

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

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# Outline

- 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

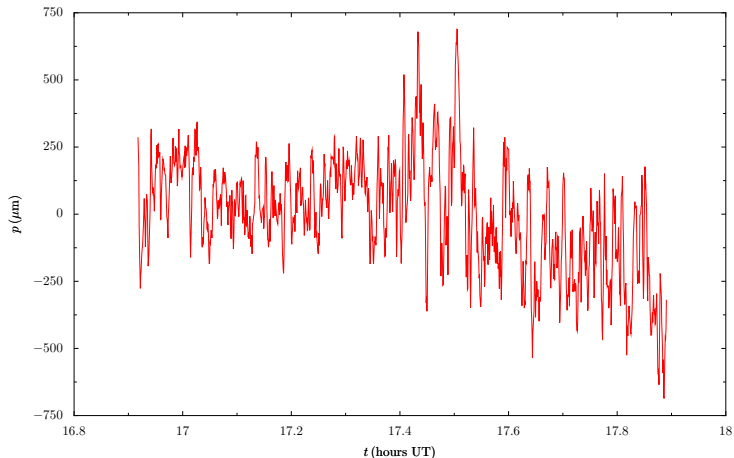
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# Atmospheric Phase errors

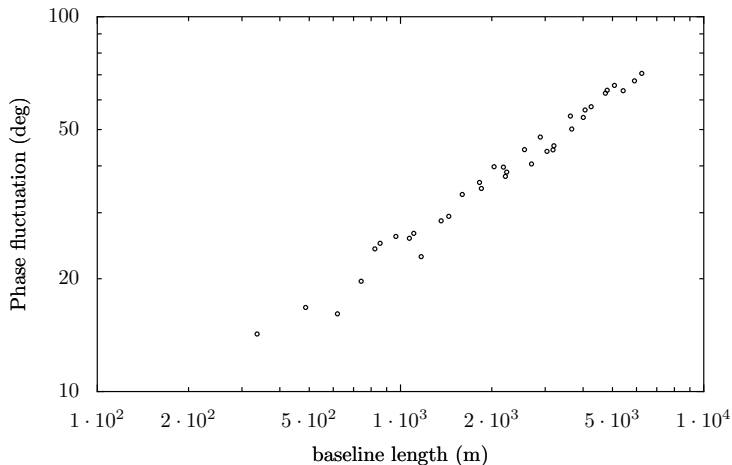
Observed path fluctuation at the SMA while tracking a quasar for one hour

( $\sigma_p = 207 \mu\text{m}$ )



# 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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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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## 2 Simulations method

### • Framework

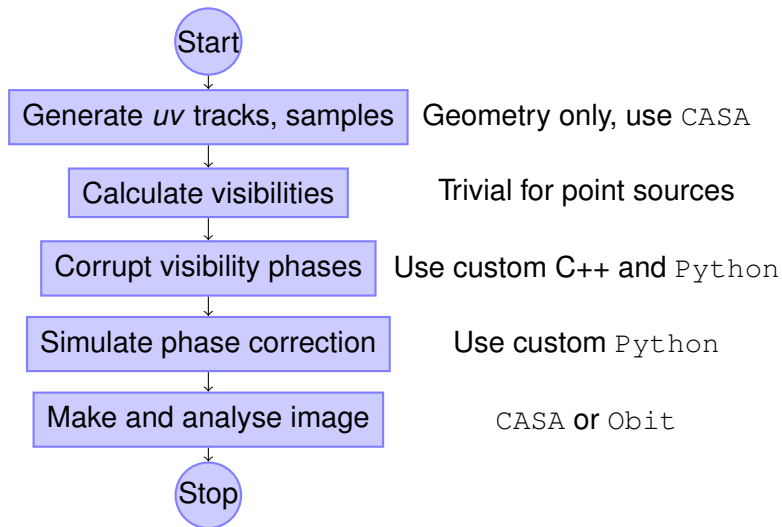
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# Simulation Flowchart



# 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

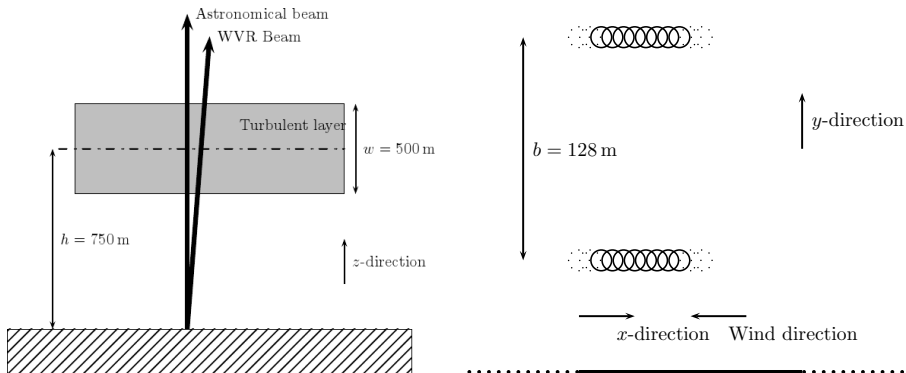
- A very straightforward flowchart!
- Factors cleanly into distinct steps
- The `FITS` format ties all of these steps together very well
- Not considering thermal noise at any stage
  - Not required for our goals, so keeping it simple
- Develop own modules separately:
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# 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<sup>-1</sup>
- Kolmogorov turbulence:

