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Phase Fluctuation at the ALMA site and the Height of the Turbulent Layer

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Abstract

Phase compensation schemes are needed for sub-mm and mm interferometry if we are to obtain high resolution images with the proposed ALMA telescope. The presence of fluctuating water vapour in the atmosphere is the main culprit as it effectively distorts the phase of the signals arriving at each element of the interferometer.

There are two possible methods of correcting for this phase distortion. The first involves fast position-switching between the astronomical source and a calibrator of known phase. The second uses a radiometer close to the antenna to measure the amount of water vapour along the line of sight. The expected phase distortion is then calculated and used to correct the astronomical signal. No matter which technique is used, it is important to know the altitude at which most of the fluctuating water vapour is to be found, so that we can set limits on the offset between the astronomical and calibration beams. If the calibration beam does not sample a similar column of water vapour as the astronomical beam, then the phase correction will be inaccurate.

We describe a method for obtaining the height at which the bulk of the turbulence occurs, using two site-testing interferometers pointing in different directions. The time-lag between the interferometers is found by cross-correlating the phase data and then converted to a height using measurements of wind speed and direction.

Our results show that much of the turbulence is close to the ground, usually within the first 500 m. This gives confidence in the use of Water Vapour Radiometers (WVR) as a means of phase compensation, as

there would be a high degree of overlap between the astronomical and calibration beams.

1 Introduction

Since the refractive index of moist air is higher than that of dry air, any fluctuating amounts of water vapour in the atmosphere coupled with its turbulent motion, will cause changes to the electrical path length of signals arriving at the elements of an interferometer (Wiedner & Hills 1999, Tatarskii 1961). At sub-mm and mm wavelengths, the resultant phase distortion degrades the signal strength and severely limits the coherence and spatial resolution.

Possible phase compensation schemes are being tested at Chajnantor, the proposed site for the ALMA telescope, in the Atacama Desert of Northern Chile. One method involves fast position-switching between the astronomical source and a nearby celestial calibrator of known phase. (This facility is also used to remove instrumental phase drifts and requires the entire telescope to be repointed.) The calibration source must be detected with sufficiently large signal-to-noise ratio, on time-scales short enough to track the atmospheric phase fluctuations (Carilli & Holdaway 1999). Any difference in the phase of the calibrator to that expected, can be used to correct the astronomical source.

A second method, uses Water Vapour Radiometers (WVR), located close to the elements of the interferometer, to measure the amount of water vapour along the line of sight. The expected phase distortion can then calculated and used to correct the astronomical signal.

Whichever technique is used, it is important to know the height at which most of the turbulent water vapour is to be found as this will allow us to set limits on the offset between the astronomical and calibration beams. If those beams diverge significantly, they will not sample a similar column of water vapour and any phase compensation will be inaccurate.

This paper describes the way in which we have evaluated the height of the turbulent layer of the atmosphere using site test interferometers (Holdaway & Radford 1998). Two such instruments measure the atmospheric phase fluctuations by monitoring the signals from two different geostationary satellites. If the turbulence arises in a thin, “frozen” layer with a known wind velocity and direction, then the time lag between the two phase measurements (found by cross-correlating the two data sets) can be used to estimate the height of the layer. We do need to assume that the wind velocity measured on the ground is a reasonable approximation to that in the turbulent layer.

2 Observations and Data Reduction

Data are collected by two interferometers, on Chajnantor, at an altitude of 5000 m. One pair was established by NRAO and the other by ESO. Each interferometer consists of two 1.8 m offset feed antennas, with an E-W baseline of 300 m and a beamwidth of 1.2 degrees. The interferometers observe unmodulated beacon signals at 11.198 GHz, broadcast from different geostationary satellites and our intstruments measure the phase difference between the signals received by each antenna pair.

The raw data files are converted from LabView data logs to text time series of the interferometer phase (Radford, Reiland, & Shillue 1996). The files typically contain 24 hours of data in 10-minute blocks with samples approximately every second. Any long term instrumental drifts and drifts of the satellite away from the antenna beam centre, are then removed by subtracting no higher than second order polynomials from each 10-minute block of data.

A comparison of the data from the two interferometers, over similar times, shows excellent agreement. Figures 1 and 2 are examples for both interferometers, of the data before and after the baseline has been removed. The numbers at the bottom of the plot represent the date (year/month/day) from which the UT is scaled, the standard deviation of the phase data (in degrees), and its variance. Midday on Chajnantor is at about UT 16 hours (or at UT 40 hours for the plots shown).

