational sites.

The comparison of 7 sites at 200 μm in 2008-2010 period (Tremblin+12)
Constraints on observations

Noise lower limits for 2 extreme ambient condition:
Austral summer & winter

Photon Noise quantified as NEP and NEFD due to
Atmosphere + Instrument
with the following conditions:

✓ 10-m in dia telescope, diffraction limited FOV each band;

✓ Not included dominant sky sources (CMB & dust);

✓ Detector noise lower than back contribution;

✓ Spillover emission neglected
Atmospheric wide spectral coverage

Radiosounding data: 1/day – a code to infer atmo in the sub-mm/mm range

Direct and frequent measurements of atmospheric transmission in a wide spectral range can provide a perfect knowledge of atmospheric influence on astronomical observations.

If the opacity measurements are done in a narrow (a few MHz) spectral coverage, it is impossible to distinguish between clear sky opacity, hydrometeors contributions and systematic errors.

A wide frequency coverage (several hundreds of GHz) is necessary to make sure we are in clear sky conditions and no instrumental offset is affecting our measurement and our analysis. In this way it is also possible to determine the dry and the wet continuum terms (Pardo, Serabyn, & Cernicharo 2001)
A viable solution: CASPER 2

A large spectral sampling can be achieved at the price of a bit complex instrument. The possibility to monitor the atmosphere towards different positions in the sky, also avoids bias due to a spatial model assuming the multi layers approximation.

A dedicated spectrometer, like the one proposed for Dome C (De Petris et al. 2005) and in operation at Testa Grigia station (3500m asl, Alps, Italy) in a spectrally limited version (100-360 GHz), CASPER 2, could be a viable solution. (Decina et al. 2010; De Petris et al., 2013)

Atmospheric monitoring in the millimetre and submillimetre bands for cosmological observations: CASPER2

M. De Petris, S. De Gregori, B. Decina, L. Lamagna and J. R. Pardo
CASPER 2 – the instrument

62-cm reflective telescope + Martin-Puplett Interferometer + 0.3K detectors + altaz mount

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope effective focal length</td>
<td>1621 mm</td>
</tr>
<tr>
<td>Primary mirror diameter</td>
<td>620 mm</td>
</tr>
<tr>
<td>Primary mirror conic constant</td>
<td>0</td>
</tr>
<tr>
<td>Primary mirror curvature radius</td>
<td>978.4 mm</td>
</tr>
<tr>
<td>Secondary mirror diameter</td>
<td>120 m</td>
</tr>
<tr>
<td>Secondary mirror conic constant</td>
<td>8.86</td>
</tr>
<tr>
<td>Secondary mirror curvature radius</td>
<td>354.9 mm</td>
</tr>
<tr>
<td>Entrance pupil diameter</td>
<td>460 mm</td>
</tr>
<tr>
<td>Field of view (FWHM)</td>
<td>26 arcmin</td>
</tr>
<tr>
<td>AΩ</td>
<td>0.05 cm² sr</td>
</tr>
<tr>
<td>Spectral range</td>
<td>Channel 1: 90–360 GHz</td>
</tr>
<tr>
<td></td>
<td>Channel 2: 90–450 GHz</td>
</tr>
<tr>
<td>Mechanical path difference</td>
<td>30 mm</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Detectors</td>
<td>Two composite NTD</td>
</tr>
<tr>
<td></td>
<td>bolometers @ 0.3 K</td>
</tr>
<tr>
<td>Calibrator</td>
<td>Eccosorb AN72</td>
</tr>
<tr>
<td>Mount</td>
<td>Altazimuthal</td>
</tr>
<tr>
<td>Star tracker field of view</td>
<td>1 arcmin</td>
</tr>
<tr>
<td>CCD field of view</td>
<td>(14.4 × 13.6) arcmin</td>
</tr>
</tbody>
</table>
CASPER 2 – the optics

f/3.5 Pressman-Camichel telescope 62-cm in dia + MPI: abs calibration procedure 1/2

\[ I_{out_1} = \Delta^+ + \Delta^- \cos \delta, \]
\[ I_{out_2} = \Delta^+ - \Delta^- \cos \delta. \]

\[ \Delta^+ = B_{in_1} + B_{in_2} \]
\[ \Delta^- = B_{in_1} - B_{in_2} \]

interferograms

where

specific brightness of ..

