Atmospheric Phase Correction using Water Vapor Radiometers

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ABSTRACT

We discuss the calibration and use of water vapor radiometers used for atmospheric phase correction on the BIMA array. Over intervals of a few minutes the WVR corrected data are consistent with the thermal noise of 100 microns. On longer time scales the calibration is currently limited by variations in the WVR passband and the atmospheric scale factor between the brightness of the water line and the path length. This is an update of BIMA memo 78.

1. WVR installation on the BIMA array

At millimeter wavelengths, refractive index fluctuations are expected to be dominated by water vapor variations, leading to the use of water vapor radiometers to measure the path length through the atmosphere. In April 1999, we installed swept frequency water vapor radiometers on three antennas at Hat Creek. The WVRs were designed to improve the phase coherence for VLBI observations (Tahmoush & Rogers, 2000). The WVR illuminates the 6.1 m antenna giving a beam with FWHM $8 - 10'$ which is offset from the radio beam by about $30'$. The WVR samples selected frequencies between 18 and 26.5 GHz to measure the water line. The data are used to estimate: $a + b\nu^2 + ch_\nu$, where the three terms represent the radiometer gain, the liquid water, and the water vapor line. The WVRs are controlled using a JAVA interface over fiber links to each antenna. The fitted parameters and the sampled water vapor spectrum are archived with the interferometer data.

2. WVR calibration of interferometer data

The Miriad program WVCAL estimates atmospheric phase corrections from WVR measurements. The fitted path lengths are interpolated to the integration times of the interferometer data and written as antenna gain phase corrections. These antenna gains can be plotted, averaged and edited using standard Miriad programs. The antenna gains can be applied when copying, plotting, and imaging the interferometer visibility data. Experience so far shows that about 50% of the interferometer data is improved after WVR calibration. In the other 50% the RMS phase is degraded by the drifts in the WVR measurements which are not present in the interferometer data.

3. Error analysis

The WVR measures the water vapor emission along a path through the atmosphere. The measured path length, $p[mm] = g[mm/K] \times T[K]$. There are error terms associated with the instrument and the atmosphere. Instrumental gain and passband variations change the temperature scale, whilst the height of the water vapor fluctuations changes the scale factor between the measured emission and the path length.

With a uniformly spaced frequency scan from 18 to 26 GHz, the thermal noise from the WVR radiometer and the atmosphere contributes about 100 microns over a 10 second integration time. The thermal noise could be reduced by using a cooled radiometer, or by using a multichannel spectrometer instead of time multiplexing.

Instrumental gain variations give an error which increases with the excess path. The excess path, $p[mm] \sim 6 \times mmh20 \times airmass$ where $mmh20$ is the precipitable water vapor. At Hat Creek the excess path may vary from 20 to 400 mm throughout the year. Over intervals of a few minutes the WVR data are consistent with the thermal noise of 100 microns. On longer time scales we see fluctuations of several hundred microns in the WVR data which increase with the measured path length and are consistent with a gain stability, $\delta g/g$, of $\sim 5\ 10^{-3}$. Thus the WVR calibration of the interferometer data is currently limited by gain variations and not by thermal noise in the WVR radiometer.

An additional source of fluctuations comes from the offset between the WVR beam and the primary beam at the observing frequency. At a height, h, the offset, θ, between the WVR beam and the observing beam gives an displacement $d \sim h \times airmass \times \theta$. There is considerable evidence for fluctuations in atmospheric boundary layers. Cross correlation of WVR fluctuations using offset or intersecting WVR beams at Hat Creek typically yield heights of 2 - 3 km, although the correlation coefficient is reduced as the WVRs are placed further apart indicating that some fraction of the turbulence is in the lower boundary layer closer to the ground. The WVR beam is offset by $\theta \sim 30'$, giving a displacement $d \sim 30$ to 60 m at a height of 2 - 3 km. The fluctuations over a distance d are given by the structure function and are expected to scale as $d^{5/6}$ over these distances. The path length fluctuations measured on a 100 m baseline at Hat Creek are typically, ~ 240 microns, so the WVR measured path may differ from the interferometer path by ~ 100 microns.

