Phase Correction for ALMA: Adaptive Optics in the Submillimetre

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Inhomogeneities in the Earth's atmosphere corrupt the wavefront of incoming submillimetre radiation and, similarly to the seeing at optical wavelengths, this limits the resolution and sensitivity of submillimetre aperture synthesis arrays. ALMA will correct for these wavefront errors by a combination of frequent observations of known nearby point sources (predominately quasars) and by measuring the properties of the atmosphere along the line of sight of each telescope using dedicated 183 GHz radiometers. These techniques are critical for enabling ALMA's goal of resolution as fine as 0.005 arcseconds.

Seeing in the submillimetre

The Atacama Large Millimetre Array (ALMA) is now under construction at its high and extremely dry site in Northern Chile, close to the existing APEX telescope and the CBI experiment. The progress in the construction of individual telescopes making up the array was reported by Stefano Stanghellini in the last issue of The Messenger. By the end of 2007, some seven 12-m antennas have been delivered to Chile, and these are currently undergoing final assembly and testing.

Operating together, the 66 telescopes that comprise this interferometric array will provide a view through the millimetre and sub-millimetre atmospheric windows that is orders of magnitude better in terms of resolution and sensitivity than what can be achieved with existing instruments. Transformational science with ALMA is eagerly anticipated.

But to achieve its ambitious goals, ALMA must solve a key problem: it must be able to correct the effects of the earth's turbulent atmosphere. These effects place a direct limitation on the sensitivity and resolution of the array. In effect, an adaptive optics system for the array must be developed.

Astronomers used to infrared and optical facilities will be familiar with this problem. At these wavelengths, the turbulent motions of the earth's atmosphere result in relatively fast and small-scale temperature fluctuations. These cells of hotter and cooler air have different refractive indices, which distort the incoming plane waves, causing the well-known seeing problem. At radio wavelengths, the turbulent atmosphere causes similar problems, but it is only at the highest radio frequencies where the effect becomes hard to correct. Unlike in the optical, at these wavelengths, the refractive index variations are dominated by the tropospheric water vapour content ('wet fluctuations'), rather than fluctuations of the dry air.

Beyond the state of the art

The best images yet made at millimetre and sub-millimetre wavelengths have a resolution of around 0.3–0.4 arcseconds (e.g. Krips et al. 2007 at the Smithsonian SubMillimeter Array – the SMA; Cabrit et al. 2007 at the Plateau de Bure in France). These images are made using the longest available baselines at these arrays, and are diffraction-limited. However, these are also close to the practical limits imposed by atmospheric turbulence. Even if these arrays had much longer baselines, only in the most phase-stable weather would it be possible to make diffraction-limited images without using an adaptive optics system. The longest baselines for these arrays are around 500–1000 m. It is intriguing that the limiting angular resolution of around 0.4 arsec is somewhat similar to the best seeing obtainable on infrared and optical telescopes, even though the cause of the seeing is different.

The goal for ALMA is to produce images with diffraction-limited resolution at the highest frequencies and most extended configuration. With baselines up to 18 km in length, this corresponds to about 5 mas resolution at the highest frequency of about 950 GHz. This is a massive step forward in resolution, and requires the ability to correct for the atmospheric errors very precisely. Although this is an extreme example of ALMA's capabilities, which will be used only in the best weather conditions, even routine ALMA science observations will require resolution in the range 50–200 mas, so that adaptive optics correction of the atmosphere must be a routine part of ALMA's capabilities.

To put this in context, the required improvement in resolution is comparable to that required for the next generation of planned optical and infrared telescopes such as the ELT. For a 50-m optical telescope operating at 1 micron wavelength, the diffraction limit is about 5 mas. To achieve this, the adaptive optics system must beat the natural seeing, which is typically 500 mas, by a factor of 100. ALMA must achieve a similar increase in resolution beyond the seeing-imposed limit to achieve its goals.

Atmospheric effects on submillimetre data

We typically characterise atmospheric effects at optical wavelengths by specifying the seeing – the angular size of an unresolved star – or by the Fried parameter r_0. In radio interferometry, it is more natural to specify the fluctuations in the phase between two points on the incoming wavefront, because this is a quantity which can be directly measured. For a point source, it is equal to the root-mean-square fluctuations of the phase of the complex visibility, measured on a given baseline. (This is the square root of the *structure function.*) Even without the atmosphere, phase errors arise from changes in the path length of the signals from each antenna to the correlator, due to electrical and opto-mechanical effects. But the design of ALMA is such that the atmosphere-induced phase errors always dominate, so that it is the atmosphere which provides the fundamental limit to ALMA's performance.

