Atmospheric phase correction for ALMA with water-vapour radiometers

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January 2009
NRAO Charlottesville

UNIVERSITY OF CAMBRIDGE

ALMA

Outline

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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

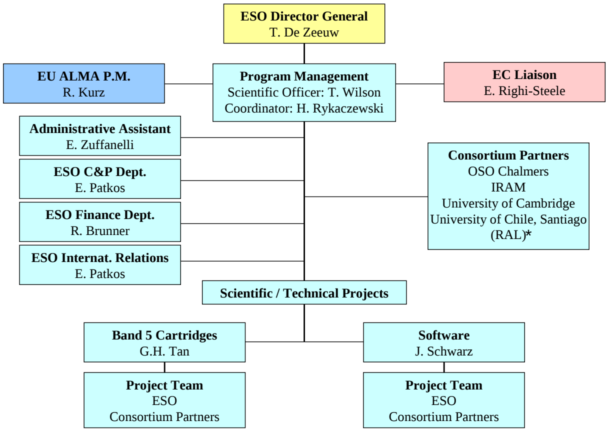
Work on Phase Calibration/Correction at Cambridge

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

FP6 “Organigram”

ALMA Enhancement FP6 Program



*: pending contract amendment approval by EC

Outline

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:

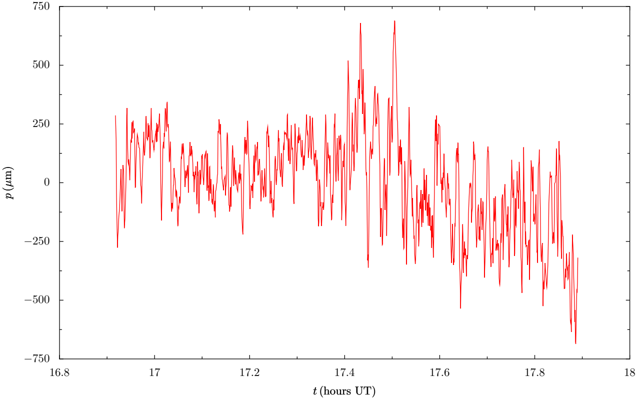
- Fluctuating quantity of water-vapour along line of sight ('wet')
- Fluctuating temperature of dry air along line of sight ('dry')

Two relevant timescales:

- Inner: Set by the smoothing effect of the $D = 12\,\mathrm{m}$ telescope beam: $\approx D/v \sim 1\,\mathrm{s}$
- Outer: Determined by the baseline length B: $5\,\mathrm{s} \lessapprox B/v \lessapprox 20\,\mathrm{minutes}$

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
- $\sigma_\phi = 207\,\mu\mathrm{m}$.

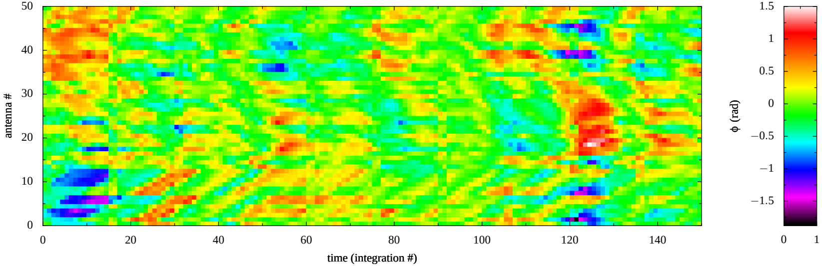
This and all other data from the SMA were collected by the ALMA WVR prototype collaboration: for full list of people involved and more details see `http://www.mrao.cam.ac.uk/~bn204/alma/smat.html`

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 $B_{\mathrm{max}} \approx 150\,\mathrm{m}$

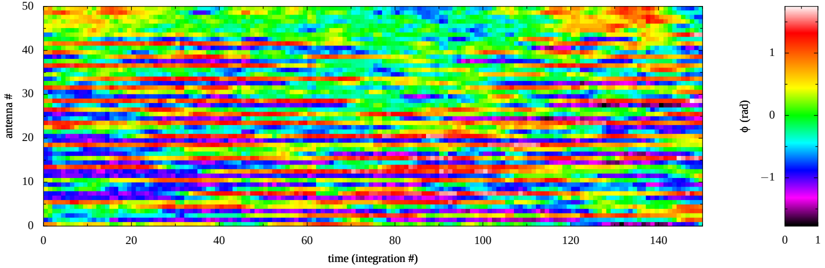


Simulated ALMA phase errors

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 $B_{\mathrm{max}} \approx 1\,\mathrm{km}$



