Tests of Radiometric Phase Correction with ALMA

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Of the many challenges facing ALMA, one of the greatest is overcoming the natural seeing limit set by the atmosphere to achieve very high resolution images. Its longest antenna separations (baselines) permit ALMA to synthesise the effect of a single antenna with a diameter exceeding 15 km, but an accurate radio "adaptive optics" system is required to ensure ALMA's images are diffraction limited. With initial test data now available from the first ALMA antennas in Chile, we describe current progress towards this goal.

Atmospheric limitations to radio astronomy

ALMA aims to synthesise an antenna with an effective diameter of over 15 km: this would have a diffraction-limited resolution of 15 milliarcseconds at a frequency of 300 GHz. (Note, however, that for most projects with ALMA, we anticipate that a more modest resolution of 50–100 milliarcseconds will be requested by scientists.) In comparison, the uncorrected radio seeing at this frequency would typically limit the resolution of images to 700 milliarcseconds if no adaptive optics corrections were applied (see Evans et al., 2003).

The seeing at sub-millimetre and millimetre wavelengths arises due to atmospheric (specifically, tropospheric) instabilities that lead to fluctuations of the refractive index and consequent path errors in the propagating wavefront. As explained in a previous *Messenger* article (Nikolic et al., 2008), the process is analogous to that affecting the optical seeing, but the dominant contribution to the refractive index fluctuations is from inhomogeneities in water vapour, rather than temperature fluctuations. ALMA is attempting to correct the effects of these fluctuations through a combination of two techniques: frequent observations of calibration sources; and direct measurement of atmospheric properties along the line of sight of each of the 54 12-metre diameter telescopes using mm-wave radiometers that measure emission of the 183 GHz water vapour line. ALMA is the first telescope to employ phase correction based on mm-wave water vapour radiometers.

Water in the atmosphere is poorly mixed and the concentration (and phase) of water varies rapidly with position in the atmosphere and with time. The underlying reason for this is of course that all three phases of water are accessible in the range of temperatures and pressures typical on the ground and in the atmosphere, leading to various localised sources and sinks of water vapour. Even at a very high and dry site like ALMA, changes of up to 50 % in line-of-sight water vapour can be observed in a matter of minutes. Additionally, water vapour has a high effective refractive index at mm and sub-mm wavelengths: one millimetre of precipitable water vapour retards radiation by an equivalent of about seven millimetres of path in vacuum. The combination of poor mixing and high refractive index leads to a corruption of the wavefront of incoming astronomical radiation. When observing with an aperture synthesis array like ALMA, these wavefront errors lead to phase errors in the recorded visibilities.

In order to correct for these errors, each of ALMA's 12-metre diameter antennas has an accurate millimetre-wave radiometer that measures the radiation passively emitted by water molecules in the atmosphere along the line of sight of the antenna. The radiometers cover frequencies around the 3_{13} -> 2_{20} rotation line of the para water molecule, which is centred at 183.3 GHz. This line lies about 200 K above the ground state and so is ideal for tracing atmospheric properties. The principle of radiometric phase correction is that these measurements can be used to compute the quantity of water vapour along the line of sight of each antenna and, consequently, the equivalent path error. Using these estimates the observed astronomical data can be corrected for the effect of path fluctuations.

Water vapour radiometers

The water vapour radiometers (WVRs) are the devices that measure accurately the absolute brightness of downwelling radiation along the lines of sight of the antennas. The prototype WVRs for ALMA were developed by a collaboration between the University of Cambridge and Onsala Space Observatory. After successful laboratory and field testing of the prototypes, an industrial partner (Omnisys Instruments AB, Sweden) was contracted for delivery of the production units. The production stage is now already fully complete and ALMA has taken delivery of radiometers for all of the planned 54 12-metre antennas.

