Atmospheric Phase Correction for ALMA & The WVRGCAL program

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ALMA

Outline

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ALMA

Recent (but already out of date) photo of ALMA with 16 antennas

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!

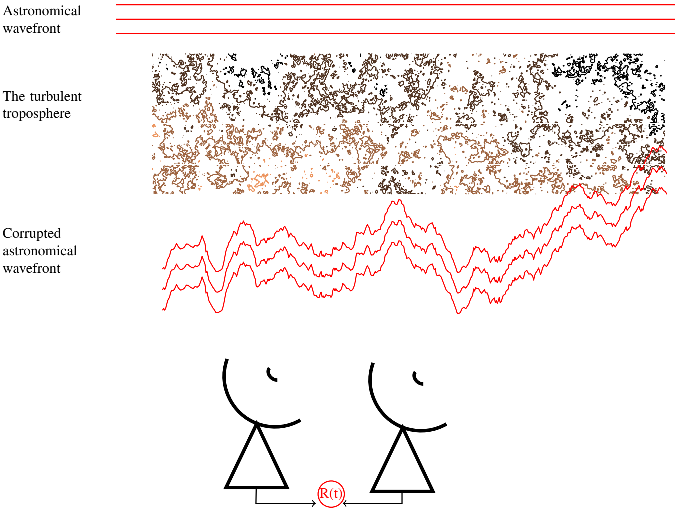
ALMA as a high resolution imager

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

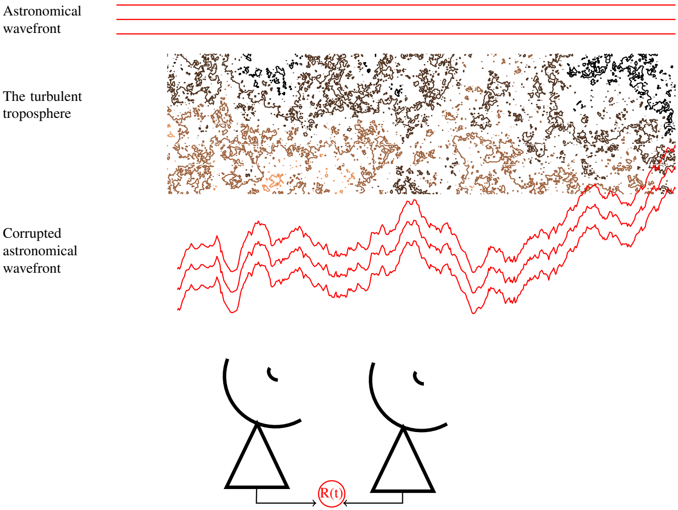
To achieve this:

