ALMA MEMO 459

Investigation of Anomalous Fast Phase Fluctuations in the Site-Test Interferometer Data from Chajnantor

May 14, 2003

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Abstract

ALMA Memos 332 and 361 reported test comparisons between phase fluctuations predicted by line-of-sight PWV measurements from 183-GHz water-vapour radiometers at Chajnantor and the phase signal measured by the NRAO site-test interferometer observing an 11.2-GHz. geostationary satellite beacon. Though data from the two methods showed good correlation for long periods, an unexpected strong high-frequency fluctuation was found to occur in the interferometer phase, sometimes persisting for several hours. No counterpart for this phenomenon was found in the radiometer data, but a similar effect was seen on the ESO site-test interferometer located on the same baseline but observing a different 11.2-GHz satellite. If the effect proved to be directly proportional to frequency it would lead to complete decorrelation of the astronomical signal at wavelengths of order one millimetre with no prospect of correction using the radiometer measurements.
This memo reports investigations of the phenomenon to establish its likely physical origin and hence how it would scale to higher frequencies. We show that the phase variations are accompanied by amplitude variations, indicating some kind of scintillation effect. Moreover the inferred velocity of the underlying disturbances (or waves) is so high as to rule out their being any kind of small-scale tropospheric irregularities not visible to the radiometers; rather, it is consistent with typical propagation speeds of ionospheric disturbances. The occurrence and time of onset in the interferometer data appear to exhibit some agreement with Range-Time-Intensity (RTI) plots from the JULIA back-scatter radar experiments from the Jicamarca Radio Observatory in Peru. We present some statistics showing the incidence of the effect in the interferometer data over a 5-year period, revealing seasonal and diurnal patterns which suggest that the predominant cause is the post-sunset ionospheric disturbances well-known to occur at low magnetic latitudes and collectively termed Equatorial Spread F.

Introduction

Phase perturbations due to atmospheric water vapour decrease both the sensitivity and resolution of an interferometer operating at millimetre and sub-millimetre wavelengths. An ongoing experimental programme is investigating prospects for estimating these phase perturbations with a view to applying a correction to the astronomical signal to counteract such effects at the ALMA site at Chajnantor. Much effort has already been invested in developing the use of radiometer measurements of the 183-GHz water-vapour line together with appropriate models to predict the additional path due to PWV in the line-of-sight column at Mauna Kea; the resulting additional interferometer phase scales linearly with observing frequency and can be subtracted from the interferometer signal (Wiedner 1998, Yun & Wiedner 1999, Delgado et al 1999). To investigate the effectiveness of adopting a similar strategy at Chajnantor, a comparison has been made between the phase measured by the NRAO 11.2-GHz radio interferometer on the Chajnantor site and that from a pair of water-vapour radiometers set up on the same baseline. This work is reported in ALMA Memos 332 and 361 (Delgado et al 2000, 2001) and showed that, while there was good correlation for a good deal of the time, there were considerable periods when there were quite large (~ ±10°) strong fluctuations in the phase measured by the 11.2-GHz interferometer while the radiometers showed no such variations (see Figure 1). This result was alarming because if these fluctuations were true path length errors (i.e. giving phase variations proportional to frequency) they would scale up to ~ 360° at 360 GHz – sufficient to destroy almost completely the coherence of the astronomical signals at wavelengths of around one millimetre – and there would be no prospect of correcting these phase errors with information from the radiometers. Memo 332 notes (and Figure 2 shows) that the effect was also seen on the ESO site-test interferometer, co-located on the NRAO baseline but observing a different 11.2-GHz satellite (Holdaway & Radford 1998), implying that it was unlikely to be due to an instrumental problem. We therefore decided to concentrate a good deal of effort on a more detailed study of a sample of affected data to establish its origin.

Detailed Investigation

In order to investigate the phenomenon in sufficient detail we had to backtrack to the 10-min batches in which the interferometer data for a particular day was received initially – a necessary but somewhat labour-intensive process. For the purpose of the following discussion, Figure 3 shows plots of relevant variables from a typical 10-min sample of affected data, with the central 200s plotted on an expanded scale in Figure 4 to show the variations in greater detail. (The residual slopes are the unremoved effects of drifts in the satellite position). We see that a distinguishing characteristic of the phase fluctuations which appeared in the interferometric data but not the radiometric data is that they are very fast, with coherence times of only about a couple of seconds, compared to the greater than ten seconds typical of water vapour fluctuations. These fast phase fluctuations are accompanied by even faster amplitude variations, suggesting some kind of scintillation effect. This would require that the interferometer be in the far field of the attendant phase screen – a condition which could only be fulfilled for disturbances at tropospheric altitudes if they were on extremely small scales. Given the dry site and the fact that the example in Figures 1 and 2 shows a night-time effect it is difficult to envisage a suitable mechanism. It might, however, be possible that the effect originated in the disturbed ionosphere, implying a scattering phase screen at altitude in the region 100-1000 km; we would then expect the variations on the amplitudes of the signals received at the individual antennas of the interferometer to be well correlated with a relative delay determined by the propagation speed of the disturbances in the direction of the 300-m E-W baseline. Although we were familiar with ionospheric scintillation at VHF or UHF radio frequencies, the suggestion that it might be seen at 11 GHz was initially greeted with some scepticism. Nevertheless, we decided to try performing the cross-correlation of the NRAO interferometer antenna amplitudes for a 10-min data sample affected by the fast phase and amplitude fluctuations: the result can be seen in Figure 5a, clearly showing a strong correlation at a delay around –1s. Moreover, we have already noted that the fluctuations were seen at the same time on the ESO site-test interferometer, which observes a different geostationary satellite at a different elevation; performing a similar cross-correlation using the ESO antenna amplitudes for the concurrent 10-min interval we obtained a similar correlation at an identical delay, as shown in Figure 5b. This enabled us to rule out the possibility that the result was an artefact particular to the interferometer or satellite used. To investigate how the delay behaved over a longer period we repeated the cross-correlation for the NRAO interferometer antenna amplitudes for a sequence of 12 10-min data samples affected by the fast fluctuations and plotted the results on an expanded scale – in each case we obtained the strong correlation at about –1-s delay shown in Figure 6, leading immediately to a propagation speed of 300 m/s in the direction of the 300-m E-W baseline (assuming a far field regime w.r.t. the satellite so that the baseline transfers directly to ionospheric altitudes). This measurement is somewhat limited by our 1-Hz sampling, but we can say that the delay is very near 1s and certainly not 0 or 2 s. The 300 m/s result is an apparent E-W velocity because it assumes an intrinsic horizontal E-W drift. Furthermore, magnetic and geographic E-W are not severely misaligned at Chajnantor (rather surprisingly, considering the huge distortion of the magnetic field in the South American sector shown in Figure 10) – even allowing for the fact that the interferometer line of sight intersects the ionosphere some distance to the NE, the misalignment would not exceed 10°. Therefore our measurement is, to a reasonable approximation, a zonal (magnetic E-W) apparent velocity in ionospheric terminology, assuming we are seeing an intrinsic horizontal drift along the magnetic E-W direction. We need to examine the validity of this latter assumption. According to Hysell (private communication), the most common source of contamination is an appreciable vertical velocity. We found that ionospheric velocity measurements from GPS scintillation observations in Brazil reported by Kil et al (2000) measured zero velocity on a magnetic N-S baseline and apparent zonal velocities of up to 200 m/s on two magnetic E-W baselines – this relates well to observational experience that ionospheric fluctuations at low magnetic latitudes are generally associated with plasma-depleted bubbles (flux tubes) elongated along the magnetic field. They also showed, using simple geometrical considerations and assuming an intrinsic W-E and rising ionospheric drift, that correlating antennas with an eastward-pointing line of sight at low elevation would tend to give an underestimate of the velocity, whereas a similar westward-pointing line of sight would give an overestimate – this gave rise to large error bars on some of their inferred zonal apparent velocities. Our measured zonal apparent velocity might be similarly contaminated, but its order of magnitude would nevertheless remain plausible for ionospheric propagation and still convincingly too high for any kind of tropospheric disturbances.

