1. Introduction

This report will describe the results of the application of the WVR correction during the three-quasar experiment of Aug 21. The WVR application was generally successful. Each section will deal with one aspect of the WVR and phase behavior, and all figures are given at the end. This report includes comments and suggestions from Bojan Nikolic.

2. WVR Application to Reduce Phase Fluctuation versus Baseline length

Fig. 1 through Fig. 5 show the results of application of the WVR data to one source, 2232+117, for a variety of baselines from antenna 0 (DV02) to antennas 1 (DV03), 2 (DV04), 3 (DV05) and 4 (DV07). All plots are for spw=0 and both polarizations have been added for increased sensitivity. The source 2232+117 is 15 deg north of the phase calibrator 3C446. The results for spw=1 are virtually identical. The plots for the shortest baseline, 1-4, are also given to illustrate the additional noise in antenna 1 (DV03). The visibility data were sampled every 1-sec.

The relevant rms phase fluctuations in degrees, before WVR correction (RMS1), and after WVR correction (RMS2), are given in Table 1. Other related RMS’s are also given (see description below table). The three antennas with no discernible problems are 0, 2 and 4. These data should be looked at most carefully to be representative of the WVR performance, and are given as the first two entries in the table.

A useful scaling factor: 1 deg of phase at 85 GHz corresponds to about 10 micros of path delay.

<table>
<thead>
<tr>
<th>TABLE 1: WVR DECREASE FOR FIELD=2 at VARIOUS BASELINES</th>
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<tbody>
<tr>
<td>BLINE</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>***ANT 0-2</td>
</tr>
<tr>
<td>***ANT 0-4</td>
</tr>
<tr>
<td>ANT 0-1</td>
</tr>
<tr>
<td>ANT 0-3</td>
</tr>
<tr>
<td>ANT 1-4</td>
</tr>
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</table>

***: The best baselines
RMS0: rms noise for 0.5*(XX-YY) should be receiver noise
RMS1: rms noise for 0.5*(XX-YY) calibration data
RMS2: rms noise for 0.5*(XX+YY) WVR corrected calibrated data
RMS(0-2): rms noise reduction by application of WVR (quadrature difference)
RMS3: rms fluctuations for WVR data signal alone.
The main conclusion is that the WVR data does decrease significantly the tropospheric phase scatter. Typically, about half of the phase variance is removed. Since there are only three baselines (0-2 and 0-4, 2-4 is not independent) with no problems, generalizations of the phase scatter with baseline length is premature. From the 28-m to the 59-m baseline, the phase fluctuation increase for the calibrated data is small. After WVR correction, the baselines have virtually the same rms phase fluctuations.

The hoped for accuracy of the WVR correction is about 10 microns (1+c) where c is the water vapor column in mm. Thus, the rms phase of about 2 degrees (for the good WVR baselines) are not much larger than the WVR specification goal, assuming c was less than 1mm.

The WVR for antenna 3 (DV05) clearly has problems (see the plot). This is a known problem. It turns out that the correction for antenna 3 for source 3 is okay, whereas that for sources 0 and 2 (that shown in Fig. 3) has the large offset.

There is extra noise in the phase data for ANT 1 (DV03), unrelated to the WVR. Both XX and YY have the same additional noise.

The application of the WVR data for spw=2 and 3, because of their phase inversion, were applied with the wrong sign. When the WVR phases are changed, its addition does decrease the scatter, probably about the same amount, although there are other previous calibration issues that somewhat increase the rms noise due to the sign flip of the phase.

### 3. WVR Application versus Source Separation from Phase Calibrator

The longest baseline, 0-2, has been chosen, and the phase fluctuations for the three sources are shown in Fig. 6. For 3c446, which was used as the phase calibrator, the average phase for each scan is set to zero. However, phase fluctuations occur over each scan, and the WVR application does decrease them. The rms fluctuations for source 2229-085 (four degrees south) and 2232+117 (fifteen degrees north) increase as expected, and they are given below:

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>SEP</th>
<th>RMS (noise)</th>
<th>RMS (data)</th>
<th>RMS (+WVR)</th>
<th>RMS (change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3c446</td>
<td>0</td>
<td>0.52</td>
<td>2.57</td>
<td>1.65</td>
<td>1.97</td>
</tr>
<tr>
<td>2229-085</td>
<td>3.9</td>
<td>0.72</td>
<td>3.08</td>
<td>2.08</td>
<td>2.27</td>
</tr>
<tr>
<td>2232+117</td>
<td>15.8</td>
<td>0.79</td>
<td>3.40</td>
<td>2.23</td>
<td>2.56</td>
</tr>
</tbody>
</table>