- 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

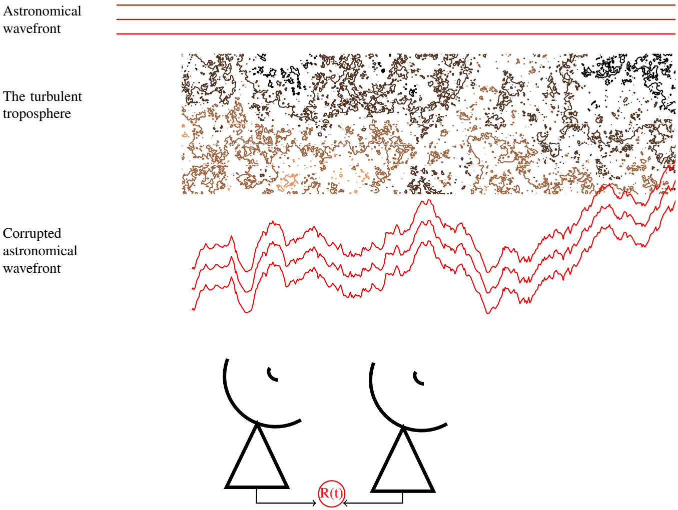
Atmospheric Phase Fluctuations



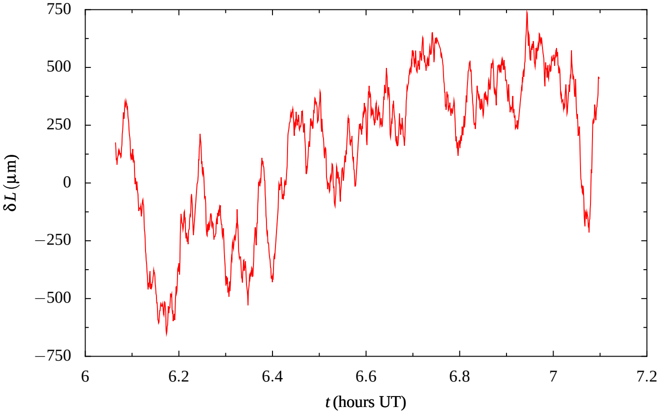
Atmospheric Phase Fluctuations



Atmospheric Phase Fluctuations



Path fluctuations due to the atmosphere



Path fluctuation on a baseline of $\sim 500\,\mathrm{m}$ inferred from ALMA observations of a quasar at $\lambda = 3.3\,\mathrm{mm}$.

Outline

Phase correction for ALMA
- Introduction
- ALMA 183 GHz WVR system

The FP6 programme

The WVRGCAL program

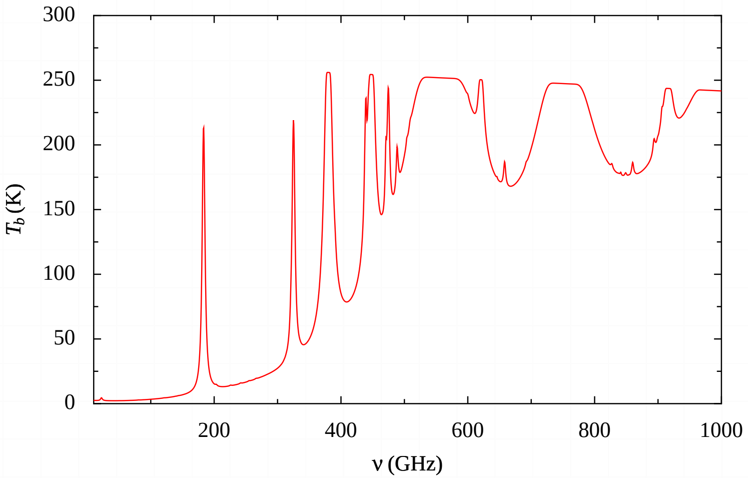
Results
- Good results
- Effect on the beam
- Poor results
- “Dry” fluctuations

