WVR Atmospheric Phase Correction for Interferometry and VLBI

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Abstract

WVRs have been designed and built for correcting mm-VLBI phases. They have demonstrated good performance on short baselines and during 3 mm VLBI observations, and they will improve the sensitivity and reliability of mm-VLBI observations at relatively low cost.

The WVR we describe uses a new wideband frequency switching approach. The oscillator is computer controlled and tunable from 18 to 26 GHz, which allows measurement of the entire 22 GHz water vapor spectrum, provides the flexibility to avoid interference, and effectively removes liquid water contributions. In addition, the line width of the water vapor fluctuations can be measured. The removal of liquid water from the measurements makes WVRs less subject to the effect of clouds than total power measurements.

Introduction

Atmospheric coherence and seeing at radio and millimeter wavelengths are dominated by variations in water vapor along the atmospheric path. The permanent electric dipole of the water vapor changes the index of refraction, affecting propagation times and decreasing the spatial and temporal coherence. The water vapor emission can be measured by WVRs and used to correct for this effect.

Design

There are several potential error sources which our design attempts to minimize. The fundamental limit to phase correction with WVRs is the noise temperature, which in our system is 350 K. The noise temperature can be decreased by increasing the cost. The second error source is the fit to the water vapor and the liquid water emission removal, addressed by our wideband frequency switching approach that fits the entire water vapor spectrum. These two error sources combine to create a noise in the phase correction of 0.22 mm in four seconds. This will improve as the fitting process is improved. This noise level is fine for VLBI, where the noise in the Hydrogen maser dominates, but we have made a newer model for short baselines with almost half of the noise. The third error source is gain stability, which is accomplished with frequency switching, low gain in the first amplifier, and a flat gain curve which minimizes the effect of oscillator drift. The fourth error source is calibration, which is a problem when comparing frequencies. A tipping curve and an ambient load have provided sufficient calibration to this point, but we may

incorporate a hot load. The fifth error source is not measuring the same atmosphere as the interferometer, which comes from pointing errors, beamshape mismatch, and offset between the beam of the WVR and the beam of the VLBI site. The best way to minimize this error is to use the same dishes as the interferometer, but we currently use small satellite television dishes attached to the side or subreflector of the interferometer dishes. The far field of these small dishes partially matches the near field of the large dishes like Haystack, and a variety of dish sizes are available. The beamsize is roughly constant across the frequencies because we underilluminate the dish. Another potential error source is interference, but with the flexibility of this WVR design we can avoid problem frequencies and choose a nearby frequency instead.

The wideband frequency switching approach allows several interesting techniques to be employed. Because the entire lineshape is measured, the conversion factor from brightness temperatures to mm of path can be determined theoretically, and this has been done in these experiments. Each variation has a different altitude and the lineshape and conversion vary with pressure, so fitting to the lineshape can improve the phase correction significantly. After using the WVRs to create an atmospheric profile and fitting to the altitude of the variation, opacity corrections can be determined. Beam mismatch corrections can also be applied when the pressure, and thus the altitude, of the variation is determined.

Experiments

Data from two separate experiments are shown. The first data set is from Hat Creek interferometer observations of Orion on a baseline of 192 meters. The second data set is from the April 1999 CMVA mm-VLBI experiment between Hat Creek and Kitt Peak. During that experiment WVRs built by Dave Woody were active at OVRO as well, but these data have not been included here. The difference when using WVRs for VLBI is that the sites have completely different atmospheres, altitudes, and elevations to be on source. In poor weather or at the lowest elevations, this can create millimeter level nonlinear effects over a six minute scan. In addition, VLBI processing maximizes the amplitude and SNR by fitting out a fringe rate from the phases. Combined with the ability to introduce shifts of 360 degrees, rate fitting is remarkably effective at minimizing the effects of the large, sharply edged features like those shown in figure 2 by lining up periods of stable phases.

The Hat Creek data are shown in figure 1, taken with the WVRs about six meters from the center of the six meter dishes. This offset was necessary to avoid blockage and to prevent collisions, but this offset in the dish centers causes timing discrepancies as the atmosphere flows across both dishes. The WVRs were held stationary for five minutes as the six meter dishes tracked through since the WVR pointing system could not track, and this added to the

offset between beams. These timing problems and beam offsets are a part of the residual rms phase errors of 0.427 mm. The rms phase errors of the interferometer data were 0.99 mm before the WVR data was used to correct for atmospheric variations. The coherent SNR of this 22 minute interferometer scan increases by almost a factor of three when the WVR data is used as a correction. This experiment did demonstrate that our WVRs can work effectively on short baselines, and with future improvements in the pointing, beam matching, fitting, and noise temperature the corrections will improve significantly.

