ngVLA Memo #74
Channel Weights for the VLA CWVRs

Bryan J. Butler
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Abstract

The use of water vapor radiometry (WVR) to correct for tropospheric phase fluctuations in interferometer data has a long history. In the late 1990s and early 2000s, WVR phase correction was performed with test devices on a few antennas at the VLA, and as a final part of that effort, a Compact WVR (CWVR) was designed with a MMIC at its core, and two were at least partly built. Those CWVRs were never tested on VLA antennas however, because of shifting priorities at the time. The baseline calibration plan for the ngVLA has WVRs as the primary correction technique for tropospheric phase fluctuations. In order to test the efficacy of phase correction using WVRs, as part of the initial ngVLA design effort the CWVR design was updated, and four units have been built and put on VLA antennas with a fifth on the way. Traditionally, WVR phase correction has been done by forming an "observable" at each antenna, which is a weighted sum of the system temperature in the channels in the radiometer. Differences in observables between antennas are then used to correct the phase and/or amplitude of the visibility on that baseline. In this memo I describe the choice of channel weights to be used in the formation of the observable for the VLA CWVRs.

1. Introduction

Using WVR for visibility phase correction has been around for decades – at least since the late 1960s (see Welch 1999 for a good description of the pre-1999 efforts). In the last twenty years, it has been used at least for some observations or tests at a number of interferometers (e.g., VLA: Chandler+ 2004a; OVRO: Woody+ 2000; BIMA: Staguhn+ 1998; CARMA: Shiao & Looney 2008; PdBI: Bremer 2002; ATCA: Indermuehle+ 2013; SMA: Battat+ 2004). It is in regular use for ALMA, with the 183 GHz line (all other efforts have used the 22 GHz line or some form of continuum), the only such regular use I am aware of currently (Maud et al. 2017; Nikolic et al. 2013).

In all of these previous (and current) uses, the number of channels in the WVR is small (< 5) (note that ALMA has 8, but it is DSB, so effectively 4 channels). There is effort at PdBI/NOEMA on a 14-channel WVR, but it is not in production yet (as far as I know). Additionally, in all of these previous efforts, the WVR phase correction technique involves the formation of a quantity I'll call the "observable" at each antenna, i, which is a weighted sum of the system temperature (T_{sys}) over the channels, j:

$$T_{obs_i} = \sum w_j \, T_{sys_{i,j}}$$

Differences between the observable on the two antennas of a baseline are then used to correct the phase (and/or amplitude) of the visibilities on that baseline. Investigation of optimal placement of these channels and their subsequent weights is an important part of WVR design. It may be as simple as a qualitative statement that one should measure the peak of the line, and subtract some average of off-peak channels (at the hinge points or in the wings of the line), so that if there were three channels: off-peak, on-peak, off-peak, one might just use weights of -0.5, 1.0, -0.5, as was done for the early VLA 3-channel designs (Butler 1999) and the OVRO design (Woody+ 2000). Or a more detailed optimization involving atmospheric modeling might be undertaken, as was done for ATCA (Sault+ 2006). Or a much more detailed line placement and weighting study can be done, as was the case for ALMA (Hills 2007; Hills 2004; Stirling+ 2004). This memo describes such an investigation for the CWVRs that have been constructed and put on VLA antennas as part of the ngVLA design work. There are other ways to determine how the WVR measurements relate to phase fluctuations on a baseline (e.g., operators: Towne 2020; line fitting: Staguhn+ 1998), but I will only consider the traditional method in this study.

2. History of WVR at the VLA

The use of WVR for phase correction at the VLA has a long history. I will not cover that all here (see Butler 1999 for a complete description), but I will give enough to explain how we got to where we are. In the late 1990s, two component-ized 3-channel WVRs were built, installed, and tested on the VLA (Chandler+ 2004a). They were bulky, and prone to temperature fluctuations, however, so a decision was made to design a more compact device, with a MMIC at its core, and 5 channels instead of 3 (Chandler+ 2004b). Two units were constructed, at least partially, but were never put on antennas, because of shifting priorities (the EVLA construction project, mostly).