Future work

Summary

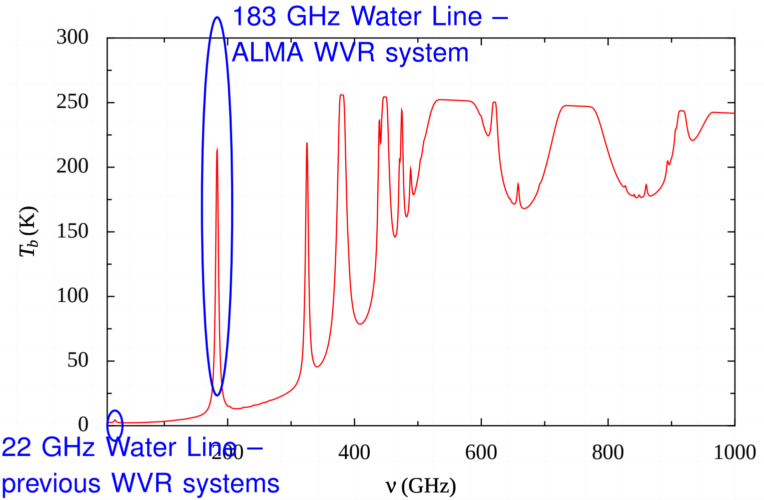
Water Vapour cm/mm/sub-mm lines

1 mm precipitable water vapour



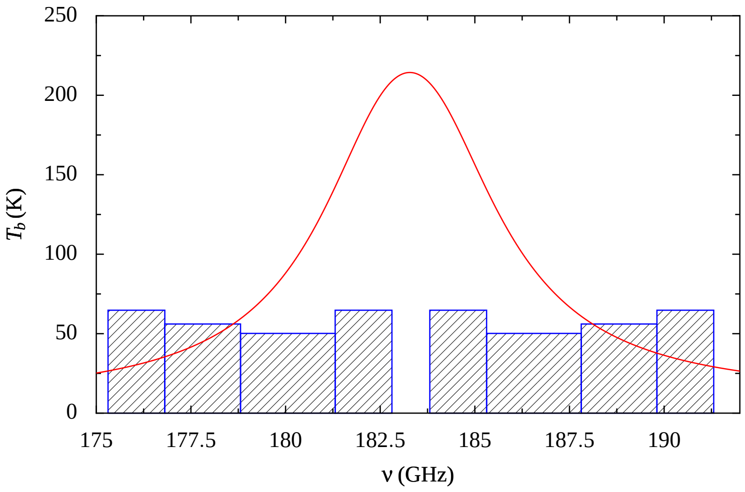
Water Vapour cm/mm/sub-mm lines

1 mm precipitable water vapour



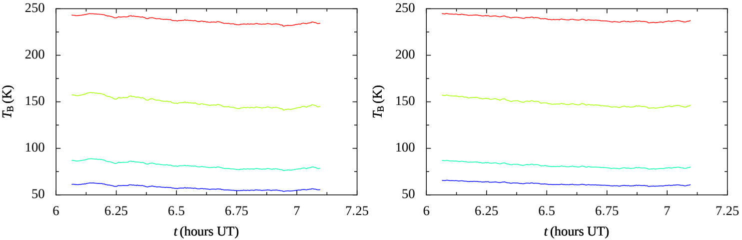
The 183 GHz Water Vapour Line

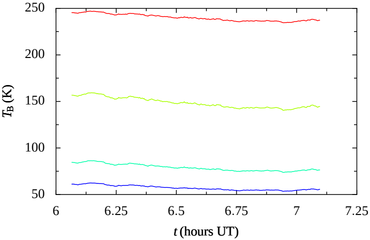
Blue rectangles are *nominal* WVR filters



WVR in the ALMA receiver cabin

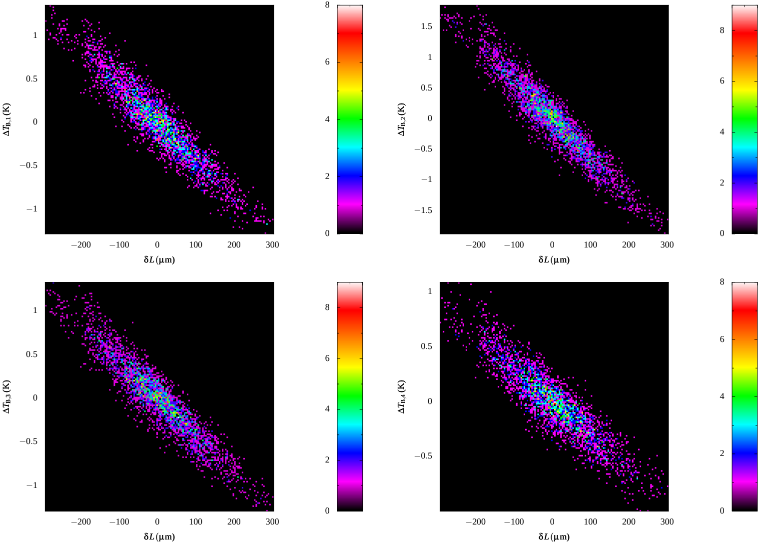
Sky brightness observed by WVRs





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



Outline

About the FP6 programme

- 'European Union Framework 6 Programme for Enhancement of ALMA Early Science'
  - Aim to enhance ALMA over-and-above the already planned/funded capabilities
  - Funded entirely separately from ALMA
  - Wide range of community groups (universities + ESO + IRAM)
  - "No drag" on the project
- Proposal to the EC in March 2004, work packages commenced Mid-2006
- Six Band-5 receivers, OTF interferometry software, and (this talk) Advanced Radiometric Phase Correction Techniques
- Similarities to the ALMA Development programme

WP 5: Advanced Radiometric Phase Correction Techniques

- The project recognised that significant R&D would be required for effective phase correction
- EC funding provided an opportunity to retain involvement of groups with lots of expertise in phase correction
- Enhancement:
  - Offline phase correction (vs on-line correction in the baseline project)
  - Advanced modelling of the atmosphere and inference of phase correction coefficients
  - Investigation of various physical effects (ALMA Memos #573, 582, 590, 592)
  - Documentation (!) (ALMA Memos #587, 588, 593)

