Atmospheric phase correction for ALMA with water-vapour radiometers

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Outline

1. Introduction
   - Goals, setting
   - Atmospheric Phase Fluctuations at mm/sub-mm wavelengths

2. Review of ALMA Phase Correction/Calibration Strategy
   - Fast-switching

3. Phase correction with WVRs
   - Water Vapour Radiometry
   - Algorithms

4. Summary
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Goals for this talk

- Introduce the work in Cambridge on *algorithms* for WVR phase correction
  - Why this is interesting
  - Where we are heading
- Very briefly present some simulations
- Also briefly review results of prototype testing at the SMA

- Firsts tests with ALMA still 6-12 months away
Work on Phase Calibration/Correction at Cambridge

A simplified summary:

- Funded by EU and organised separately from baseline ALMA
- Intended as an ALMA enhancement
- Managed by ESO on behalf of EU
- Initial band 5 receivers and IRAM work on the on-the-fly interferometry funded through this framework too
ALMA Enhancement FP6 Program

ESO Director General
T. De Zeeuw

Program Management
Scientific Officer: T. Wilson
Coordinator: H. Rykaczewski

ESO Director General
T. De Zeeuw

EC Liaison
E. Righi-Steele

ESO C&P Dept.
E. Patkos

ESO Finance Dept.
R. Brunner

ESO Internat. Relations
E. Patkos

Consortium Partners
OSO Chalmers
IRAM
University of Cambridge
University of Chile, Santiago
(RAL)*

Scientific / Technical Projects

Band 5 Cartridges
G.H. Tan

Project Team
ESO
Consortium Partners

Software
J. Schwarz

Project Team
ESO
Consortium Partners

*: pending contract amendment approval by EC
Introduction

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Causes of Phase Errors at mm/sub-mm wavelengths

Instrumental

- Sources: Mechanical/ Optical/ Electronic
- Timescales: from about 30 minutes to very long timescales (e.g., the diurnal cycle)
- Mitigation: Stable designs and astronomical phase calibration

Atmospheric – Tropospheric

Two sources:

- Fluctuating quantity of water-vapour along line of sight (‘wet’)
- Fluctuating temperature of dry air along line of sight (‘dry’)

Two relevant timescales:

- Inner: Set by the smoothing effect of the $D = 12 \text{ m}$ telescope beam:
  $\approx \frac{D}{v} \sim 1 \text{ s}$
- Outer: Determined by the baseline length $B$:
  $5 \text{ s} \lesssim \frac{B}{v} \lesssim 20 \text{ minutes}$
Example of observed path fluctuations
SMA, Mauna Kea, Hawaii

- Measured path fluctuation while observing a quasar
- 200 m baseline
- About 3.5 mm line-of-sight water
- $\sigma_\phi = 207 \mu m$.

This and all other data from the SMA were collected by the ALMA WVR prototype collaboration: for full list of people involved and more details see http://www.mrao.cam.ac.uk/~bn204/alma/smat.html
Simulated ALMA phase errors
Details of simulations at http://www.mrao.cam.ac.uk/~bn204/alma/

Based on a 3D Kolmogorov turbulence model – see ALMA memos # 573, 582

Compact configuration $B_{\text{max}} \approx 150$ m
Simulated ALMA phase errors

Details of simulations at http://www.mrao.cam.ac.uk/~bn204/alma/

Based on a 3D Kolmogorov turbulence model – see ALMA memos # 573, 582

Medium configuration $B_{\text{max}} \approx 1 \text{ km}$
Impact of poorly corrected phase errors

General impact on science

- Phase errors increase with baseline length
  \[ \Longrightarrow \text{ limit on maximum usable baseline length} \]
  \[ \Longrightarrow \text{ limit on possible resolution} \]
- Loss of sensitivity due to de-correlation

Impact on snapshot + mosaics

Further effects due to time-variance of phase fluctuations

- Amplitude calibration
- Astrometric accuracy

Top level specification for ALMA

\[
\delta p_{\text{corrected}} \leq \left( 1 + \frac{w}{1 \text{ mm}} \right) 10 \mu m + 0.02 \times \delta p_{\text{raw}}
\] (1)
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ALMA phase correction strategy