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

- 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**

# Generating large 3D Kolmogorov volumes

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

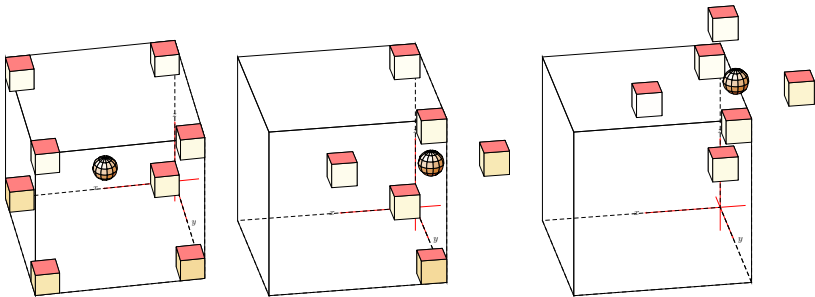
Need to generate volumes with  $> 10^9$  elements, aliasing makes FFT-based methods inefficient

See: <http://www.mrao.cam.ac.uk/~bn204/alma/>

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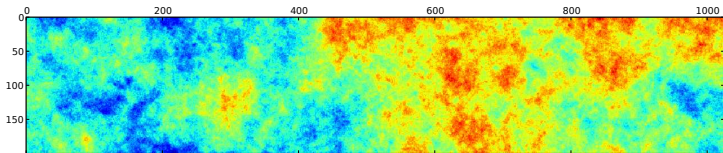
## Alternative: Large-eddy simulation

- 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

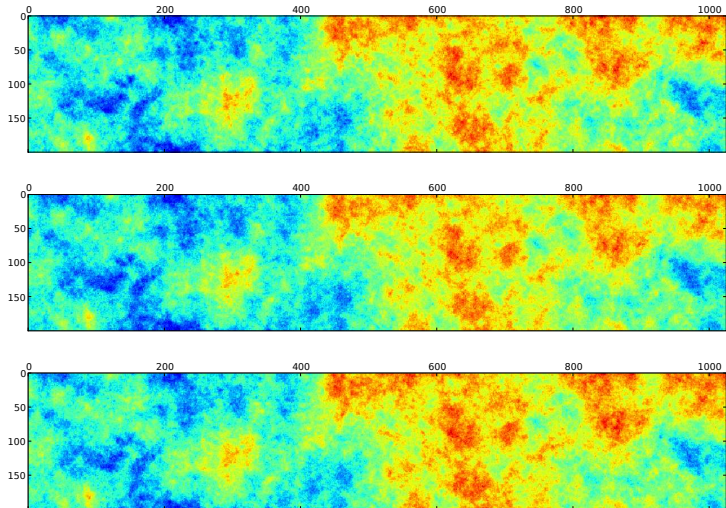
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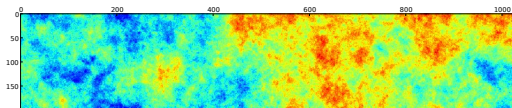
# Two-dimensional Kolmogorov screen



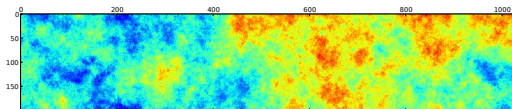
# Two-dimensional Kolmogorov screen + two adjacent screens



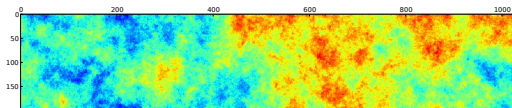
# Adding slices produces steepening



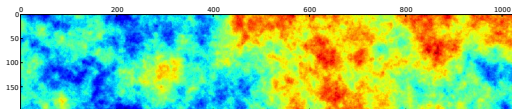
1st slice



2nd slice

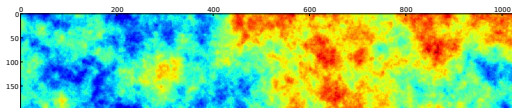


3rd slice

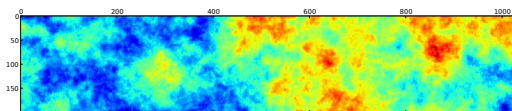


$\sum$  1st–10th slices

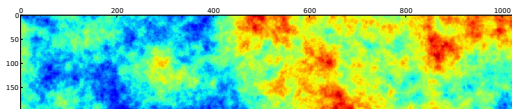
# Adding slices produces steepening II



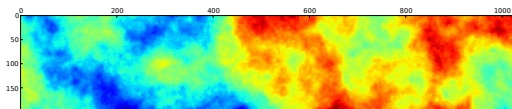
$\Sigma$ 1st–10th slices



$\Sigma$ 10th–20th slices

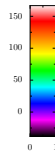
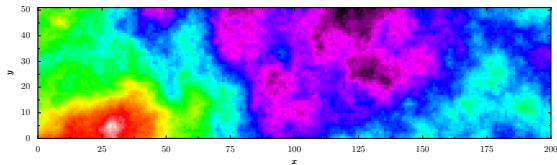


$\Sigma$ 20th–30th slices

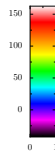
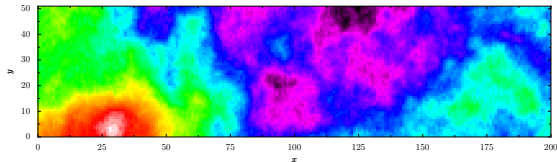