The ALMA radiometers are unique among the radiometers used for phase correction in that they measure sky brightness around 183 GHz, as opposed to 22 GHz, which is the spectral region where most other WVR systems are designed to observe. This has a number of advantages, primarily based on the very high strength of the water vapour line at 183 GHz (see Figure 1 for plots of brightness in typical conditions), which is about 150 times stronger than the line at 22 GHz. This means that fluctuations in water vapour content produce much higher, more readily observed fluctuations in the observed brightness at this frequency. Besides this, the high strength of the line means that radiation from sources other than atmospheric water vapour has a smaller influence on the predicted phase corrections. For example, clouds, spill-over past the primary reflector of the antenna and man-made radio frequency interference (RFI) all have a smaller effect relative to the strength of the line.

Measurements at these higher frequencies do, however, also present a number of challenges:
1. Design and production of the hardware is more complex and expensive, requiring custom components and high precision machining.
2. Calibration is more difficult as it needs to be based on very frequent (10 Hz

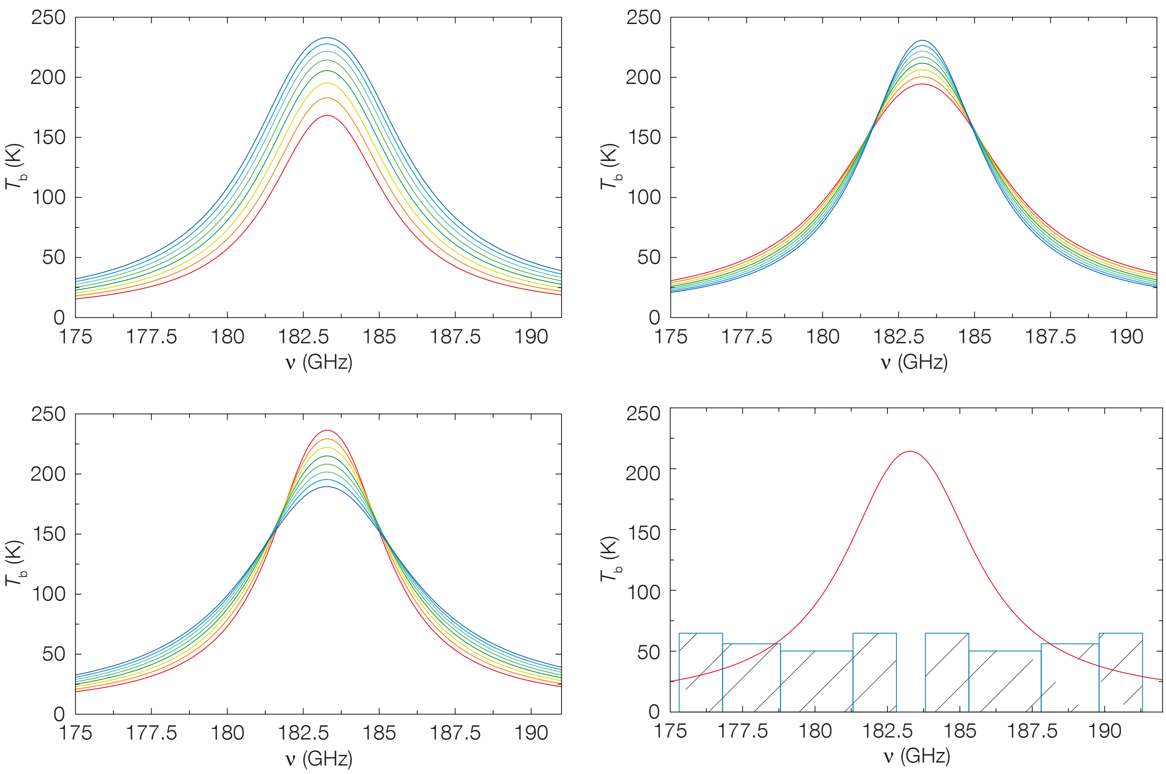

Figure 1. The water vapour line at 183 GHz. The upper left, upper right and lower left panels show how the simulated brightness of the atmospheric 183 GHz water vapour line varies with changes in total contents of the water vapour, the atmospheric temperature and atmospheric pressure. The lower right panel shows the nominal filter passbands for the ALMA 183 GHz water vapour radiometers. The detection system is double-sideband and so only the average signal of the two filters symmetric around the line centre is measured.

in the case of ALMA) observation of physical internal calibration loads.

