FP6 Workpackage 5: Advanced Radiometric Phase Correction (ARPC)
JAO – ALMA Enhancement Team Meeting

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ALMA is attempting to improve the angular resolution of (sub)mm-wave images by a factor of 50 over current facilities:

- Aiming for 5 mas on longest baselines/highest frequencies
- Phase errors due to atmospheric turbulence are the major obstacle
  - This is because the effect of atmospheric phase error is greatest on long baselines required for high-resolution imaging

Other consequences of phase errors (e.g. Memo # 582):

- Loss of sensitivity
- Astrometry errors (snapshot/mosaic only)
- Flux calibration errors (snapshot/mosaic only)
High-z quasar observation with the SMA


[Image of two contour plots showing the results of high-z quasar observations with the SMA. The plots display the distribution of 1mm continuum flux, with color scales representing optical images (HST Archive) and flux values in mJy/beam.]
Simulated proto-planetary disk with ALMA

This is the aim [Wolf & A’Angelo, 2005. (50+100pc, 1+5 $M_{\text{jupiter}}$)]:

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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 limited number of cases
Fast switching phase calibration
(Simulation)

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The 183 GHz Water Vapour Line
Blue rectangles are the production WVR filters
Goal for ALMA Phase Calibration

- Formally:

\[ \delta L_{\text{corrected}} \leq \left( 1 + \frac{W}{1 \text{ mm}} \right) 10 \mu m + 0.02 \times \delta L_{\text{raw}} \]  

- For most projects, the above means atmospheric fluctuations are eliminated as a scheduling constraint.

- ALMA will rely on accurate phase correction.
  → If it doesn’t work as expected for a project, the scientific objectives are likely to be compromised.
Description of work

Develop more sophisticated atmospheric models both ab initio but also through the empirical analysis of the radiometric data already taken at the Sub-Millimeter Array (Hawaii) and later from the ALMA site in Chile, from Early Science onwards. Implement and test these methods as part of the ALMA software system, with the deliverable being a turnkey system in the ALMA pipeline by the end of the project.

Deliverable D9
Complete software package for correcting phase and amplitude errors applied to the ALMA astronomical data integrated into the ALMA system. The software will be released in stages in accordance with the standard ALMA Computing release cycle, with increasing functionality in each 6-monthly release.
Radiometric phase correction is a part of baseline ALMA.

It was however recognised that

- phase correction by water vapour radiometry is a complex technique that needs an extended research and development process to become a simple and usable solution for astronomers and the observatory;
- ALMA had limited resources in the Science and Computing IPT budgets for this work;
- Leadership and expertise in this within European institutions made it attractive to continue the technical development in here.

WP5 grew out of this: we recognised that we could significantly enhance ALMA’s scientific capabilities using European expertise. Enhancement comes in two forms: better phase correction (hence better imaging and sensitivity) for a given observation; and capabilities to exploit wider range of weather conditions (efficiency).
Summary of current status of WP5

- All internal milestones as agreed at the start of the project have been achieved so far (and associated payments made by ESO to UC)
- Project is fully staffed (Richer/Nikolic/Curtis)
- 4 ALMA memos covering aspects of WVR phase correction
- First field trip to the site commencing tonight!
  - Tests at the OSF
  - Discussion/collaboration with ALMA staff
- We have requested a zero-cost extension to the work package to allow it to overlap with Early Science – end date Dec 2011
- No realistic test data yet – all work so far either theoretical or with short sections of SMA data
- ‘Baseline’ radiometric phase correction only now being designed and implemented
### Internal Milestones

*Assuming Dec 2011 completion*

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone Description</th>
</tr>
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<tbody>
<tr>
<td>1 Apr 2008</td>
<td>Initial version of on-line stub code. Reports on implications of observing strategies and antenna vs baseline correction.</td>
</tr>
<tr>
<td>1 Oct 2008</td>
<td>Initial version of physics-based algorithms and report on this.</td>
</tr>
<tr>
<td>1 Apr 2009</td>
<td>Refined version of physics algorithm. Initial version of machine-learning based algorithm</td>
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<tr>
<td>1 June 2011</td>
<td>Near-final algorithms based on extensive AOS testing</td>
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<tr>
<td>31 Dec 2011</td>
<td>Final revised versions of algorithms and documentation, and report on their performance after Early Science feedback</td>
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Primary outputs of WP5 so far I