$\Sigma$ 1st–100th slices

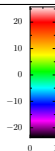
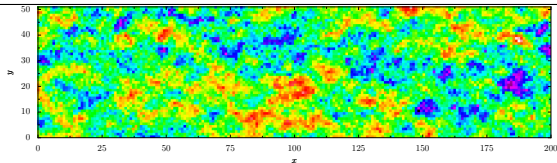
# Line of sight effect



At zenith



10° from  
zenith



difference

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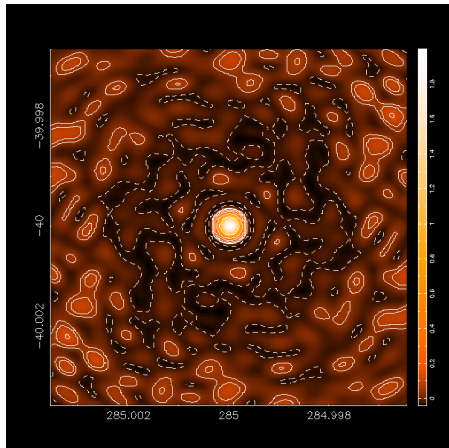
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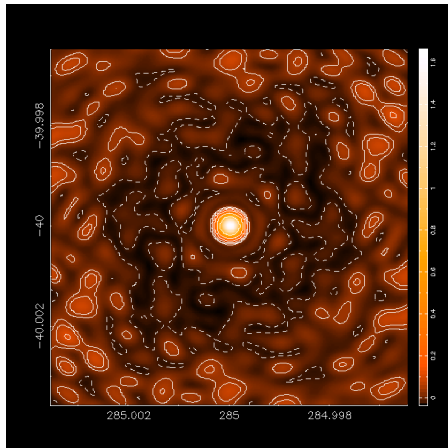
# No phase correction, long integration