3. The water vapour line is close to saturation and thus subject to non-linear effects, leading to significantly more complex software requirements.

Over the past twelve months, extensive testing of the first WVR systems has been carried out at the ALMA site. The preliminary results of these tests suggest that the development and production stage has successfully met these challenges. So far, the units installed on the ALMA antennas appear to be performing well in terms of noise, stability and reliability.

Technique

The WVRs provide measurements of sky brightness in the four filters illustrated in the lower right plot in Figure 1. As ALMA WVRs employ a double-sideband mixing system, only the average brightness of the sky at frequencies symmetric around the centre of the line is measured. The maximum readout frequency from the WVRs is 5 Hz, although normally we read out at 1 Hz, which is fast enough to capture essentially all the path variations.

The task of the phase correction software is to turn these 1 Hz measurements in four filters into phase rotations to be applied to the observed astronomical signal. The first step in the analysis is to use the four observed sky brightness temperatures, together with ancillary weather information, to make an inference about the total quantity, temperature and pressure of the water vapour. This is important because the profile of the water vapour line is a strong function of these parameters, as shown in Figure 1, and because the near-saturation of the line means that the observed sky brightness is not in general linearly related to the total path error.

The second stage of analysis is to turn the *fluctuations* in the observed sky brightness into estimates of fluctuation of effective path to each of the antennas in the array. We only consider the fluctuations because, as an interferometer, ALMA is sensitive to only the difference in path errors to each of the antennas and we do not need to try to retrieve the total extra path due to the water vapour in the atmosphere. Additionally, frequent observation of point-like sources will allow ALMA to calibrate the expected "zero" phase and it is only the departures from this that are important.

The close relationship between fluctuations in sky brightness and the path errors is illustrated in Figure 2, which is based on recent observations by ALMA. During this observation, the telescope was tracking a quasar (i.e., a point-like source) at a known location on the sky, so for a perfect interferometer we would expect to measure visibilities with constant phase and amplitude. The phase we actually measure is therefore an estimate of the differential path along the two lines of sight due to atmospheric fluctuations. This is plotted on the horizontal axis of the diagrams, and on the vertical axis we plot the difference in observations by the WVRs on these two antennas. What can be seen in Figure 2 is that there is a high degree of correlation between the two quantities, meaning that as long as we can forecast the slope of this correlation then we can convert