Impact of poorly corrected phase errors

General impact on science

- Phase errors increase with baseline length
  $\Longrightarrow$ limit on maximum usable baseline length
  $\Longrightarrow$ 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

$$\delta p_{\mathrm{corrected}} \leq \left(1 + \frac{w}{1\,\mathrm{mm}}\right) 10\,\mu\mathrm{m} + 0.02 \times \delta p_{\mathrm{raw}} \quad (1)$$

Outline

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

Outline

Fast-Switching offset calibration

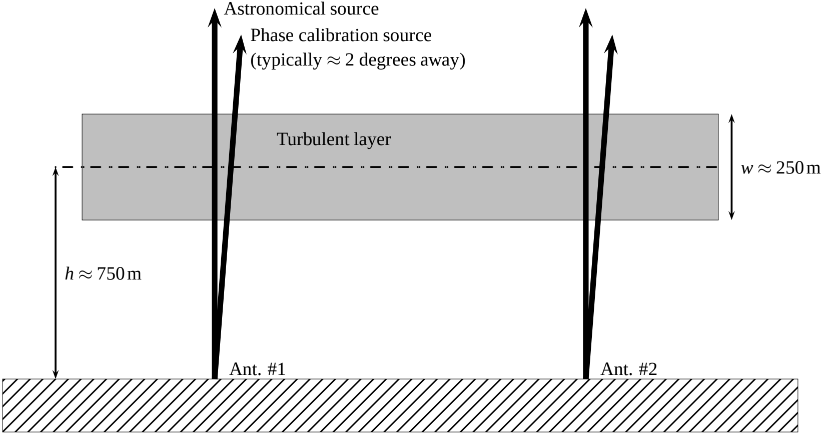
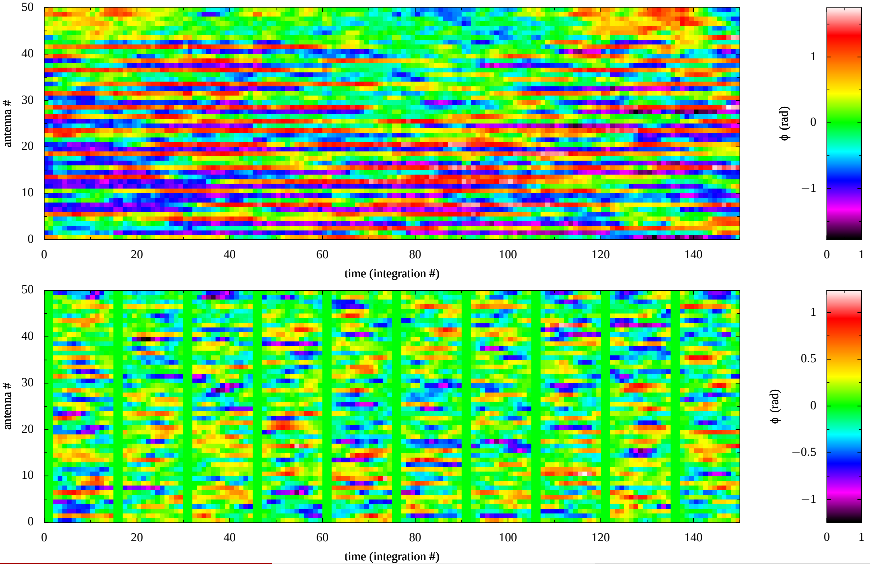


Illustration of the geometry of the turbulent layer and the directions to astronomical and calibration sources.