Finally, we needed to verify that the amplitude correlation described above was not observed when the fast fluctuations were not present – Figure 5c shows the cross-correlation result obtained for a 10-min data sample from which they were absent. Nor was there any significant correlation between corresponding antennas of the NRAO and ESO interferometers when the fast fluctuations were present – indeed, given that the pointings to the observed satellites differ by about 5 degrees, we would not expect the fluctuations to be correlated in this case since the diverging antenna beams would be separated by of order 100 km at ionospheric altitudes. It would not however seem surprising that E-W zonal drifts in the ionosphere should have systematic velocities over these kinds of scales, as the identical delays measured independently by the NRAO and the ESO antenna pairs appeared to indicate.

On the basis of these findings we were reasonably certain that the anomalous fast fluctuations originated in disturbances in the ionosphere. We sought further evidence by looking at records of ionospheric activity from experiments with the JULIA back-scatter radar at the Jicamarca Radio Observatory in Peru. Range-Time-Intensity (RTI) plots from these experiments existed for two sample days from our initial detailed investigation period in November 1999. Both days showed post-sunset ionospheric disturbances at Jicamarca; on the first we saw the fast fluctuations in our data after sunset, though they appeared to be of longer duration in our observations; on the second we had no such detection at a similar time. This may not be surprising if we note that Jicamarca has a geographical position 11.95° S, 76.87° W and is situated approximately on the magnetic equator with the JULIA radar operating at 50 MHz towards the magnetic zenith and sensitive to structure of scale $\lambda/2 = 3$m. We compare this with Chajnantor at 23° S, 67.75° W at a magnetic latitude approximately 10° S with the interferometers observing 11.2-GHz satellites to the NE at elevation ~ 35°. The kind of disturbances we saw on the RTI plots are thought to have spatial extents of order 1000 km and structure on cm to 100-km scales (Hysell, private communication), but this would not necessarily imply one-to-one correspondence between observations at the two sites. In the next section therefore we look at some statistical evidence.

Statistical Investigation

Ionospheric fluctuations are due to fluctuations in plasma density, giving rise to phase errors which scale as 1/frequency, and so will not be a major limitation on the performance of ALMA, (though they may still have some effect at its lowest observing frequency of 30 GHz). However, their presence in the interferometer data which has been used to characterise the site means that the statistics will have been somewhat distorted. We therefore undertook an investigation to see how much of the data was affected and whether there were patterns in the occurrence of the effects, which might also further substantiate their ionospheric origin. As explained above, a full investigation of a given 10-minute data set to be sure that the fluctuations are ionospheric in nature is quite time consuming, since it requires reprocessing the raw data and looking at the correlations between the amplitude fluctuations as well as the phases. It was however found that a good indication of their presence can be obtained by finding the total rms phase fluctuation over a 10-min interval and the rms of fast fluctuations occurring on timescales of less than 10 seconds during the same interval, and then taking the ratio of these two quantities. We will refer to this ratio as ‘fraction fast’. For water vapour fluctuations the ratio fraction fast is typically around 0.1, rising to perhaps 0.25 when there is strong convection, e.g. on summer afternoons – the plot in Figure 7a shows a typical example of a day affected in this way. At times when the full analysis had shown that ionospheric fluctuations were present, the ratio fraction fast rose to at least 0.3 and often to 0.5 – a strong example occurs on the day shown in figure 7b. In using the magnitude of the ratio as a diagnostic there would inevitably be some intermediate cases which were not so clear-cut, so two criteria were defined to indicate the presence of ionospheric fluctuations with differing degrees of confidence:

(i) Fraction fast > 0.4 with concurrent fast phase rms > 2° was considered a 'strong' indicator and
(ii) Fraction fast > 0.3 with concurrent fast phase rms > 1° a 'marginal' indicator

of their presence.(The thresholds on fast phase rms were to prevent false positives in cases where both fast and total phase fluctuations were very small.)

Plots similar to the examples shown in Figure 7 were made for a representative selection of days of data from the interferometer – typically two days per month over the past five years' observations – and examined against these criteria. This produced a date-based record of periods of ionospheric fluctuation as a function of time of day, in which a distinction was maintained between the 'strong' and 'marginal' cases. In either case, diurnal and seasonal patterns were immediately obvious. The results are presented in Figure 8 in the form of histograms showing aggregates over the five-year period for a particular season (quarter-year) accumulated in U.T. bins of width 6 h : a given observation generates a count within a 6-h bin if ionospheric fluctuations are deemed to be present for a duration of at least one hour in that 6-h period ; counts have been normalised by the number of selected observation dates contributing to that quarter-year. The solid histograms correspond to the 'strong' criterion for ionospheric fluctuations with the dotted lines showing any difference in statistics if the 'marginal' criterion is adopted instead – in practice the differences may be seen to be fairly small. The ionospheric fluctuations are clearly most common in the period 00–06 h U.T. (1930–0130 h local time) in the southern summer (October – March) : over 50 percent of the summer observations in this time-slot appear to be affected. Though not restricted to these times, the phenomenon appears to be much less pervasive at other times of day and year – possibly up to 10 or 15 percent of days might be affected at a given time of day in some seasons, whereas in others hardly any effect is seen at all. Since the Chajnantor site is at a magnetic latitude of ~ 10° S and the line of sight of the interferometers is to the north, it is plausible that the high incidence of the effect in the summer in time-slot 00–06 h U.T. (1930–0130 h local time) may be attributable to the post-sunset ionospheric disturbances well-known to occur at low-latitudes and collectively termed Equatorial Spread F (ESF). A broad resemblance is seen to the patterns of occurrence of ESF over the period 1996-2000 in long-term studies with the JULIA radar at Jicamarca in Peru, reported by Hysell & Burcham (2002). They show for the Peruvian sector that conditions favouring its occurrence are complicated, but it is typically seen for a few hours after sunset and appears to show a tendency to avoid the June solstice. Whether it occurs on a particular night does not seem to depend strongly on the solar flux , so does not invalidate our stacking of our seasonal statistics over the period 1996–2001, which roughly spans the period from solar minimum to maximum. Hysell points out that when comparing results from

Chajnantor (67.75°W) and Jicamarca (76.87°W) we should bear in mind that the occurrence of ESF varies strongly with longitude; nevertheless the main statistical trends in the two datasets are strikingly similar. The less frequent occurrences of the effect in our data in time-slots other than 00–06 h U.T. may be due to Spread F at other times or to other kinds of ionospheric disturbance – the JULIA RTI plots do indeed show disturbances at other times of day as well as after sunset.

As we commented earlier, it may seem surprising that the ionosphere should have a significant effect on observations at a frequency as high as 11 GHz. We know of its impact on low-frequency (VHF, UHF) radio astronomy but tend to expect that the inverse proportionality to frequency would render its effect negligible at cm wavelengths and beyond. However, it is interesting to note that even in the early years of geostationary communications satellites in the 1970s we can find technical articles on ionospheric scintillation at frequencies as high as 4 and 6 GHz . In the present era there is much investment in studying the ionosphere at L-band with GPS – some interesting maps of global total electron content are available on the ionospheric studies section of the JPL website at URL

http://iono.jpl.nasa.gov/latest_rti_global.html

showing a very strong enhancement in the region within 15 or 20 degrees of the magnetic equator. Furthermore, a commercial research company, Northwest Research Associates Inc., has initiated an industry developing models to predict the effects of ionospheric scintillation on communication and navigation satellite systems for the professional market – a particularly striking map from these predictions can be seen at the Northwest Research Associates website at URL

http://www.nwra-az.com/ionoscint/wbmod.html

which shows that the most intense scintillation is expected to occur just after local sunset, along two bands spaced roughly 15 degrees north and south of the magnetic equator.