Increasing magnitude of phase-fluctuations

Peak: 2 Jy



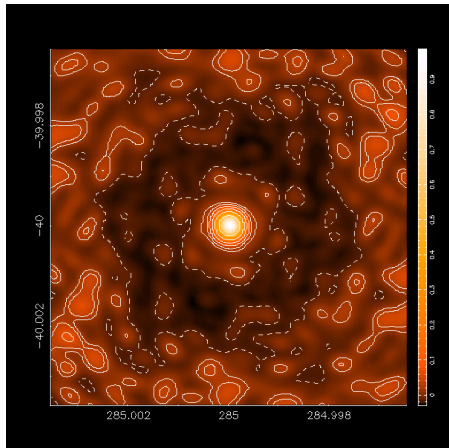
Peak: 1.66 Jy



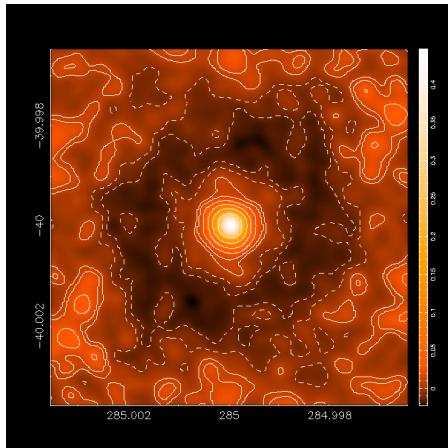
# No phase correction, long integration

Increasing magnitude of phase-fluctuations

Peak: 0.98 Jy

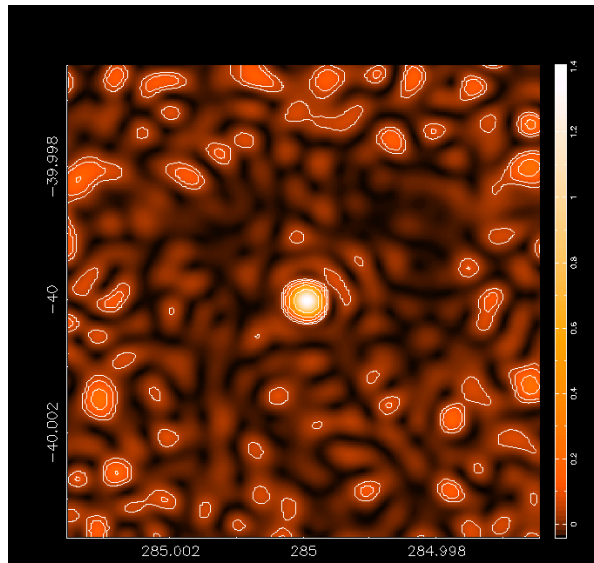


Peak: 0.45 Jy



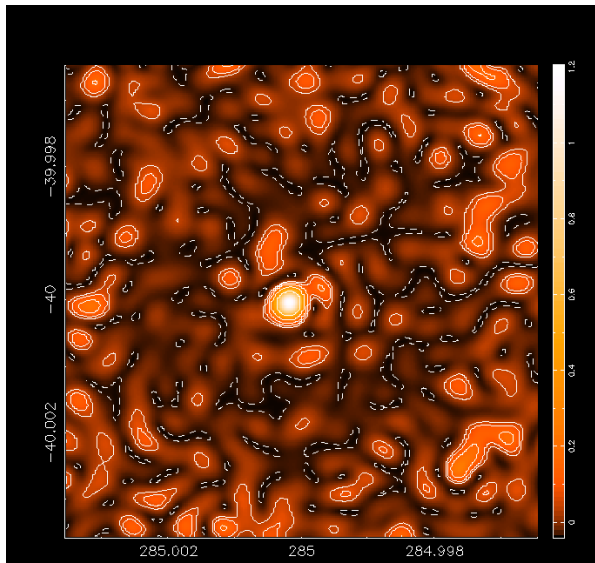
# No phase correction, snapshots

Sequence of snapshots separated by about 3 minutes in time



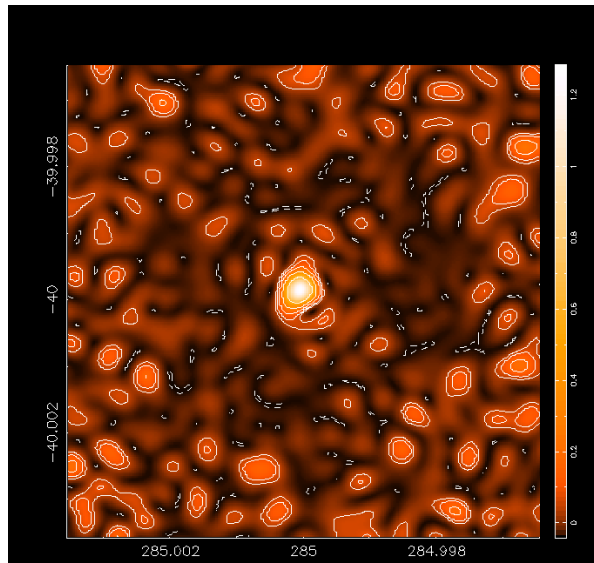
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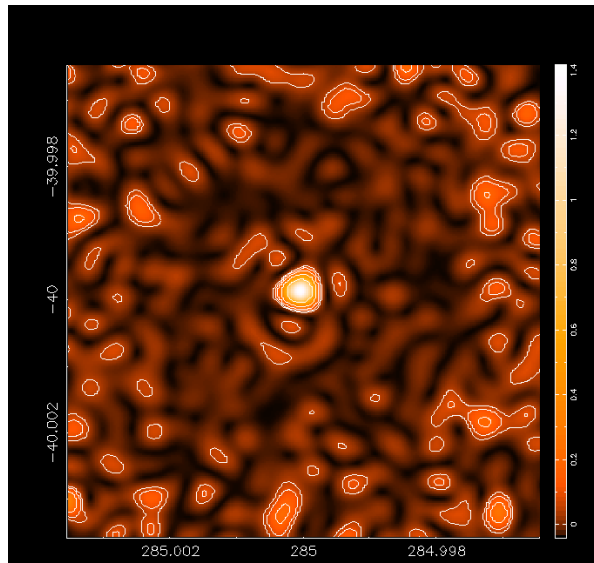
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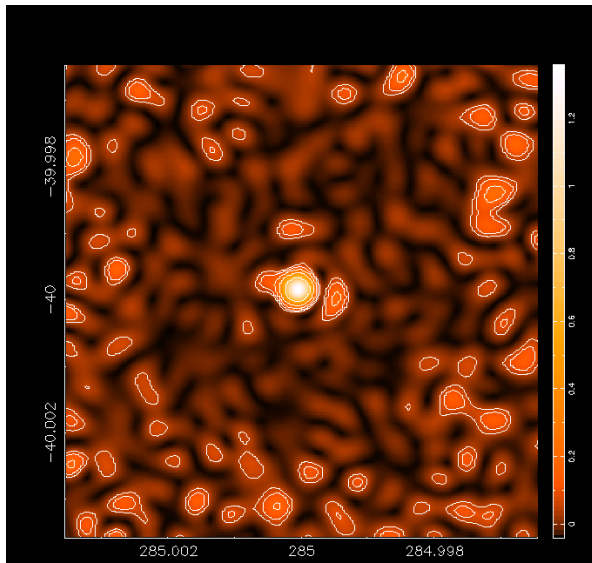
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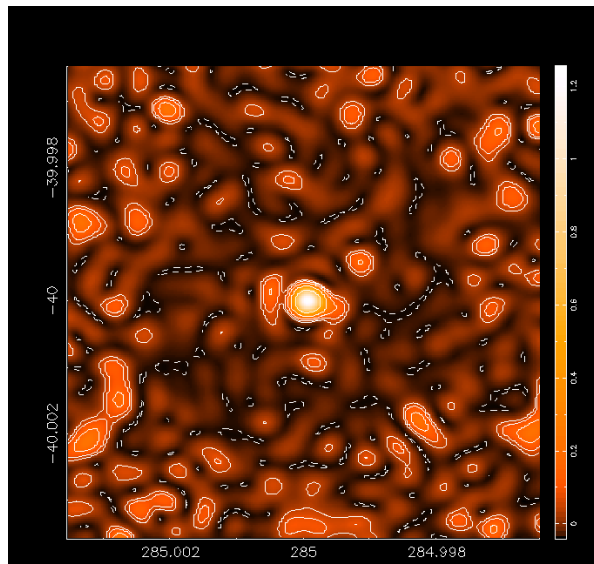
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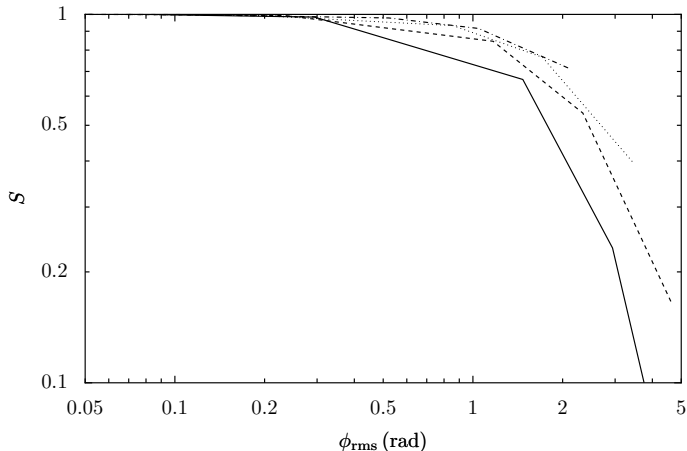