3 Cross correlation

Once matching times have been found for both interferometer data sets, a check is made for availability of wind direction and speed. The data are

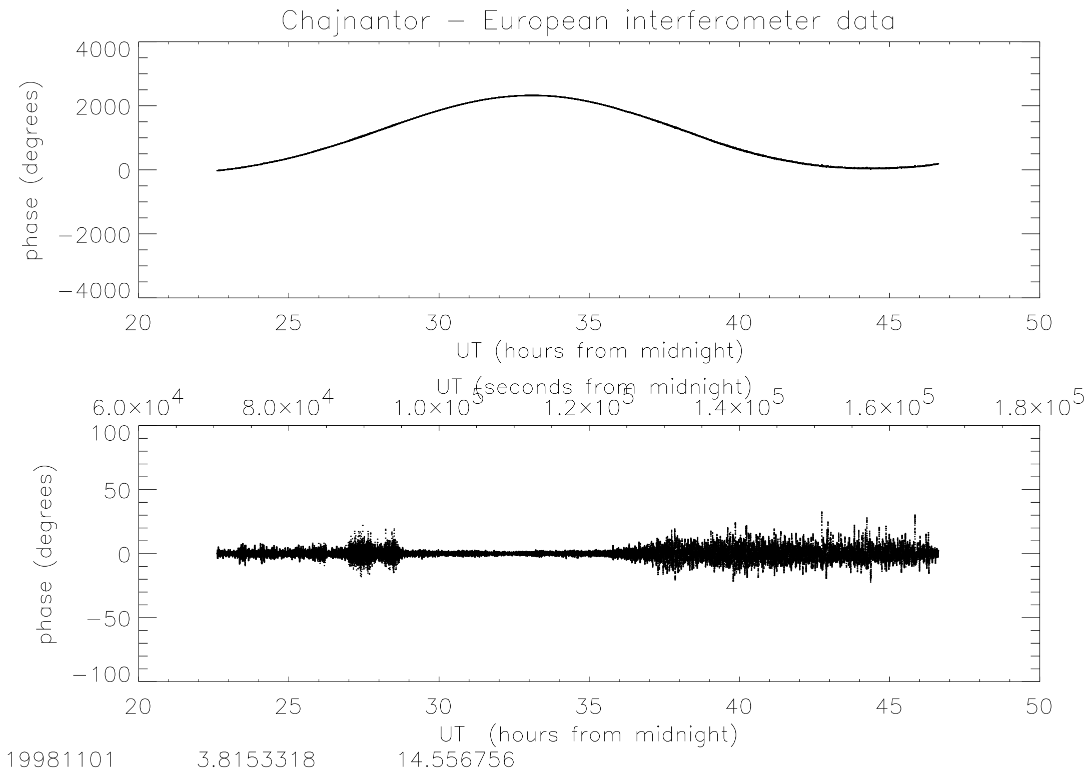

Figure 1: Baseline removal from ESO interferometer data

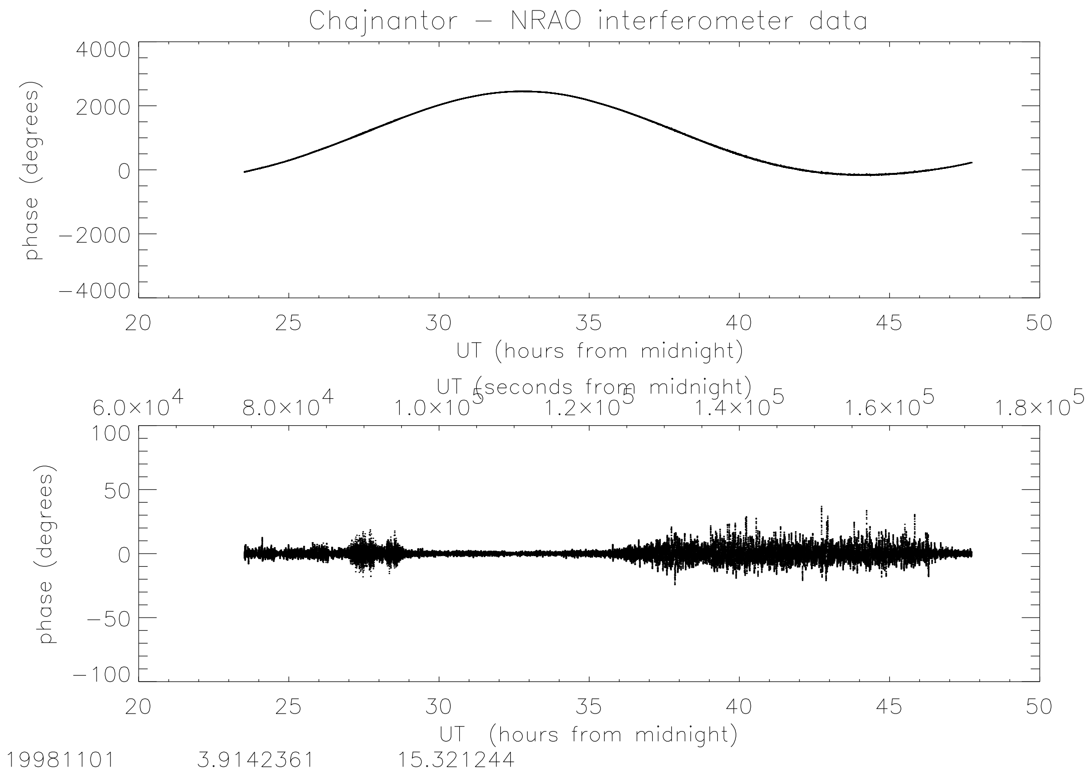

Figure 2: Baseline removal from NRAO interferometer data

processed in 1000-second blocks and any gaps of up to three seconds are interpolated. For gaps larger than this, the data are discarded. The phase information for these matching times is then cross-correlated to yield a lag-time indicative of the time it takes for a cloud to pass from one interferometer to the other.

Figure 3 shows a strong cross-correlation result with a lag of about 40 seconds. The plots show the lag in seconds on the horizontal axes and the lower plot uses an expanded scale. The standard deviation in the phase data for the NRAO interferometer is 10.56 deg., and for the ESO interferometer it is 9.73 deg.. These values are annotated below the plot.

It is possible that the higher phase noise in the data from the NRAO interferometer is due to the lower elevation of the satellite (or a weaker signal, or both).

The method does not always yield a good cross-correlation result (for example, Figure 4). Here the standard deviation in phase is 1.73 deg. for the NRAO interferometer and 1.31 deg. for the ESO interferometer and may be an indication that the instrumental noise is becoming significant. It is also possible that under these quiescent conditions, the small remaining atmospheric phase fluctuations do not arise in well-defined layers.

4 Model Assumptions and Geometry

In order to calculate the height of the turbulent layer from the results of our cross-correlation, two assumptions are necessary:

a) The turbulence arises in a thin "frozen" layer.

b) The wind speed and direction measured on the ground are a reasonable approximation to that in the turbulent layer.

The height of the turbulent layer can then be calculated in the following manner:

$$H = \frac{(E-W\ component\ of\ wind\ speed)\ \times\ Lag-time}{Beam\ Separation\ Factor}$$

where :

H - the height of the turbulence (in metres).

Lag-time - the lag, in seconds, as measured by the cross-correlation result.