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 $\lambda = 3\,\mathrm{mm}$ to the observing frequency.
  Benefits:
  - Quasars are much brighter at $\lambda = 3\,\mathrm{mm}$ 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 $\lambda = 1\,\mathrm{mm}$ is dispersive
  - Instrumental phase stability between $\lambda = 3\,\mathrm{mm}$ 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

Outline

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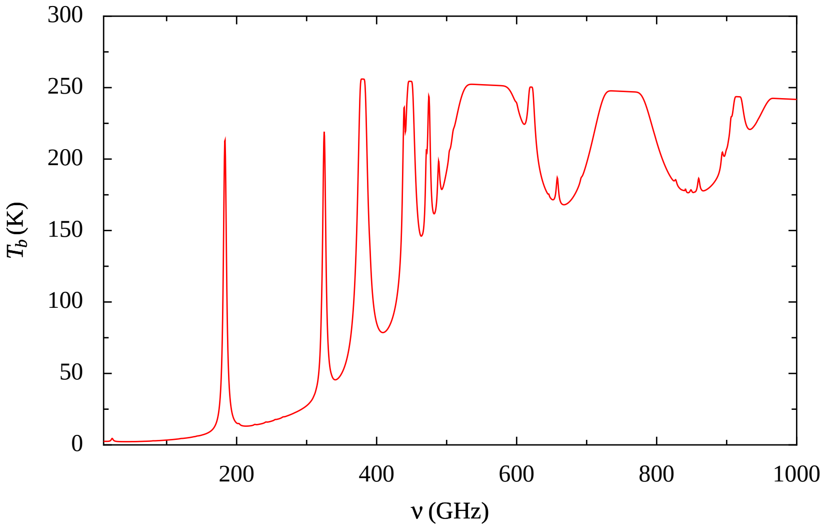
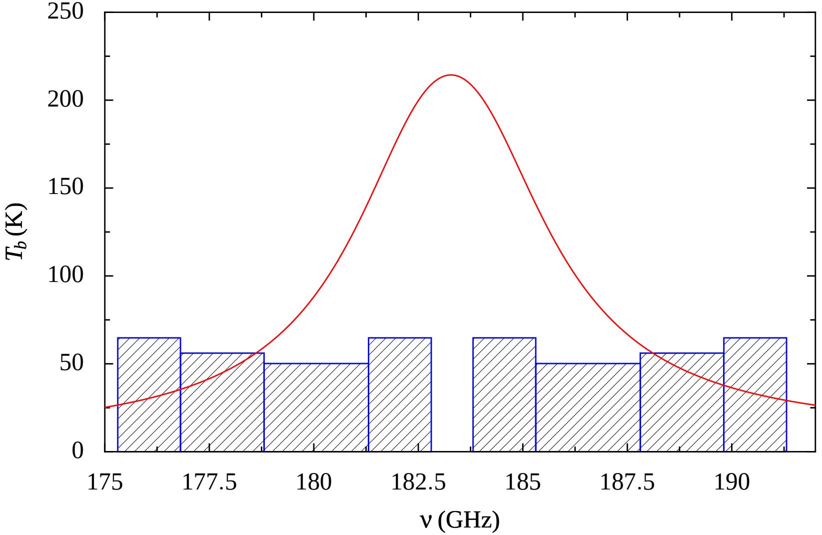
Water Vapour cm/mm/sub-mm lines