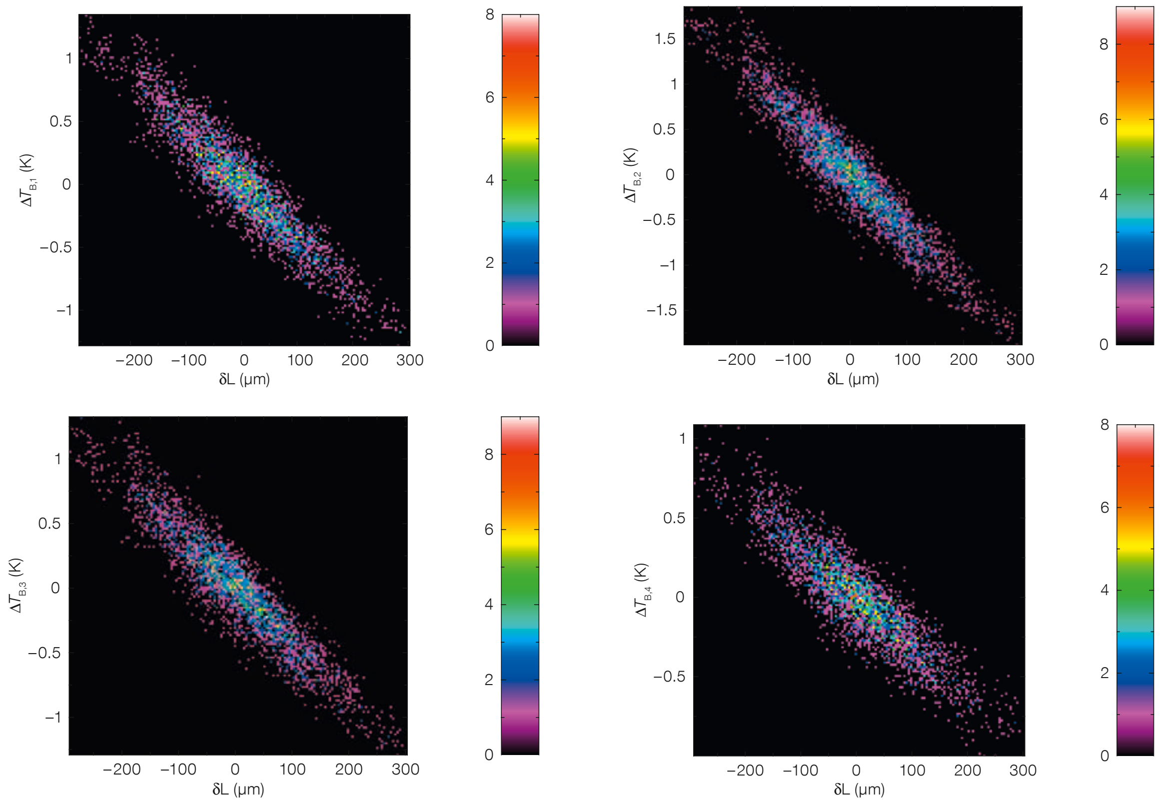

Figure 2. Correlation between the atmospheric path error estimated from observations of bright point-like objects (horizontal axis) and the differenced WVR signal (vertical axis). Each plot is a two-dimensional histogram where the colour scale shows how many points fall in each bin. The four panels correspond to the four channels of the radiometers (1–4 designated by the axis label).

fluctuations of WVR outputs to path fluctuations for a general observation.

The final stage of the analysis is to turn estimates of path fluctuations into a phase correction that needs to be applied to the astronomical data. This is generally straightforward, although it is important to take into account the dispersive effects of the atmosphere and also to ensure that rotations applied using estimates derived from WVR data interact correctly with other calibrations applied to the astronomical data.

Development of phase correction software for ALMA under FP6

Our recent involvement in WVR phase correction for ALMA has been primarily through development of software and algorithms that process the raw data observed by the WVRs and use these to calibrate and correct the astronomical data. This work is separate from the baseline ALMA software and has been funded as an ALMA enhancement by the European Union Framework Programme 6. (This programme also supports development of Band 5 receivers for ALMA [see Laing et al., 2010], and on-the-fly interferometry techniques).

The software we have been developing is designed primarily for off-line phase correction, i.e., it operates on the observed data after these have been stored on disk. Some of the principal features of our software are:
- It is closely integrated with the official ALMA off-line data reduction suite (CASA), which allows it to be used in a straightforward manner by scientists.
- The software has a rapid development cycle, with new features and improved algorithms appearing regularly.
- It uses a robust Bayesian statistical inference framework to derive optimal corrections.
- When certain WVRs are missing from an observation, the software has the ability to interpolate available data to provide phase correction estimates at those antennas lacking accurate WVR measurements.
- The software is easy to distribute as a binary package that works in conjunction with CASA.

The software (wvrgcal) for phase correction is available freely under the Gnu Public License in both source code and binary formats[1]. We also operate a mailing list[2] for discussion, improvement suggestions and community support of the software.

Tests of phase correction

Since about January 2010, ALMA has been collecting significant amounts of test observations designed to measure the effectiveness of WVR phase correction and to guide the further development of algorithms used to translate sky brightness measurements to the phase rotations. In order to fit with the numerous other ALMA commissioning activities, most of these observations were taken with the antennas in relatively compact configurations, i.e., most data are with baselines in range 30–100 m, with some data on baselines of up to 600 m. These data have already provided a good demonstration of effectiveness of phase correction on these relatively modest baselines. However, we know that the phase correction will be most challenging on long baselines (up to 15 km in length for ALMA); this is because the root structure function of the atmosphere increases as roughly the 0.6 power of baseline on typical ALMA baselines. Long baseline test data are awaited to investigate the effectiveness of the technique when ALMA is making its highest resolution images.