E-W component of wind speed - the wind direction and speed are used to

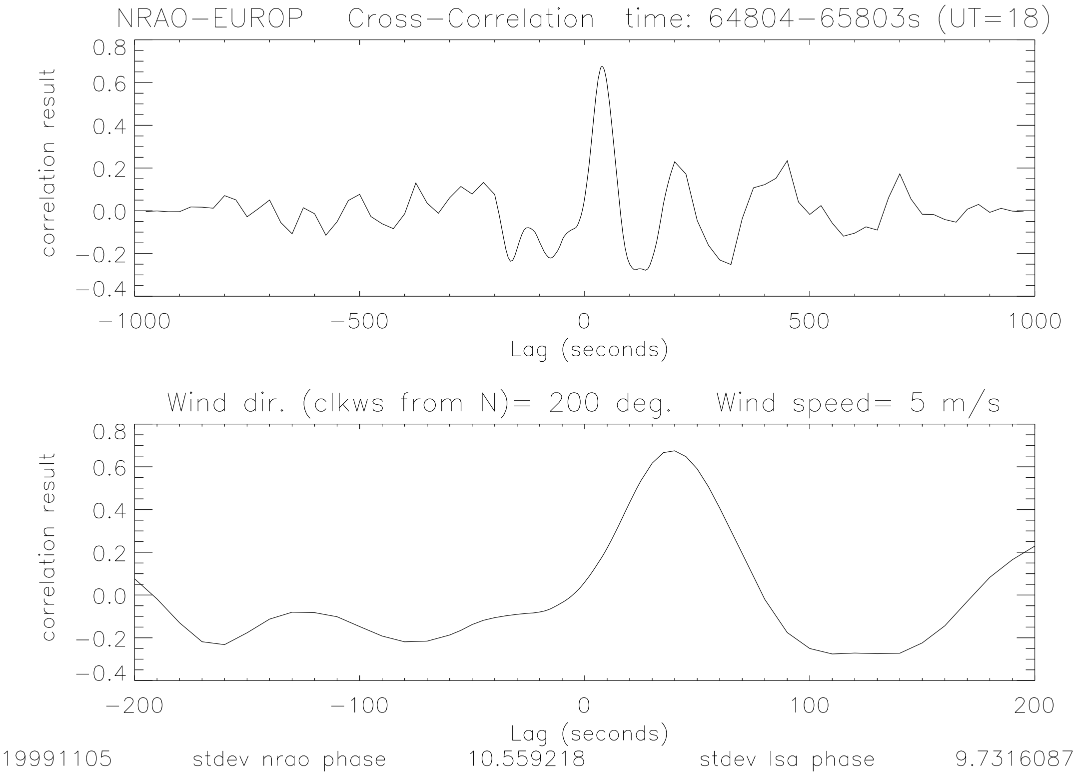

Figure 3: A strong cross-correlation result of NRAO and EUROPEAN interferometer phase data is seen here. The second graph uses an expanded scale in the time domain to show the offset and indicates a lag-time of about 40 seconds.

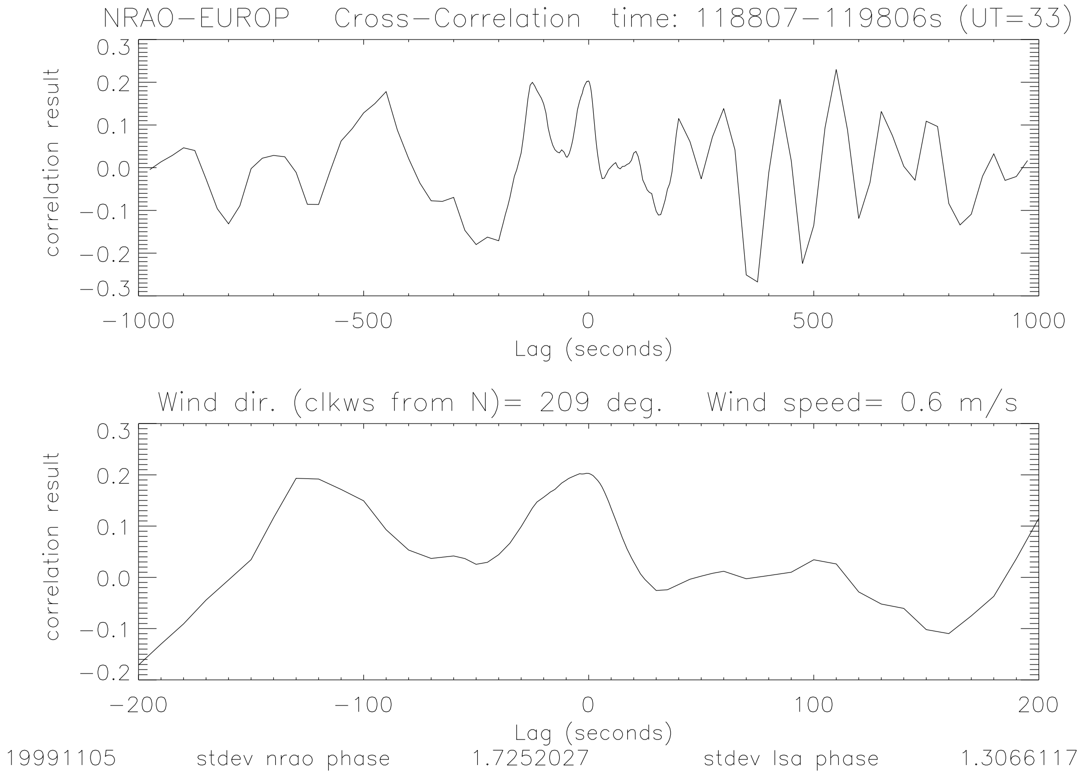

Figure 4: No strong cross-correlation result is evident for the NRAO and EUROPEAN interferometer phase data.

obtain the East-West wind component in metres per second; i.e. the component in the same direction as the interferometer baseline.
Beam Separation Factor - This depends on the geometry of our observations. The interferometer beams are pointing at different geostationary satellites, thus their beams diverge with altitude, increasing the horizontal beam separation with height above the site.

