Mid-Term Review: Workpackage 5

Advanced Radiometric Phase Correction (ARPC)

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May 2009

Need for accurate phase correction

- ALMA is attempting to improve the angular resolution of mm-wave images by a factor of 50.
  - Current limits $\sim$ 250 mas at SMA, Plateau de Bure, CARMA.
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- Path errors monitored on 300-m baselines (see ALMA Memo 471):

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measured ϕ_{rms}	[μm]		ν_{limit} [GHz] 30°	70°	345 GHz b_{max} [m]	θ_{see}
75 %	394	5.3°	63	148	52	2.40″
50 %	187	2.5°	134	313	181	0.69″
25 %	89	1.2°	281	655	625	0.20″
10 %	49	0.7°	510	1189	1691	0.07″

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Phase correction for ALMA is critical to its success

ALMA Phase Correction Strategy

- Combination of two techniques:
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WVR at 22 GHz trialled at CARMA, Plateau de Bure, VLA.

WP5 within the ALMA Project

It was recognised that

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WP5 Description from Contract

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.

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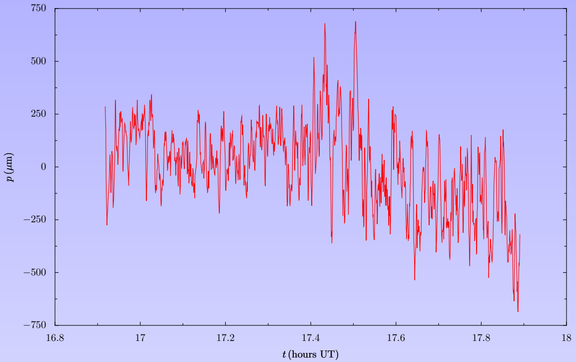
Deliverable D9

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.

Example of observed path fluctuations

SMA, Mauna Kea, Hawaii



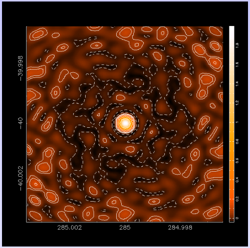
- Measured path fluctuation while observing a quasar
- 200 m baseline
- About 3.5 mm line-of-sight water
- $\sigma_\phi = 207\,\mu m$.

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`

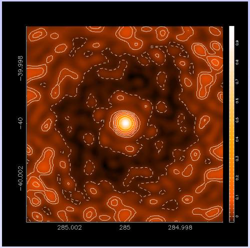
Effect of phase fluctuations

- Published in Memo # 582 and on web:
  `http://www.mrao.cam.ac.uk/~bn204/alma/memo-turb.html`
- Loss of sensitivity
- Loss of resolution
- Further effects on snapshot/mosaic observations
  - Astrometry
  - Flux calibration