Two typical examples of path fluctuations computed from WVR observations are shown in Figure 3. For these plots we have used data from three antennas, shown by different colours in these plots. Since these are absolute path estimates from the WVRs, it is the *differences* between the three traces that correspond to the phase rotations to be applied. For these observations, the antennas were relatively close to each other and therefore these differences are quite small. These plots illustrate very well the wide variety of conditions that are present at the ALMA site: total fluctuations are different by about two orders of magnitude between the two observations. It can be seen that the total (peak-to-peak) fluctuations on the upper panel of Figure 3 are about 50 μm on timescales of about five minutes; this is significantly less than 350 μm, the shortest wavelength at which ALMA will observe. On the lower panel of Figure 3, the fluctuations are greater than 3.5 mm, i.e, they are larger than the longest wavelength at which ALMA will initially observe.

Figures 4 and 5 show two examples of WVR phase correction at work. In both plots, the red trace represents the phase of the recorded visibilities while observing a quasar. In the absence of atmospheric and instrumental phase errors we would expect this phase to be constant in time — the variations actually observed are due to the combination of atmospheric effects and instrumental errors. The uncorrected phase in Figure 4 is varying by more than 360 degrees, i.e., by a full rotation, which means that in these conditions it would not be possible to make any measurements on faint sources. The blue line shows the phase after correction using our wvrgcal software.

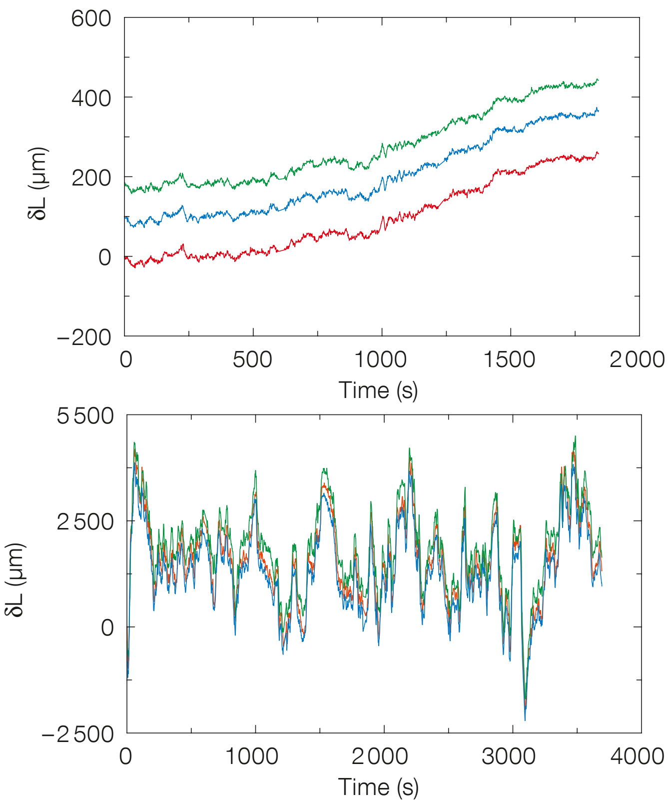

Figure 3. Path fluctuation estimated from WVR data for two observing sessions. Times are expressed in UT, so the upper panel corresponds to night-time, while the lower panel to a time around midday. Note that the vertical scale is different between the two panels.