To check if this might be a major source of error, we made some interferometer observations of water maser sources at 22 GHz using the same beam as the WVR radiometer. The signal from the WVR at 18-26 GHz was coupled into a second harmonic mixer and cross correlated to produce interferometer spectra of the water maser sources. If the beam offset was a major source of error, we would expect that the WVR path length would correlate much better with the water maser fringe phase, than it usually does with the interferometer phase for 1 or 3mm observations. The success of the WVR correction was not improved during the 22 GHz observations. Whilst lack of success is not an ideal test, the beam offset is probably not the major source of error.

The water vapor line shape depends on the height of the water vapor. For example, at a temperature of 273 K and pressure 900 mb, the scale factor is 4.41 mm per Kelvin at line center. At 800 mb, the factor is reduced to 4.16. The sensitivity of the scale factor, $g[mm/K]$, to the height of the water vapor is reduced by observing frequencies around 18-20 and 24-26 GHz, but the scale factor may still vary by about 10% for the path lengths fitted to the spectra between 18-26 GHz (see table 2 in Tahmoush & Rogers 2000). Where the temperature is close to the dew point, there will be constant interchange between the liquid and vapor phase which may lead to fluctuations at varying heights above the antennas. Ground level turbulence creates fluctuations in water evaporated from the ground. Water vapor fluctuations in multiple layers make it difficult to determine the scale factor from the water line spectra shape, so in practice we do not fit this.

The WVR data are currently asynchronous with the interferometer data. Since we see substantial decorrelation in the interferometer phase over intervals of $\sim$ 10 s on long baselines, the atmospheric phase correction will be improved by sampling the interferometer data and applying the WVR on intervals of a few seconds. The WVR data should be averaged over the same time intervals as the interferometer data. This requires control of the WVR by the observing program. After applying the WVR correction, the interferometer data can be integrated up to the Nyquist sample interval and written out to disk. Since it is then not possible to undo the WVR correction, we also wish to write out the uncorrected interferometer data averaged in the same way. Thus there are two averaged data sets, one with the WVR correction applied, the other without.

4. Possible calibration schemes

4.1. Gain and Temperature scale

The radiometer calibration determines the receiver noise temperature and gain using ambient and cold absorber placed in front of the WVR feed. Measurements in the laboratory are repeatable to about 0.5%. The gain is stored in units of counts measured on the ambient load, and can be recalibrated more easily than the system temperature which requires liquid nitrogen. Experiments in the laboratory show that the bandpass (the gain as a function of frequency) varies with temperature. Although the temperature inside the WVR box is regulated, the bandpass changes with ambient temperature or with orientation of the WVR, causing variations in the fitted path length of several mm. The variations in fitted path length with orientation produce phase offsets between source and calibrator observations after WVR corrections are applied, effectively preventing the absolute phase calibration of the astronomical data. The WVR calibration improves the phase *coherence*, but the absolute phase is lost. This is OK for VLBI, but not for phase coherent imaging. The bandpass variations with orientation, which are probably due to thermal and mechanical instability inside the WVR box, were reduced by replacing coaxial cables with sma elbows, and filling the box with noodles to restrict convection inside the box.

4.2. sky tips

Errors in the temperature scale, or temporal changes in the atmospheric scale factor to convert from Kelvin to path length lead to phase offsets between the source and the calibrator. There are also slow changes in the corrected phase of the source and a loss in sensitivity of the WVR correction for each baseline since the WVR correction for each pair of antennas is subtracted. By measuring the change in path when the antennas are all tipped through the same airmass, one can make the scale factor the same for all antennas. Sky tips at Hat Creek show that the WVRs are consistent with each other within 0.5 %, and consistent with the precipitable water estimated from the local temperature and humidity. However, since path length variations of $\sim$ 1 mm are measured on a 1 km baseline over several minutes, one would have to average over several hours to obtain the accuracy required to calibrate the absolute phase of the source with respect to the phase calibrator, and the scale factor may be changing on shorter time scales.

4.3. empirical calibrations

We attempted to correct the scale factor by scaling the measured path by the relative slope for each WVR (wvcal options=scale). If the slope is due to the path length change with elevation, then the slopes should all be the same as the antennas track the source. This worked moderately well when the elevation was changing quickly, but poorly when it was not.

An alternate strategy, which combines WVR calibration with rapid switching between source and calibrator, is to subtract the average phase change for each antenna (wvcal options=subtract), so that the average phase for the source and the calibrator remain unchanged by the WVR calibration. Again, this only worked some of the time.