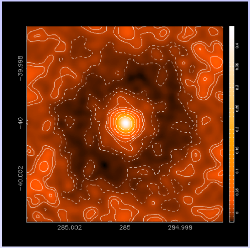
Peak: 2 Jy



Peak: 0.98 Jy

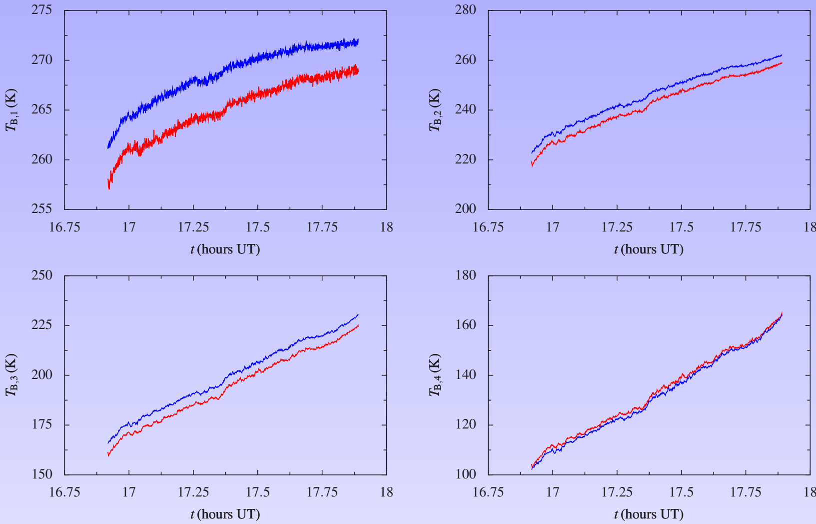


Peak: 0.45 Jy

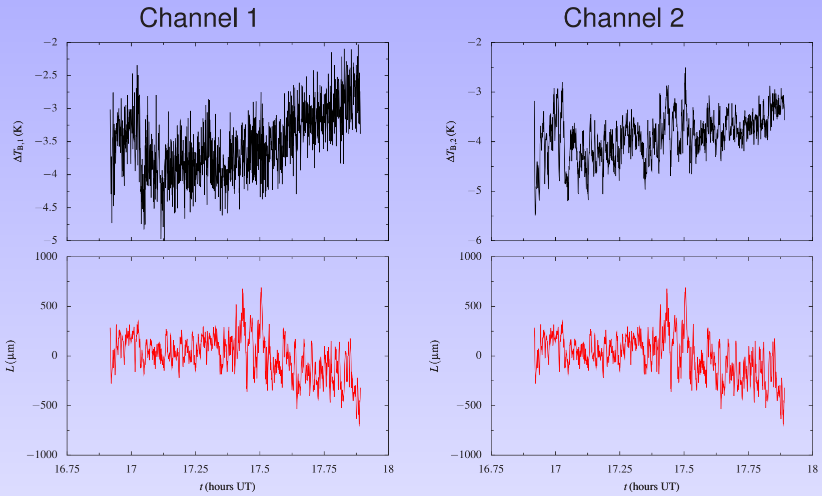


Observed data from SMA

4 channels observed on two antennas



Observed data from SMA: δT_B vs Path



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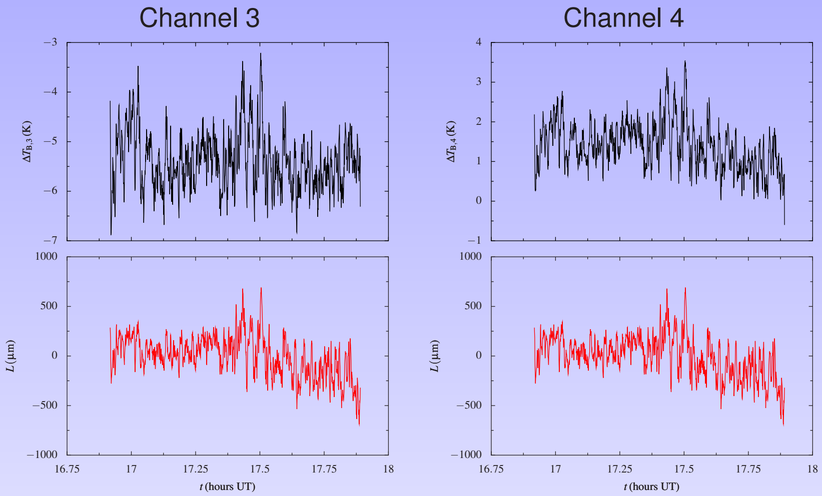


Algorithms for WVR phase correction

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

$$\delta L \approx \sum_i w_i \frac{dL}{dT_{\mathrm{B},i}} \delta T_{\mathrm{B},i} \quad (1)$$

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

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

Our current (initial) model

We begin with a *minimal* stripped down model, and use the available information to constrain it

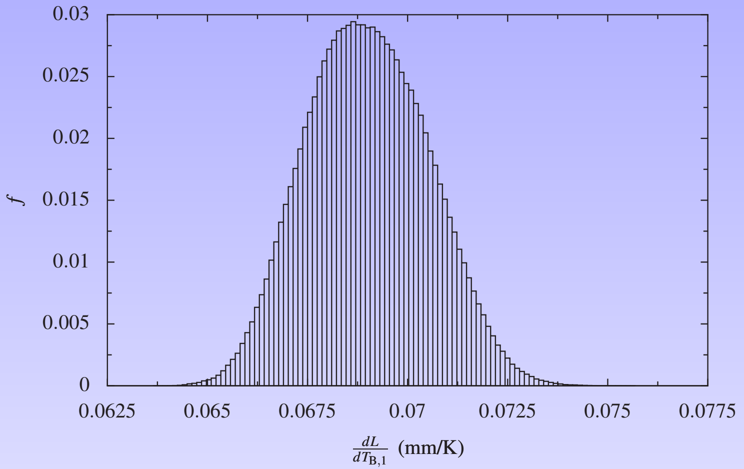
- Single, thin layer of water vapour
- Three parameters: column density of water, pressure and temperature
- Can also model spillover to ground