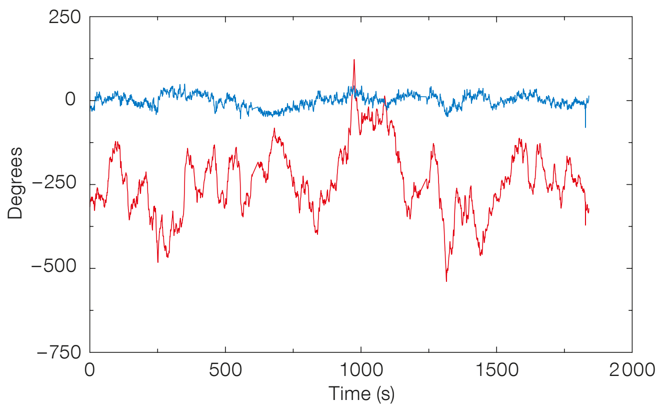

Figure 4. Test observation of a sub-mm bright quasar on a roughly 650-metre baseline with ALMA. The red line is the phase (in degrees) of the observed (complex) visibility on this baseline — note that for a quasar (or other point-like) source at the tracking centre of the interferometer we expect a constant phase in time. The blue line is the visibility phase after correction of the data based on the WVR signals and using the wvrgcal program.

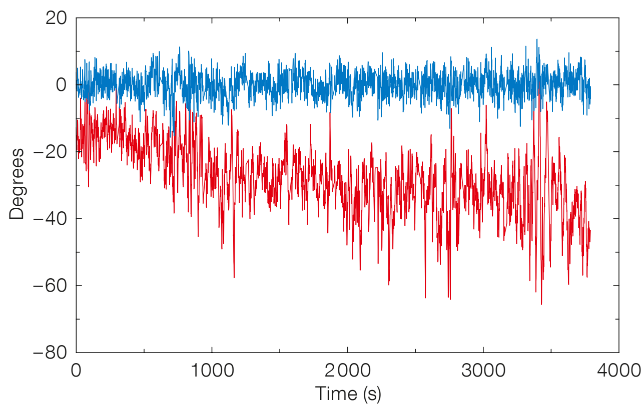

Figure 5. Like Figure 4, this is a test observation of a strong quasar, but on a baseline of around 60 m and during stable weather. The red line is again the uncorrected observed phase (in degrees) of the visibility, while the blue line is the phase after WVR-based correction. Note the change of vertical scale between Figure 4 and this figure.

