ALMA Phase Calibration, Phase Correction and the Water Vapour Radiometers

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Outline

1. Introduction/Overview
   - Water Vapour Radiometry Overview
   - ALMA WVRs

2. Tests at the SMA

3. Analysis of limitations/error sources
   - Errors due to beam mis-match

4. Simulation of observations and imaging
   - Results

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ALMA Phase Cal and the WVRs
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Atmospheric Phase Fluctuations

- Physical properties of atmosphere along line of sight of each telescope are different and vary with time
- Water most important
- Also ‘dry’ fluctuations (due to temperature)
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Overview of phase calibration for ALMA

- The overall goal is to be able to do diffraction limited imaging at 900 GHz on 10 km baselines.
- Atmospheric path fluctuations are going to be the dominant source of phase errors.
- Calibrate phase by by:
  1. Fast-switching to nearby calibrator sources;
  2. *And* measurement of path fluctuations while on science target using the Water Vapour Radiometers (WVRs).
- Antenna slew and settle specifications allow fast-switching on timescales as short as 30 s if necessary.
- Probably will switch to calibrators on time-scales of about 3 to 5 minutes and correct the shorter term fluctuations with the WVRs.
The 183 GHz Water Vapour Line

\[ T_b (K) \]

\[ \nu (GHz) \]

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ALMA Phase Cal and the WVRs
The radiometers

- Two prototype WVRs were built by a collaboration between Cambridge and Onsala.
- The final design is a classical Dicke-switched radiometer with room temperature mixers/electronics and hot/ambient loads.
- Contracts for the production radiometers (for all of the 12 m antennas + spares) signed in the summer with industry partners.
- First devices scheduled for delivery in September.
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The Sub-Millimetre Array (SMA)
The two prototype WVRs were tested at the SMA

- Of the established mm and sub-mm interferometric sites, Mauna Kea has the closest atmospheric conditions to the ALMA site at Chajnantor.

- Lots of people involved.

- **Aims were to test:**
  - Engineering: sensitivity, stability, maintenance
  - Interfacing
  - Performance in tracking phase fluctuations

- Most interesting: antennas tracking a quasar to measure interferometric phase + the WVRs taking data – can see how well we can predict the phase fluctuations.
Sample observation (Feb. 17, 200 m baseline)
Path as measured by the interferometer (red) and as predicted by radiometers (blue)

- Observed
  \[ \sigma_\phi = 207 \, \mu m. \]
- Fluctuation around 5-min average:
  \[ \sigma_\phi = 153 \, \mu m. \]
- Residual after correction:
  \[ \sigma_\phi = 62 \, \mu m . \]
- 1 hour observation
Sample observation (Feb. 17, 200 m baseline)
Path as measured by the interferometer (red) and as predicted by radiometers (blue)

- Observed
  \[ \sigma_\phi = 207 \mu m. \]
- Fluctuation around 5-min average:
  \[ \sigma_\phi = 153 \mu m. \]
- Residual after correction:
  \[ \sigma_\phi = 62 \mu m. \]
- 25-minute section
Sample observation (Feb. 17, 200 m baseline)

Path as measured by the interferometer (red) and as predicted by radiometers (blue)

- Observed
  \[ \sigma_\phi = 207 \mu m. \]
- Fluctuation around 5-min average:
  \[ \sigma_\phi = 153 \mu m. \]
- Residual after correction:
  \[ \sigma_\phi = 62 \mu m . \]
- 5-minute section
## Log of SMA testing results

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UT)</th>
<th>Elev (deg)</th>
<th>Baseline (m)</th>
<th>Raw $\sigma_\phi$ (µm)</th>
<th>5-min$\sigma_\phi$ (µm)</th>
<th>Res. (µm)</th>
<th>c (mm)</th>
<th>Spec (µm)</th>
<th>Sampling (s)</th>
<th>Comment</th>
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<tbody>
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<td>20060217</td>
<td>16.9–17.9</td>
<td>16–30</td>
<td>212</td>
<td>207</td>
<td>153</td>
<td>62</td>
<td>3.6</td>
<td>68</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>—</td>
<td>19.8–20.2</td>
<td>38–44</td>
<td>212</td>
<td>238</td>
<td>239</td>
<td>73</td>
<td>2.0</td>
<td>47</td>
<td>2.6</td>
<td></td>
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<tr>
<td>20060224</td>
<td>18.4–19.4</td>
<td>25–40</td>
<td>212?</td>
<td>81</td>
<td>79</td>
<td>47</td>
<td>2.5</td>
<td>51</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>—</td>
<td>20.0–21.75</td>
<td>47–72</td>
<td>212?</td>
<td>258</td>
<td>241</td>
<td>72</td>
<td>2.4</td>
<td>52</td>
<td>2.6</td>
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<td>20060503</td>
<td>15.3–16.8</td>
<td>44–65</td>
<td>64</td>
<td>54</td>
<td>37</td>
<td>28</td>
<td>1.4</td>
<td>35</td>
<td>2.6</td>
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<td>5.1–5.7</td>
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<td>2.6</td>
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<tr>
<td>—</td>
<td>5.9–8.8</td>
<td>55–64</td>
<td>212</td>
<td>90</td>
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<tr>
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<td>57–64</td>
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<td>40</td>
<td>31</td>
<td>2.4</td>
<td>48</td>
<td>2.6</td>
<td></td>
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<tr>
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<td>7.3–8.3</td>
<td>55–63</td>
<td>212</td>
<td>154</td>
<td>72</td>
<td>56</td>
<td>2.4</td>
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<td>2.6</td>
<td></td>
</tr>
<tr>
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<td>40–62</td>
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<td>271</td>
<td>163</td>
<td>56</td>
<td>2.3</td>
<td>50</td>
<td>2.6</td>
<td>11 s offset, timing issues.</td>
</tr>
<tr>
<td>20060920</td>
<td>4.2–5.5</td>
<td>27–41</td>
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<td>83</td>
<td>71</td>
<td>60</td>
<td>3.1</td>
<td>60</td>
<td>1.3</td>
<td>High intf. noise. Timing issues.</td>
</tr>
<tr>
<td>—</td>
<td>6–6.7</td>
<td>46–61</td>
<td>64</td>
<td>72</td>
<td>62</td>
<td>50</td>
<td>2.3</td>
<td>48</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>20061030</td>
<td>19.3–20.3</td>
<td>67–72</td>
<td>415</td>
<td>332</td>
<td>282</td>
<td>139</td>
<td>7.0</td>
<td>119</td>
<td>1.3</td>
<td>Very wet conditions. Quality of fit limited by time drift.</td>
</tr>
</tbody>
</table>