In 2017, with an understanding that more WVR experience would be needed in order to properly design WVRs for ngVLA, an effort was begun to resuscitate one of the CWVR units (one was mostly still intact; what was left of the other was in pieces on shelves in the lab). It was successfully resurrected (mostly, one channel didn't work well), and bench tests were done (Gill+ 2017). Later that year it was decided to construct 5 CWVR units (along with some re-design of some elements), to put on VLA antennas, as part of the ngVLA project. The re-design and construction of the bulk of these CWVR units was done by Nathan Towne, with help from others. To date, 4 have been constructed and put on VLA antennas (credit to Craig Hennies and others for the installations), and 1 is in construction. Note that WVR is part of the reference design; it is assumed that it will be the way that tropospheric phase fluctuations will be measured and used to correct visibilities (Hales 2019).

3. Characteristics of the CWVR

Details of the CWVR design and properties are in Gill+ (2017), but I will repeat here the portion relevant to this study: channel placement and width. The CWVR has 5 channels spread across the available bandwidth of the VLA K-band receiver (~18-26.5 GHz). These channels are shown graphically in Figure 1 – both a notional representation, and an actual measurement of the passbands of one of the units.

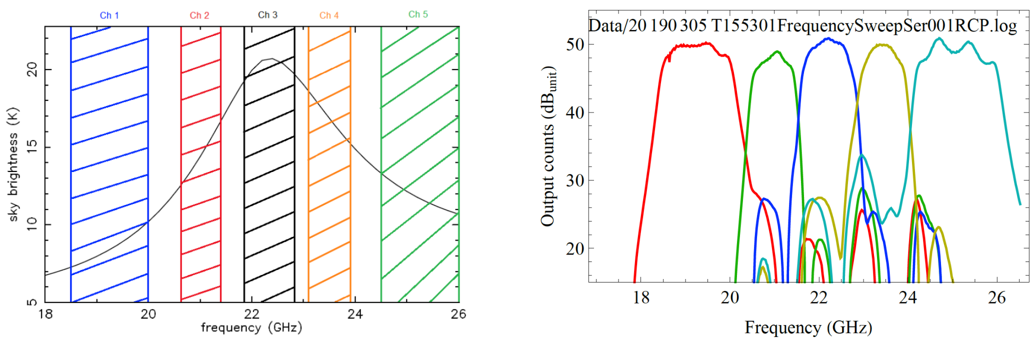

Figure 1. Notional (left, from Gill et al. 2017), and measured (right, from Towne 2019) bandpasses for the CWVRs.

The approximate center frequencies and bandwidths (defined by half-power points) are shown in Table 1.

Table 1. Channel properties for the CWVRs.

Channel	Center Frequency (GHz)	Bandwidth (GHz)
1	19.25	1.50
2	21.00	0.75
3	22.25	1.00
4	23.50	0.75
5	25.25	1.50

4. Determining Channel Weights

As noted above, determination of placement of channels (center frequency and bandwidth) and their weights is an important part of WVR design. Here the problem is simpler, as we have pre-determined channel placements and need only determine the weights. To determine those weights, I follow the method used by Bob Sault to determine the channel weights for the ATCA WVR (Sault+ 2006), slightly modified. Instead of using sonde launches (the closest sonde launch facility is in Albuquerque, which is an OK analog for the VLA site, but different enough geographically, and lower altitude), I use atmospheric models with varying properties (similar to the methodology in Staguhn+ 1998, Butler 1999, and Stirling+ 2004). The atmospheric model is described in great detail in Butler (1999), so I won't go into detail describing it here, but fundamentally it is based on the Liebe (1989) model. I vary surface temperature (0-20 C), water vapor scale height (1-3 km), precipitable water vapor (PWV; 0.5-12 mm), and the height of the excess water vapor (0.5-3 km) to simulate observing in a wide variety of conditions. For a given channel weighting scheme and amount of excess water vapor, I run a number of trials (100 for these particular simulations), and find the mean (the observable T_{obs}), and the "noise" (given by the fluctuations across the trials).

