Atmospheric Phase Correction for ALMA with 183 GHz Water Vapour Radiometers

B. Nikolic[1], J. S. Richer[1], R. Bolton[1], and R. E. Hills[2]

[1] University of Cambridge, Cavendish Lab., Cambridge CB3 0HE, UK; b.nikolic@mrao.cam.ac.uk, jsr@mrao.cam.ac.uk, rosie@mrao.cam.ac.uk

[2] Joint ALMA Observatory, Santiago, Chile; rhills@alma.cl

Abstract

One of the great challenges for ALMA is overcoming the natural limits set by the turbulence in the atmosphere to achieve resolutions as fine as ten milli-arcseconds. A critical component in the strategy to achieve this are mm-wave radiometers on each of the 12 m diameter telescopes that observe the emission from the atmospheric water vapour line at 183 GHz. The information from these radiometers can be used to compute the fluctuations in total water vapour along the line of sight of each telescope, and from this, the fluctuation in effective path to each antenna. The estimates of path fluctuations are then used to phase-rotate recorded visibilities leading to much increased coherence. In this paper we briefly review the design of the radiometers, describe the software processing steps to derive phase corrections and show some of the first results from the ALMA site in Chile.

1 Introduction

The maximum attainable spatial resolution of an aperture synthesis telescope is defined by the length of baselines formed by the telescope and the wavelength at which it observes. The Atacama Large Millimetre Array (ALMA) is aiming for baselines as long as 15 km which, at the highest observing frequencies, will give resolutions of a few mill-arcseconds. In order to achieve these high resolutions, ALMA will need to correct for the effects of the atmosphere on the incoming astronomical radiation. In particular, natural variation in the effective refractive index of the atmosphere leads to a fluctuation of the apparent paths to each of the telescopes in the array; the *difference* in the apparent paths to the two telescopes forming a baseline leads to a fluctuation error in the phase of the measured visibility. In compact telescope configurations, these differences in apparent path are relatively small because the lines-of-sight of the telescopes transverse parts of the atmosphere that are physically close. However, as the length of baseline increases, the differences in properties of the atmosphere along the lines of sight also increases and leads to increasing fluctuation of the phase errors in visibilities. If uncorrected, these errors lead to a loss of sensitivity (because of incoherent averaging) and place an effective limit on the maximum usable baseline.

The dominant contribution to the fluctuation of effective path to telescopes at the frequencies at which ALMA observes is due the water vapour in the troposphere. This is because water vapour has a high effective index of refraction and is typically poorly mixed, and there is often turbulent flow in the troposphere leading to disordered transport of the water vapour. Because water vapour is the dominant cause, atmospheric phase correction for ALMA is based in large part on measuring the quantity of the water vapour along the line of sight of each telescope using mm-wave radiometers that measure the down-welling radiation at frequencies around the $3_{13} \rightarrow 2_{20}$ rotational line of the para water molecule, which is centred at 183.3 GHz. These water-vapour radiometers (WVRs) will be installed on each of the 54 12 m-diameter ALMA antennas and ALMA is the first telescope to routinely employ phase correction based on millimetre-wave water vapour radiometers (most previous telescopes used cm-wave radiometers working at around 22 GHz).

Like other radio aperture synthesis telescopes, ALMA also calibrates the phase of the telescope by observing strong point-like sources. In contrast to other sub-millimetre telescopes however, ALMA will have a high enough sensitivity to be able to use sources which are rarely more than two degrees away on the sky from the science target; in addition, the ALMA antennas have powerful and accurate drives which mean that observation of calibration sources can be interleaved on timescales as short as 10 seconds. These observations of calibration sources complement the phase corrections derived from WVRs by very effectively removing longer-timescale phase drifts due to the atmosphere or the instrument itself.

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

The formal specification for ALMA atmospheric phase correction is that the per-antenna path fluctuations due to water vapour are reduced to:

$$\delta L_{\mathrm{corrected}} \leq \left(1+\frac{c}{1\,\mathrm{mm}}\right) 10\,\mu\mathrm{m} + 0.02 \times \delta L_{\mathrm{raw}} \quad (1)$$

where c is the line-of-sight precipitable water vapour column, δL_{raw} is the uncorrected path fluctuation on the baseline and $\delta L_{\mathrm{corrected}}$ is the path fluctuation after corrections have been applied. In practice, this specification essentially aims to remove the stability of atmosphere as a scheduling constraint on ALMA; i.e., if the atmospheric content of water vapour is sufficiently low that atmospheric transparency is good enough for observing at a particular frequency then the residual path fluctuations will also be low enough for observing at this frequency.