Water vapour is the component of the atmosphere with typically the greatest impact on observations at millimetre and submillimetre wavelengths. The water molecule's high dipole moment gives water vapour a high index of refraction: at frequencies far away from the strong water emission lines (where dispersion becomes important), one millimetre of precipitable water vapour in the atmosphere corresponds to about 6.8 mm of extra optical path.

The effect of opacity is of course irreversible: it attenuates the signal from the science target and increases the background noise against which this signal must be detected. Therefore, sites with the minimum of water vapour in the atmosphere are essential for submillimetre astronomy and this was one of the main criteria for the choice of the ALMA site. However, although Chajnantor is a spectacularly dry site, the turbulent fluctuations of the water content are significant.

The magnitude of atmospheric path fluctuations at the site of ALMA has been continuously monitored at 11 GHz on a 300 m long baseline over the course of several years by the site-testing interferometer. The findings, which are summarised in ALMA memo 471, show that the median path fluctuations are 187 μm, and that in the best 10 % of the weather, the fluctuations are less than 49 μm. Additionally, the magnitude of path fluctuations was found to be not perfectly correlated with total column density of water vapour, and so best transparency conditions are not necessarily associated with the most stable phase conditions. In other words, there are periods of excellent dry weather when one wants to observe at the highest frequencies, but when the seeing is rather poor.

Where do the fluctuations arise? We know that in general most of the moist air is located close to the ground, typically within 1 km. During the night time, models suggest that an exponential distribution of water with a scale height of around 1 km is appropriate. During the day, strong solar-driven convection mixes the water up, and a more uniform distribution is expected from the ground up to a height of the order of 1 km, where a temperature inversion is often seen. Regardless of the overall water vapour distribution with height, the fluctuations in water vapour content which give rise to the phase errors are often thought to be dominated by thin layers where the fluctuations are strong. Using two site-test interferometers, it has been possible to infer the height of the dominant fluctuations on several occasions and these results, published in ALMA memo 345, show that the dominant fluctuations are typically within 400–800 m of the ground at the ALMA site.

As in the optical and infrared regimes, the magnitude of path fluctuations increases with increasing length of the baseline, placing a limit on the maximum usable baseline. This increase is not as steep as it is in the regime of most optical telescopes because the lengths of baselines of ALMA are comparable and exceed the thickness of the turbulent layer giving rise to water vapour fluctuations. This change of the properties of the effective phase screen with the change of relative thickness of the turbulence is illustrated by simulations shown in Figure 1. As an ex-ample from the lower radio frequency regime, the measured phase errors and their dependence on baseline length at the Very Large Array in New Mexico is shown in Figure 2. This shows the power-law behaviour expected of Kolmogorov turbulence. In this case, the exponent is close to 0.6, which is also typical for data from the ALMA site.

Correction of ALMA phase errors

ALMA will operate up to frequencies just below 1 THz, which corresponds to a wavelength of 300 microns. To achieve good image quality, we need to measure the phases of the complex visibilities to better than 30 degrees, or one twelfth of a turn of phase. This implies correcting the path to better than 25 microns. As we have seen, even on 300-m baselines, the fluctuations are known to be typically 200 microns of path. So it is clear that a very precise path correction system is needed by ALMA. Note that the scale of the path error increases typically as the baseline to the power 0.6, for baselines up to a few km, so this problem gets worse as we go to longer baselines. But also note that the problem is reduced for longer wavelengths: at 3 mm (100 GHz), we can tolerate an order of magnitude greater path error (i.e. 250 microns) and still measure the phase to 30 degree accuracy.