1 mm water vapour



The 183 GHz Water Vapour Line

Blue rectangles are the production WVR filters

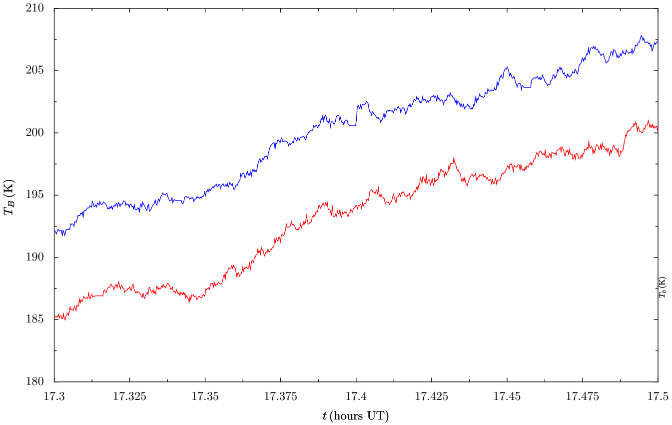


The 183 GHz Water Vapour Radiometers

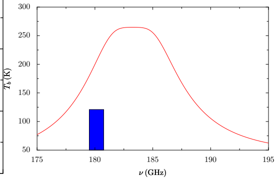
- Un-cooled mixer, double-sideband, with $\approx 1000\,\mathrm{K}$ receiver noise
- Total bandwidth $\approx 18\,\mathrm{GHz}$ split into four DSB channels
- Dicke-switched with a chopper wheel against loads at two temperatures allowing continuous calibration
- Specifications:
  - Sensitivity: 0.08–0.1 K per channel RMS in one second
  - Stability: 0.1 K peak-to-peak over 10 minutes + 10 degree tilts
  - Absolute accuracy: 2 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

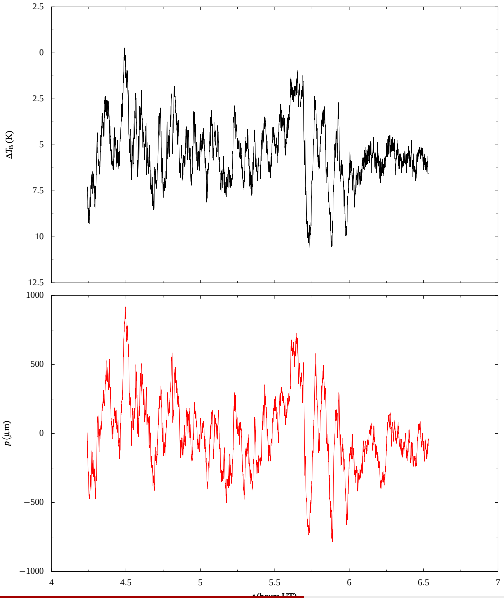
From the ALMA WVR prototype testing campaign in 2006



- Blue line: radiometer # 1
- Red line: radiometer # 2

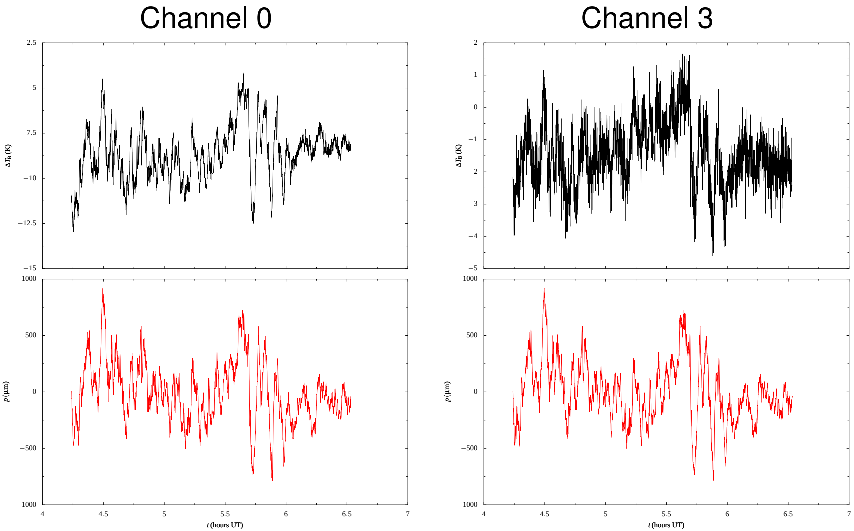


Interferometer path vs. radiometer difference



- 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



Algorithms for WVR phase correction

δL change in excess path to antenna

$\delta T_{\mathrm{B},i}$ change in i-th channel sky brightness observed by a WVR

w_i weight of i-th channel

$$\delta L \approx \sum_i w_i \frac{dL}{dT_{\mathrm{B},i}} \delta T_{\mathrm{B},i} \quad (2)$$