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ALMA Phase Cal and the WVRs
Summary of SMA testing

- Both radiometers performed better than spec
- Clearly demonstrated that they measure very useful information for estimating atmospheric phase
- Appears that the specs can be met in most if not all conditions.
- Problems: timing issues, unknown contribution of instrumental phase fluctuations
- Insufficient data to understand the factors limiting performance at the SMA.
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Aims

Overall aim

Understand how:
- instrumental effects (inc. noise and stability)
- uncertainties in the properties of the atmosphere
- inaccuracies in atmospheric models

degrade the estimation of atmospheric path to each telescope.

Here I will show results published in ALMA memo 573, on the effect of beam mismatch between the radiometer and astronomical beams.
Offset between astronomical beams and the radiometer beam from ALMA is between 4′ (highest frequencies) and 9′ (lowest frequencies).
Beam shapes
Voltage response of astronomical beam Vs power response of radiometer beam

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Statistical realisations of 3D turbulent screens
Illustration of sub-sections of 1 m, 10 m and 100 m thick screens
Beam mismatch simulations

- Generate simulated time series of radiometer measurements using the power response pattern
- Compute phase fluctuation using the complex voltage response pattern of the antenna
- Find accuracy as function of beam offset, atmospheric properties, baseline length
Fractional error due to the mismatch between the astronomical and water vapour radiometer beams. For each layer height, the error for four layer thickness have been calculated: thin-screen (solid line), 10 m thick layer (dashed line), 100 m thick layer (dotted line) and 500 m thick layer (dash-dot-dash line).
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Introduction/Overview
Tests at the SMA
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Aims

Overall aim
Understand how the combined effects of:
- atmospheric phase fluctuations,
- fast-switching phase calibration,
- and water-vapour radiometer phase correction,
will affect science observations with ALMA.

Use this to
- Optimise phase calibration/phase correction techniques
- Understand impact of residual errors on science results
- Constraints on scheduling
Effect on science

Roughly in order of most thought about to least thought about:

- Sensitivity to point sources
  - Mainly depends on the RMS of residual fluctuations – ALMA specs based on this only
- Resolution/image fidelity
  - Magnitude of fluctuation as function of baseline length/orientation
- Astrometry and absolute flux measurement, especially of snapshot observations
- Mosaic / on-the-fly observations
Simulation framework

1. Use \texttt{casa} to generate \textit{uv} tracks and data
2. Simulate effects of the atmosphere:
   - Kolmogorov three-dimensional phase screens
   - ‘Large-Eddy Simulation’ (LES) physical models
   Produces corrupted \textit{uv} data
3. A separate calibration stage
   - Fast switching calibration
   - WVR phase correction
   Produces corrupted+calibrated \textit{uv} data
4. Finally use \texttt{casa} for imaging
Simple results: no calibration, long integration

Peak: 2 Jy

Peak: 1.66 Jy

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Simple results: no calibration, long integration

Peak: 0.98 Jy

Peak: 0.45 Jy
Simple results: no calibration, snapshot
Sequence of snapshots separated by about 3 minutes in time
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Fast Switching Phase Calibration
300 m thick screen; uncalibrated and calibrated antenna phases.
Fast Switching Phase Calibration

3 km thick screen; uncalibrated and calibrated antenna phases.

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Fast Switching Imaging (Conf 14, max baseline ≈ 1km)

300 m thick turbulent screen; 30 s calibrator-target-calibrator cycle, 12 m s⁻¹ wind

Raw; peak: 76%

Calibrated; peak: 86%
Fast Switching Imaging
3 km thick screen; single 30 s calibrator-target-calibrator cycle

Raw

Calibrated

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Next Steps

- Incorporate WVR measurement + correction!
  - Initially only a simple error model
  - Refine as we learn more radiometer simulation + real life testing
- More realistic atmospheres – LES.