Finally, it may be also be instructive to compare the results we have obtained in this memo with those shown in the contour plot of median rms phase fluctuations at the zenith at Chajnantor from the Chajnantor site characterisation statistics, shown in Figure 9. Here the green 'fingers' ingressing into the plot from the lower edge between about November and March are probably due to the ionospheric fluctuations described here, and the blue bands peaking after local noon are due to the water vapour fluctuations caused by the strong convection in summer afternoon weather fronts. The plot is also useful in showing the blank periods for which no interferometer data were available.

Conclusion

Our investigations of the anomalous fast phase fluctuations seen in the site-test interferometer data but not by the radiometers have shown that ionospheric disturbances offer the most plausible explanation of their origin. In support of this we advance the following evidence : scintillation effects are observed (amplitude variations are seen which are even faster than the phase variations) ; the propagation speed of the underlying disturbances (the phase screen) is consistent with velocities of physical phenomena in the ionosphere rather than those in the troposphere ; and the statistics of the occurrence of the effect during a five-year period 1996-2001 exhibit diurnal and seasonal patterns which appear consistent with their originating predominantly in the post-sunset ionospheric disturbances well-known at low magnetic latitudes and collectively termed Equatorial Spread F. Ionospheric disturbances observed at other times of day at these latitudes are also implicated to some extent. (We note that our observations over 1996-2001 spanned the period from approximately solar minimum to maximum). It may still seem somewhat surprising that the effects are so strong at 11 GHz – sometimes as much as $\sim \pm 10°$ phase on a 300-m baseline. However, we note that the effect of ionospheric scintillation on the early INTELSAT communication satellites operating at a few GHz was documented as far back as the 1970s (Taur, 1973); also there is now available on the WWW at least one research company making a business of predicting its effects on modern GHz communication and navigation satellites, presumably indicating that it does present a significant problem. In conclusion, we note that phase fluctuations due to the ionosphere will scale inversely with frequency and therefore will not represent a problem for the ALMA observing frequencies, though their presence may have added a pessimistic bias to the atmospheric statistics in the site-characterisation data.

Acknowledgements

We are grateful to Prof. Henry Rishbeth for helpful discussions at the outset of this investigation. We thank Dr. David Hysell for use of his database of observations obtained with the JULIA radar and for his generosity in responding to our many questions with illuminating advice on ionospheric topics. We also thank Mr. James Secan and Dr. Edward Fremouw of Northwest Research Associates for generous assistance and allowing us to reference their scintillation model. Finally, we are indebted to NRAO and ESO staff at Chajnantor for their ongoing effort in support of the site-study instrumentation programme.

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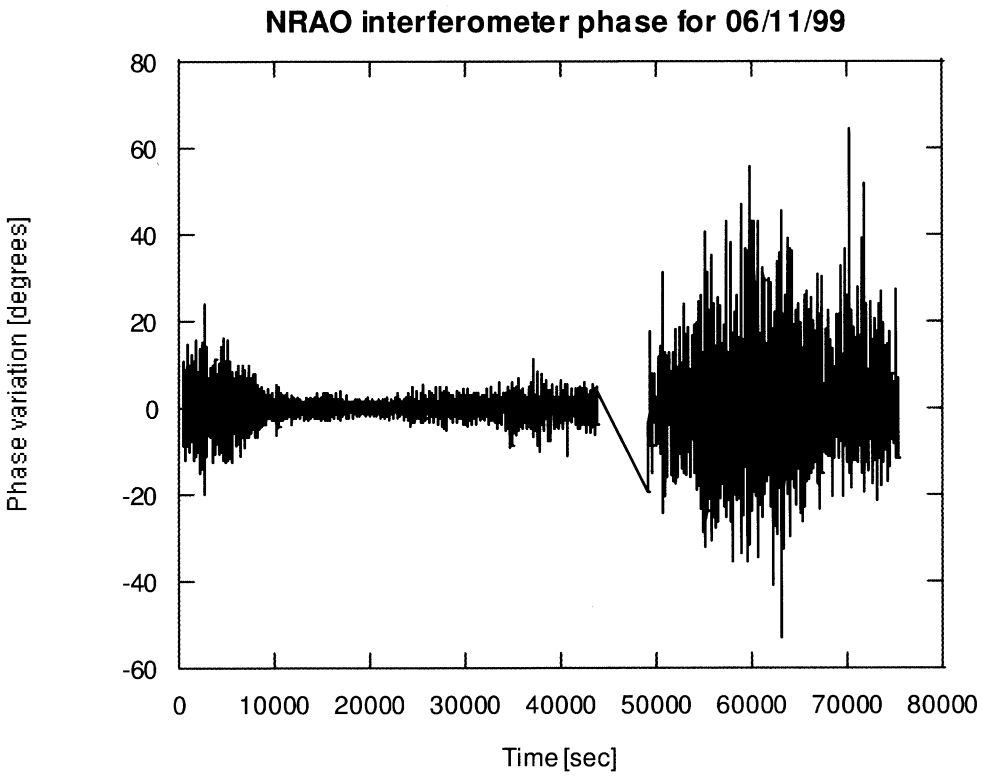
Northwest Research Associates Inc.: http://www.nwra-az.com/ionoscint/wbmod.html

JULIA RTI plots of F region – see : http://landau.geo.cornell.edu



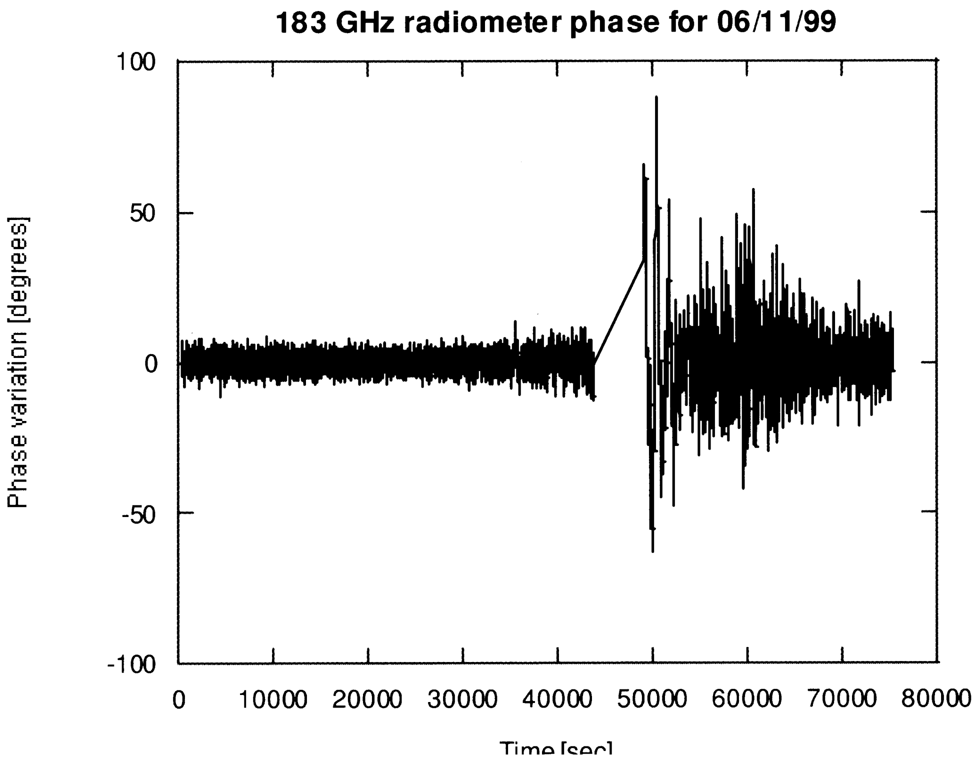


Figure 1. Records for 19991106: the rapid phase fluctuations seen on the NRAO interferometer during the first 1000s (0-3h U.T.) are not seen on the radiometer record. Note that there is a 1-h data gap near 50000s. Chajnantor Local Time = U.T. – 4h 31min.