4.4. bootstap calibration

These difficulties suggest an iterative procedure. At intervals determined by the stability of the atmosphere we observe the astronomical source and two phase calibrators close to the source. The a-priori WVR calibration is used to correct the wavefront for the source and the phase calibrators, so that the interferometer data for each can be coherently integrated. If the positions of the two quasars are well known, then there should be no phase offset between them. The measured WVR path difference between the 2 quasars can be used to correct the scale factor of the WVRs with respect to a reference antenna. The interferometer measures a phase change $\delta path = \delta b \times \delta s$, where δb is the antenna position error, and δs is the change in position between 2 quasars. The antenna position error is about $\lambda/20$ at 100 GHz, so that for 2 quasars within about 10 deg in the same part of the sky as the target source, the error from this calibration is about 50 microns.

5. Conclusions

1. Gain fluctuations in the WVR currently limit the atmospheric phase correction. These might be reduced by using correlation radiometers.

2. The WVR correction should be averaged synchronously with the interferometer data and applied at intervals of a few seconds. The interferometer data can then be averaged.

3. Both corrected and uncorrected averaged visibility data should be archived.

4. The thermal noise could be reduced by cooling the WVR and by replacing the swept frequency spectrometer with a multichannel or correlation spectrometer.

5. Changes in the atmospheric scale factor due multiple layers or variations in the height of the fluctuations could be calibrated by observing two quasars close to the astronomical source.

6. The offset between the WVR and the observing primary beam may be a problem for fluctuations at large distances from the antennas, but is currently not the limiting factor.

REFERENCES

Tahmoush, D., & Rogers, A.E.E., 2000, " Correcting atmospheric path variations in millimeter wavelength VLBI using a scanning WVR", Radio Science 35 (5):1241-1251.

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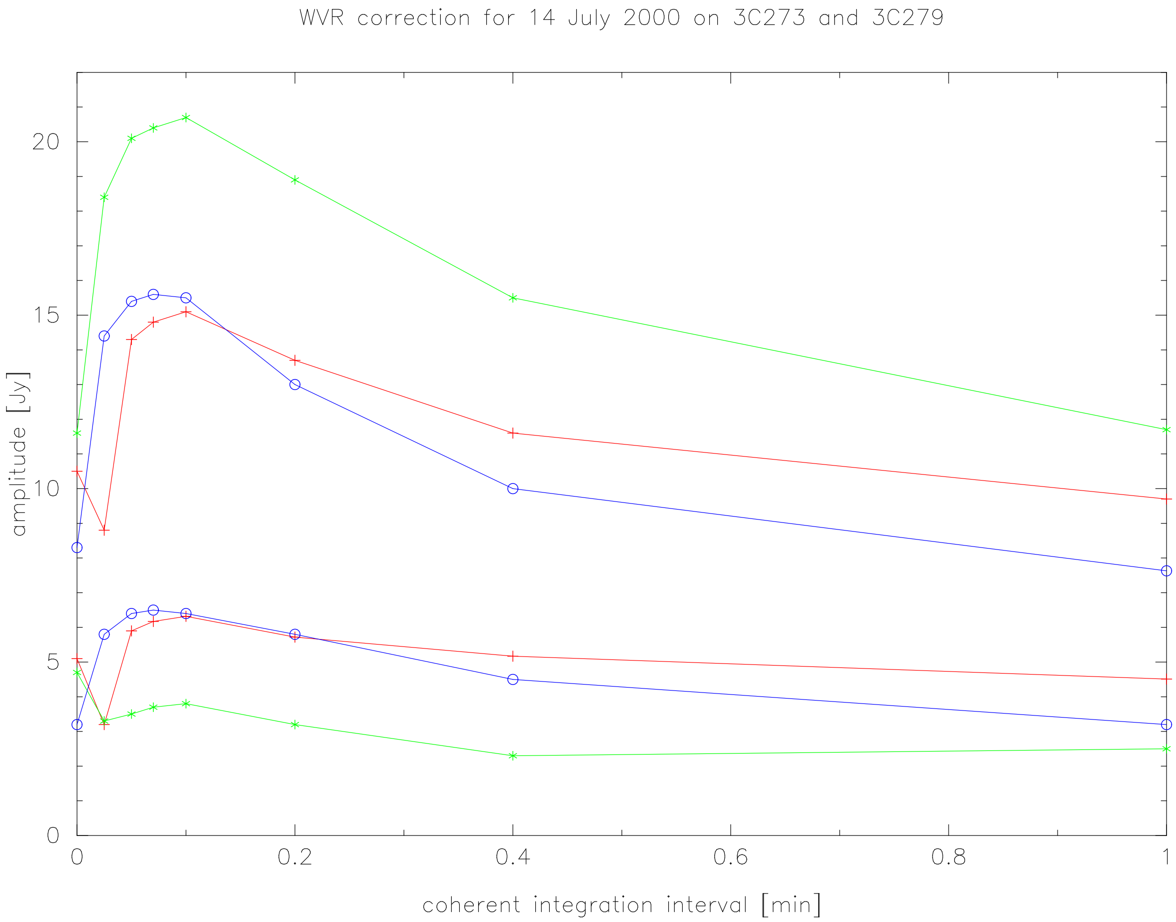

