Atmospheric Phase Correction for ALMA with 183 GHz Water Vapour Radiometers

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Summary

1. ALMA WVRs observe at 183 GHz and are continuously calibrated radiometers: technically more challenging, performance and systematics much better
2. Hardware is complete, in Chile, and in continuous use
3. Software is early-science ready (although currently using relatively simple algorithms), in daily use at JAO+ARCs
4. Tests on baselines available (up to 500 m) are very encouraging, specification met in reasonable conditions
5. The (relatively small) Problems: cloud, ‘dry’ fluctuations
6. Still to come: Long baselines!
Outline

Introduction

ALMA 183 GHz WVR system

Data processing

Examples of results
  Good results
  Effect on the beam
  Poor results
  “Dry” fluctuations

Outlook
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Outlook
ALMA as a high resolution imager

- ALMA is aiming to improve the routinely available resolution at mm/sub-mm by $50 \times$ from $\sim 0.5$ to $\sim 0.01$ arcseconds
- Comparable to the improvement introduced by the *Hubble* space telescope at optical wavelengths

Images of M13 from http://hubblesite.org courtesy of NASA, ESA, and the Hubble Heritage Team (STScI/AURA). Approximately scaled by eye... Do not use for science!
ALMA as a high resolution imager

- ALMA is aiming to improve the routinely available resolution at mm/sub-mm by 50× from ~ 0.5 to ~ 0.01 arcseconds
- Comparable to the improvement introduced by the Hubble space telescope at optical wavelengths

To achieve this:
- ALMA will observe at $\lambda \sim 350 \mu$m on baselines up to 15 km long
- Will need to correct for the effects of the troposphere
Atmospheric Phase Fluctuations

Astronomical wavefront

The turbulent troposphere

Corrupted astronomical wavefront

WVR Phase Correction for ALMA

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R(t)

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Path fluctuations due to the atmosphere

Path fluctuation on a baseline of $\sim 500$ m inferred from ALMA observations of a quasar at $\lambda = 3.3$ mm.
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Water Vapour cm/mm/sub-mm lines

1 mm precipitable water vapour
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Water Vapour cm/mm/sub-mm lines

1 mm precipitable water vapour

183 GHz Water Line – ALMA WVR system

22 GHz Water Line – previous WVR systems
The 183 GHz Water Vapour Line

Blue rectangles are *nominal* WVR filters

![Graph showing the 183 GHz Water Vapour Line and nominal WVR filters.](image-url)
WVR in the ALMA receiver cabin

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ALMA 183 GHz Water Vapour Radiometers

Technical concept of the units

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## Features of the WVR hardware

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Noise</td>
<td>$&lt; 0.07 - 0.1 \text{ K RMS in 1 second}$</td>
</tr>
<tr>
<td>Gain calibration</td>
<td>Continuous calibration against two internal loads</td>
</tr>
<tr>
<td>Absolute calibration</td>
<td>$&lt; 2 \text{ K in all channels}$</td>
</tr>
<tr>
<td>Stability</td>
<td>$&lt; 0.1 \text{ K stability over 10 minutes of time /10 degrees elevation change}$</td>
</tr>
<tr>
<td>Spill-over</td>
<td>Less than 2% past sub-reflector; More than 16 dB edge taper on the primary</td>
</tr>
<tr>
<td>Pointing</td>
<td>Along bore-sight of the antenna; rigid mounting on the FESS inside the receiver cabin</td>
</tr>
</tbody>
</table>
Sky brightness observed by WVRs

Observed brightness temperatures of WVR on the three antennas involved in this test observation. The four colours in each panel are the four channels of the WVRs.
Correlation between WVRs and paths

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- **ALMA 183 GHz WVR system**
- **Data processing**
- **Examples of results**
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**wvrgcal off-line phase correction tool**

- Produces a CASA “T” Jones gain calibration table
  - Calibration applied together with others in usual way in CASA
  - Can be inspected by user in CASA
- Bayesian inference of phase correction coefficients (close to optimal, but so far tested on short baselines only)
- Quality Assurance features, which help to detect:
  - Problematic or noisy WVRs
  - Incorrect phase correction coefficient
  - Shadowing, clouds, shutter problems...
- Public source code and binaries, in use at JAO and ARCs
On-line phase correction

- Implemented in the correlator and TelCAL software written by IRAM
- Advantage:
  - Can average data over a longer time before writing to disk
- Disadvantage:
  - Only get one go to correct the full time resolution data
  - Can only use information from the past
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Data-set A002_Xb9f5d_X1: Long baseline
Red: uncorrected phase; Blue: corrected phase
Data-set A002_Xa0705_X1
Another example, only short baselines
March dataset X1849a5_X191
Very wet weather, ~ 600 m baseline
Best result – minimum phase errors
This is for short baselines and very rare! (A002_X219601_X5c7)

- Uncorrected phase $\sim 14$ micron ($< 3$ min timescale)
- WVR-corrected phase $\sim 7$ micron
- $\rightarrow$ This is almost good enough for mid-infrared interferometry!
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Inner ALMA pad positions

From [http://www.alma.cl/~dbarkats/pad_position_plotter/plots/ALMA_pad_viewer_zoom2.html](http://www.alma.cl/~dbarkats/pad_position_plotter/plots/ALMA_pad_viewer_zoom2.html)
The effect of WVR correction on the ALMA synthesised beam

No phase correction

WVR phase correction

Short observation with very inhomogeneous $uv$ distribution – one antenna was on a long north baseline and others were close together in a cluster.
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Data-set A002_Xba2ed_X1

Short baselines, leak-through phase fluctuations (offset in coefficients due to time-constant cloud?)

Very short baseline (A0-A1), essentially no phase fluctuations to correct
Data-set A002_Xba2ed_X1

Short baselines, leak-through phase fluctuations (offset in coefficients due to time-constant cloud?)

Also a very short baseline (A0-A2), some atmospheric-like phase fluctuation seen and corrected
Data-set A002_Xba2ed_X1
Short baselines, leak-through phase fluctuations (offset in coefficients due to time-constant cloud?)

Slightly longer baseline (A0-A3): atmospheric phase fluctuations clearly seen, corrected somewhat but clear “leak-through”
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Evidence for ‘dry’ fluctuations
Baseline length \(\sim\) 100 m
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Spatial power spectrum of water vapour fluctuations
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Topography of the ALMA site (cntrs at 25 m)
Future work

1. Long baselines?
2. + High frequencies (dispersion? phase wraps?)
3. Local geography? (Altitude differences, ridges, moisture accumulation)
4. Quality assurance? (Lots of data, all to be reduced by ALMA staff!) Cycle 0 and further...
5. Project scheduling? (Will this observation work in this weather?)
6. Interpolation for the ACA?
1. Our work in Cambridge has been funded by European Union Framework Programme 6 project “Enhancement of ALMA Early Science”

2. The production WVR hardware was designed and manufactured by Omnisys Instruments, Gothenburg, Sweden

3. A large number of ALMA and partner agencies staff have worked and continue to work on aspects of WVR hardware integration, software development and testing of WVR phase correction