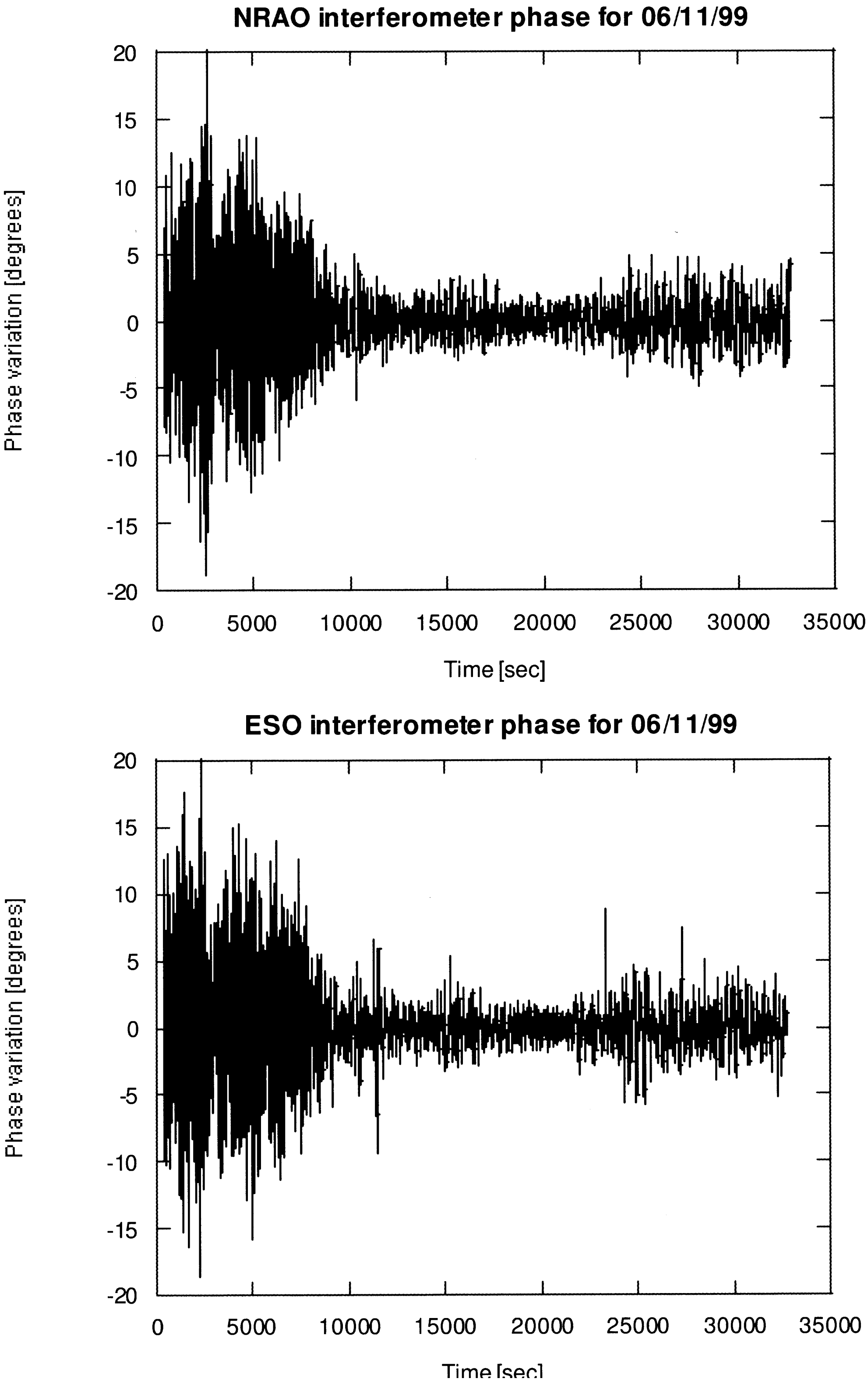


Figure 2. Records for 19991106: the rapid phase fluctuations during the first 1000s (0-3h U.T.) are seen on both the NRAO and the ESO interferometer. Local Time = U.T. – 4h 31min.

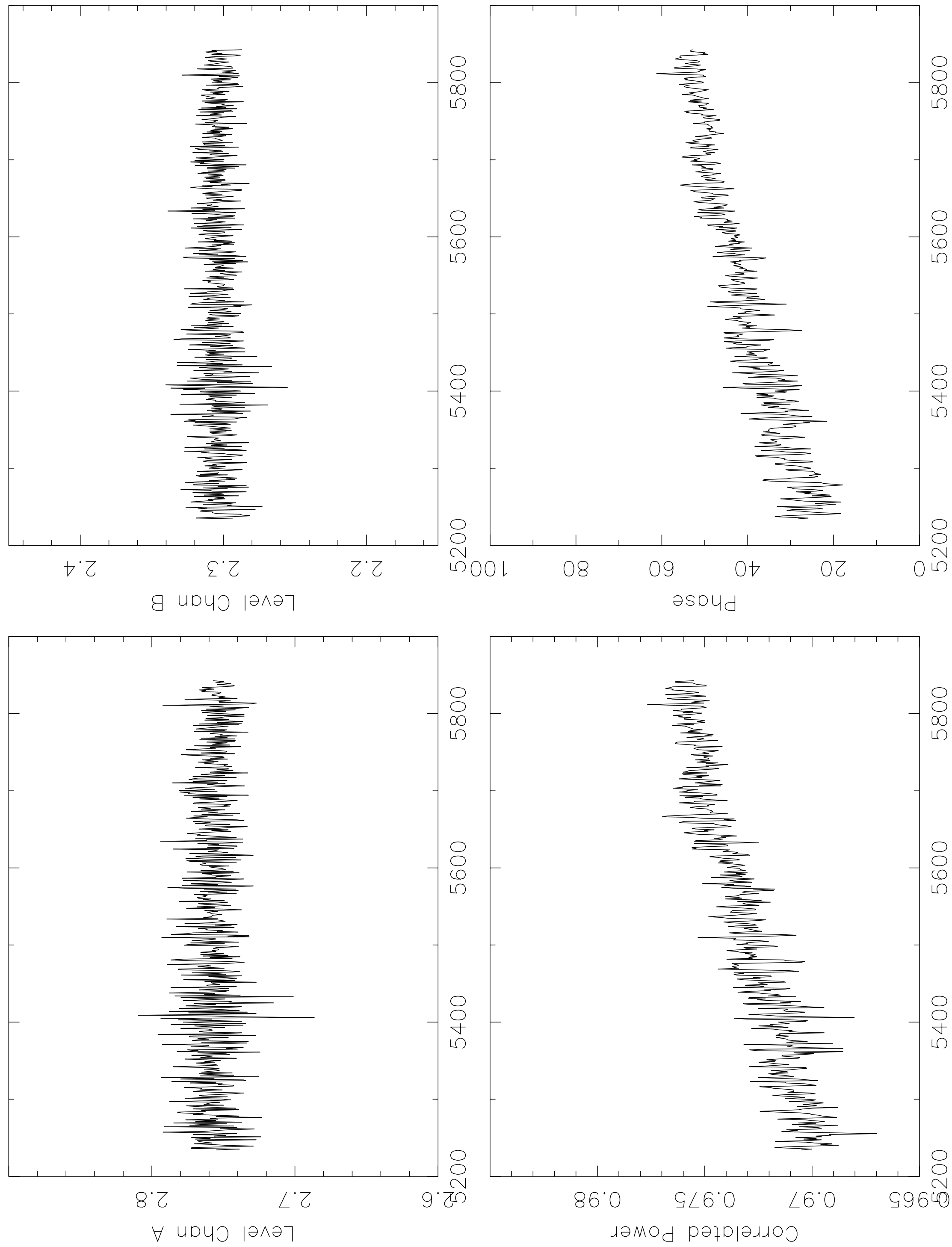


Figure 3. For a typical 10-min data batch displaying the fast phase fluctuations, the plots show : the individual antenna amplitudes (Level Chan A, B) ; the interferometer correlated power ; and the interferometer phase output. Each quantity is plotted as a function of time in seconds measured from 0h U.T. on 19991106. (Residual slopes are the unremoved effects of drifts in the position of the observed geostationary satellite).