# Parametrisation of magnitude of phase fluctuation

- 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

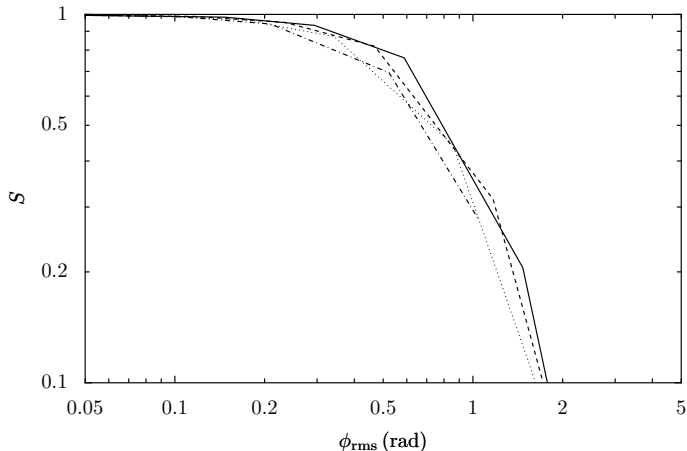
## Compact configuration



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

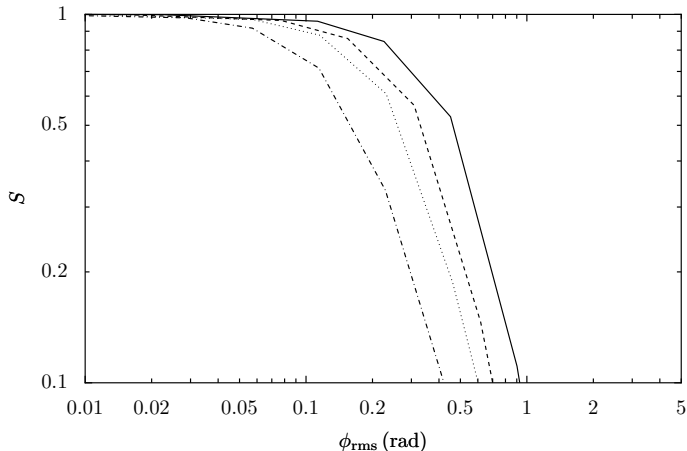
Medium configuration



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

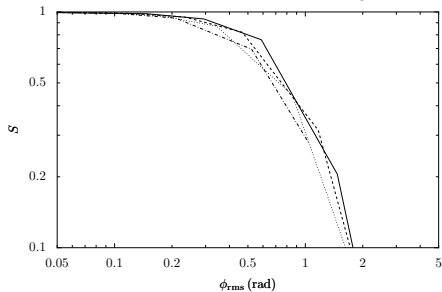


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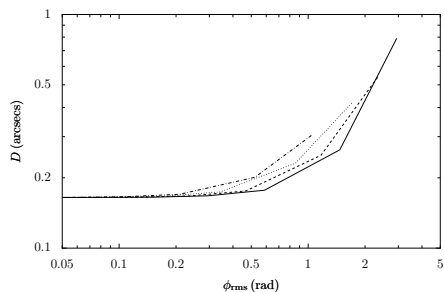
# No phase correction: beam size