2 ALMA 183 GHz Water Vapour Radiometers

The ALMA WVRs are un-cooled easily interchangeable units separate from, but positioned next to, the main ALMA front ends. Pick-off optics consisting of two mirrors couple the radiation from the centre of the focal plane of the telescope to the devices. Therefore, the WVR line of sight is along the boresight of the ALMA antennas while the lines of sight of the astronomical receivers are arranged around the boresight with offsets of 2 to 8 arc-minutes. This arrangement minimises the divergence of the WVR and astronomical beams.

The receiver system consists an ambient-temperature sub-harmonically pumped Schottky mixer followed by a low-noise amplifier, four filters, square-law detectors and a simple digitisation circuit. The four filters cover IF frequencies from 0.5 to 8 GHz which spans essentially the whole width of the water vapour line. Since the detection is double-sideband the effective bandwidth of the system as a whole is 15 GHz. The WVR units also contain an internal calibration system based on a chopper with curved surfaces that is rotating continuously at 5 Hz and an ambient and hot load with effective temperatures separated by about 80 K. The internal calibration system is *essential* for removing errors due to fluctuations in the gain of the receiving system and for establishing the absolute calibration of the radiometers.

Prototypes for the radiometers were designed and built by a collaboration between the University of Cambridge and Onsala Space Observatory. The contract for the subsequent production of more than 50 units was let to Omnisys Instruments AB, Gothenburg, Sweden. These units have now all been delivered to ALMA and they meet the specifications which can be briefly summarised as follows: the noise in one second integration in each of the filters is less than 0.1 K; the stability of measurements over 10 minutes in time and a tilt of 10 degrees is better than 0.1 K; the absolute calibration of each of the channels is better than 2 K.

3 Algorithms and software

The process of converting readings from WVRs (which are already calibrated in Kelvin) to corrected visibilities of the astronomical signal can be roughly divided into three stages: (i) inference of properties of the atmosphere (e.g., total water vapour column density, the vertical distribution of the water vapour, presence of cloud) resulting in derivation of 'phase correction coefficients'; (ii) conversion (using the phase correction coefficients) of the *fluctuations* in WVR readings to estimates of fluctuations of the effective path to each antenna; (iii) application of derived phase rotations to the visibilities of the astronomical data. At ALMA this process can be done *on-line*, i.e., in near real-time and before the visibilities are first written to disk; or, *off-line* together with the other standard aperture synthesis telescope calibration and map-making steps.

Our recent involvement has been in the *off-line* system which we have named `wvrgcal` and which we describe here. For the first stage of processing, the inference of atmospheric properties, we have developed a Bayesian statistical analysis method based on the Nested Sampling algorithm. The advantages of this method are that it provides a robust fit as well as error estimates, and estimates of the goodness-of-fit of the model, regardless of the number of parameters; that it is possible to marginalise parameters which are not relevant and so automatically remove the effects