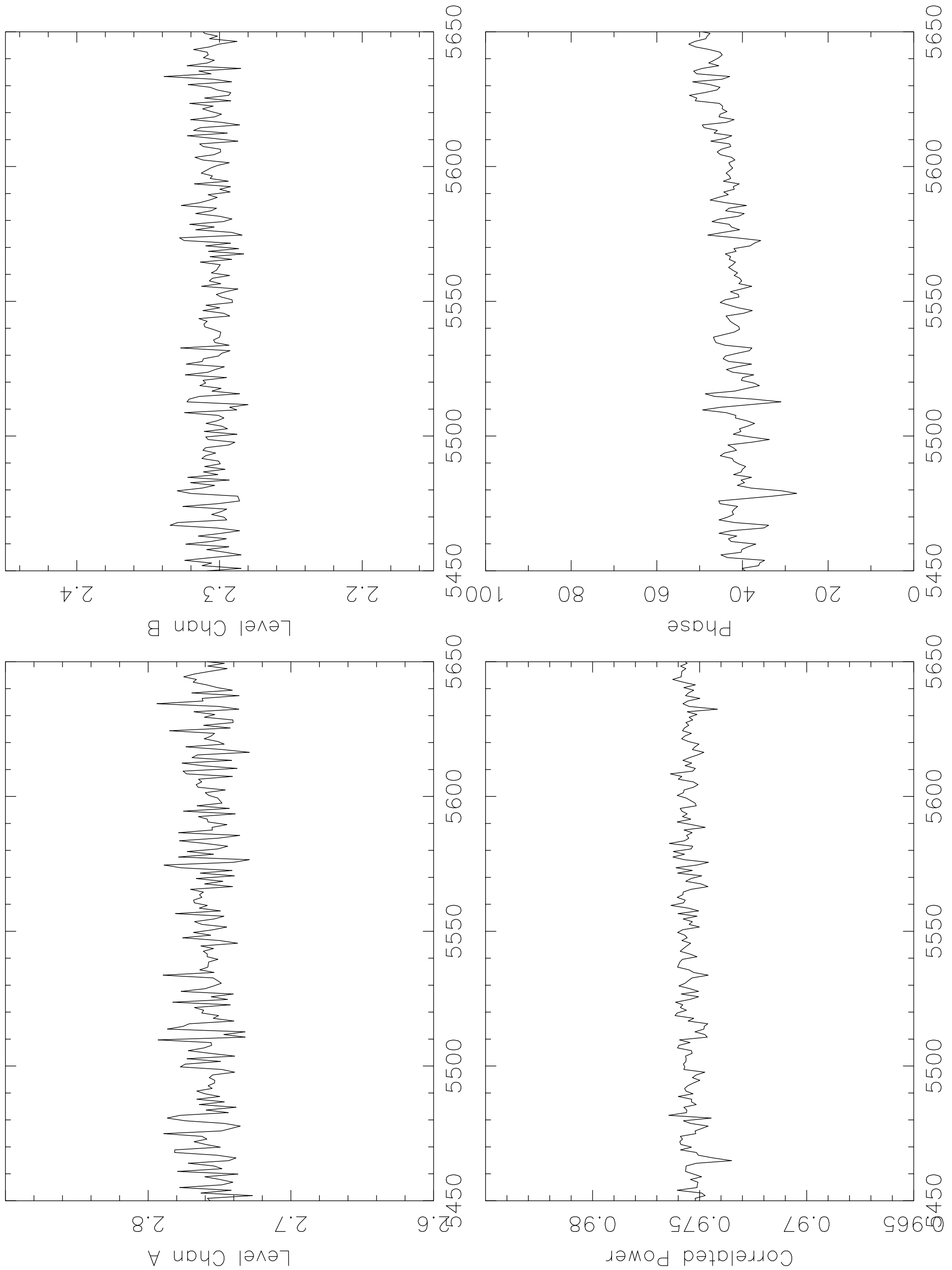
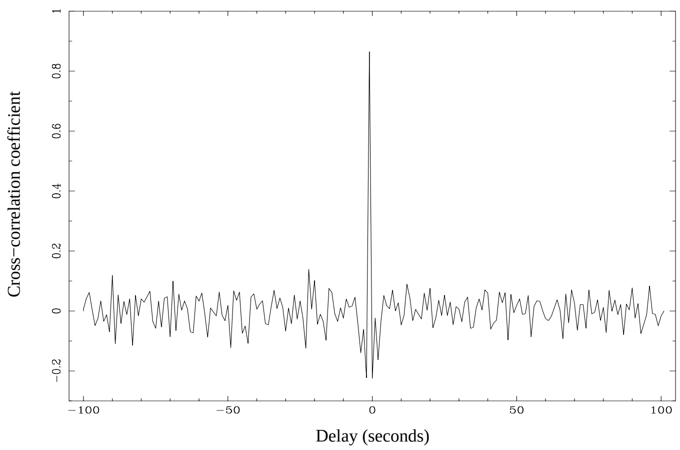
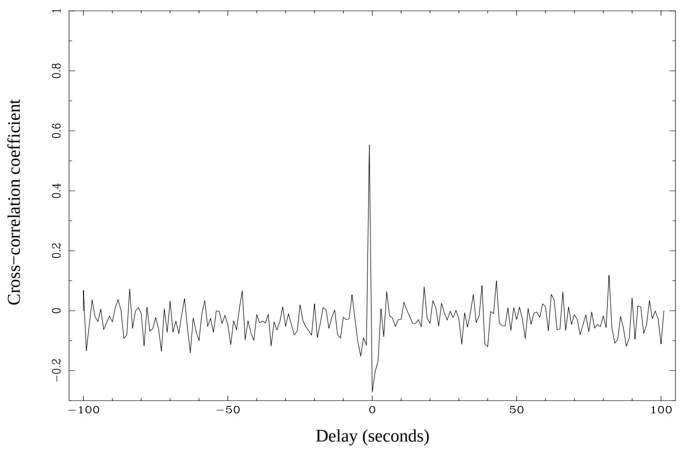


Figure 4. The central 200 seconds of the data from figure 3, plotted on an expanded scale to show the variations of each quantity in detail.