I include the noise in each channel in the simulations, since the channels are not of equal bandwidth, and have different system temperature. Following Butler (1999), assume that gain and calibration diode temperature fluctuations are small, and write the noise in the j^{th} channel of antenna i as:

$$\sigma_{T_{sys_{i,j}}} = \frac{2}{\sqrt{B_j \tau}} \frac{T_{sys_{i,j}}^2}{T_{cal_{i,j}}}$$

where T_{cal} is the calibration diode temperature, T_{sys} is the total system temperature, B is the channel bandwidth, and τ is the integration time for a given WVR measurement. Assume that the total system temperature is comprised of three elements: receiver (T_{Rx}), antenna (spillover, T_{spill}), and the atmosphere (T_{atm}): $T_{sys} = T_{Rx} + T_{spill} + T_{atm}$. For the VLA antennas, T_{Rx} ~ 20 K, and T_{spill} ~ 15 K at K-band (Perley+ 2006). The value of the calibration diode temperatures are designed to be roughly 10% of total system temperature, and are of order 5 K at K-band (it varies from antenna-to-antenna, and across the band for a given antenna and polarization but not by more than factor 2). To estimate the peak noise value to be expected, note that the peak value of T_{atm} from the model is of order 40 K (only in the center channel, but this will be worst case). Plugging these values into the above equation, and using a bandwidth of 1 GHz and an integration time of 1 second gives noise of order 70 mK. While this is much smaller than the temperature in the channels, I include it for completeness. To properly calculate the noise in each channel in the simulations, I take the value of the atmospheric temperature, and calculate Gaussian random variables with the appropriate width to determine the noise to add.

For the simulations, the metric I want to maximize is the ratio of the observable (T_{obs}) to the "noise" in the simulation, which as noted above is just the rms in the observable over all of the trials. The channel weighting should be varied until this maximum is found. I assume that any linear combination of channels will produce an observable (T_{obs}) that is linear vs. amount of excess water vapor (which was shown in Butler 1999). Given that, choosing any amount of excess water vapor will do – I choose 100 microns. I further assume that the weights should be robust to offsets, linear, and quadratic variations in the T_{sys} of the WVR (Sault 2006; Lay 1998). This means that:

$$\sum w_i = 0; \quad \sum w_i \nu_i = 0; \quad \sum w_i {\nu_i}^2 = 0$$

Finally, I assume two things about the weights, taking into account the knowledge of the shape of the 22 GHz water line, and the channel placements. I assume that the central channel should have the largest weight (in absolute value) and should be positive, and that the first and fifth, and second and fourth channels should not have values that are drastically different (by more than factor 2), because they are roughly symmetric about the line center. These latter assumptions are done to reduce the parameter space.

An optimization scheme is needed to find the best channel weighting. There are 5 unknowns, with 3 equations and 4 constraints. The solution to this is not particularly amenable to common least-squares techniques, because evaluation of the model, and particularly of its derivative, is expensive. Brute force grid search could do, but would also be computationally expensive – if values can be between -1 and 1.5 (a reasonable range), and a grid with 0.01 spacing is desired, then 250^5 (minus the constraints) simulations would need to be done. On my desktop workstation, it takes about 10 seconds for a single simulation (100 trials), so this would be prohibitively long, even parceled out to the 12 cores on that machine. The saving grace here is something that has come from the machine learning community – random sampling is better than grid searching anyway (Bergstra and

Bengio 2012). So, I ran 100,000 trials with random channel weights, in batches of 1000 each, and accumulated the results. While the SNR shape is relatively shallow, there is a clear minimum around the values shown in Table 2, consistently found in each of the runs.

Table 2. Optimized channel weights for the VLA CWVRs.

Channel	weight
1	-0.57
2	-0.14
3	1.27
4	-0.12
5	-0.44

These should not be taken as precise values for the weights, because the SNR is relatively shallow. Looking at the variation of the 50 simulations with the highest SNR, uncertainties are of order ± 0.1. It is interesting to note that the "hinge point" channels (those around the half-power point in the line) are weighted much less than those in the wings of the line (by factor ~3-5). This is almost certainly a result of the fact that the difference between the wing channels and the center channel is larger than for the hinge points, and probably means that the importance of using the hinge points for WVRs is less than some had believed in the past.

5. Conclusion

For any analysis using the VLA CWVR data in the traditional way (by forming a weighted sum of the channel T_{sys} for each antenna) that uses *ab initio* channel weights, the values shown in Table 2, or something similar, should be used.

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