\[ B_{in_1}(\nu) = \epsilon_{atm}(\nu)BB(T_{atm}, \nu) + \epsilon_{tele}(\nu)BB(T_{tele}, \nu), \]
\[ B_{in_2}(\nu) = BB(T_{ref}, \nu), \]
CASPER 2 – the optics
f/3.5 Pressman-Camichel telescope 62-cm in dia + MPI : abs calibration procedure 2/2

\[
\tilde{I}_{\text{out}1}(\nu) = R_1(\nu)\varepsilon_1(\nu)A\Omega(\nu) \left[ B_{\text{in}1}(\nu) - B_{\text{in}2}(\nu) \right] \\
= F_1(\nu) \left[ B_{\text{in}1}(\nu) - B_{\text{in}2}(\nu) \right],
\]
\[
\tilde{I}_{\text{out}2}(\nu) = R_2(\nu)\varepsilon_2(\nu)A\Omega(\nu) \left[ B_{\text{in}2}(\nu) - B_{\text{in}1}(\nu) \right] \\
= F_2(\nu) \left[ B_{\text{in}2}(\nu) - B_{\text{in}1}(\nu) \right].
\]

spectra (baseline removed)
calibration functions
estimated by filling \( in_1 \) with a well-modeled source (77K BB)

\[
I_{\text{atm}i}(\nu) = \frac{I_{\text{out}i}(\nu)}{F_i(\nu)} + BB(T_{\text{ref}}, \nu) - \epsilon_{\text{tele}}(\nu)BB(T_{\text{tele}}, \nu)
\]

2 identical inputs = \textit{Null} interferogram

To put a constraint on the minimum detectable contribution on the PWV content:
discriminate spectra with \( \Delta \text{PWV} = 0.01 \text{ mm} \) at least for PWV<1 mm
CASPER 2 – the optics

MPI efficiency \textit{versus} telescope altitude

Fixed detector \Rightarrow dependence of ZPD output signals with altitude angle, $\alpha$

$I_{out_{1,2}} = \Delta^+ \pm \Delta^- \cos^2 \alpha$

$\Delta^+ = B_{in_1} + B_{in_2}$

$\Delta^- = B_{in_1} - B_{in_2}$

 Blind region around alt= 45 deg
CASPER 2 – OPD modulation

3 different signal modulations can be performed:
✓ amplitude modulation (AM),
✓ fast-scan (FS) and
✓ phase modulation (PM).
CASPER 2 – cold detectors & bands

Channel 1: 90 – 360 GHz
Channel 2: 90 – 450 GHz
(to explore high-frequency atmospheric emission, more sensitive to PWV fluctuations)

2 Ge-bolometers with NEP $\sim 10^{-15}$ W Hz$^{1/2}$
cooled down to 290 mK by a wet cryostat
(Infrared Labs, HDL-8)
CASPER 2 – spectra acquisition timescale

GOAL: maximise the number of recorded independent spectra with high S/N.

The maximum number of spectra, that can be averaged, is constrained by the timescale resulting on a tradeoff between thermal noise and atmospheric fluctuation regime.

Appropriate statistical approach: Allan Variance

White noise appears with a slope of $-1$
Drift noise with a slope of $\sim +1$

The combination of both results:

The typical Allan plot has a minimum at some well defined time.

$$S_f(T, t_j) = \frac{1}{T} \sum_{i=j+1}^{j+T} s_f(t_i)$$

$$\sigma_A^2(T) = \frac{1}{N-2} \sum_{j=2}^{N-1} \left( \frac{S_f(T, t_{j-1}) + S_f(T, t_{j+1})}{2} - S_f(T, t_j) \right)^2$$

CASPER 2 – spectra acquisition timescale

Allan Variance estimated at 5 fiducial frequencies: in-band & out-band

87 atmospheric zenithal spectra recorded at MITO (3450 a.s.l. Alps)

Maximum timescale to average multiple spectra ~100 s

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CASPER 2 – 2 bands spectrum

Example of results:
averaged atmospheric zenithal spectra recorded with fast scan procedure at MITO on July 16th 2010, 03:53 AM. The red line is the best fit obtained with ATM

CH1
pwv = 6.53 ± 0.16 mm

CH2
pwv = 6.84 ± 0.16 mm

The lack of consistency between the data and ATM spectra at high frequencies supports the necessity to accurately calibrate the dry continuum and the H$_2$O pseudo-continuum terms in the simulated atmosphere = code validation

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Conclusions

A semi-empirical approach (data+code) to infer atmospheric performance at Dome C at several observational bands starting from 100 GHz up to 1.5 THz useful for present and future cosmological projects;

IF strong limitations with this approach are evident (see time sampling, code validation, ...), a possible alternative

A wide range spectrometer to continuously measure the atmosphere: CASPER (antartized version) could be a possible solution.

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Thank you!