(a) Cross−correlation of NRAO antenna amplitudes



(b) Cross−correlation of ESO antenna amplitudes



(c) Cross−correlation of NRAO antenna amplitudes in absence of fast phase signal

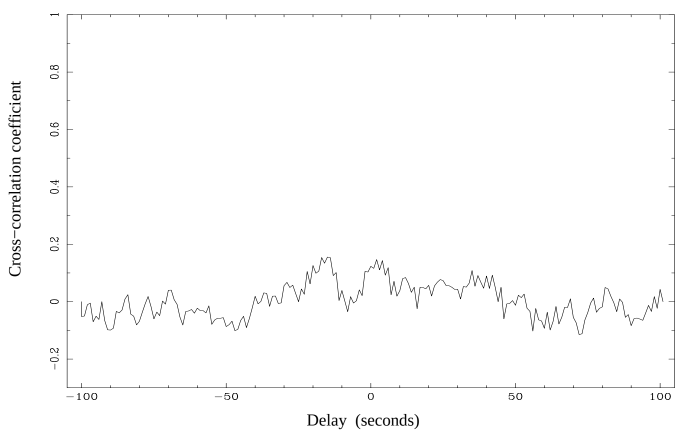


Figure 5. Cross-correlation of individual antenna amplitudes: (a) shows the result obtained from a 10-min sample of data received at the NRAO antennas in presence of fast phase fluctuations. (b) shows result for data received over the concurrent 10-min time interval on the ESO antennas. (c) shows result obtained for the NRAO antennas in absence of fast phase fluctuations.

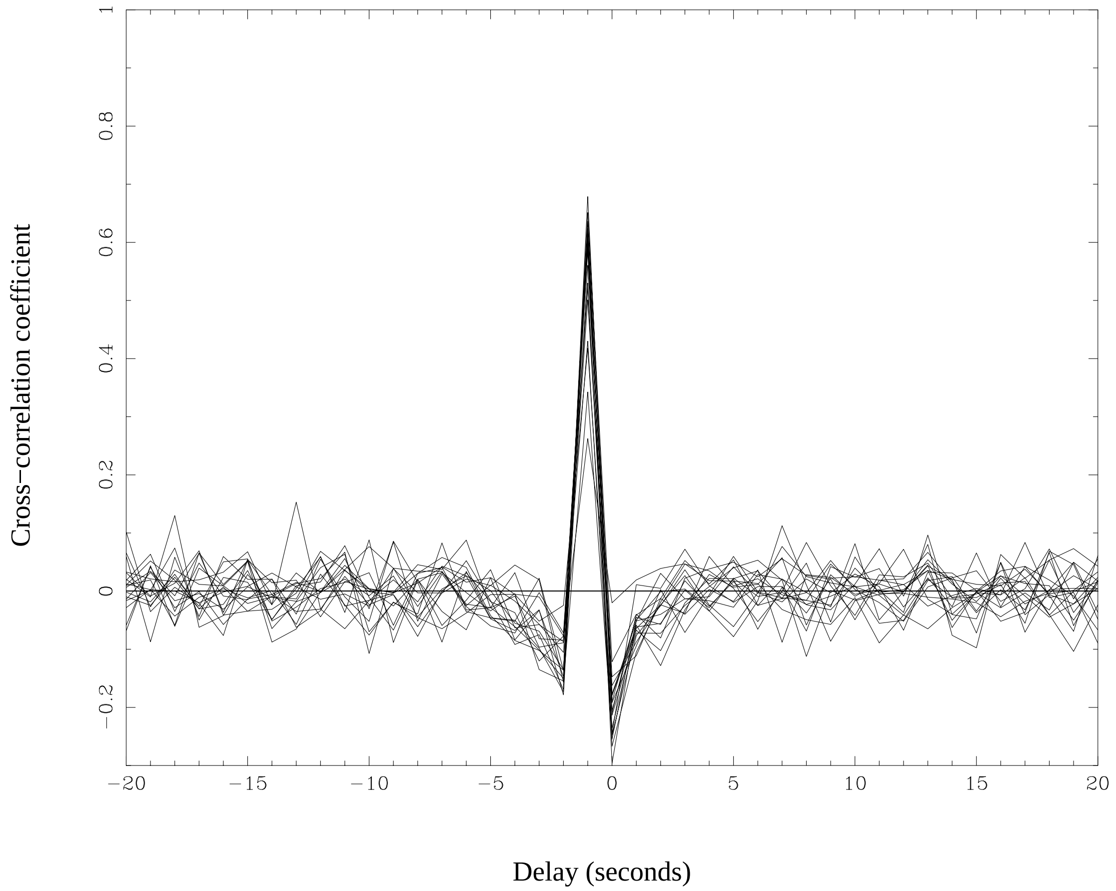
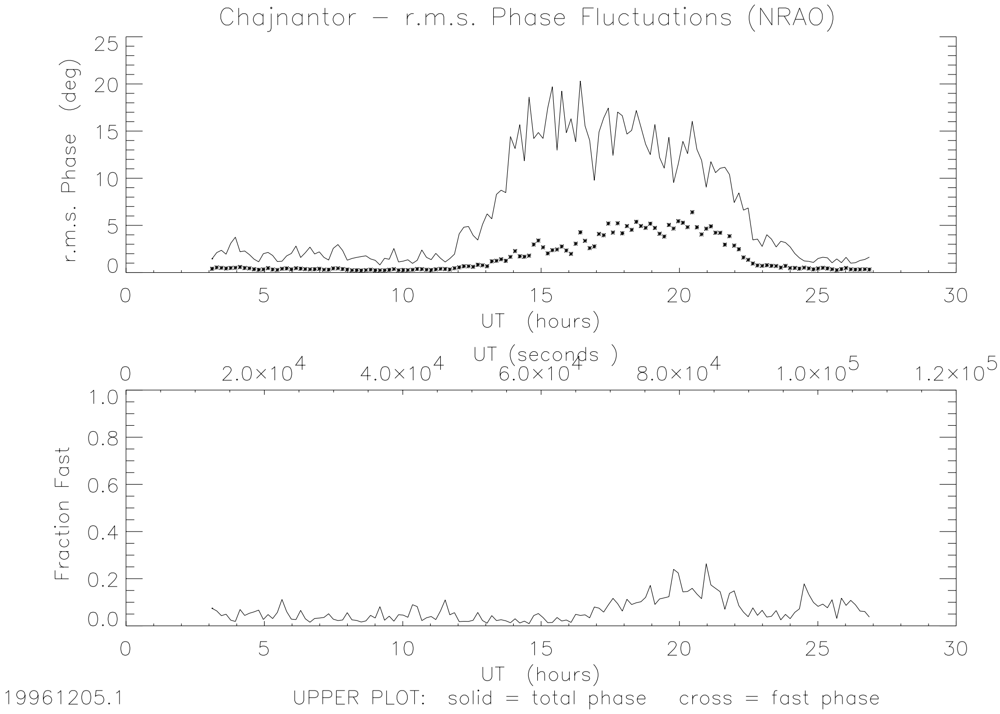


Figure 6. Cross-correlation of the amplitudes received at the individual antennas of the NRAO interferometer as a function of delay. The individual curves show independent results obtained by performing this cross-correlation for each of a sequence of 12 of the 10-min (raw data) time intervals, in all covering a 2-h period on 19991106 during which the anomalous fast fluctuations were present.