Medium configuration

## Point-source sensitivity



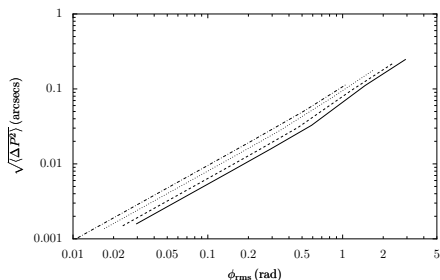
## Gaussian beam size



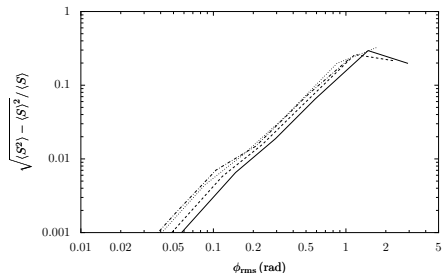
# No phase correction: snapshot errors

Medium configuration

## Positional error

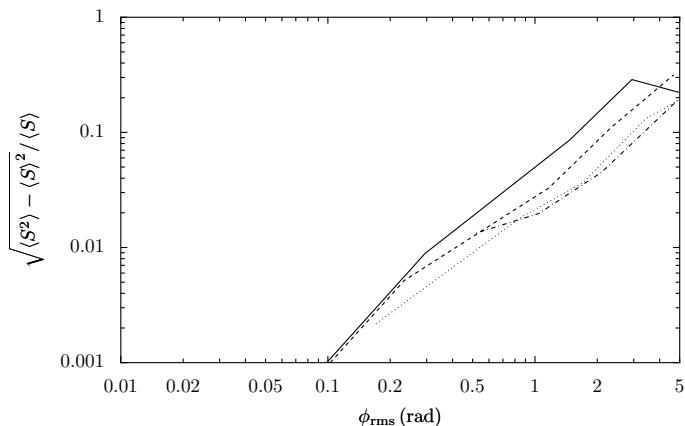


## Fractional flux error



# Snapshot observation: sensitivity variance

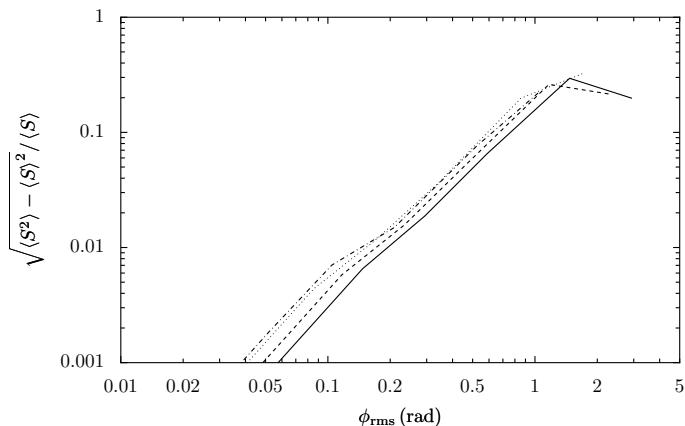
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Standard deviation of relative point source sensitivity as function of phase rms on a 300 m baseline, for four thicknesses of the turbulent layer and no phase correction.

# Snapshot observation: sensitivity variance

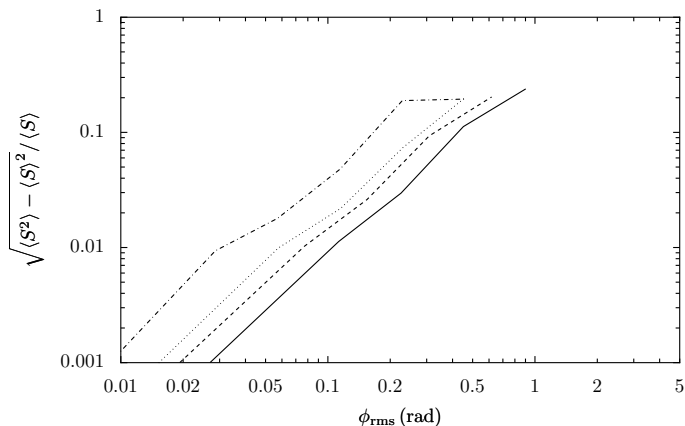
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# Snapshot observation: sensitivity variance

## Extended configuration



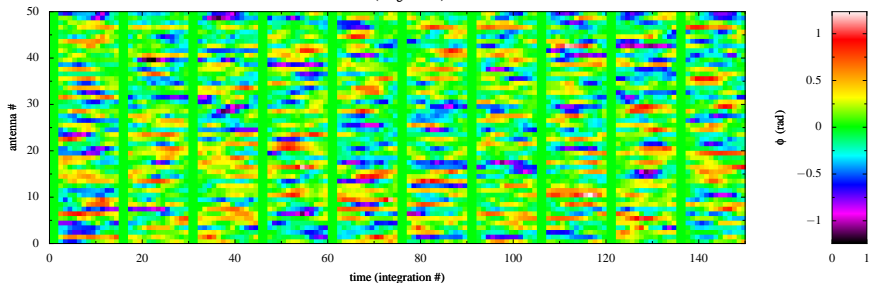
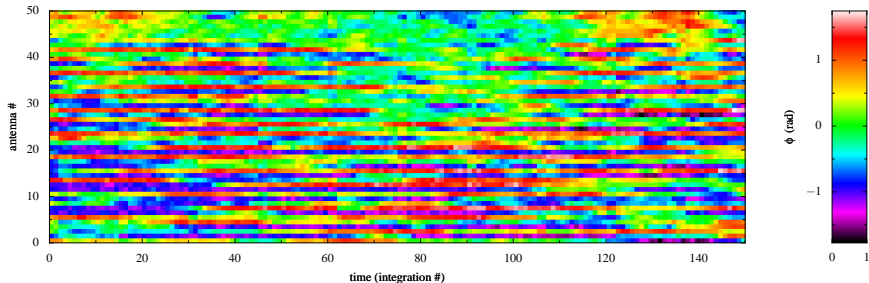
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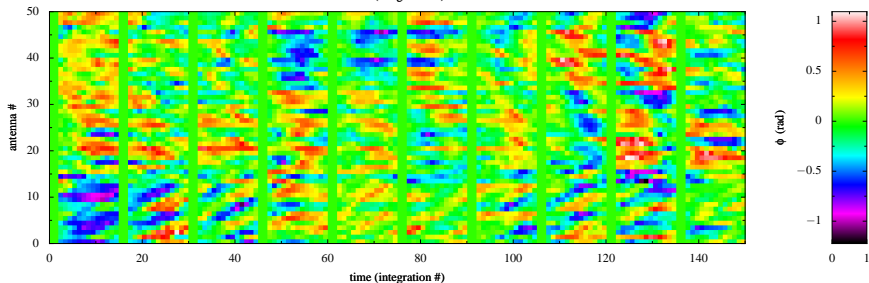
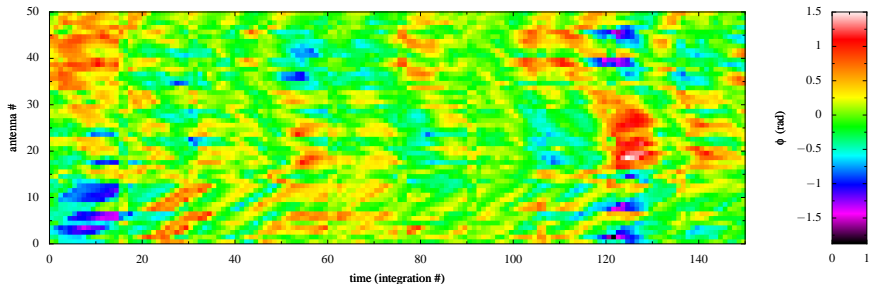
# Fast switching phase calibration