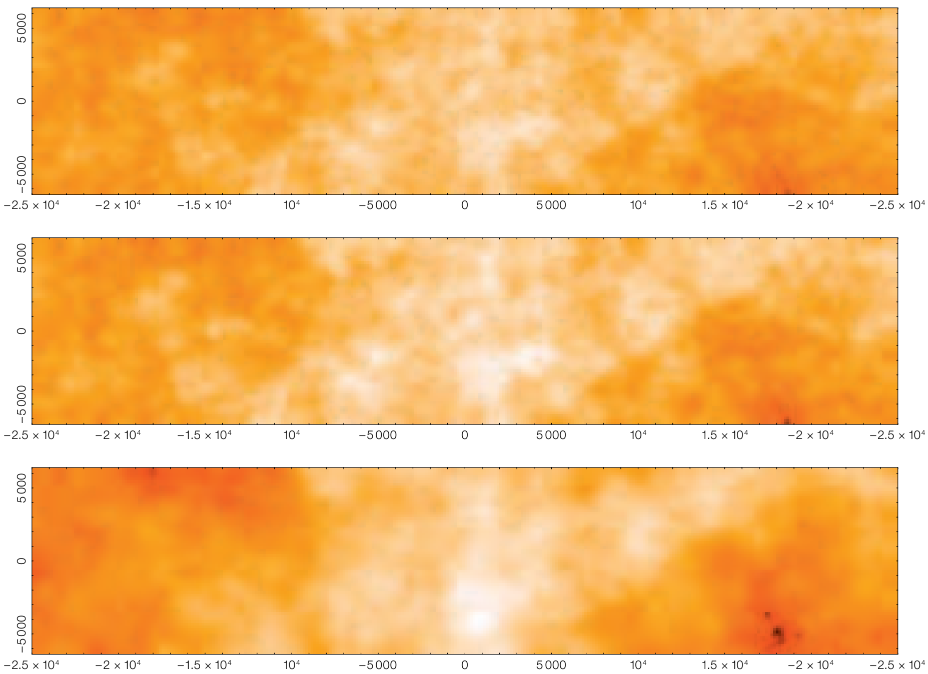


Figure 1: Maps of vertically integrated models of water vapour content generated assuming three-dimensional Kolmogorov statistics. The three maps (top to bottom) correspond to increasing vertical thicknesses of the turbulent volume showing the expected steepening (i.e., increasingly more power on the larger scales) of the fluctuation structure function. The horizontal dimensions of the maps are 50 km × 14 km and the resolution is 24 m.

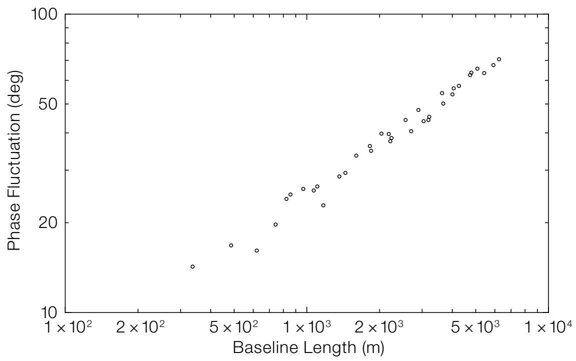


Figure 2: Measured phase fluctuations at the VLA at 22 GHz as a function of baseline length. The baselines shown in this plot are all between the antennas of one of the arms of the VLA and so are co-linear.

In order to meet the specifications and deliver on its promise of outstanding imaging resolution, ALMA will employ a combination of two techniques for correction of phase errors introduced by the atmosphere: fast switching, and water vapour radiometry (WVR). The established technique of fast-switching involves regularly observing known nearby point sources, and will be used for correcting phase fluctuations on the longer time scales. In addition, measurements from the 183 GHz water vapour radiometers (WVRs) installed at each telescope will be used to make corrections on time scales as short as 1 s.

The fast-switching technique is in some ways analogous to adaptive optics, in that point-like astronomical sources are used to infer the variation of atmospheric properties across the telescope (or array of telescopes in ALMA's case) and correct for these. Instead of using stars, ALMA will observe the brightest quasars. However, the field of view of the ALMA antennas (about one arcminute at an observing wavelength of 3 mm) means that typically there is no usable calibration source within it, so the telescopes have to periodically point ('switch') to a nearby calibrator and back to the science target. This fast switching requires extremely agile telescopes, which can accelerate and decelerate rapidly: calibrators of sufficient strength are expected to be typically one to two degrees away from the science target and the ALMA antennas are required to be able to do calibrator-target-calibrator cycles as short as 10 seconds. This ability to switch quickly was one of the key design drivers for the ALMA 12-m antennas, resulting in very stiff designs with powerful drive motors.