(a) Typical water vapour profile showing passage of summer afternoon weather front



(b) Typical profile of the fast phase fluctuations presumed to be of ionospheric origin

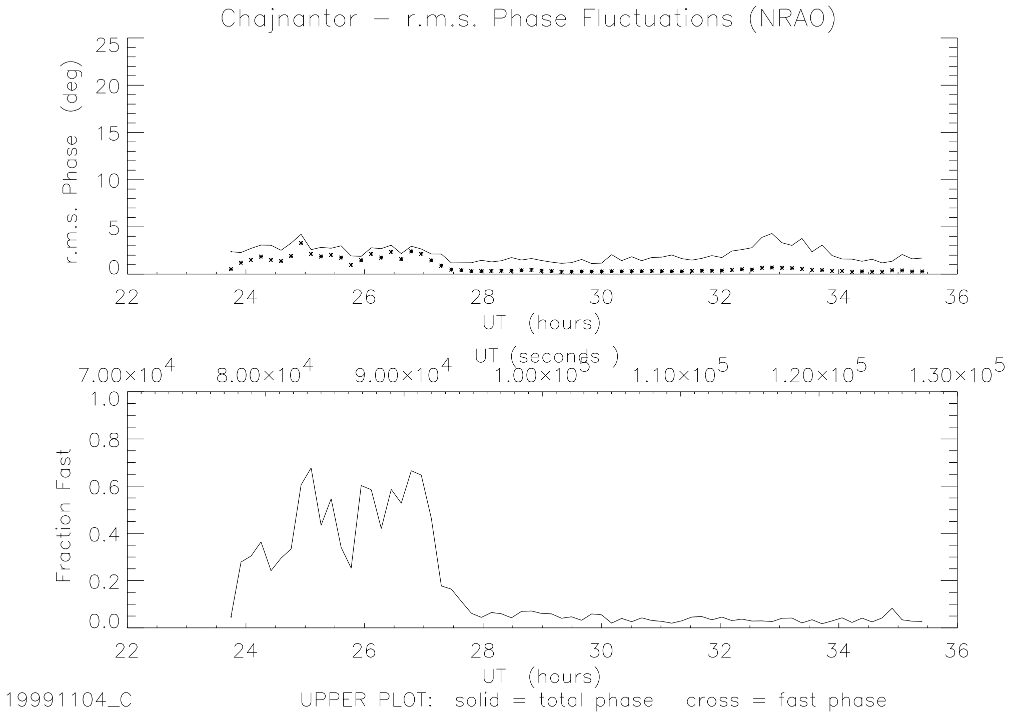


Figure 7. Phase fluctuations on 2 days at Chajnantor, as measured on a 300-m E-W baseline by the NRAO interferometer observing an 11.2-GHz geostationary satellite beacon. The upper plot of each pair shows the total rms phase for each 10-min interval (solid line) and rms of fast fluctuations on timescales less than 10s in the same interval (separate crosses); the lower plot shows fraction fast (the ratio fast/total rms). The magnitude of fraction fast can be used to discriminate between fluctuations due to water vapour, even when these rise during the passage of a weather front (a), and the anomalous fast fluctuations presumed of ionospheric origin (b).

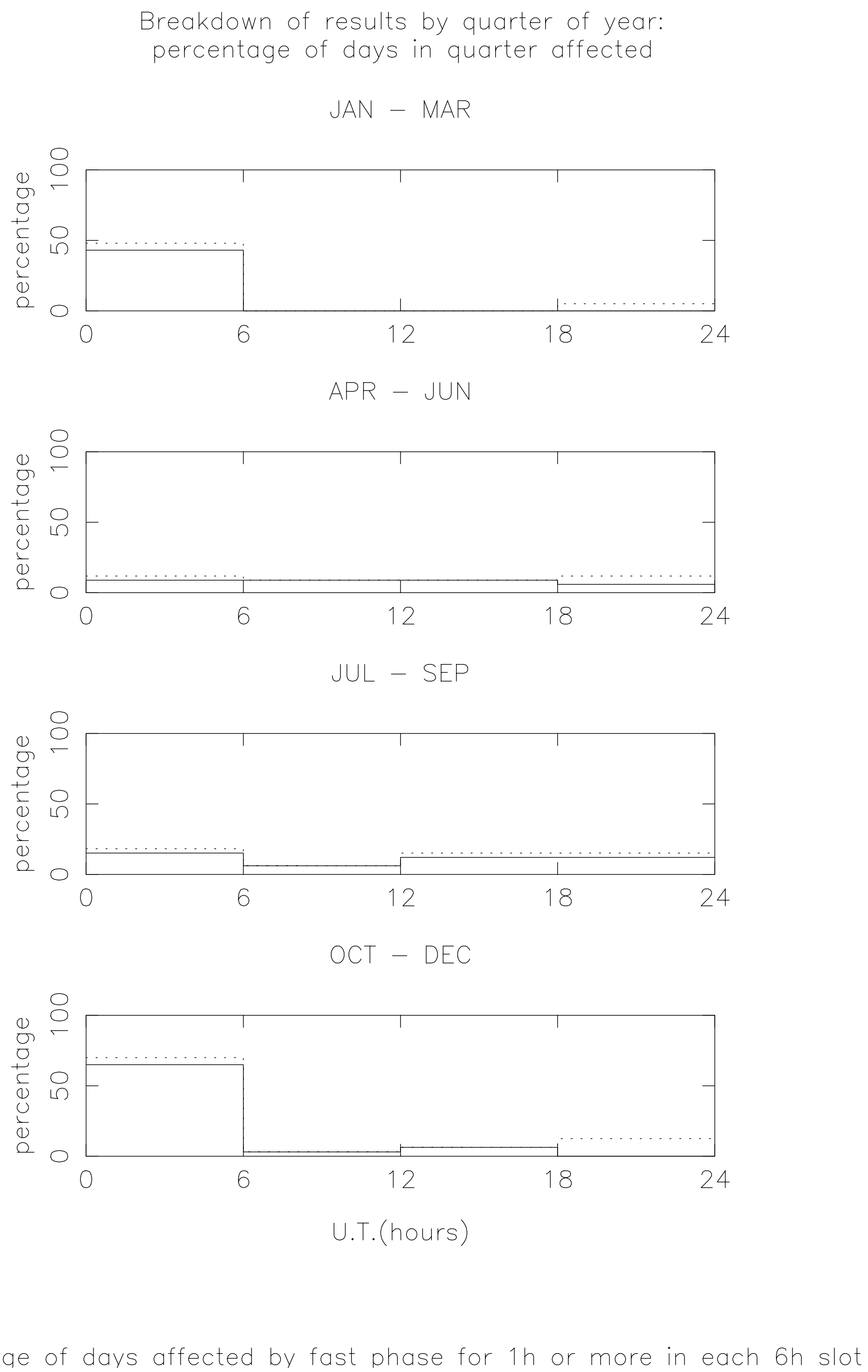


Figure 8. Histograms showing the incidence of the anomalous fast phase phenomenon as diagnosed by the use of the ratio fraction fast as explained in the text. The solid histograms are based on the ‘strong’ criterion and the dotted lines show differences if the ‘marginal’ criterion is used. A count is generated in a given 6-h bin if the ionospheric fluctuations are deemed to be present for a duration of at least 1h in that 6-h period; counts are normalised by the number of observation dates contributing to that bin. Chajnantor Local Time = U.T. – 4h 31min.

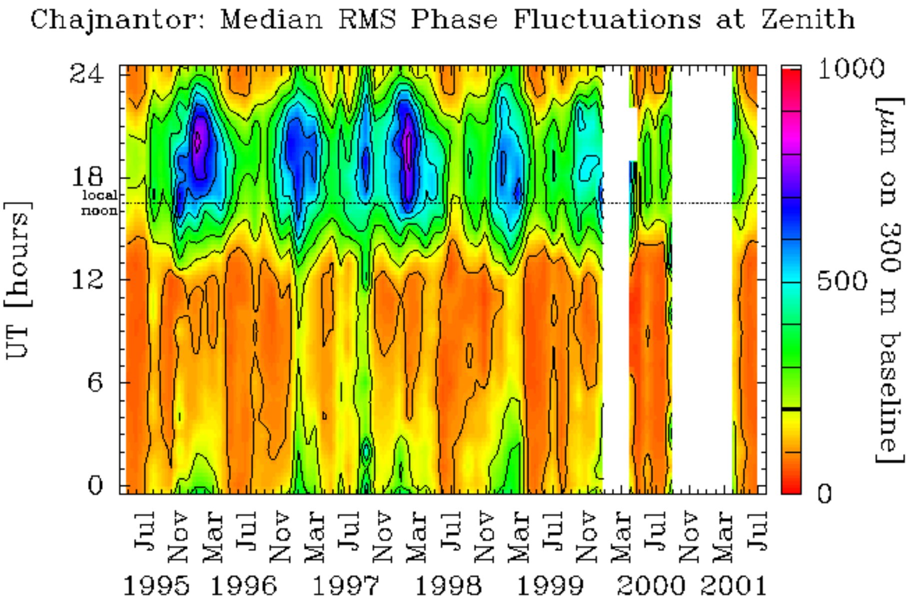


Figure 9. Additional pathlength in microns on the 300-m NRAO site-test interferometer baseline as compiled for Chajnantor site-characterisation statistics over the period 1995-2001. The green fingers ingressing into the bottom of the plot between November and March are probably due to the ionospheric effects reported here rather than path fluctuations due to water vapour. The results may include some minor enhancement due to ionospheric effects at other times of day and seasons. The gaps show periods for which no data were available.