Medium configuration, 15 s cycle



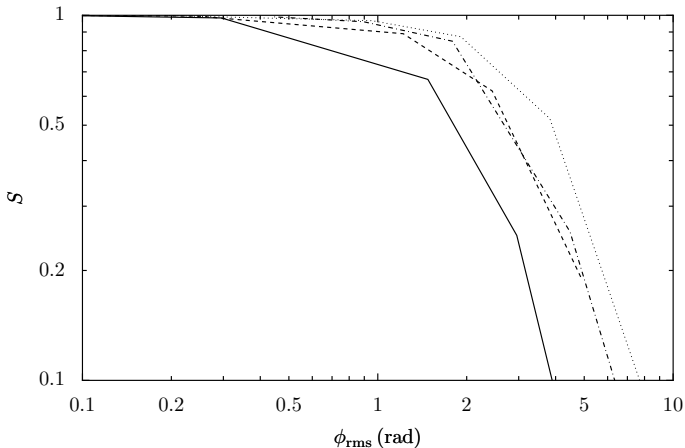
# Fast switching phase calibration

Compact configuration, 15 s cycle



# Fast-switching calibration: point source sensitivity

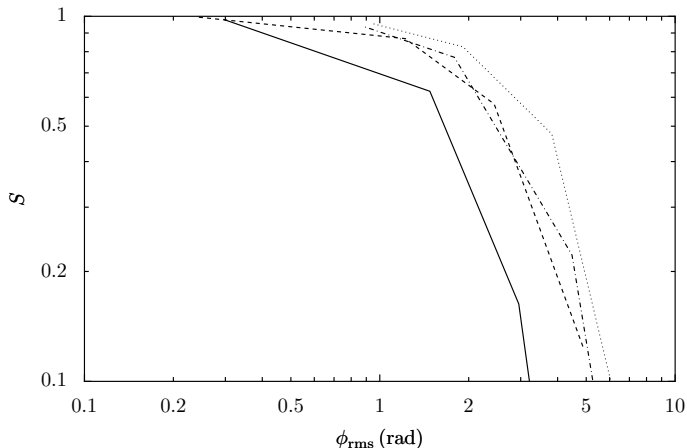
## Compact configuration



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

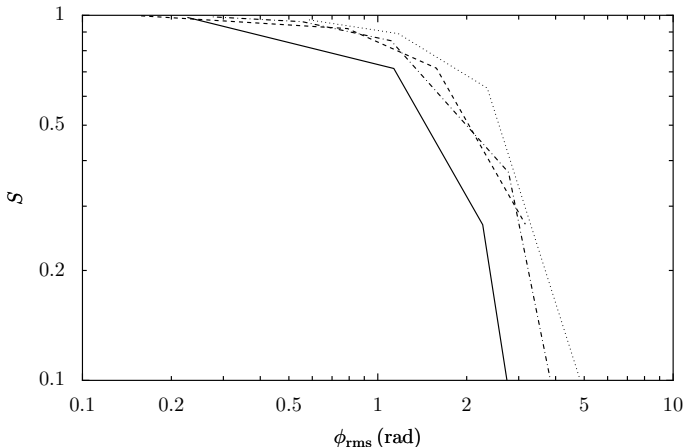
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# Fast-switching calibration: point source sensitivity

## Extended configuration

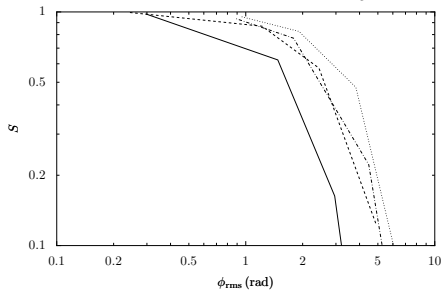


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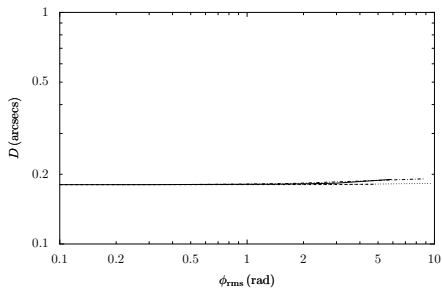
# Fast-switching: beamsize

15 s calibration cycle, 1.5 degree offset to calibrator

## Point-source sensitivity



## Gaussian beam size



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## Radiometric phase correction