Fig. 1.— Interferometer amplitude on 3C273 and 3C279 as a function of the averaging time for the WVR calibration. For short averaging times, WVR noise reduces the coherent amplitude. For long averaging times, atmospheric fluctuations reduce the amplitude. These observations suggest that the WVR correction should be made on averages of a few seconds, and the WVR noise reduced so that it does not add noise with these averaging times.

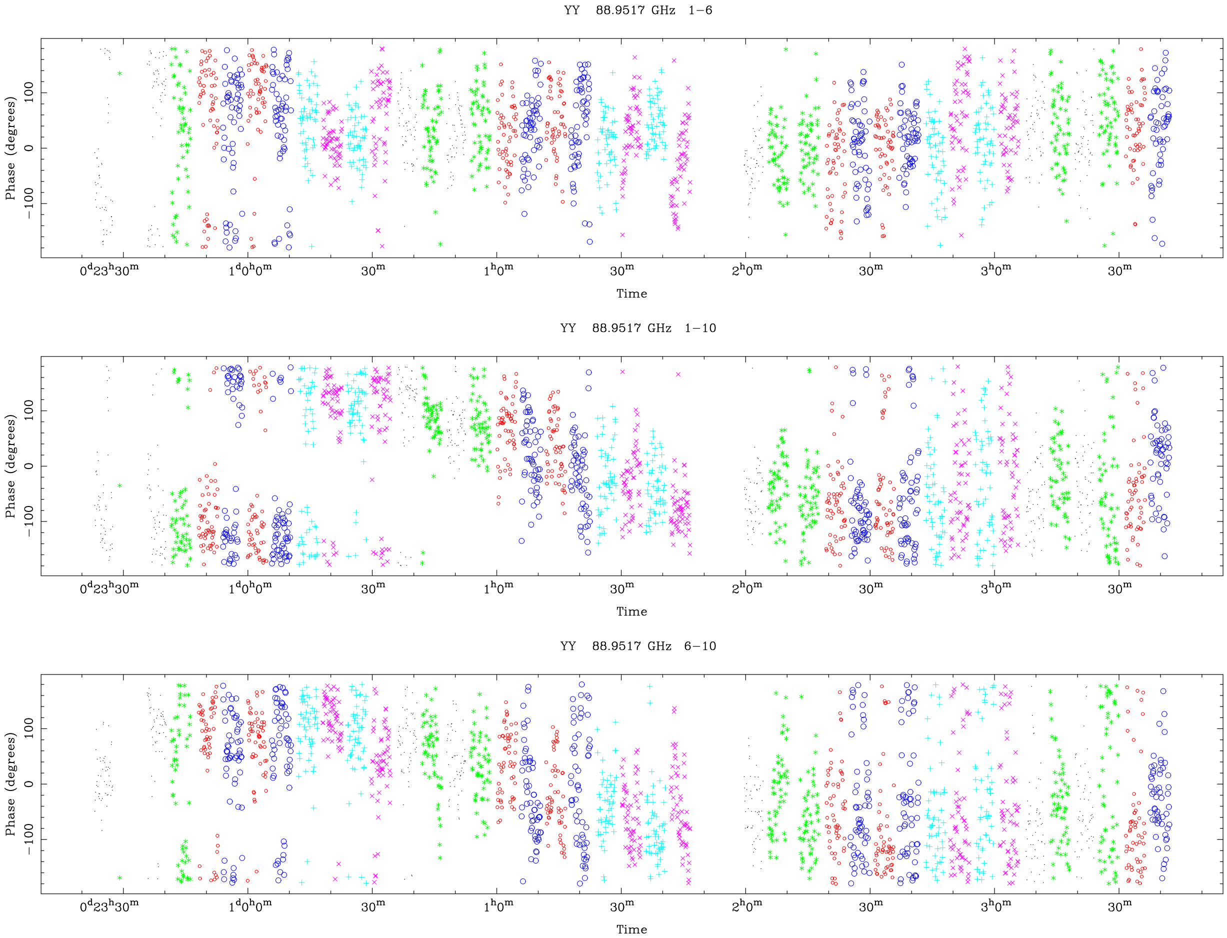