The relevant satellite locations (azimuth, elevation) above Chajnantor for the data collected in 1998 and 1999 are:
NRAO - Intelsat 603 (67.47 deg., 34.95 deg.)
ESO - Intelsat 605 (65.24 deg., 37.75 deg.)
this gives a Beam Separation Factor of about 0.15; so the horizontal separation of the NRAO and ESO interferometer beams increases by about 15m per 100m of altiude above the site.

5 Results

Histograms showing the wind direction, wind speed and height of turbulence are presented. Caution is needed when using these results since they are highly selective and depict only those data for which a STRONG cross-correlation result has been obtained. However, these may be easier to find in times of poor phase stability, which are the most important conditions for performing phase corrections.

In Figure 5 the wind direction is shown from all possible angles. However, for the bulk of the time, the wind blows from the West (at about 270 degrees). For these data the wind speed (Figure 6) never gets above 15 m/s and is most often about 6 m/s. The height of turbulence histograms shown in Figure 7 suggest that the turbulent layer is relatively close to the ground for much of the time, generally below about 500 m for 70 percent of the data analysed. The lower plot uses an expanded scale with bin sizes of 100 m.
Another plot (Figure 8) is included in an attempt to understand if the height of turbulence varies with wind speed and direction. There may be an indication in the upper plot that the turbulence is even closer to the ground (200 m) and with a smaller spread in height, when the wind speed is low (0 - 4 m/s). However, as the wind speed increases, so too does the range of heights at which the turbulence may be found.

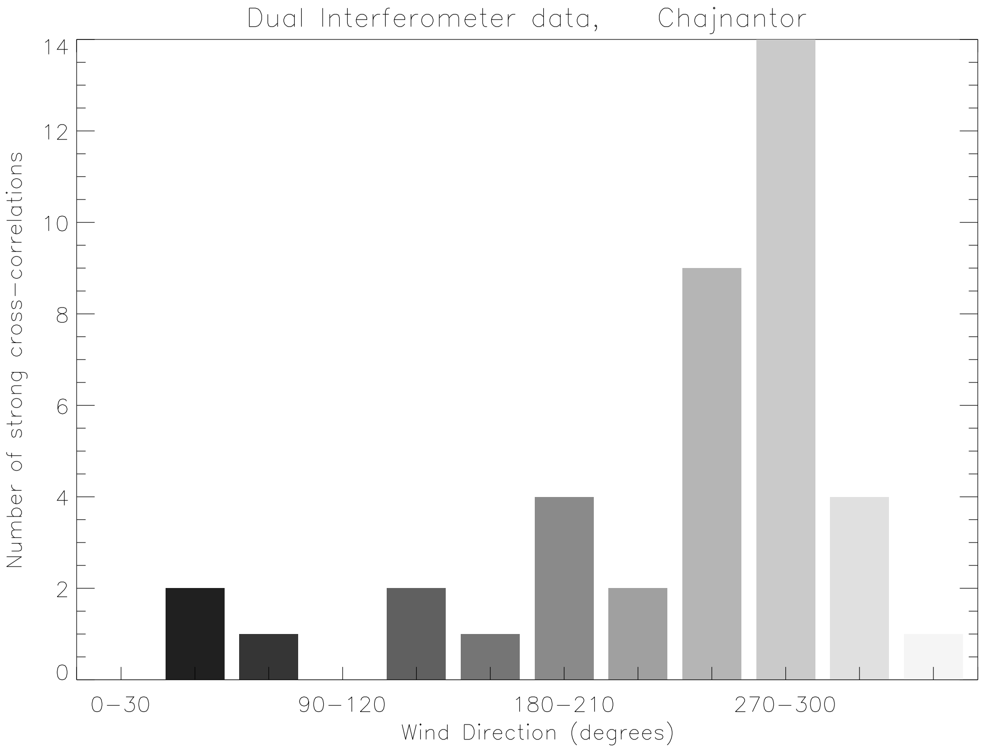

Figure 5: Wind direction (degrees) for data showing a strong cross-correlation result