Outline

Offline radiometric phase correction

Advantages:

1. Opportunity to inspect, flag, manipulate the data
2. Can have several tries at correction (different parameters/strategies)
3. Opportunity to identify and correct any issues with WVR data
4. Can use information from forward as well as backward in time
5. Simplifies data taking & processing

Disadvantages:

1. Need to record data at one second dump time (faster than intrinsic limit at most frequency/baseline length combinations)

WVRGCAL: Inputs/Outputs

Inputs: All directly from the measurement set

1. WVR data (recorded as if an auto-correlation)
2. Pointing table
3. SPWs, scan intents, field/source info
4. (Ground meteorological, WVRs SPWs)

Outputs:

1. CASA "T" Jones gain calibration table
2. Diagnostic print out
3. (Calculated Path information in HDF5 format)

Using WVRGCAL

- A separate, pure C++ executable
- Fully callable and scriptable from CASA

```
# Python/CASA
wvrgcal("uid___X02_X545f3_X1.ms", "uid___X02_X545f3_X1.W",
        toffset=-1.0, segfield=True)
```

or call the executable directly

```
# Python/CASA
!wvrgcal uid___X02_X545f3_X1.ms uid___X02_X545f3_X1.W --toffset \
        -1.0 --segfield
```

- Error status is returned
- Not a CASA *task*
  Can not do inp(wvrgcal) and go

WVRGCAL diagnostic output I

```
    Input WVR data information:
_______________________________________
Timestamp       Ant. #   [Chn 0, Chn 1, Chn 2, Chn 3]    Elevation       STATE_ID
4.82415e+09     0        [203.95, 112.95, 64.03, 47.10]  0.879331        10
4.82415e+09     0        [185.27, 97.06, 54.25, 39.98]   1.2491  2
4.82415e+09     0        [182.96, 95.22, 53.27, 39.28]   1.32064 22
4.82415e+09     0        [201.12, 110.41, 62.78, 46.28]  0.89608 2
4.82415e+09     0        [202.65, 111.75, 63.32, 46.64]  0.948044        26

Calculating the coefficients now...done!
      Retrieved parameters
________________________________________________________________________
Evidence        PWV      PWV Error       dTdL     dTdL     dTdL     dTdL
4.06901e-25     1.05784  0.0113119       8.00164  8.40131  5.14256  3.53637
4.37288e-23     1.03764  0.00938764      11.32    9.62416  5.4269   3.65468
1.38594e-23     1.03341  0.00833841      11.7391  9.76709  5.46462  3.67295
6.67496e-24     1.0291   0.00994679      8.4328   8.58773  5.23842  3.60326
4.39244e-24     1.09548  0.0111935       8.18877  8.4811   5.17959  3.56128
```

WVRGCAL diagnostic output II

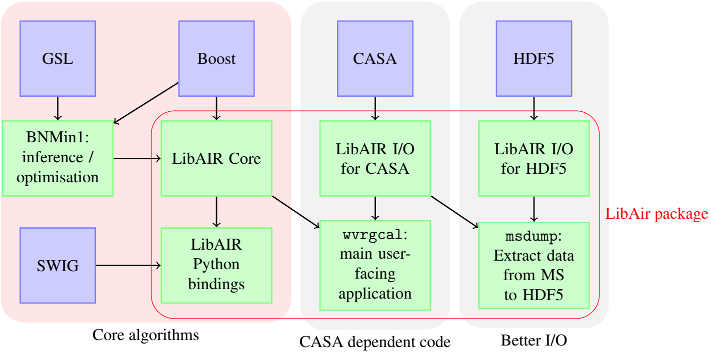
Antenna/WVR information:

#	Name	WVR?	Flag?	RMS (um)	Disc (um)
0	DA41	Yes	No	162	26.4
1	DA42	Yes	No	199	30.7
2	DV02	Yes	No	153	30.9
3	DV03	Yes	No	171	22.9
4	DV05	Yes	No	159	21.3
5	DV06	Yes	No	180	24.6
6	DV08	Yes	No	145	34.2
7	DV11	Yes	No	192	25.1
8	DV12	Yes	No	192	24
9	DV13	Yes	No	171	24.4
10	DV14	Yes	No	158	20.1
11	PM01	Yes	No	184	27.3
12	PM02	Yes	No	173	23.1
13	PM03	Yes	No	172	25.7
14	PM04	Yes	No	149	24.2