Fig. 2.— Interferometer phase on three baselines as a function of time. Observations of 3C273 and 3C279 were alternated using three different frequency patterns for the WVR measurements. Different symbols of used for each. This figure shows the uncorrected phases.

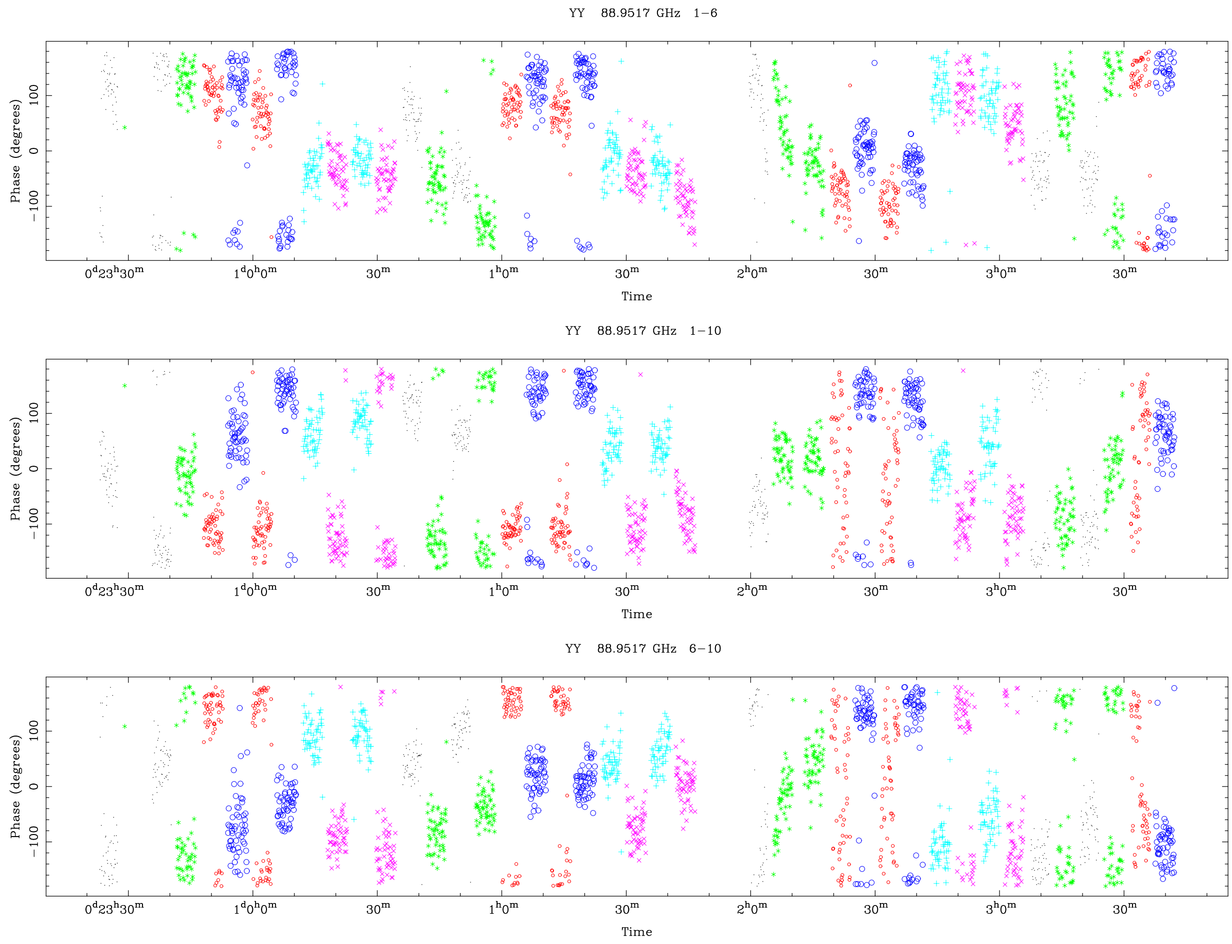

Fig. 3.— Interferometer phase with WVR calibration applied. The RMS phase for each source is reduced, but there are large, time variable, phase offsets between the sources.

