Simulating Atmospheric Phase Errors, Phase Correction and the Impact on ALMA Science

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1. Introduction

2. Simulations method
   - Framework
   - Simulating a turbulent volume
   - 2d projections and steepening of structure fn

3. Results
   - Results without phase correction
   - Fast-switching phase calibration
   - WVR + Fast-switching

4. Summary/Links
Outline

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4 Summary/Links
Atmospheric Phase errors

Observed path fluctuation at the SMA while tracking a quasar for one hour
($\sigma_p = 207 \, \mu m$)
Atmospheric Phase errors vs baseline

Phase fluctuation measured at 22 GHz at the VLA by observing a quasar for about thirty minutes. Correlations along one arm of the VLA only shown.
Why Simulate Phase Errors?

ALMA phase correction/calibration/mitigation strategies

- Fast switching
- 183 GHz Water Vapour Radiometry
- Self-calibration
- Scheduling
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The science end-user:
Interested only in residual phase errors after calibration/correction
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Algorithm design, scheduling, hardware design:
Need to understand the phase errors in detail, and how each of the correction techniques can be used to its best potential
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Simulation Flowchart

Start

Generate $uv$ tracks, samples

Calculate visibilities

Corrupt visibility phases

Simulate phase correction

Make and analyse image

Stop

Geometry only, use CASA

Trivial for point sources

Use custom C++ and Python

Use custom Python

CASA or Obit
Simulations Framework

- A very straightforward flowchart!
- Factors cleanly into distinct steps
- The FITS format ties all of these steps together very well
- Not considering thermal noise at any stage

- Develop own modules separately:
  - Minimise dependencies
  - Maximise re-usability for other projects
  - Everything driven from Python (using SWIG when necessary)

- Can be incorporated into user-orientated simulators or used for algorithm development
Simulations Framework

- A very straightforward flowchart!
- Factors cleanly into distinct steps
- The **FITS** format ties all of these steps together very well
- Not considering thermal noise at any stage
  - Not required for our goals, so keeping it simple
- Develop own modules separately:
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4. Summary/Links
The method and Kolmogorov hypothesis

- Assume a frozen atmospheric *volume* translated across the array.
The method and Kolmogorov hypothesis

- Assume a frozen atmospheric *volume* translated across the array
- Wind-speed 10–15 m s\(^{-1}\)
- Kolmogorov turbulence:

\[
\langle [q(r') - q(r' + r)]^2 \rangle = D_q(|r|) = D_q(r) = 6.88 \left( \frac{r}{r_0} \right)^\xi
\]

- In two-dimensional approaches, exponent \(\xi\) depends on geometry of the turbulent volume
  - For a thin sheet \(\xi \rightarrow 2/3\)
  - For a thick sheet \(\xi \rightarrow 5/3\)

- In our approach, *directly simulate the three dimensional volume*
Simulations method
Simulating a turbulent volume

Generating large 3D Kolmogorov volumes

- **Array size** $\sim 15\text{km} \times 15\text{km}$
- **Wind:** $1\text{ hour} \times 10\text{ ms}^{-1} = 36\text{ km}$

Need to generate volumes with $> 10^9$ elements, aliasing makes FFT-based methods inefficient

See: [http://www.mrao.cam.ac.uk/~bn204/alma/](http://www.mrao.cam.ac.uk/~bn204/alma/)
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Alternative: Large-eddy simulation

- Alison Stirling’s memos
- Much more physics, more input parameters → likely to be much more accurate
- Computationally very expensive
- Not feasible to LES a large enough volume, at sufficient resolution, but a hybrid technique probably possible
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4. Summary/Links
Two-dimensional Kolmogorov screen
Two-dimensional Kolmogorov screen + two adjacent screens
Adding slices produces steepening

1st slice

2nd slice

3rd slice

∑1st–10th slices
Adding slices produces steepening II

\[ \sum_{1\text{st}–10\text{th slices}} \]

\[ \sum_{10\text{th}–20\text{th slices}} \]

\[ \sum_{20\text{th}–30\text{th slices}} \]

\[ \sum_{1\text{st}–100\text{th slices}} \]
Line of sight effect

At zenith

10° from zenith

difference
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No phase correction, long integration