Analysis using the Markov Chain Monte-Carlo algorithm:

- Estimates of model parameters
- Estimates of phase correction coefficients
- Confidence intervals an all quantities intrinsically calculated

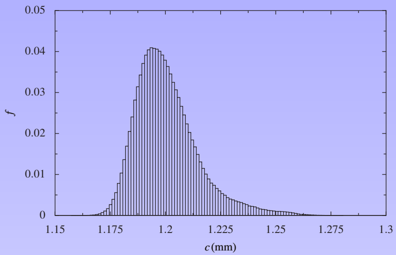
Simple example retrieval

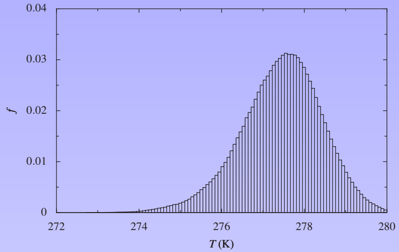
Posterior distribution of a correction coefficient

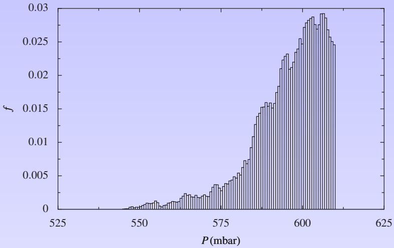