Fast-switching
- Observe nearby quasars
- Calculate antenna phase errors
- Calibration cycle down to 10–15 s (fast antennas!)
- Expect calibrators about two degrees from science target
- Can calibrate at 90 GHz and transfer up to 950 GHz

Water Vapour Radiometry
- Measure atmospheric properties along the line of sight of each telescope
- Use dedicated 183 GHz radiometers on each telescope
- Measurements at about 1 Hz
- Infer excess path
- Correct either in correlator or in post-processing

+ Self-Calibration in a very limited number of cases
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4 Summary
Fast-Switching offset calibration

Illustration of the geometry of the turbulent layer and the directions to astronomical and calibration sources.
Simulated fast-switching phase calibration
Medium configuration, 15 s cycle (http://www.mrao.cam.ac.uk/~bn204/alma/)
Fast-switching phase calibration

- Use standard algorithms to determine antenna phase errors from observed visibilities
- Phase transfer from $\lambda = 3 \text{ mm}$ to the observing frequency.
  
  **Benefits:**
  - Quasars are much brighter at $\lambda = 3 \text{ mm}$ than in the sub-mm
  - Phase errors are unlikely to be large enough to cause phase wraps

  **Potential challenges:**
  - Atmosphere is *dispersive* in the sub-mm so the transfer of gain solution requires modelling or itself needs calibration: E.g.: 10% of total path due to water vapour at $\lambda = 1 \text{ mm}$ is dispersive
  - Instrumental phase stability between $\lambda = 3 \text{ mm}$ and observing bands needs to be good

- Residual phase errors depend on the atmospheric conditions and the calibration cycle, but *not* on the baseline length
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Water Vapour cm/mm/sub-mm lines

1 mm water vapour
The 183 GHz Water Vapour Line
Blue rectangles are the production WVR filters
The 183 GHz Water Vapour Radiometers

- Un-cooled mixer, double-sideband, with $\approx 1000\ \text{K}$ receiver noise
- Total bandwidth $\approx 18\ \text{GHz}$ split into four DSB channels
- Dicke-switched with a chopper wheel against loads at two temperatures allowing continuous calibration

Specifications:
- Sensitivity: $0.08\text{–}0.1\ \text{K}$ per channel RMS in one second
- Stability: $0.1\ \text{K}$ peak-to-peak over 10 minutes + 10 degree tilts
- Absolute accuracy: $2\ \text{K}$ maximum error

- Prototypes designed and built by Onsala and Cambridge
- Simplified design for production and the manufacture of $\approx 60$ units by industry partners
- Delivery of first production units to Chile expected toward end Q1–2009
Signal from two prototype WVRs mounted on SMA antennas
From the ALMA WVR prototype testing campaign in 2006
Interferometer path vs. radiometer difference

- July 18 2006 test at the SMA with the ALMA prototype WVRs
- Black line: difference between channels 2 on the two radiometers
- Red line: interferometric path fluctuation
Interferometer path vs. radiometer difference

Channel 0

Channel 3

$\Delta T_B$ (K)

$r$ (hours UT)

$p$ ($\mu$m)
Algorithms for WVR phase correction

\[ \delta L \] change in excess path to antenna

\[ \delta T_{B,i} \] change in \( i \)-th channel sky brightness observed by a WVR

\[ w_i \] weight of \( i \)-th channel

\[ \delta L \approx \sum_i w_i \frac{dL}{dT_{B,i}} \delta T_{B,i} \] (2)

\( \delta T_B \): WVR hardware design

- Low noise
- High bandwidth
- High stability

\( w_i \frac{dL}{dT_{B,i}} \): (primarily) algorithm design

- Optimal use of information
- Atmospheric models + physics
- Experience at the site
- ‘Ancillary’ information
Will this work? Optimize $w_i \frac{dL}{dT_B,i}$ directly as a test

SMA test data, total fluctuations: $\sigma_L$ reduced from 271 to 75 $\mu$m
More SMA prototype test observations
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WVR algorithms

Goals:
- Figure out $\frac{dL}{dT_{B,i}}$ and $w_i$
- Confidence estimates on the above
- Tighter coupling to the offset phase calibration?
WVR algorithms: available information

- Four absolute measurements of sky brightness: i.e., $T_{B,i}$ rather than $\delta T_{B,i}$
- The observed correlation between $\delta L$ and $\delta T_B$
- Ground-level temperature, pressure, humidity, wind-speed
- Information on the profile of atmospheric temperature versus height from a single 60 GHz $O_2$ sounder at the centre of the array
- Library of radio-sonde measurements
- Short-term meso-scale meteorological forecast

Will we need all of this information?