But fast switching will not alone correct all the phase errors. First, although the 10-second cycle is relatively short compared to existing aperture synthesis telescopes, we know there are significant atmospheric fluctuations on timescales as short as 1 second: this timescale is given roughly by ratio of the diameter of the antenna (12 m) to the wind speed (typically 10 m/s). The second reason is that observations of a calibrator some one or two degrees away gives a measurement of the atmospheric properties in a slightly different direction to the science target that we actually wish to correct. Therefore applying this correction will leave some residual phase error. This problem is similar to the limited size of the isoplanatic patch in adaptive optics.

For these reasons, ALMA will also employ the second phase correction technique: water vapour radiometry. This technique exploits the fact that the same water molecules which delay the incoming wavefronts also emit thermal radiation in the form of rotational transitions. In particular, there is a convenient and strong rotational emission line of water at 183 GHz, shown in Figure 3. Each antenna is equipped with a well-calibrated and sensitive 183-GHz radiometer looking along the line of sight to the astronomical source. It is then possible to infer to high accuracy the quantity of water along each line of sight. With the assistance of an atmospheric model, we can infer the absolute delay due to the water vapour at each antenna. Finally, for a given baseline, we subtract the delays to each antenna to predict the phase error due to atmospheric water. This phase error can then be removed from the given baseline either off-line in the final data processing, or in real time in the correlator.

This WVR technique bears some similarities to laser guide star adaptive optics at optical and near-infrared wavelengths. In that technique, artificial stars are stimulated by lasers shone out along the line of sight, and their resulting stellar images are used to infer and correct the atmospheric effects. In the submillimetre, life is somewhat easier because the water molecules emit passively in the submillimetre bands, so no laser excitation is required.

WVRs for ALMA

For ALMA, the atmospheric water emission will be measured by dedicated absolute microwave radiometers situated next to the main astronomical receivers at the Cassegrain focus of the antennas. One radiometer is needed for each antenna, and the lines of sight of the radiometer beams are very closely aligned with those of the astronomical beams. This ensures that the radiometer beam samples as closely as possible the volume of air causing the extra optical path, so allowing the greatest possible accuracy in the phase correction. As part of the ALMA design and development project,

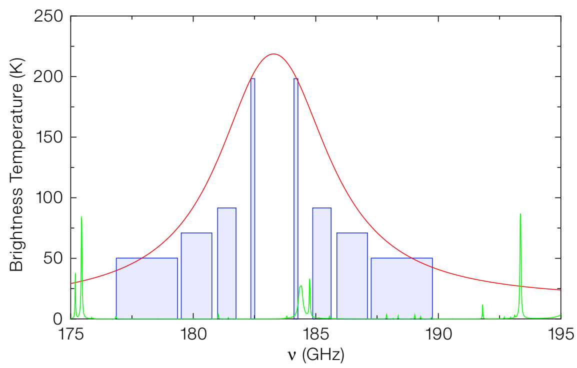


Figure 3: The brightness temperature of the 183 GHz water vapour line for a precipitable water vapour column density of 1 mm (red line) and the four double sideband channels of the prototype system (rectangles) with heights scaled in inverse proportion to bandwidth to illustrate their relative sensitivity. Also shown is exaggerated ozone emission (green lines).

two prototype radiometers of different designs were built by a collaboration between Onsala Space Observatory and Cambridge University. Both met the ALMA specifications by a comfortable margin.

After laboratory testing, the two prototypes were taken to the SubMillimetre Array (SMA) on Mauna Kea for further testing (Figure 4). Each was installed on an SMA 6-m antenna using purpose-built relay optics. The magnitude of the atmospheric phase fluctuations at this site are similar to those on Chajnantor, although the absolute water content is significantly higher. The aim was to test both the engineering performance of the radiometers and also how well they could be used to correct the astronomical phase fluctuations.

Figure 4: The two prototype water vapour radiometers on Mauna Kea, in initial tests before installation on the SMA.

The most relevant tests consisted of observing a strong point source – a quasar typically – and recording both the phase of the interferometric visibility on the relevant baseline as well as the outputs of the two radiometers. We then computed the linear combination of radiometer outputs which optimally matches the observed phase (this consists of fitting for four parameters). This results in the best possible phase correction for given radiometer outputs, which would only be achievable in real life if we had very good models for the atmosphere. A sample result from one such test is shown in Figure 5. In this example, one can see that the predicted phase error tracks the observed quasar phase extremely well. In fact, by subtracting the predicted phase error, the rms phase fluctuations on the quasar are reduced from around 200 to 62 microns of path.