Distribution of model parameters

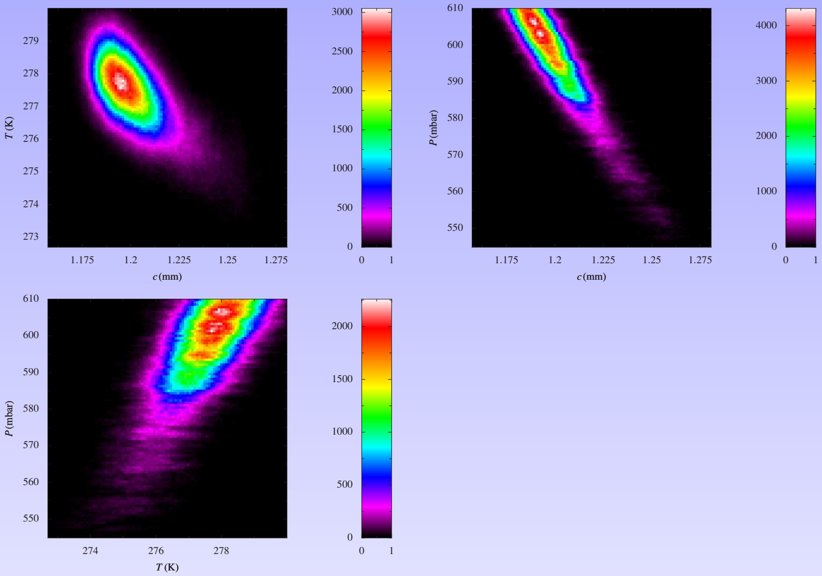
SMA example





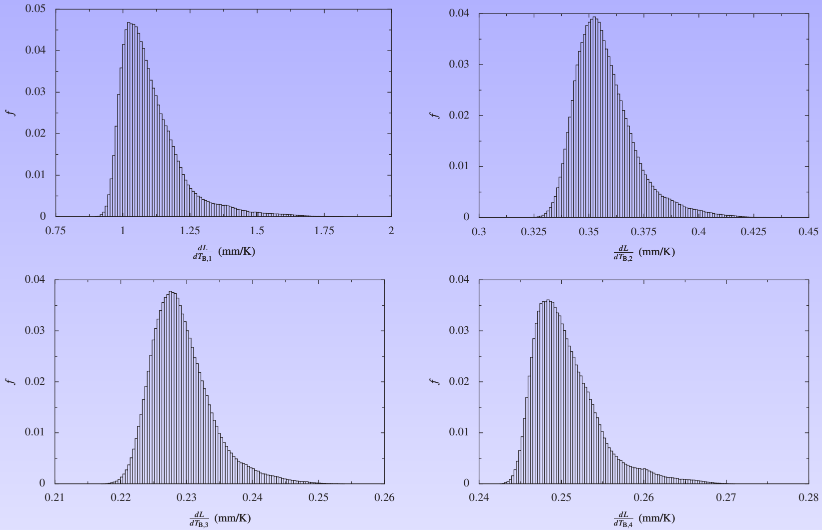


Correlation between model parameters
SMA example

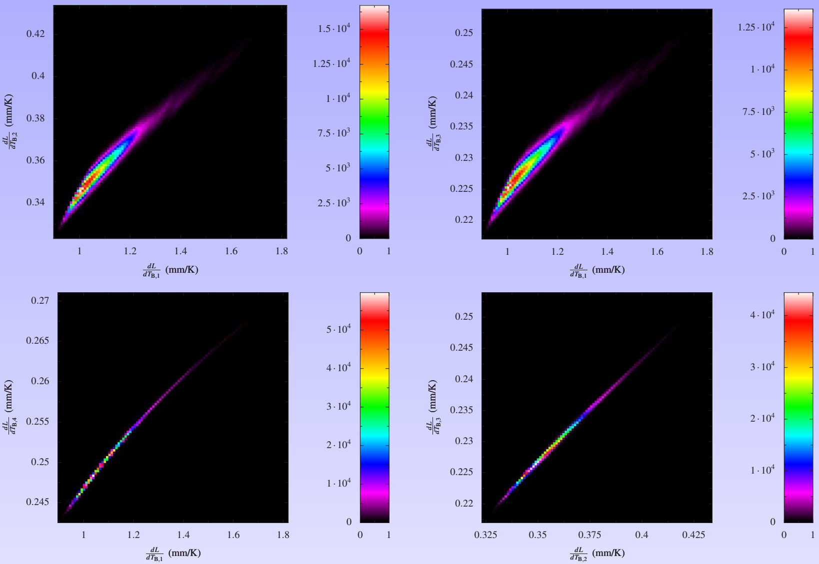


Distribution of phase correction coefficients

SMA example



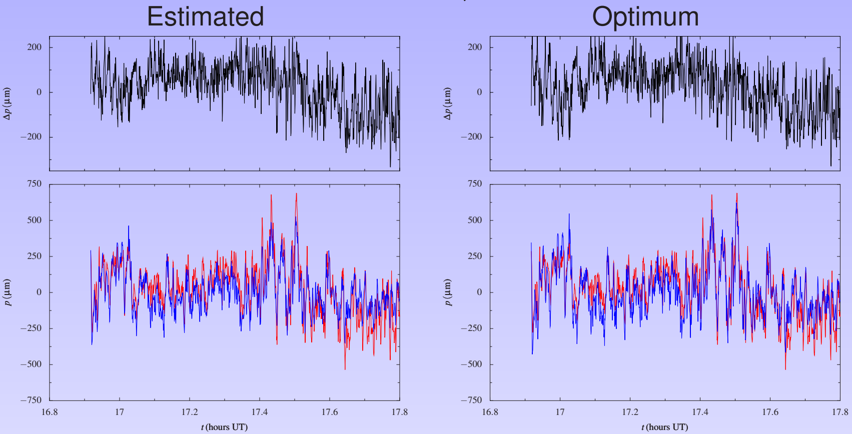
Correlation between dL/dT_B coefficients