δT_{B}: WVR hardware design

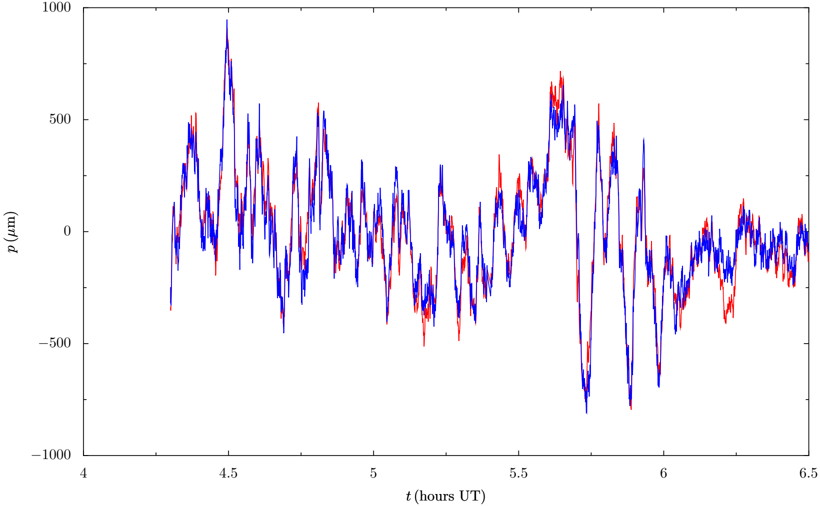
- Low noise
- High bandwidth
- High stability

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

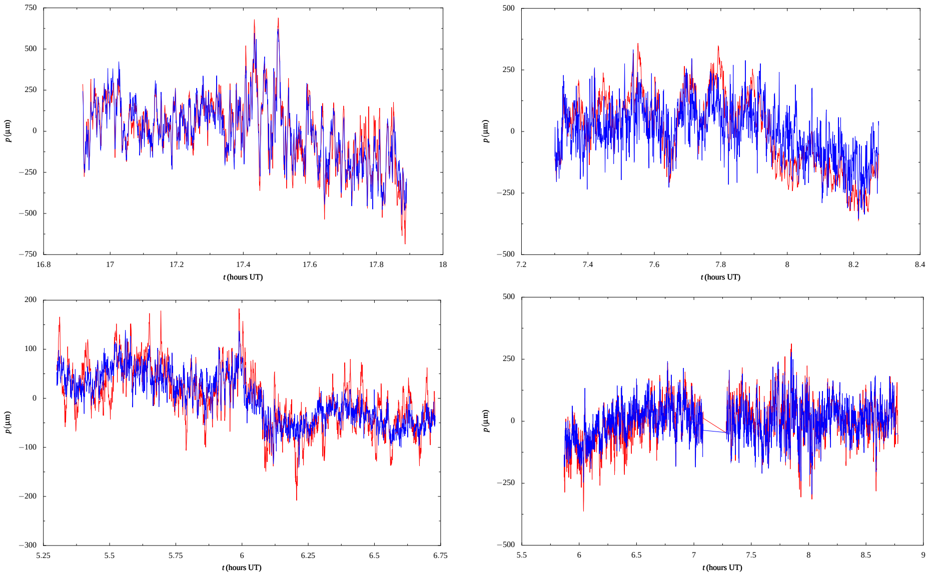
- Optimal use of information
- Atmospheric models+physics
- Experience at the site
- ‘Ancillary’ information

Will this work? Optimise $w_i \frac{dL}{dT_{\mathrm{B},i}}$ directly as a test

SMA test data, total fluctuations: σ_L reduced from 271 to 75 μm



More SMA prototype test observations



Outline

WVR algorithms

Goals:

- Figure out $\frac{dL}{dT_{\mathrm{B},i}}$ 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., $T_{\mathrm{B},i}$ rather than $\delta T_{\mathrm{B},i}$
- The observed correlation between δL and δT_{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 $\sum_i w_i \frac{dL}{dT_{\mathrm{B},i}}$
- 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 $\frac{dL}{dT_{\mathrm{B},i}}$
$\rightarrow$ Marginalise *all* model parameters, get probability distributions for $\frac{dL}{dT_{\mathrm{B},i}}$.