Expected performance

* Estimated WVR thermal contribution to path fluctuations (micron per antenna): 5.34387
* Greatest Estimated path fluctuation is (micron on a baseline): 168.165
* Rough estimate path error due to coefficient error (micron on a baseline): 1.13354

Software architecture



- High level of modularity, computation/data input-output/user interfaces separated
- Uses CASA as a C++ library (the way it was intended)

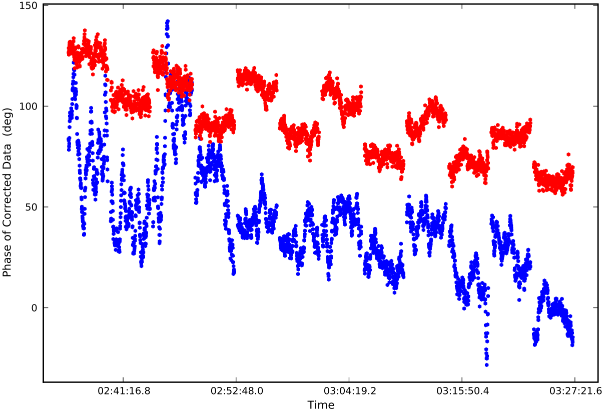
WVRGCAL summary

- Takes a measurement set and produces calibration table
- User can view, apply, modify the calibration table using standard CASA tools (applycal, accum, calsmooth, calplot)
- Choose to apply the correction in combination with other calibrations, self-cal, etc

Outline

First application – February 2010

Courtesy of Al Wooten

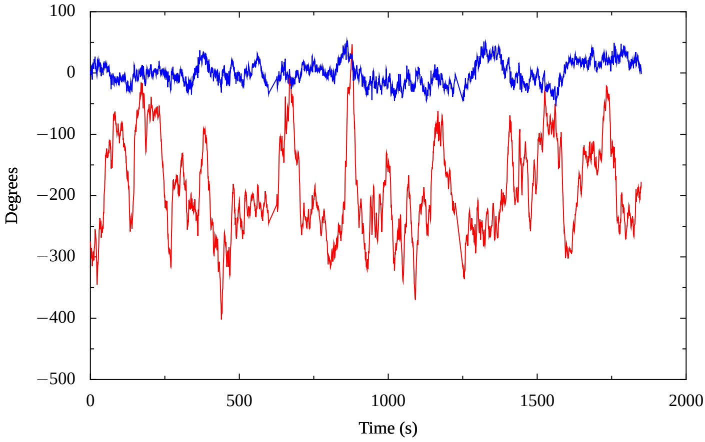


This was an observation switching between two quasars. Blue: uncorrected phase; red: corrected phase