Correction of SMA data

Channel 3

Raw RMS 157 μm



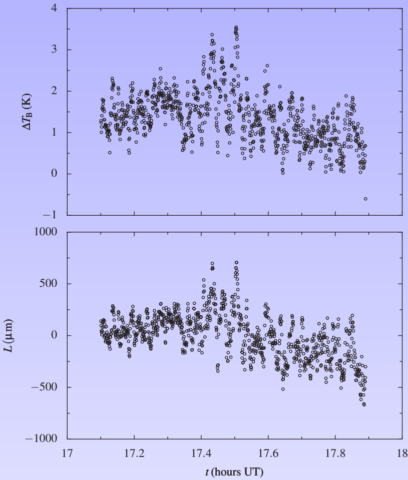
Residual RMS 74 μm

Residual RMS 71 μm

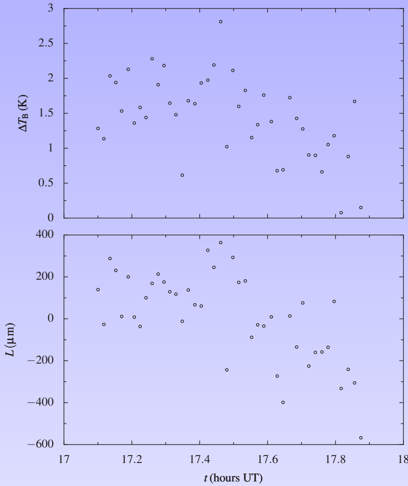
Adding ‘empirical’ information

SIXTH FRAMEWORK PROGRAMME

Every integration



Every one minute



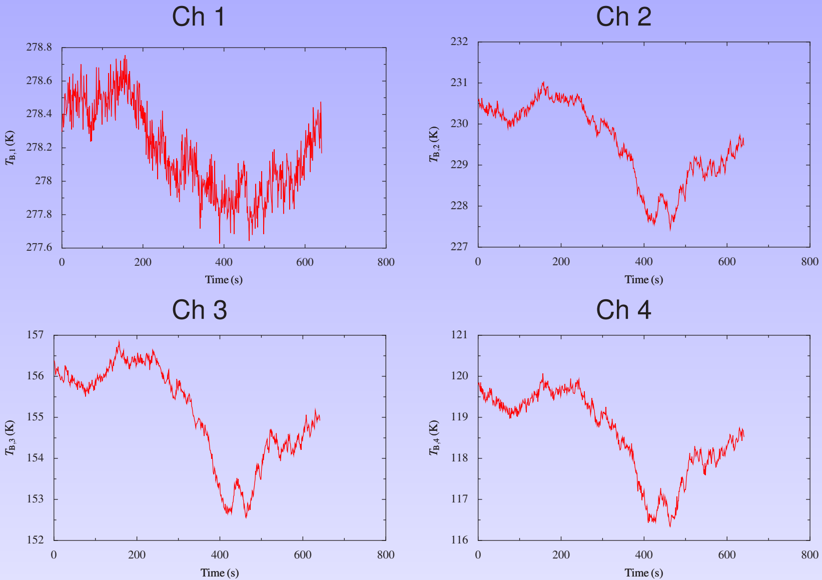
‘Empirical’ coefficients for the SMA dataset

Interval (s)	Ch 1 (μm/K)	Ch 2 (μm/K)	Ch 3 (μm/K)	Ch 4 (μm/K)
2.5	-161	94	286	316
25	-181	88	300	313
60	-199	7	286	304
125	-275	34	285	308

- $\Longrightarrow$ A phase cal every 60 s allows direct *empirical* constraint on the coefficients