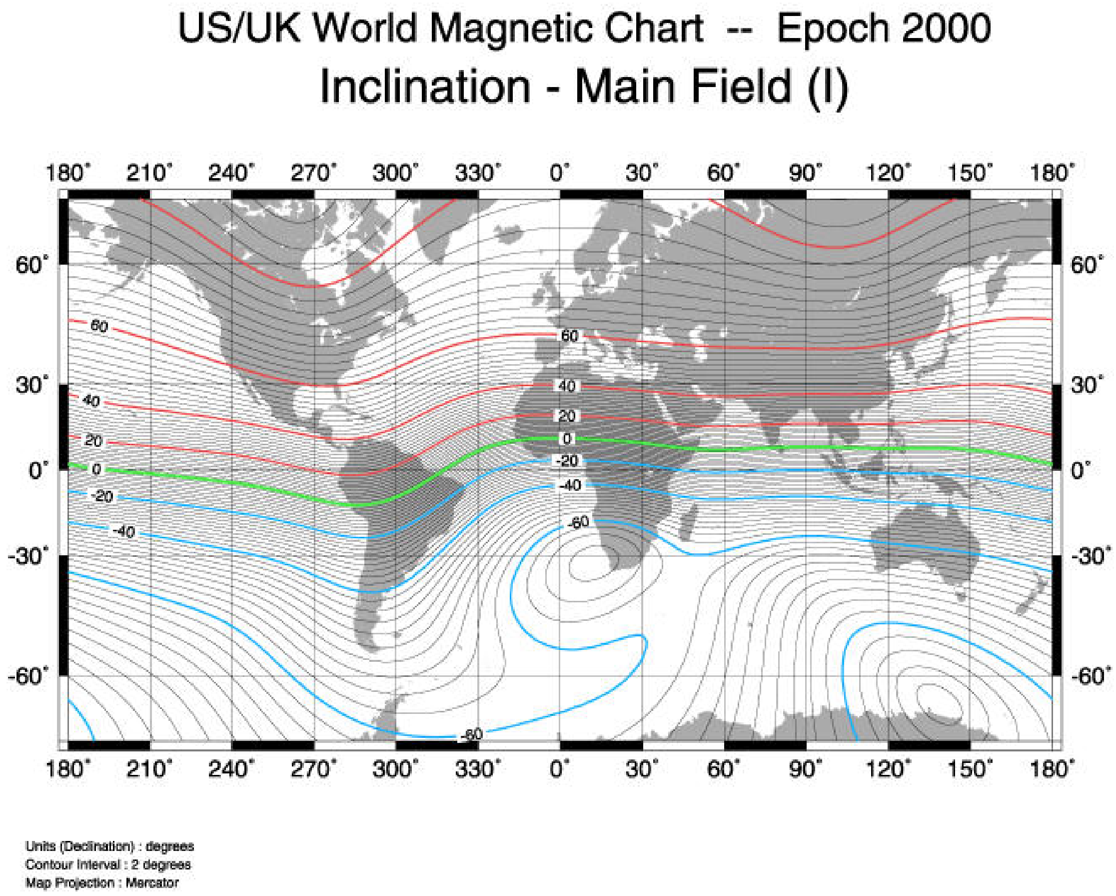
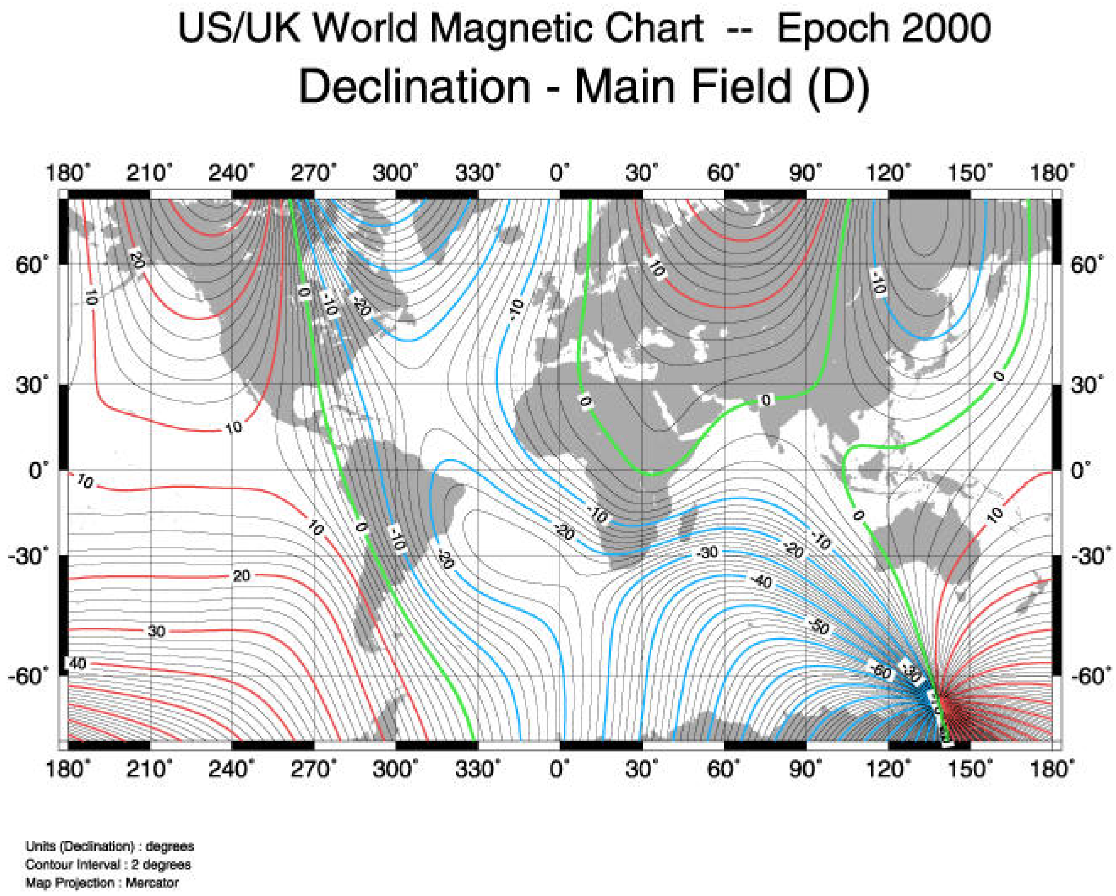


Figure 10. World Magnetic Chart in Mercator projection showing lines of constant magnetic inclination or dip angle at epoch 2000. Note that the magnetic inclination or dip angle I is related to the magnetic dip latitude λ by the relation tan I = 2 tan λ . A similar chart in Mercator projection (next page) shows lines of constant magnetic declination or deviation D at epoch 2000. Both charts are reproduced courtesy of Dr. John Quinn of the U.S. Geological Survey, co-author of the World Magnetic Model 2000.



Second part of figure 10 – see caption on previous page.