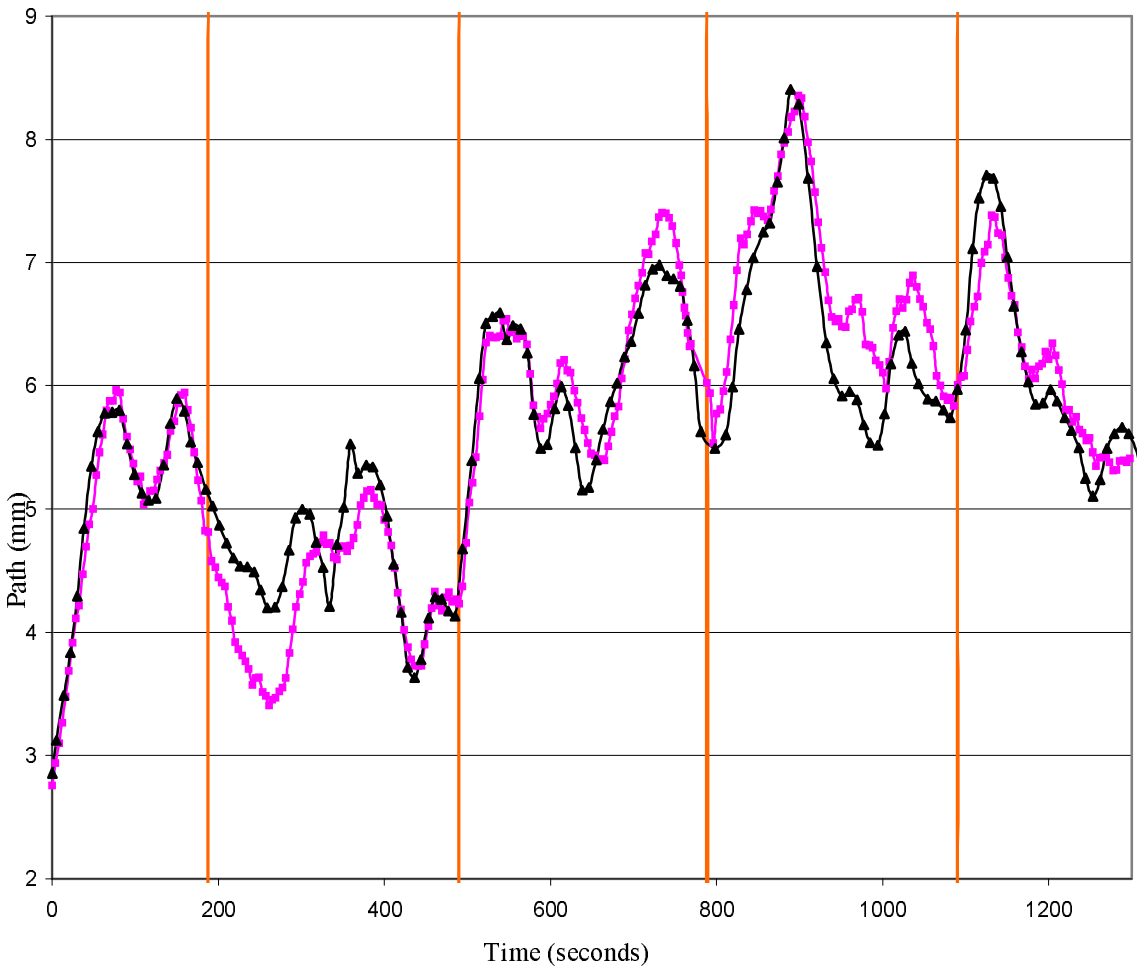

Figure 1. Comparison of Hat Creek interferometer observations of Orion at 86 GHz and WVRs on a baseline of 192 meters. The rms phase variations of the interferometer data were reduced from 0.990 mm to 0.427 mm by incorporating the WVR correction. The interferometer data are the dark triangles, and the WVR data are light squares. One phase wrap was removed from the interferometer data. The vertical lines are when the WVRs moved.

The CMVA experiment data are shown in figure 2. In this experiment the WVRs were attached directly to the Kitt Peak and Hat Creek dishes. The WVR at Kitt Peak was attached behind the subreflector, but the WVR at Hat Creek was attached to a dish at the edge of the array, about fifty meters from the center of the combined beam. This created a time delay between the WVR correction and the interferometer phases of twenty seconds, and the time-shifted correction is shown in figure 2. The time shift was determined empirically from the data, not from an analysis of local weather conditions, but other scans do require time shifts as well. Correcting a phased array spread over one hundred meters with a single WVR is one of the added difficulties of