These tests showed that the radiometers mounted at the SMA can meet the top level specifications most of the time. The primary limiting factors of performance of radiometers in this system appeared to be related to interfacing issues rather then fundamental sensitivity, which bodes very well for their performance on ALMA.

Integrating WVR into ALMA

For ALMA, each of the 54 12-m antennas will be instrumented with an identical 183-GHz radiometer. After an open tender process, the contract to build the production radiometers was let by ESO to Omnisys Instruments AB, Sweden. Their preparations for production have been progressing well and the Project expects to receive the first production radiometers in September of this year.

The majority of the computing effort to integrate the radiometers into ALMA and make best use of them is being coordinated by ESO: the low level interface layer is being written at ESO; the on-line telescope calibration system (TelCal) will have the basic algorithms for phase correction using the WVRs and is being developed primarily at IRAM, Grenoble; and at Cambridge we are funded under the European Union Framework Programme 6 to develop advanced phase correction algorithms.

Modelling the atmosphere

There has been a significant effort to model atmospheric properties and phase fluctuations recently, both under previous agreements with ESO, and as a part of our current work. The primary motivation in the first stages was to relate the top level specification to the engineering specifications for the radiometers; presently, the main motivation is to create the tools needed to develop the algorithms which will correct the phase fluctuations as well as possible, and to understand the impact of any residual phase fluctuations that remain after the correction.

We have been using two different approaches to model the atmospheric properties at Chajnantor. Large Eddy Simulations (LES) are meteorological hy-

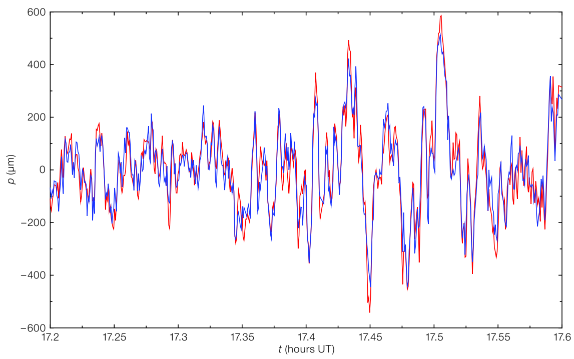


Figure 5: A sample of results from the Water Vapour Radiometer prototypes at the SMA. The red line is the fluctuating atmospheric path difference measured by the interferometer; the blue line is the best possible estimate from the radiometers.

drodynamic codes that solve the Navier-Stokes equation for a given set of boundary conditions, and accurately follow the air and water properties. An example of the results of such a simulation is shown in Figure 6, showing both the inhomogeneity of the horizontal distribution of water vapour and its vertical profile. These simulations have been used to predict the structure function of phase fluctuations as well as the relative importance of 'wet' (due to water vapour content) and 'dry' (due to temperature differences) fluctuations (these results are published in ALMA memo 517). Although the LES models represent the physics that gives rise to water vapour density fluctuations very well, they are extremely computationally expensive and so are both of limited spatial extent and of limited resolution.

For detailed modelling of the performance of the radiometers and of the final imaging performance of ALMA, we therefore use models based on statistical realisations of idealised Kolmogorov turbulence. Rather than simulating two-dimensional phase screens, we generally simulate complete three-dimensional volumes. The reason for this is that the ALMA baselines are of the order of the vertical extent of the turbulent layer and also because we wish to simulate the divergence of the astronomical and WVR beams as they travel through the atmosphere. When the three-dimensional turbulence is flattened by integrating in the line-of-sight direction, the expected steeping of the structure function is naturally reproduced (Figure 1).

The resulting phase screens can be used to simulate in detail both the phase fluctuations in ALMA data and the outputs of the radiometers. For example, Figure 7 shows a sequence of simulated images of a point source in the presence of turbulence. Both the decrease in sensitivity and the random shift in apparent source position can be seen in the sequence. This simulation also illustrates the similarity of the effect of seeing on submillimetre and optical/infrared imaging.