Framework features

- A model for accuracy of absolute measurements $T_{\mathrm{B},i}$
- Incorporate empirical $\frac{dL}{dT_{\mathrm{B},i}}$ as *observation*
- Other information naturally fit in as priors

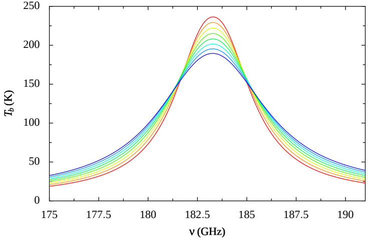
Short advertisement & request: ATM

- 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

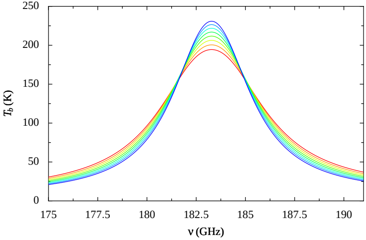
Prediction of $\frac{dL}{dT_{\mathrm{B},i}}$ from $T_{\mathrm{B},i}$ only

Single, thin layer; non-dispersive water vapour delay only; prototype filter set

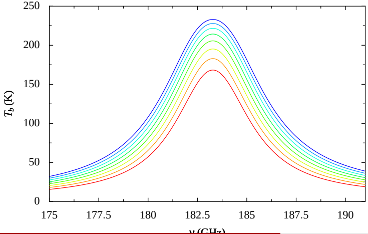
Pressure variation



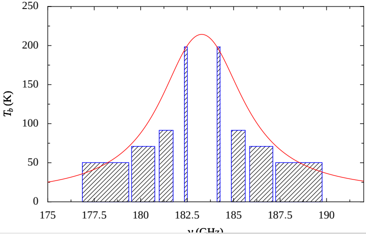
Temperature variation



Amount of Water

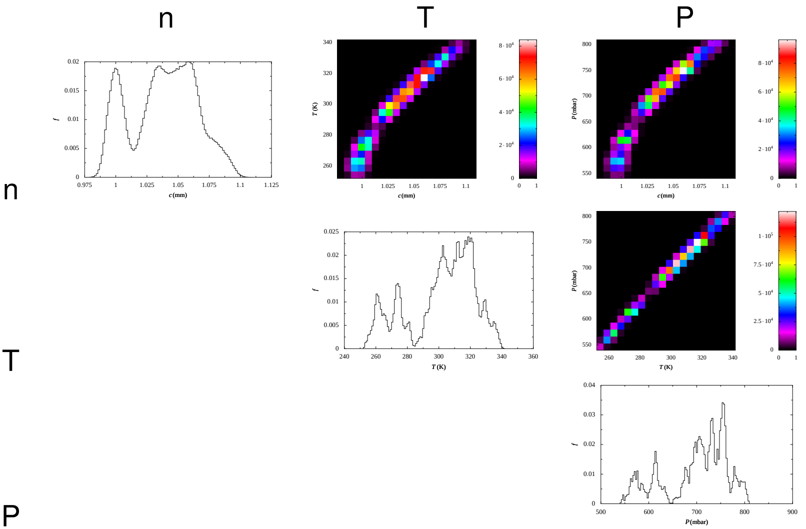


Filters



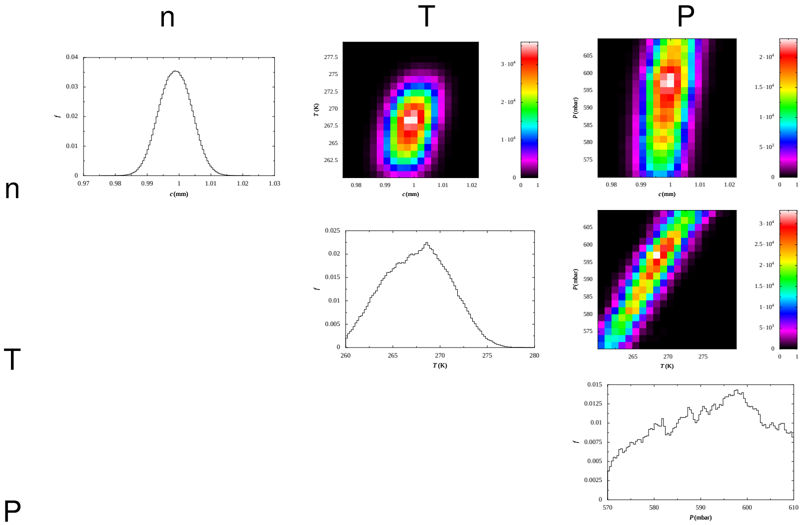
Prediction of $\frac{dL}{dT_{\mathrm{B},i}}$ from $T_{\mathrm{B},i}$ only