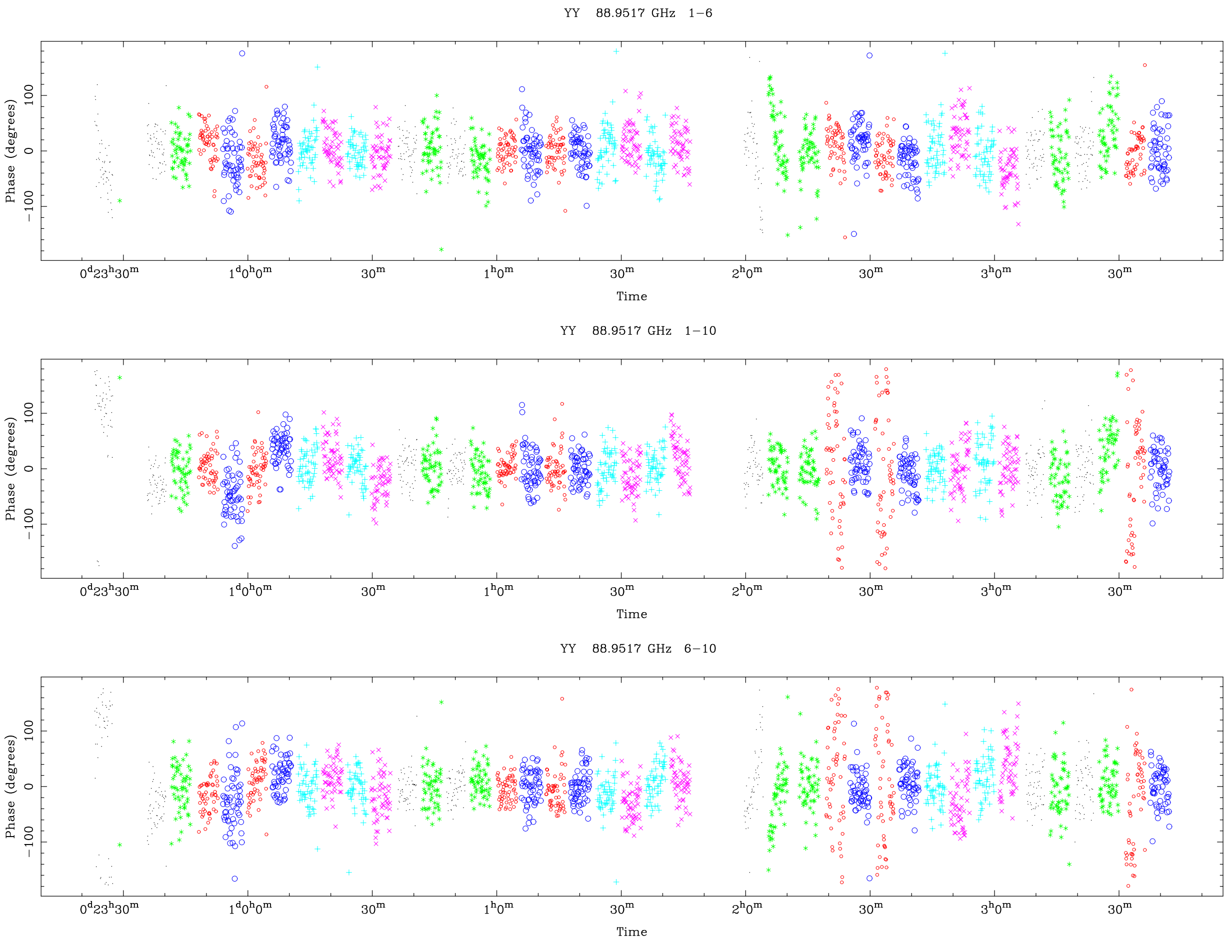

Fig. 4.— Interferometer phase with WVR calibration applied, followed by a self calibration with a 30 min averaging interval which removes the phase offsets between sources.