Increasing magnitude of phase-fluctuations

Peak: 2 Jy
Peak: 1.66 Jy
No phase correction, long integration

Increasing magnitude of phase-fluctuations

Peak: 0.98 Jy

Peak: 0.45 Jy
No phase correction, snapshots
Sequence of snapshots separated by about 3 minutes in time
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Parametrisation of magnitude of phase fluctuation

- Have to specify somewhere how good/bad the atmospheric stability is
- Chose to do this by specifying the *phase* fluctuation RMS on a 300 m baseline
  - 300 m baseline to be able to relate directly to the site-testing interferometer data
  - Parametrisation in terms of phase to make clear the wavelength dependence
- The thickness of the turbulent layer is probably around $\sim 200$ m – several values shown in the plots below
Uncalibrated: point source sensitivity
Compact configuration

Point source sensitivity (relative to no atmospheric phase fluctuations) as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.
Uncalibrated: point source sensitivity
Medium configuration

Point source sensitivity (relative to no atmospheric phase fluctuations) as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.
Uncalibrated: point source sensitivity

Extended configuration

Point source sensitivity (relative to no atmospheric phase fluctuations) as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.
No phase correction: beam size
Medium configuration

Point-source sensitivity

Gaussian beam size
No phase correction: snapshot errors

Medium configuration

Positional error

Fractional flux error
Snapshot observation: sensitivity variance

Compact configuration

Standard deviation of relative point source sensitivity as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.
Snapshot observation: sensitivity variance

Medium configuration

Standard deviation of relative point source sensitivity as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.
Snapshot observation: sensitivity variance
Extended configuration

Standard deviation of relative point source sensitivity as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.
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Fast switching phase calibration
Medium configuration, 15 s cycle
Fast switching phase calibration

Compact configuration, 15 s cycle
Fast-switching calibration: point source sensitivity

Relative point source sensitivity, perfect fast-switching calibration with a 15 s duty cycle, 1.5 degree offset to calibrator, calibration transfer from lower frequency band.
Fast-switching calibration: point source sensitivity

Medium configuration

Relative point source sensitivity, perfect fast-switching calibration with a 15 s duty cycle, 1.5 degree offset to calibrator, calibration transfer from lower frequency band.
Fast-switching calibration: point source sensitivity

Extended configuration

Relative point source sensitivity, perfect fast-switching calibration with a 15 s duty cycle, 1.5 degree offset to calibrator, calibration transfer from lower frequency band.
Fast-switching: beamsize
15 s calibration cycle, 1.5 degree offset to calibrator

Point-source sensitivity

Gaussian beam size

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Radiometric phase correction

- Expected to work in combination with switching on a $\sim 3$ minute time scale
- Want to correct:
  - Phase fluctuation in between phase calibration scans
  - Phase error due to transfer of the phase solution from the quasar
- The specification is very ambitious:
  $$\delta p_{\text{rms}}^{\text{corrected}} = (1 + c)10 \mu m + 0.02 \times \delta p_{\text{rms}}^{\text{uncorrected}}$$  \hspace{1cm} (1)
  - The additive (left-hand) term is expected to be due to thermal noise in the radiometer, so Gaussian-distributed, uncorrelated between antennas, independent of baseline length
- Some encouraging test results, but:
  - Dry fluctuations?
  - Need to get the models almost perfect to meet the proportional part of error budget
183 GHz WVR Testing at SMA results

Total fluctuations (no running mean removed): $\sigma_\phi$ reduced from 271 to 75 $\mu$m
**183 GHz WVR Testing at SMA results**

Fluctuations from five minute average: $\sigma_\phi$ reduced from 164 to 56 $\mu$m
WVR phase correction: point source sensitivity

Assuming wet path fluctuations only and to-spec performance

If to-spec:

![Graph showing the relationship between $\phi_{rms}$ (rad) and sensitivity $S$.]
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If phase correction techniques work as well as we hope, the user will only ever need to include thermal-like phase errors in simulations.

Simulations useful for algorithms development, especially as a fully 2D array at the high site is at least a couple of years away.

In this case, the simulations steps are separable, linked by a standard file format:
- Can easily use a range of available tools
- Easy to integrate own tools
- Components can be easily re-used in other projects

Full writeup, results, code available at:

http://www.mrao.cam.ac.uk/~bn204/alma/memo-turb
Workshop on Simulations for ALMA, Grenoble 2008
http://www.mrao.cam.ac.uk/~bn204/almasim08/

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W. Cotton
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http://www.cv.nrao.edu/~bcotton/Obit.html
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