Model parameters retrieval *without* priors



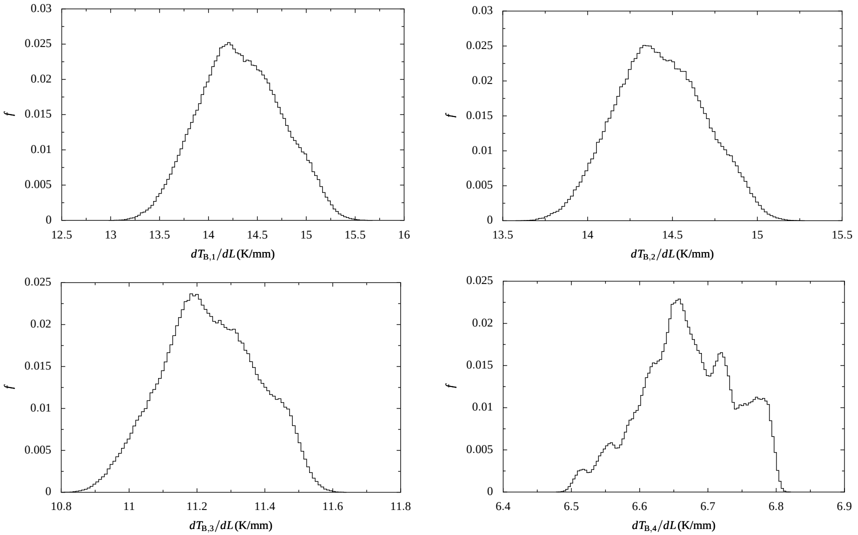
Prediction of $\frac{dL}{dT_{\mathrm{B},i}}$ from $T_{\mathrm{B},i}$ only