Outline

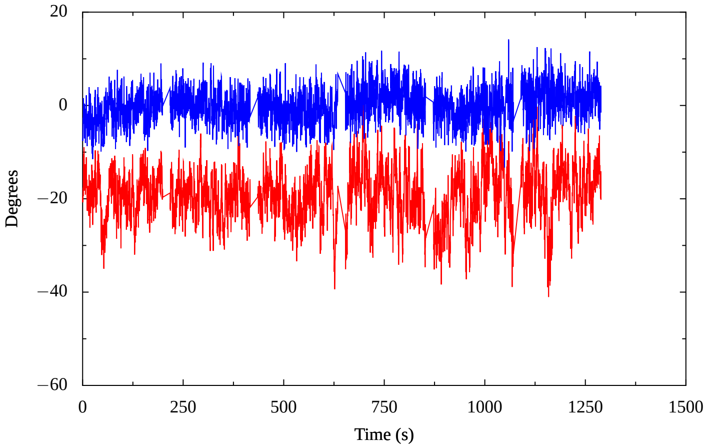
Data-set A002_Xb9f5d_X1: Long baseline

Red: uncorrected phase; Blue: corrected phase



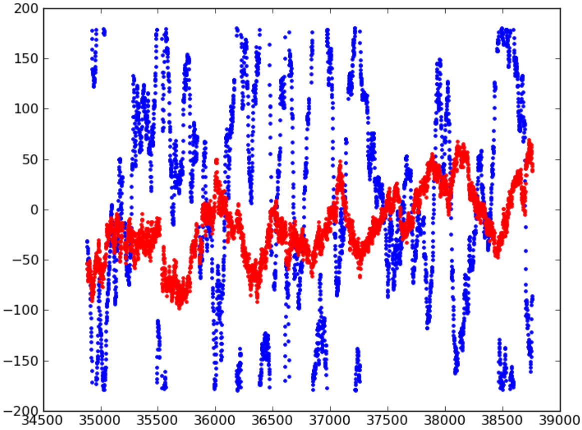
Data-set A002_Xa0705_X1

Another example, only short baselines



March dataset X1849a5_X191

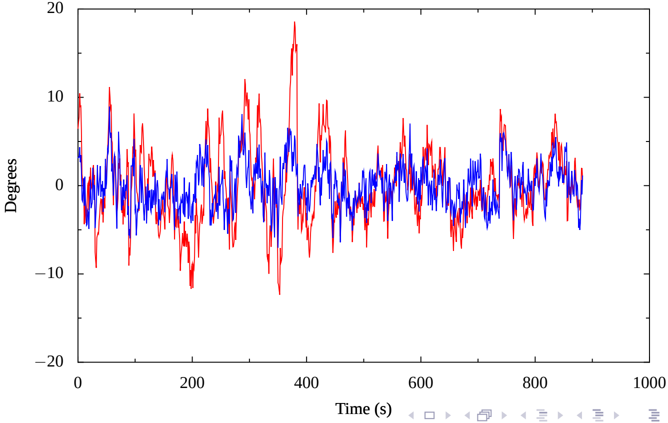
Very wet weather, ∼ 600 m baseline



Best result – minimum phase errors

This is for short baselines and very rare! (A002_X219601_X5c7)

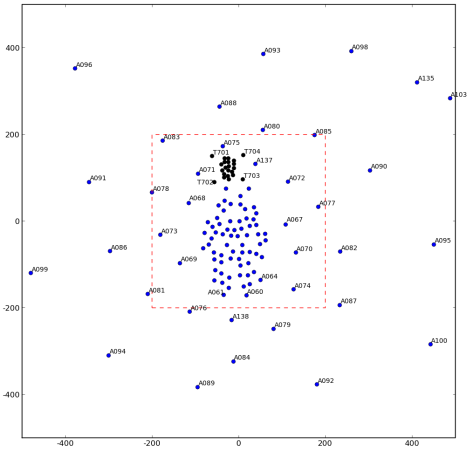
- Uncorrected phase $\sim$ 14 micron ($<$ 3 min timescale)
- WVR-corrected phase $\sim$ 7 micron
- $\rightarrow$ This is almost good enough for mid-infrared interferometry!



Outline

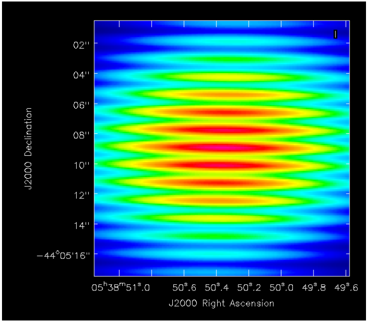
Inner ALMA pad positions

From http://www.alma.cl/~dbarkats/pad_position_plotter/plots/ALMA_pad_viewer_zoom2.html

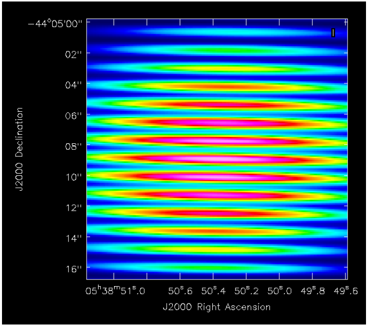


The effect of WVR correction on the ALMA synthesised beam

No phase correction



WVR phase correction

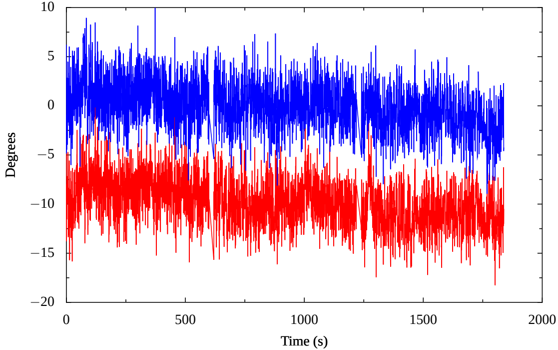


Short observation with very inhomogeneous *uv* distribution – one antenna was on a long north baseline and others were close together in a cluster