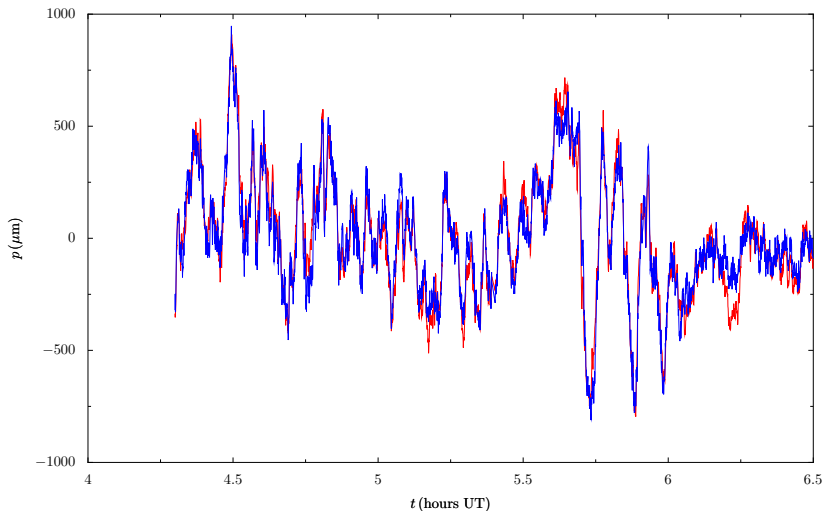
- Expected to work in combination with switching on a  $\sim 3$  minute time scale
- Want to correct:
  - Phase fluctuation in between phase calibration scans
  - Phase error due to transfer of the phase solution from the quasar
- The specification is very ambitious:

$$\delta p_{\text{rms}}^{\text{corrected}} = (1 + c)10 \mu\text{m} + 0.02 \times \delta p_{\text{rms}}^{\text{uncorrected}} \quad (1)$$

- 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

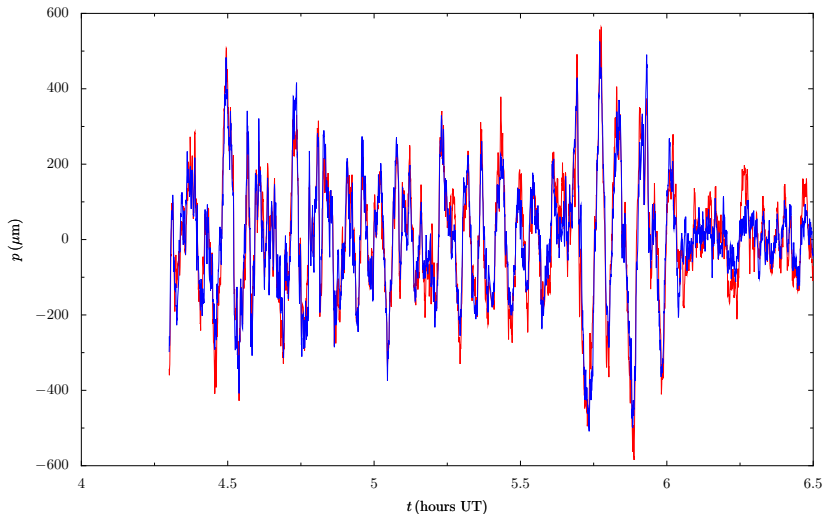
# 183 GHz WVR Testing at SMA results

Total fluctuations (no running mean removed):  $\sigma_\phi$  reduced from 271 to 75  $\mu\text{m}$



# 183 GHz WVR Testing at SMA results

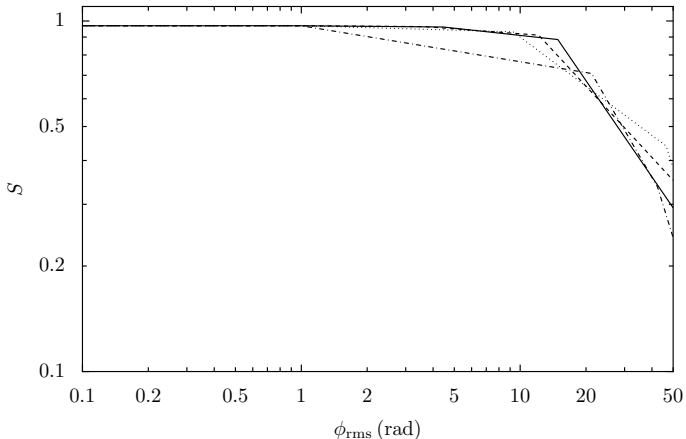
Fluctuations from five minute average:  $\sigma_\phi$  reduced from 164 to 56  $\mu\text{m}$



# WVR phase correction: point source sensitivity

Assuming wet path fluctuations only and to-spec performance

If to-spec:



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# Summary

- 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>

# References/Links I



## Workshop on Simulations for ALMA, Grenoble 2008

<http://www.mrao.cam.ac.uk/~bn204/almasim08/>



## B. Nikolic, et al.

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

ALMA Memo to be published

<http://www.mrao.cam.ac.uk/~bn204/alma/>



## W. Cotton

Astronomy Software for Algorithm Development

<http://www.cv.nrao.edu/~bcotton/Obit.html>

## References/Links II



B. Nikolic, et al

Phase Correction for ALMA: Adaptive Optics in the Submillimetre

<http://www.eso.org/sci/publications/messenger/archive/no.131-mar08/>



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