Model parameters retrieval with priors

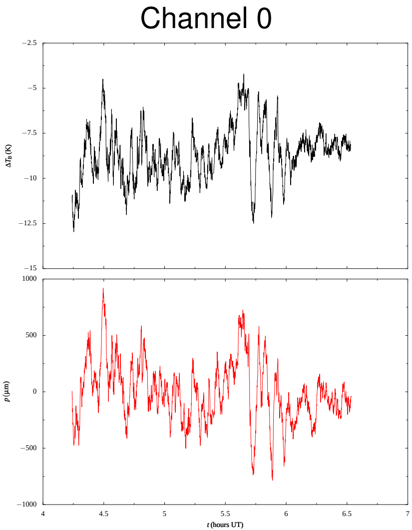


Prediction of $\frac{dL}{dT_{\mathrm{B},i}}$ from $T_{\mathrm{B},i}$ only

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

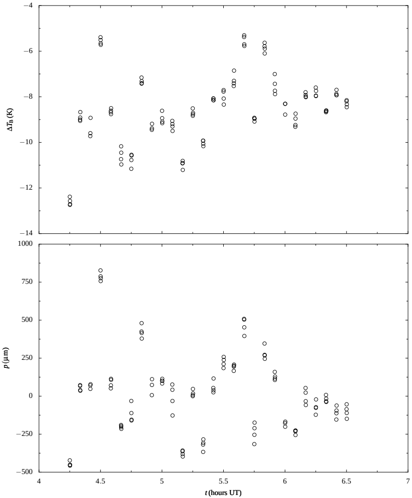


Estimating $dL/dT_{\mathrm{B},i}$

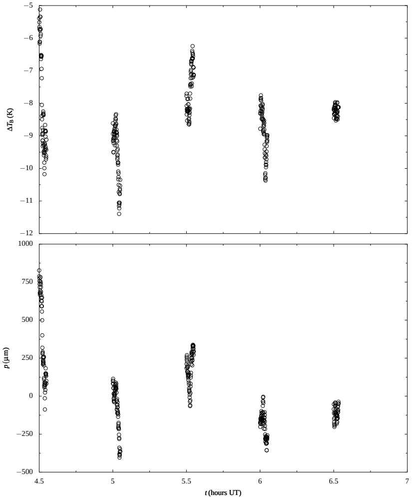


Estimating $dL/dT_{\mathrm{B},i}$

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



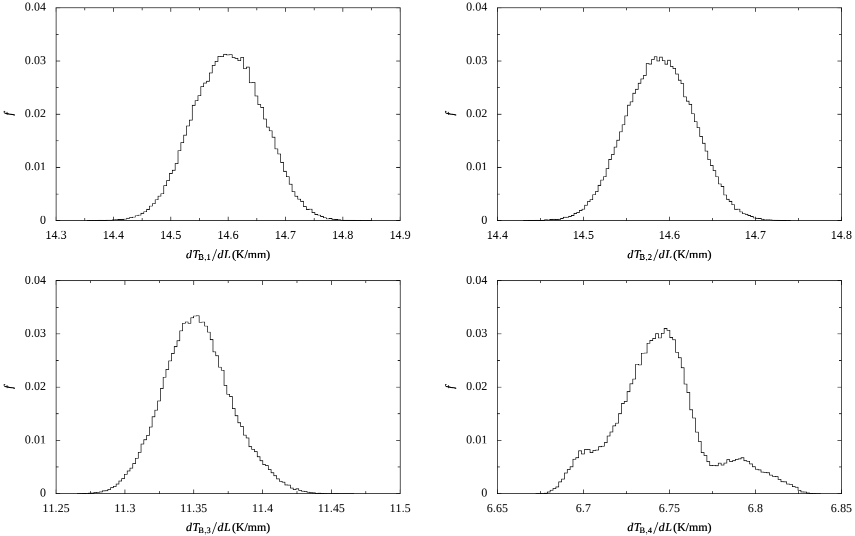
Specialised scan
Cycle: 30mins/ Cal: 3 min



Including the empirical correlation between δL and δT_{B}

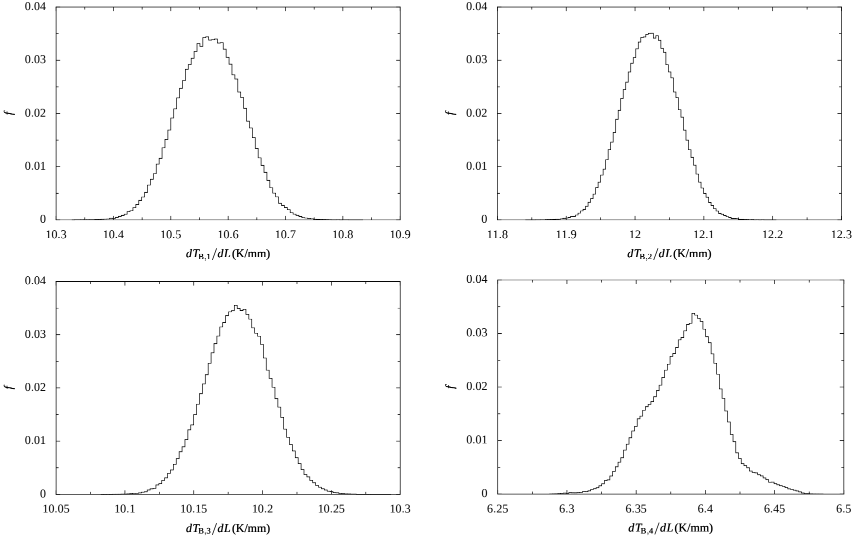
- The correlation between δL and δT_{B} when observing a quasar gives us *directly* the information we need to do phase correction
- But, must minimise time spent on this observation instead of science
- $\Longrightarrow$ Use the observed correlation, and a physical model for atmosphere to allow inference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

Prediction of $\frac{dL}{dT_{\mathrm{B},i}}$ from $T_{\mathrm{B},i}$ and correlation δL vs δT_{B}



Prediction of $\frac{dL}{dT_{\mathrm{B},i}}$ from $T_{\mathrm{B},i}$ and correlation δL vs δT_{B}

Transferred to an airmass 25% higher



Outline

Summary

- 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
  $\rightarrow$ need different set of $\frac{dL}{dT_{\mathrm{B},i}}$ for each antenna
- In some correlator modes, need to apply correction in semi-real-time
  $\rightarrow$ need to get the $\frac{dL}{dT_{\mathrm{B},i}}$ 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