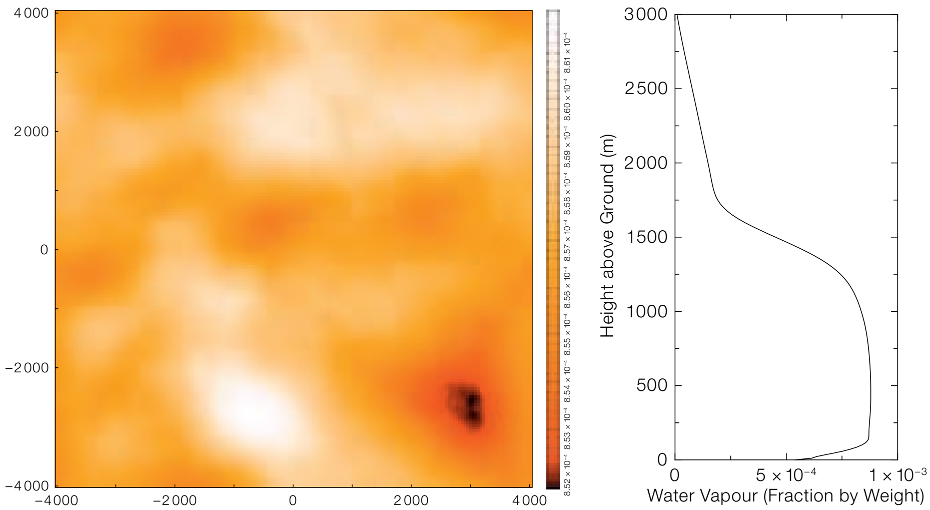
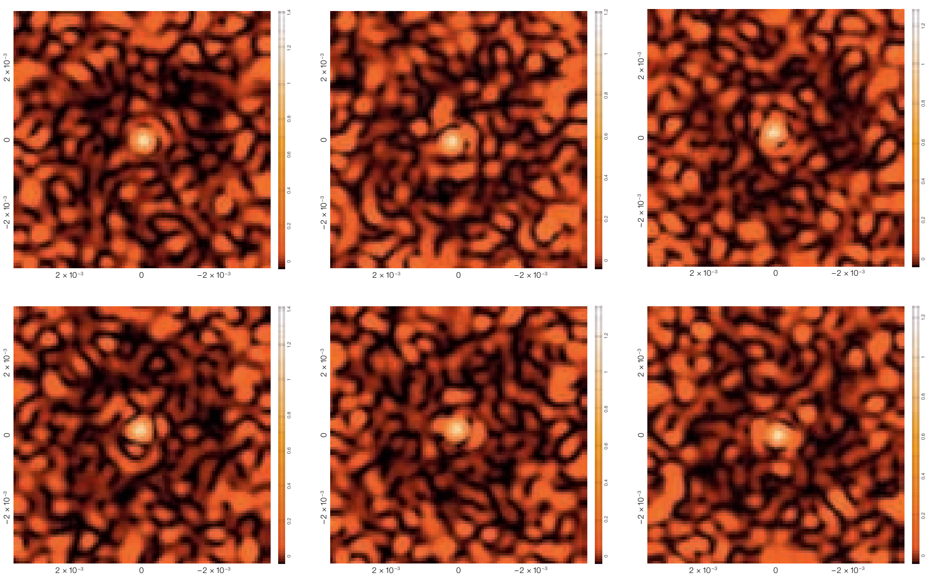


Figure 6: Results of Large Eddy Simulation of night time atmospheric conditions at Chajnantor. **Left:** Horizontal cross section of water vapour density at a height of 850 m (colour bar indicates density of water vapour by weight; overall horizontal dimensions are 8 km by 8 km). **Right:** The mean vertical profile of water vapour.

Figure 7: Time sequence of simulated 'dirty' snapshot images of a point source with ALMA with the presence of uncorrected phase fluctuations due to turbulence. Intrinsic source strength was 2 Jy.



Future plans

Now that the SMA tests are complete, we are focusing our attention on simulating the phase correction problem for ALMA, and developing algorithms that can be used to correct optimally the phase errors, incorporating both fast switching and water vapour radiometer techniques. Within 12 months or so, there should be a working interferometer in Chile, plus the first production WVR systems from Omnisys. As part of the ALMA commissioning process, it will then be possible to further test and refine the ALMA phase correction technique using test data from the ALMA hardware. The ultimate goal is a sophisticated hardware and software system which can correct the majority of atmospheric phase errors in a wide range of conditions, and so allow astronomers to exploit ALMA to the full.

References

Cabrit S. et al. 2007, A&A 468, L29
Krips M. et al. 2007, ApJ 671, L5