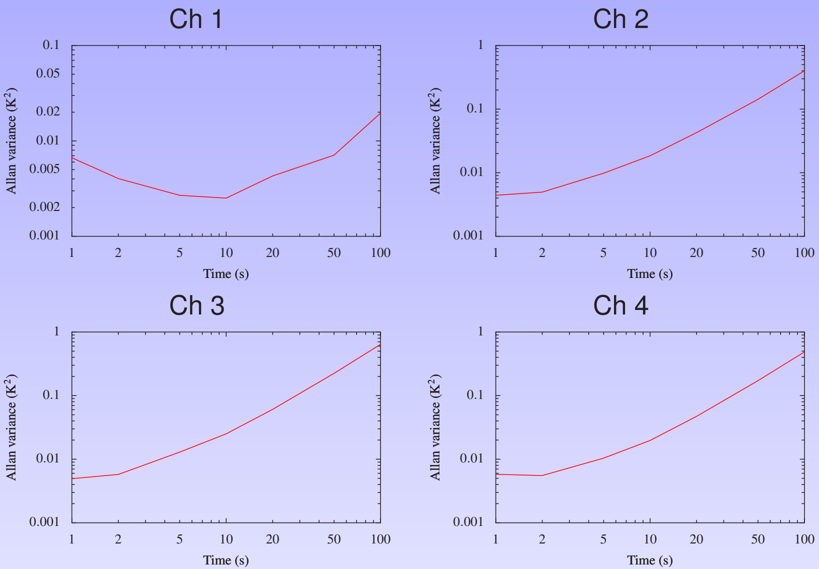
First Data from WVR on ALMA Antenna

Total power toward zenith



First Test Data from ALMA

Allan variance of WVR mounted on antenna pointing at zenith



Delivered Documents/Code

- ALMA Memo # 573, Limits on Phase Correction Performance Due to Differences Between Astronomical and Water-Vapour Radiometer Beams
- ALMA Memo # 582, Simulating Atmospheric Phase Errors, Phase Correction and the Impact on ALMA Science
- ALMA Memo # 587, Inference of Coefficients for Use in Phase Correction I
- Standalone source code packages `libAIR` and `bnmin1` with the full functionality described in memos (updated at quarterly intervals)

WP5 Status and Planning

Progress to date

- Complete analysis of SMA test data
  - Presented at Wetzell meeting
- Development of interfaces to atmospheric modelling tools
- Discussions with IRAM TelCal group in Grenoble
- Contribution to production water vapour radiometer reviews (Omnisys)
- Filter passband specification and impact
- Analysis of beam offset problem
- Detailed CASA simulation environment
  - 3D phase screens creation
  - Detailed WVR simulations ongoing
- Development of, and initial technical reports on, *ab initio* and *a posteriori* algorithms
- Preliminary investigation of oxygen sounder requirements for thermal profiling

Project Plan in Original Contract

- 60-month program starting Jan 2006, deliver end 2010
- The program calls for, in its early phases, essential research and development of the WVR technique, leading later to software development, testing, and deployment in Chile
- Envisaged 18-months of access to test data from commissioned Early Science ALMA array (2009 Q2 — end 2010)

Project Internal Milestones

As agreed at project start

1 Oct 2007	Report on the testing at SMA. Report on effect of beam-mismatch.
1 Apr 2008	Initial version of on-line stub code. Reports on implications of observing strategies and antenna vs baseline correction.
1 Oct 2008	Initial version of physics-based algorithms and report on this.
1 Apr 2009	Refined version of physics algorithm. Initial version of machine-learning based algorithm
1 Oct 2009	Report on initial testing at the AOS. Refinement of physics algorithms. Measurement of empirical correlation phase and WVR output.
1 Apr 2010	Machine-learning algorithms based on real data. Report on this approach.
1 Oct 2010	Revised versions of algorithms and report on their performance

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- In a strong position to complete the project successfully

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ALMA delays make testing of system against extensive real data, and support of first science, impossible to achieve in current schedule.
For example, initial schedule contained 18 months of work post Early Science.

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The principal advantages are

- Better access to test data — critical input into our work. Necessary to test technique with data that covers
  1. a wide range of baselines, including long and short ones;
  2. a wide range of frequencies, including the high frequencies;
  3. range of weather conditions.
- Access to a more stable software environment. Both ASDM (ALMA Science Data Model) and CASA under active development — allow us to access more stable versions of these systems.
- More time to integrate systems

Crucially, this will also allow us to develop the technique until Early Science with ALMA is achieved, when external scientists use ALMA for the first time.

Proposed Revised Internal Milestones

For 2011 completion

1 Oct 2007	Report on the testing at SMA. Report on effect of beam-mismatch.
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1 Dec 2010	Machine-learning algorithms based on real data. Report on this approach.
1 June 2011	Near-final algorithms based on extensive AOS testing
31 Dec 2011	Final revised versions of algorithms and documentation, and report on their performance after Early Science feedback