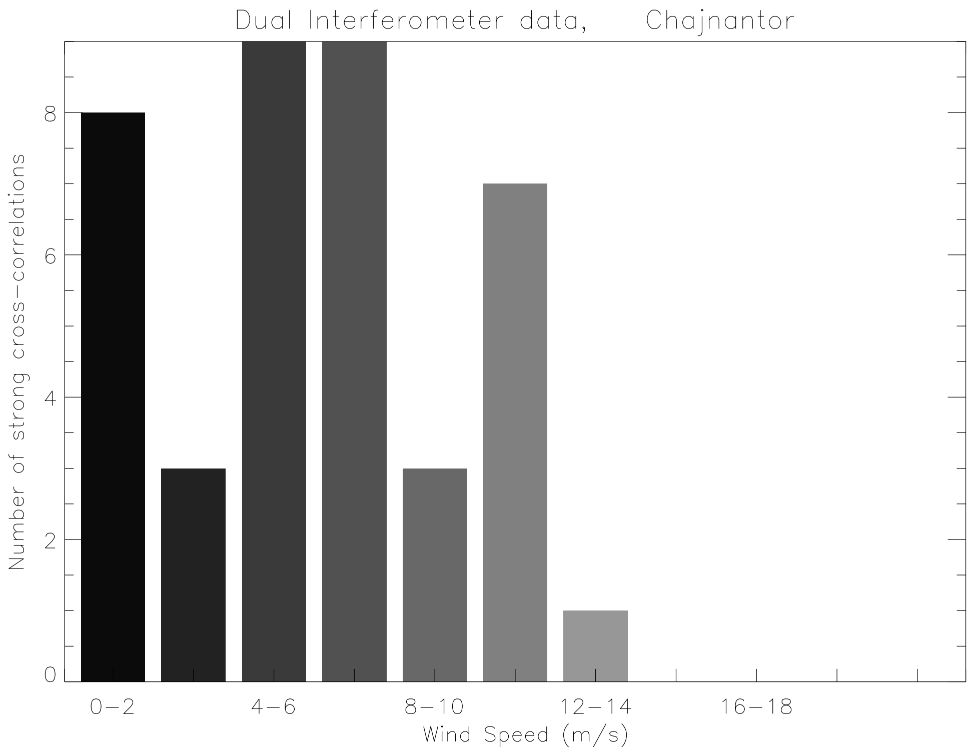

Figure 6: Wind speed (m/s) for data showing a strong cross-correlation result

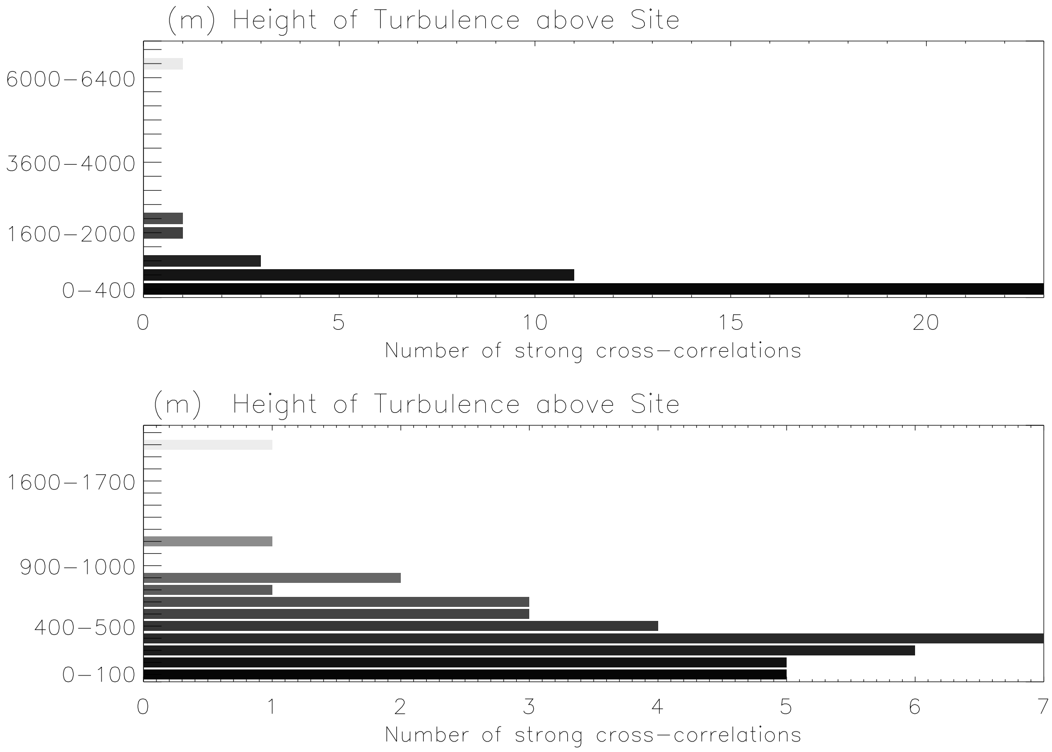

Figure 7: Height of Turbulence (m) on Chajnantor for data showing a strong cross-correlation result. Lower plot uses an expanded scale with bin size of 100 m.

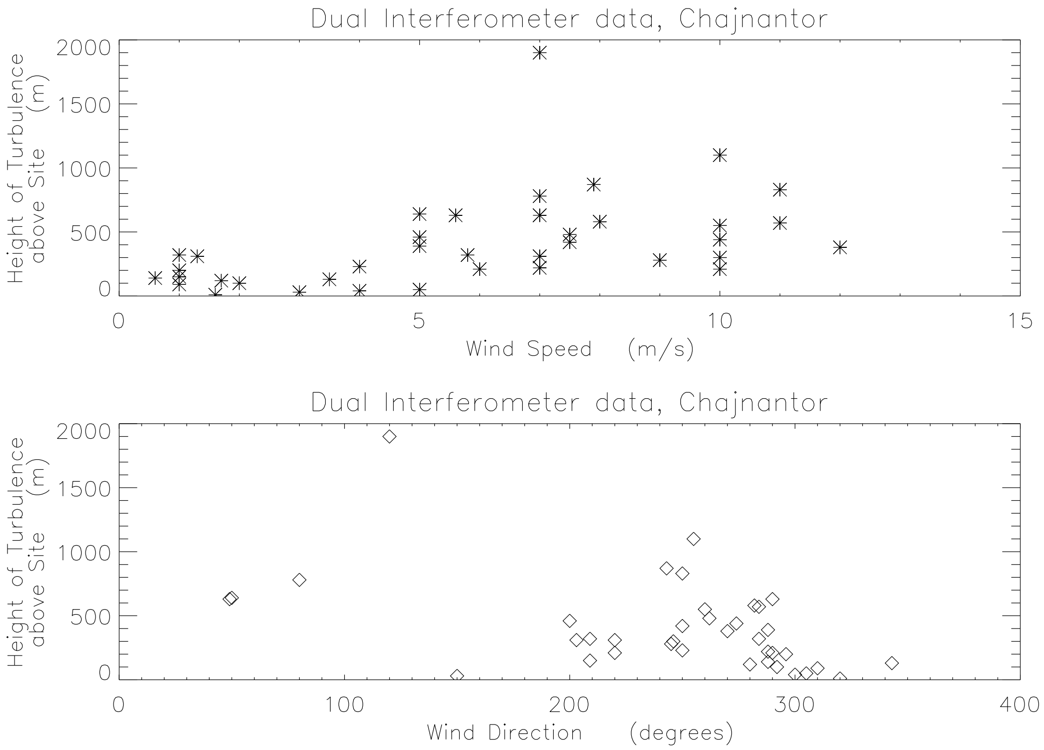

Figure 8: Wind Speed (m/s) and Wind Direction (deg) vs Height of Turbulence (m) above site.

6 Conclusion

One of the primary concerns in using a phase compensation scheme to correct for phase distortion due to fluctuating water vapour, is to minimise the offset between the calibration beam and the astronomical beam so that they sample a similar column of water vapour. This method, using dual site-testing interferometers, offers a cheap and simple way of obtaining the height of the turbulent layer of the atmosphere. Our results indicate that on Chajnantor, the proposed site for the ALMA telescope, most of the turbulent water vapour is close to the ground, generally within 500 m. This is excellent news since there is a greater degree of overlap between the astronomical and calibration beams closer to the ground, so increasing confidence in the use of any phase compensation technique.

7 Acknowledgements

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