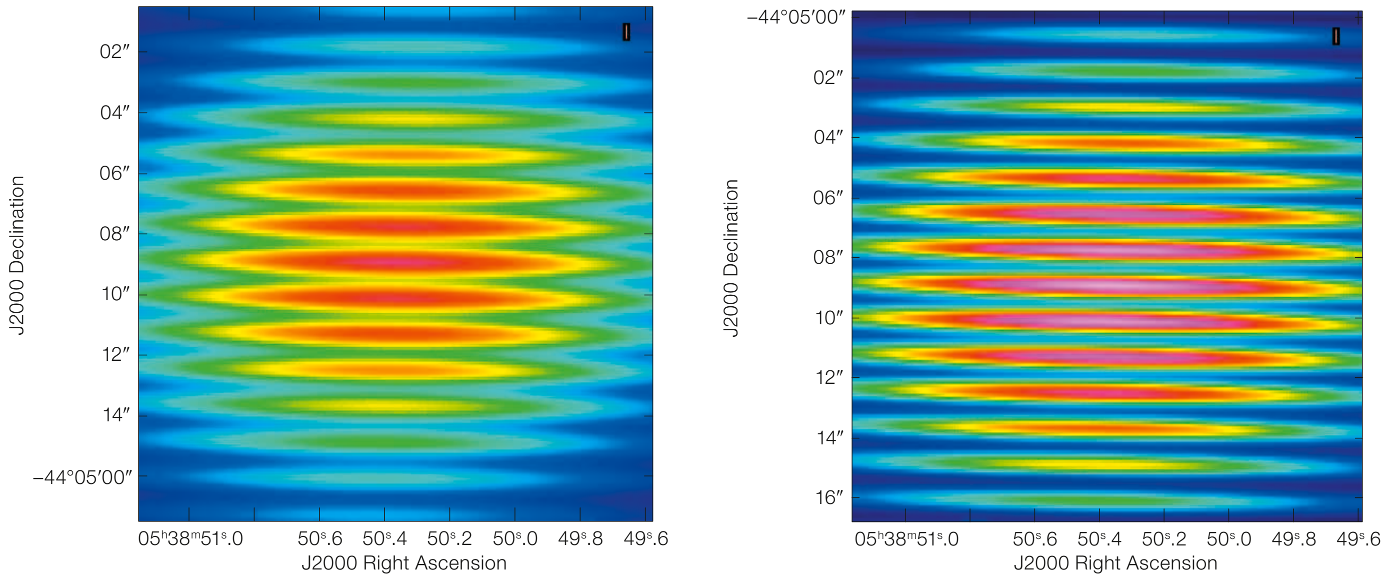

Figure 6. Un-deconvolved images of a quasar (which is unresolved) with ALMA in a very heterogeneous configuration: four of the antennas were very close together while the fifth was about 650 metres away. The heterogeneity leads to the rapid modulation in the north–south direction, which corresponds to the long baseline. The image on the panel on the left was made with no phase correction while the image in the panel on the right has had WVR phase correction applied. It can be seen that the phase fluctuations, when uncorrected, lead to an almost complete wash-out of fringes on the long baseline.

The phase errors can be seen to be reduced by an order of magnitude, to a level where meaningful averaging of the data can be done.

The example shown in Figure 5 is less extreme — the uncorrected data have a phase root-mean-square deviation of about 20 degrees. However, even in these much more stable conditions, application of WVR phase correction leads to much improved phase stability. Also notable in this example is that variations in uncorrected phase at longer timescales are also very effectively reduced by WVR phase correction.

As an illustration of the effect of WVR-based phase correction on imaging, in Figure 6 we show an un-deconvolved ("dirty") map of a point source with ALMA in an unusual configuration with north-south baselines much longer than the others. We have made the map both with the raw data, and with the data after WVR-based phase correction. It can be seen that the fringes in the map made from corrected data (right panel) are much sharper and have much higher contrast compared to the map made from uncorrected data. After deconvolution (and completing the baseline coverage) this increase in sharpness directly corresponds to an increase in resolution and fidelity.

Future challenges

The data presented in this article represent by far the most extensive tests of the capabilities of 183 GHz phase correction ever attempted. They demonstrate that the technique should increase significantly the sensitivity of ALMA, by reducing the decorrelation caused by phase errors, and increase the fidelity of ALMA images by ensuring visibility phases are more accurately measured. In addition, they should improve the efficiency of ALMA operations, by permitting observations to take place when atmospheric instabilities cause rapid large amplitude phase fluctuations.

However, much work remains to be done. It is vital that ALMA can demonstrate that its phase correction strategy works to specification in a wide range of atmospheric conditions and on baselines all the way out to the maximum allowed by the configuration designs. In addition, it remains a challenge to ensure that the software tools are easy for astronomers to use, so they can automatically remove the distorting effects of the atmosphere and allow them to focus on the novel science in their ALMA datasets. Nonetheless, ALMA already has made great progress towards this goal, and can already claim to have an effective and ground-breaking adaptive optics system.

Acknowledgements

The results shown in these plots are of course the result of the efforts of many tens, if not hundreds, of people who have been involved in ALMA over the years. Phase correction tests require everything in the ALMA system to be working perfectly, so a great deal of credit is due to all of those involved, from the designers of the systems to those keeping the observatory running in Chile. The specific work described here, including the analysis of test data and development of the wvrgcal program has been carried out by the Astrophysics Group at the Cavendish Laboratory, University of Cambridge, as part of the ALMA Enhancement Programme, an enhancement to the baseline ALMA project. This work is funded by the European Union's Sixth Framework Programme.

References

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Nikolic, B. et al. 2008, The Messenger, 131, 14

Links

[1] Source code for wvrgcal available at: http://www.mrao.cam.ac.uk/~bn204/alma/wvrsoft.html
[2] Mailing list for wvrgcal updates: https://lists.cam.ac.uk/mailman/listinfo/mrao-wvrgcal