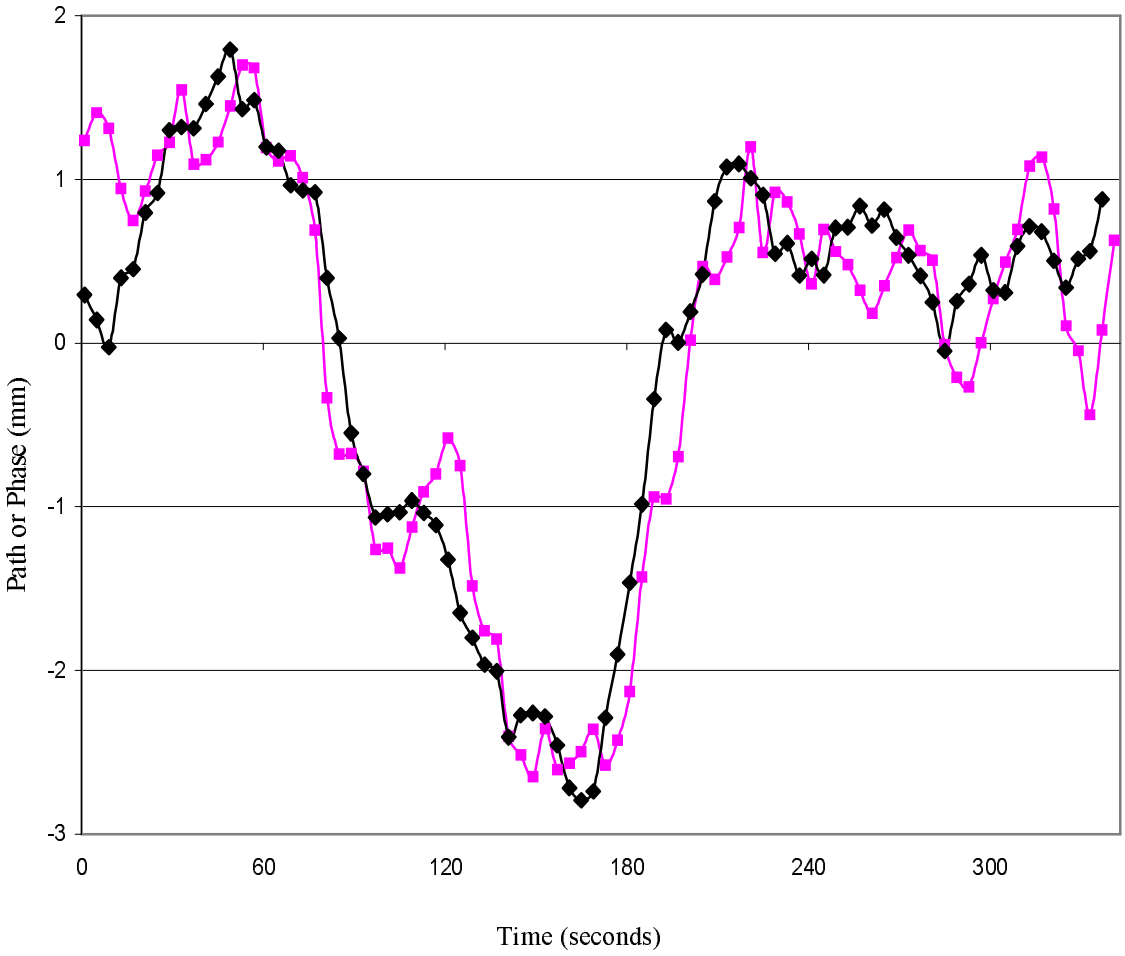

Figure 2. Comparison of CMVA phases on 3C273B and WVR data. The WVR data are the dark diamonds and the VLBI data are the light squares. The WVR data is shifted by twenty seconds as discussed in the text. The rms phase variations of the interferometer data went from 1.24 mm to 0.45 mm with the WVR correction.

CMVA corrections. The phase rms went from 1.24 mm uncorrected to 0.45 mm when corrected. Without the shift in time the correction left a residual of 0.81 mm. Even with this large decrease in the rms phase variations, the coherent SNR increased by less than a factor of two because of the phase structure of the scan. With a phase wrap at both ends of the large feature in figure 2 and a good rate fit, the much of the amplitude of the scan is retained. These types of direct comparisons of CMVA and WVR phases can only be done on strong sources since high SNR is necessary in the CMVA data to reduce the phase noise. Work is now in progress to incorporate WVR data into the analysis software to correct the VLBI phases, thereby improving the coherence and allowing the detection of weaker sources.

Future Plans

Encouraged by the performance of these prototype WVRs, we have started building two more instruments with improved performance. We plan to integrate the WVR data, and also total power data, into the VLBI analysis. A complete study of the April 1999 CMVA experiment will give us a better understanding of the value of these instruments. We are also going to continue testing on shorter baselines to study systematic errors such as beam mismatch. The main operational goal is to equip all of the CMVA antennas.

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