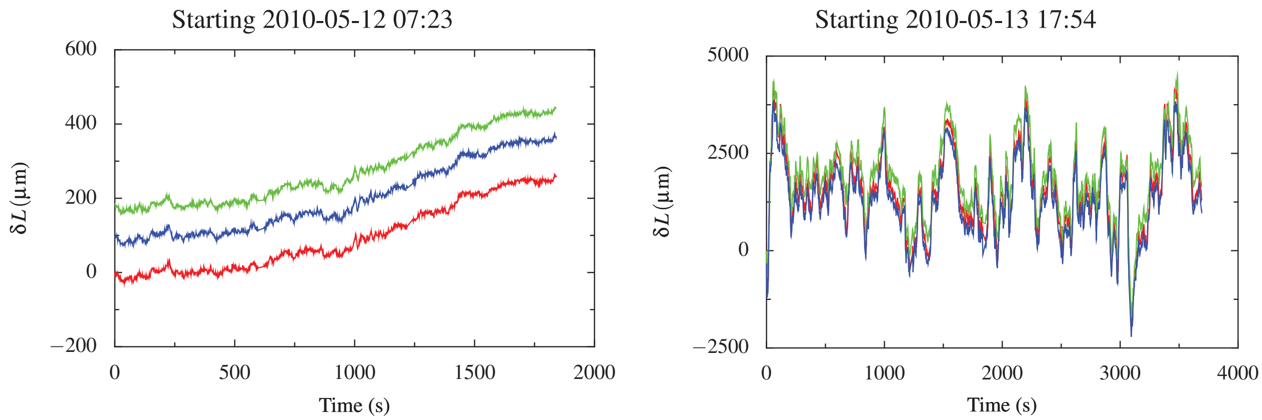

Figure 1: Path fluctuation estimated from WVR data for two observing sessions. Times are expressed in UT, so the left panel corresponds to night time, while the right panel to a time around midday. Note that the vertical scale is different on the two panels.

of model degeneracies which are not relevant to the computation of phase correction coefficients; and that *a-priori* known constraints ('priors') can be naturally incorporated into the fitting routine. The conversion of WVR fluctuations to path fluctuations is relatively straightforward although we have found that small improvements in performance can be obtained by taking into account non-linearity in the conversion (due to saturation of the water vapour line) and by down-weighting saturated and outermost channels further than would be indicated by simple thermal noise considerations. For the final stage of applying the phase rotations to the visibilities, we have closely integrated the `wvrgcal` software with the main ALMA off-line data reduction package CASA. This close integration means that user can inspect the phase corrections before they are applied to the data, apply WVR-based phase correction in arbitrary order to other off-line calibrations and generally handle these corrections in the same way as all other calibrations which are available in CASA.

The `wvrgcal` software is publicly available in both binary and source code form and is in use at a number of sites across the world.

4 Initial results at ALMA

At the time of writing ALMA has been making test observations at its 5000 m-high site for over a year. One of the many tasks during that year has been commissioning and testing the phase correction techniques based on WVRs. Therefore during this time a significant quantity of relevant test data has been obtained which we describe here to illustrate both the effectiveness of the technique and properties of the atmosphere at the site.

The fluctuations of effective path to three antennas are illustrated in Figure 1 for two observing sessions separated by about a day and a half. It can be seen in the figure that the paths derived from WVR data are of high quality, free of glitches or other artifacts and not significantly affected by the internal WVR noise. The great variation in the magnitude of total fluctuations at different times of the day is also well illustrated by this figure which shows that, in this case, the daytime session (right panel) suffered fluctuations which were two orders of magnitude greater than the night time session (left panel).

In Figure 2 we show, for a typical test observation, the correlation between the difference in fluctuations of outputs of WVRs on two antennas *and* the inferred differential path fluctuation derived from the astronomical visibilities (the telescope was observing a strong point-like source at the phase centre of the interferometer, so in the absence of atmospheric effects we would expect a constant visibility). It can be seen that there is a strong correlation between the two quantities, demonstrating that short-term fluctuations in WVR outputs can be accurately transformed into estimates of path fluctuations as long as the slope of the correlation is known accurately enough *a-priori*. The phase-