- We are aiming for very challenging 2% accuracy in $\sum_i w_i \frac{dL}{dT_{B,i}}$
- For operational efficiency important to understand how well phase correction will work (also the opacity too of course)
Algorithm framework: Bayesian

We are developing a Bayesian framework to optimally combine all available information together with models of the atmosphere.

Why Bayesian?

We are not interested in model parameters such as pressure, temperature, lapse rate, turbulent layer height, etc. All we want are the $\frac{dL}{dT_{B, i}}$.

$\rightarrow$ Marginalise all model parameters, get probability distributions for $\frac{dL}{dT_{B, i}}$.

Framework features

- A model for accuracy of absolute measurements $T_{B, i}$
- Incorporate empirical $\frac{dL}{dT_{B, i}}$ as observation
- Other information naturally fit in as priors
The work presented here is based only on the 183 GHz line and non-dispersive delay: these are both trivial model.

For predicting dispersive effects and also for absolute calibration, ALMA will use Juan Pardo’s ATM.

This version is now available for everybody to download and use under the open-source GPL licence:

http://www.mrao.cam.ac.uk/~bn204/alma/atmomodel.html

Any comments on accuracy of this code would be greatly appreciated by the project.
Prediction of \( \frac{dL}{dT_{B,i}} \) from \( T_{B,i} \) only

Single, thin layer; non-dispersive water vapour delay only; prototype filter set
Phase correction with WVRs

Algorithms

Prediction of $\frac{dL}{dT_{B,i}}$ from $T_{B,i}$ only

Model parameters retrieval \textit{without} priors

\[ n \]

\[ T \]

\[ P \]

B. Nikolic (University of Cambridge)

WVR phase correction for ALMA

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Prediction of \( \frac{dL}{dT_{B,i}} \) from \( T_{B,i} \) only

Model parameters retrieval with priors
Prediction of $\frac{dL}{dT_{B,i}}$ from $T_{B,i}$ only

Retrieved $\frac{dL}{dT_{B,i}}$ (with priors)
Estimating $dL/dT_{B,i}$

Channel 0

![Graph showing data over time](image-url)
Estimating $dL/dT_{B,i}$

**Normal phase cal**
Cycle: 5 mins/ Cal: 10 sec

**Specialised scan**
Cycle: 30 mins/ Cal: 3 min
Including the empirical correlation between $\delta L$ and $\delta T_B$

- The correlation between $\delta L$ and $\delta T_B$ when observing a quasar gives us directly the information we need to do phase correction.
- But, must minimise time spent on this observation instead of science.
- $\implies$ Use the observed correlation, and a physical model for atmosphere to allow inference of $w_i \frac{dL}{dT_{B,i}}$ at:
  - Different airmass
  - Different total water column
  - ...
- This approach naturally fits into the Bayesian framework.
Prediction of $\frac{dL}{dT_{B,i}}$ from $T_{B,i}$ and correlation $\delta L$ vs $\delta T_B$
Prediction of $\frac{dL}{dT_{B,i}}$ from $T_{B,i}$ and correlation $\delta L$ vs $\delta T_B$

Transferred to an airmass 25% higher
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WVRs phase correction is an important part of the ALMA phase correction plan.

Initial results from SMA promising.

The algorithm design is challenging but hopefully tractable.

But need to:

- Get ALMA phase-stable and observing at sub-mm frequencies at the AOS (the high site).
- Get the WVRs commissioned, integrated into the ALMA system, and the observation and data recording software systems working.

And then the real challenges for phase correction start...
Challenges

- 15 km baselines with substantial elevation difference between parts of the array → need different set of $\frac{dL}{dT_{B,i}}$ for each antenna
- In some correlator modes, need to apply correction in semi-real-time → need to get the $\frac{dL}{dT_{B,i}}$ right
- ‘dry’ fluctuations: very little direct information, need to rely on correlation with ‘wet’ fluctuations
- Optimisation of fast-switching and phase transfer calibration stages
- Understanding of atmospheric physics and models