**SEP:** Separation in degrees from 3c446  
**RMS:** All rms’s are in degrees of phase  
**RMS (noise):** 0.5*(XX-YY). 3c446 is stronger than the other two sources  
**RMS (data):** Phase variations of normally calibrated data 0.5*(XX+YY)  
**RMS (WVR+):** Phase variations after WVR correction  
**RMS (change) = sqrt(RMS(data)^2 - RMS(+WVR)^2)**

The general properties of the WVR removal of the phase fluctuations as a function of source separation is shown in Fig. 6:

1. The WVR removes somewhat more than half of the fluctuation variance for all
2. For 3c446, which is phase-zeroed for each scan, the rms fluctuations over a scan per point is 2.57 deg. With the WVR correction applied, the noise drops to 1.65 deg.

3. For the other two sources, the rms phase fluctuations increases, but much more slowly than linearly with source separation, perhaps as the third power of the source separation.

4. More baseline and angle coverage are needed to specify both the ground and angle dependence of the phase fluctuations, with and without the WVR data.

5. For 2232+117 at the beginning of the observation (Fig. 6) the phases were systematically low by about 3 degrees. Most of this systematic offset over the first scan has been removed by the WVR application.

4. Very short-term Phase Noise

These appears to be short-term phase noise with a timescale of one to three seconds that is unexplained. This is shown in Fig. 7. The four plots down the left side show the phases for one scan of 3c446. The actual phase data from the 0.5*(XX+YY) data in the second row has more scatter from point to point than expected from the noise 0.5*(XX-YY) in the top row. This is probably too fast for troposphere. Clearly, the WVR-corrected data still contains most of this very short-term phase noise. Data for one scan from 3c446 (left) and 2229-017 (right) are shown. Have there been any other investigations of short-term phase noise using strong sources?

There are many possible reasons for this short-term phase noise, and more investigations over future, longer experiments are needed: Hardware/software instabilities, delay tracking steps are a possibility; short-term tropospheric fluctuations that should depend on the wind-speed are also a possibility. The somewhat different sky area covered by the WVR and the astronomical observations could be contributing. Also, there may be a time offset between the WVR and data streams of 1 sec.

5. WVR scaling

This is not worth any diagrams, but the scale of the WVR corrections were change by 1.33 times and 0.75 times that recommended. The different rms's for the best baselines for each of the sources are given in the follow table. It is not a large difference. How is the 'effect' related to the general scaling properties of the WVR emission versus phase fluctuations. Is it possible that an 'ad-hoc' scaling, which cannot be determined from meteorological properties, will be needed? Perhaps, a few minutes observations on a strong calibrator within about ten degrees of the target-calibrator region can determine any such scaling?

<table>
<thead>
<tr>
<th>BSL SRC</th>
<th>RMS1</th>
<th>RMS2</th>
<th>RMS3</th>
<th>RMS4</th>
<th>RMS5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>0.529</td>
<td>2.571</td>
<td>1.650</td>
<td>1.543</td>
<td>1.814</td>
</tr>
</tbody>
</table>
For this set of data, it appears that an increase factor of 1.2 in the WVR correction would decrease the rms phase residuals somewhat.
Fig. 1.— Y-axis are phase in degrees, X-axis are relative times in seconds. This plot is for baseline 0-1 (DV02-DV03). The source is 2232+117 which is 15° north of the phase calibrator and spw=0 data are shown. The data are sampled every 1-sec. The plots in descending order are: (1) 0.5*(XX+YY) phases for the calibrator data; (2) 0.5*(XX-YY) as an estimate of the receiver noise error; (3) 0.5*(XX+YY) for the WVR-corrected calibrated data; (4) The WVR correction signal, converted to phase.
Fig. 2.— See caption for Fig. 1.
Fig. 3.— See caption for Fig. 3.
Fig. 4.— See caption for Fig. 1.
Fig. 5.— See caption for Fig. 1.
Fig. 6.— The phases for spw=0 and baseline 0-2 as a function of source distance from the phase calibrator: The first column shows the calibrated 0.5*(XX+YY) phases; the second column shows the calibrated 0.5(XX-YY) phases for the receiver noise. The third column shows the calibration 0.5*(XX+YY) phases after adding in the WVR corrections.
Fig. 7.— The phases for spw=0 and baseline 0-2 for one scan for two sources. The first line is 0.5*(XX-YY), the noise estimate. The second line is the calibrated data 0.5*(XX+YY). The third line is the calibrated data with the WVR correction made. The last line is the WVR correction. The data were sampled every one second.