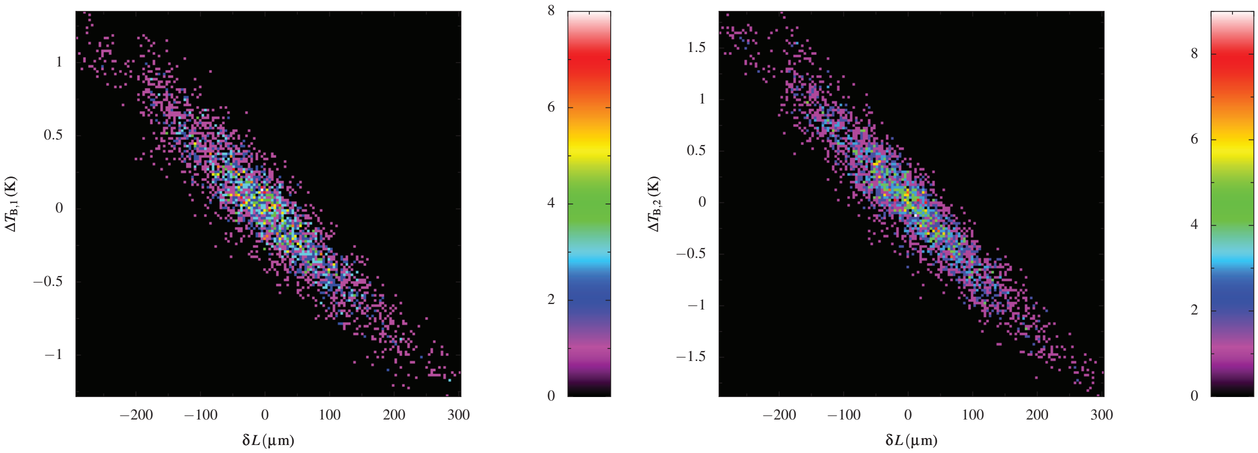

Figure 2: Correlation between the the atmospheric path error estimated from observations of bright point-like objects (horizontal axis) and the differenced WVR signal (vertical axis). A three-minute running mean was removed from both the path and WVR fluctuations, in order to emphasise the time scales on which the WVRs are expected to correct the atmospheric effects. Each plot is a two-dimensional histogram where the colour scale shows how many points fall in each bin. The two panels correspond to two of the four channels of the radiometers.

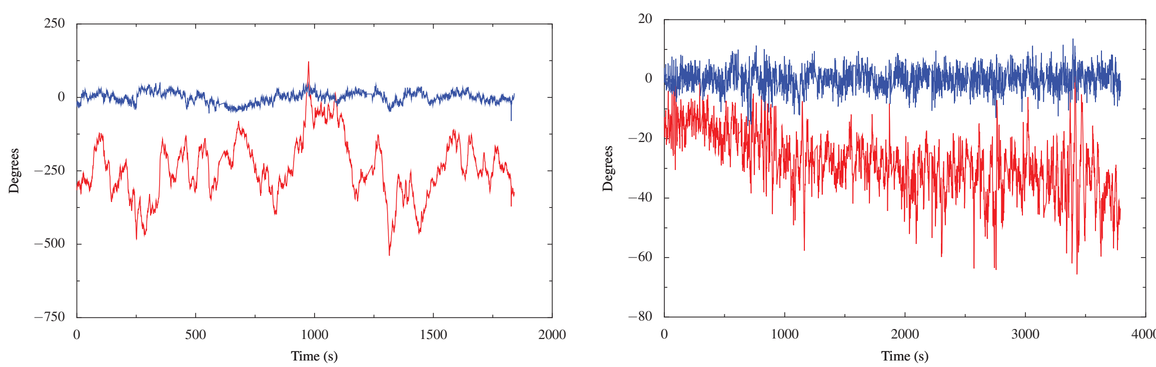

Figure 3: Two test observations of a strong quasar; the left panel shows a medium length baseline (650 m) during relatively unstable atmospheric conditions while right panel shows a short baseline (60 m) during stable weather. The red line is the phase of the observed (complex) visibility on this baseline. The blue line is the visibility phase after correction of the data based on the WVR signals and using the `wvrgcal` program.

correction coefficients are to first order the predictions of the slopes of these correlations and we have found that our current model matches the observed slopes to a sufficiently high accuracy that residuals errors are dominated by other effects. Finally, in Figure 3 we show two examples of applying the WVR-based phase correction to observed visibilities using `wvrgcal` and CASA and plotting the original (red) and residual (blue) phase. The left panel of the figure shows typical results on during unstable but not cloudy weather on a medium length baseline. It can be seen that the un-corrected phase covers almost a full turn, meaning that averaging of these data in time would lead to an almost complete loss of signal. The corrected phase has a phase RMS fluctuation of only 30 degrees or so, meaning it would suffer from negligible losses due to the fluctuations. The right panel shows results more typical for stable weather and shorter baselines. In this case the magnitude of improvement due to the WVR-based phase correction is smaller but clearly still noticeable in that both the short term fluctuations are reduced and the long-term drift of phase eliminated.