- Full analysis of test data from the SMA
  - Written up as a note distributed to the project

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<th>Time (UT)</th>
<th>Elev (deg)</th>
<th>Baseline (m)</th>
<th>Raw $\sigma_\phi$ (µm)</th>
<th>5-min $\sigma_\phi$ (µm)</th>
<th>Res. (µm)</th>
<th>$c$ (mm)</th>
<th>Spec (µm)</th>
<th>Sampling (s)</th>
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<td>3.1</td>
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</table>

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Primary outputs of WP5 so far II

- Simulation of errors due to partial overlap of WVR and astronomical beams
  - Documented as ALMA Memo # 573
  - Implemented in C++/Python and publicly available under LPGL

Turbulent layer at 250 m

Turbulent layer at 750 m
Primary outputs of WP5 so far III

- Simulation of ALMA phase correction strategy as a system
  - Documented as ALMA Memo # 582
  - Implemented in C++/Python, publicly available under LPGL, and compatible with CASA

Positional error

![Positional error graph](image)

Fractional flux error

![Fractional flux error graph](image)
Primary outputs of WP5 so far IV

- Calculation of phase correction coefficients from ab-initio and empirical methods
  - Documented in detail as ALMA memos #587 and #588
  - Fully implemented in standalone C++ and made publicly available under LPGL

Estimated

Optimum

Residual RMS 74 μm

Residual RMS 71 μm

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Primary outputs of WP5 so far V

- Technical input for reviews of the production WVR hardware design
Highlight of recent progress

- Basic versions of both ab-initio and empirical algorithms implemented and shown to produce encouraging results with the SMA test data
- Emily Curtis joined us in April (working part-time on phase correction) and she’s now up to speed on the project
- First data from the OSF with production WVRs this month
- Mid-term review successfully passed
Near-term plans

- Trip to OSF/AOS to collect WVR sky brightness data, talk to ALMA staff, and familiarise with the operation of the telescopes (next two weeks)
- Analysis of sensitivity of the dispersive scaling factor to atmospheric conditions (e.g., ground level temperature, water vapour scale height) (some results already available)
- Analysis of the WVR sky brightness data from OSF/AOS (next three months)
- Initial design of the CASA interface (probably commence in September)
Test Data

Realistic test data is a critical input to our work, in order to

- Understand in which directions to further develop the algorithms we already have
- Test how well the algorithms work and tune them from use in production

Currently we have:

- About five hours of useful test data from the SMA with the prototype WVRs
- Sky-brightness data from production WVRs in the lab at OSF (collected in the beginning of July)

Near term test plan exists and we fully support it:

- Distributed by Richard Hills
- 18 items of which about 5 completed already
Ideally we would have simultaneous interferometric and WVR sky brightness data:

- With good instrumental phase stability
- Taken at the AOS (but at OSF would be useful too)
- Over a range of atmospheric conditions (daytime/nighttime and winter/summer)
- In a number of different configurations (compact to most extended, where the challenge is greatest)
- Over a range of observing frequencies (to understand dispersive effects)

Extension of work to December 2011 is crucial to getting the majority of these data
Integration plans

▶ It will be possible to do phase correction both *on-line* (based in the TELCAL package) and *off-line* (CASA)
▶ All code already developed is standard C++/Python and compatible with both systems
▶ The plan is to first integrate into CASA
  ▶ Offline correction is better except in cases where limited by high data rates
  ▶ Initial testing of algorithms will always be done off-line
  ▶ This integration is straightforward and can largely be done independently of main CASA development
▶ One proven, some algorithms will be integrated into TELCAL
  ▶ Only a subset of algorithms will be suitable for use in TELCAL
  ▶ Code already produced can be called from TELCAL
  ▶ Integration will be more straightforward once baseline algorithms are implemented
Risks/issues to keep in mind

▶ Availability of suitable quality/quantity test data
  ▶ Much reduced with the extension to Dec 2011
▶ Loss of key personnel
▶ Will phase transfer from 90GHz work well enough? If not alternative strategies will need to be developed
▶ User experience of (offline) phase correction
  ▶ Integration into pipeline processing?
  ▶ Added complexity to off-line data reduction?
▶ Role of WVRs in absolute flux calibration?
▶ Input from phase correction algorithms into scheduling software
  ▶ How well can we predict residual phase fluctuation?
  ▶ How do we decide on fast-switching cycle time?