Outline

Data-set A002_Xba2ed_X1

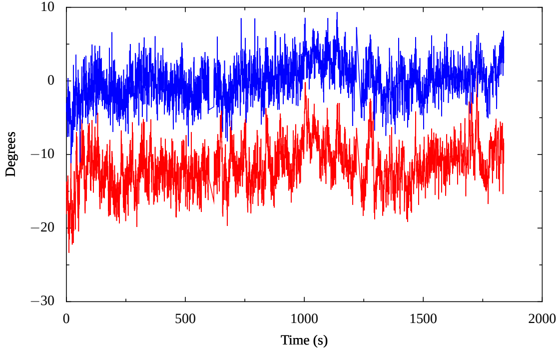
Short baselines, leak-through phase fluctuations (offset in coefficients due to time-constant cloud?)



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

Data-set A002_Xba2ed_X1

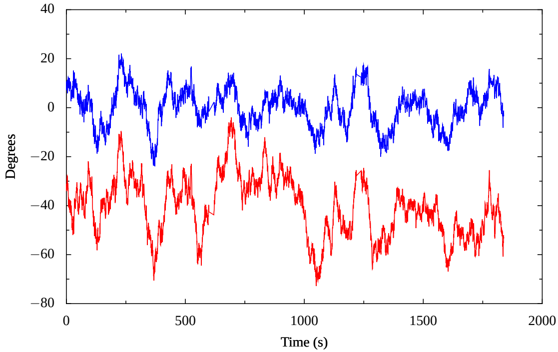
Short baselines, leak-through phase fluctuations (offset in coefficients due to time-constant cloud?)



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?)

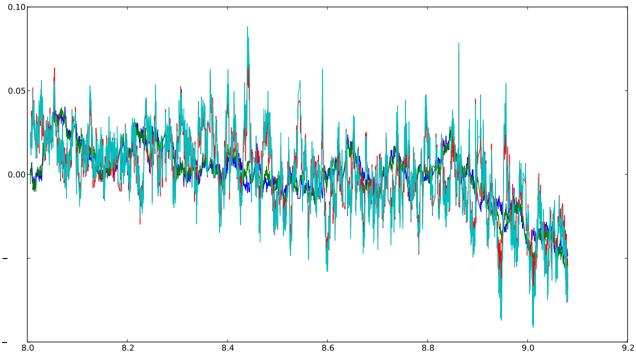


Slightly longer baseline (A0-A3): atmospheric phase fluctuations clearly seen, corrected somewhat but clear "leak-through"

Outline

Evidence for ‘dry’ fluctuations

Baseline length $\sim$ 100 m



Outline

Remaining work

1. Long baselines? (Hardest part still left to do!)
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?

But will require some new source of funding!

Outline

Summary

1. WVR phase correction for ALMA is working
2. WVRGCAL reduces phase errors in all measurements, often by a large factor
3. WVRs are in continuous use, WVRGCAL is currently used for all Science Verification and Early Science projects
4. Writing C++ programs using CASA is quite possible, not a "drag" on either the project or the developer
5. Delivery from a software development project!
6. External groups can work successfully and productively with the ALMA project

Some lessons

1. Our group was involved in the entire lifecycle of the WVR system for ALMA:
   - Initial research of the technique (JCMT-CSO interferometer)
   - Prototyping of hardware
   - Review of production hardware
   - Commissioning and testing
   - Software development

   It is intellectually satisfying and very efficient to be able to do this...
2. Knowledge of C++ was essential for this work (CASA Python bindings are minimal)
3. Don't start the software too early!
4. Open mailing list, open source publicly available source code: <u>not overwhelmed!</u>

What could we have differently?

1. One programmer project –
   Maintenance? Support? Bug fixes?
   Better to involve ALMA staff early on (but would be against the boundary condition!)
2. A lot of emphasis on sophisticated computation
   In fact in the beginning basic computation + thorough <u>data checking</u> and <u>diagnostics</u> were most important