ngVLA Memo No. 140

Assessment of the VLA Water Vapor Radiometers and Next Steps

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ABSTRACT

The next-generation Very Large Array (ngVLA) plans to use water vapor radiometer (WVR) systems on each antenna to decrease calibration overheads for tropospheric phase correction on the high frequency bands (5 & 6; 30.5-116 GHz) to levels lower than feasible with just using fast switched reference gain calibration. The new Compact Water Vapor Radiometer (nCWVR) is a pathfinder project that uses existing Very Large Array (VLA) K-band receivers and custom back ends to integrate WVRs on VLA antennas. The project's primary goal is to demonstrate the use of 22 GHz WVR for phase correction and give specific insights to the feasibility of the technique at the VLA site.

In this memo, we outline the status of the nCWVR project and give recommendations for next steps. We give hardware and system level assessments of the nCWVR units and compare them to historical tests. We highlight design mistakes made early in the project and how ngVLA WVR can learn from these errors to build a more robust system. The sensitivity we measure at the detector output stage is an order of magnitude better than previously measured sensitivity through the readout and recording stages as currently implemented. Approaches to re-implementing these sections of the system to preserve sensitivity, which is necessary for the nCWVR project to be operationally useful, are outlined.

1. INTRODUCTION & MOTIVATION

Temporally variable water vapor in the troposphere will introduce delay error to observations made with next-generation Very Large Array (ngVLA). This delay has both spatial and temporal variability due to the inherent non-homogeneity of water vapor in the Earth's atmosphere. For interferometric observations, this causes phase fluctuations on the baselines which negatively affects the sky images reconstructed from the visibilities (see examples in Nikolic et al. 2008). Tropospheric delay causes phase fluctuations which scale with baseline length (up to the outer scale of turbulence), causing decorrelation (a reduction of the measured signal amplitude) and spurious features. Both of these effects reduce the dynamic range of the observation. The ngVLA will need to use phase correction in order to meet dynamic range requirements (Hales 2019; Sridharan et al. 2024; Sridharan & Bhatnagar 2023). A common approach to reduce phase error introduced by tropospheric delay, fast switching, requires the array to periodically slew off of science targets to a calibrator source during observations to calibrate the total delay on timescales as short as possible. A goal of the ngVLA is to achieve an observing efficiency of 90%, which would not be possible relying solely on fast switching. A second approach is self-calibration, which is viable if there is a source with sufficient signal to noise ratio within the science observing field. Self-calibration is a least-mean-squares method to derive the complex antenna gains (see Chapter 11 of Thompson et al. 2017). Based on the dynamic range requirements of ngVLA, self-calibration will be a sufficient calibration strategy for most observations in bands 1-4 (Sridharan & Bhatnagar 2023), but not bands 5 and 6. Due to the limitations of these calibration techniques, a dedicated water vapor radiometer (WVR) system, which continually tracks changes in the water vapor column density in the main antenna beam, has been deemed essential for ngVLA to meet its 90% observing efficiency goal (Hales 2019).

This will be similar to ALMA's WVR phase correction system (Nikolic et al. 2013) which observes the 183 GHz water line, however, ALMA is located in one of the driest sites on Earth and at an altitude of 5000 m. Meanwhile, the core of the ngVLA will be located in central New Mexico at 2000 m and the Long Baseline sites will be located at a variety of climates and altitudes. The atmospheric precipitable water vapor was estimated at the Very Large Array (VLA) site based on surface weather from 2010 to 2017 and over the entire year the median over all hours was 5.4 mm (Selina et al. 2022). ALMA's WVR system would saturate at most of the ngVLA sites, necessitating the design of a new WVR system sensitive to the 22 GHz water line. An initial design for a wide band receiver based WVR system has been proposed (Duverneay et al. 2022), but not yet prototyped and tested. This design uses 100 MHz channels over 19.7 - 31.0 GHz, allowing for sensitivity to the pressure broadened 22 GHz water vapor line in a variety atmospheric conditions. Radio frequency interference (RFI) mitigation is also considered by a redundant level of channelization. The design uses a custom front end with discrete RF components and two modified band 4 (K-band) ngVLA Integrated Receiver and Digitizers (IRD). This design prevents doubling of labor as the ngVLA already requires a K-band IRD for science. The RF components will be RFI shielded and kept at a stable temperature through nested room temperature cold plates (this approach has been demonstrated with JPL AWVR: Tanner & Riley 2003). These are heterodyne systems so they will require a stable LO source. While some high level requirements have been defined for this system (such as aperture size, thermal isolation from environment and RFI shielding) more granular requirements such as per channel sensitivity and gain stability are still being defined. The use of the K-band science receiver of the ngVLA for water vapor radiometry has also been proposed and is under evaluation (Sridharan et al. 2025). K-band based atmospheric calibration has been demonstrated in a handful of operational systems. The state of the subfield is described in detail in Sridharan (2026).

22 GHz Water Vapor Radiometry (WVR) for phase calibration has been a topic of discussion and design at the Karl G. Jansky Very Large Array (VLA) for over twenty years. In 2004 results of a successful demonstration of a three-channel WVR system installed on two VLA antennas was published (Chandler et al. 2004b). The three-channel WVR was tested for a year and was able to improve the rms phase, for observing frequencies ranging from 8 GHz to 43 GHz. It was most successful at phase correction on observing days with no cloud cover and high tropospheric humidity. In the same year the core design of the five channel monolithic microwave integrated circuit (MMIC)

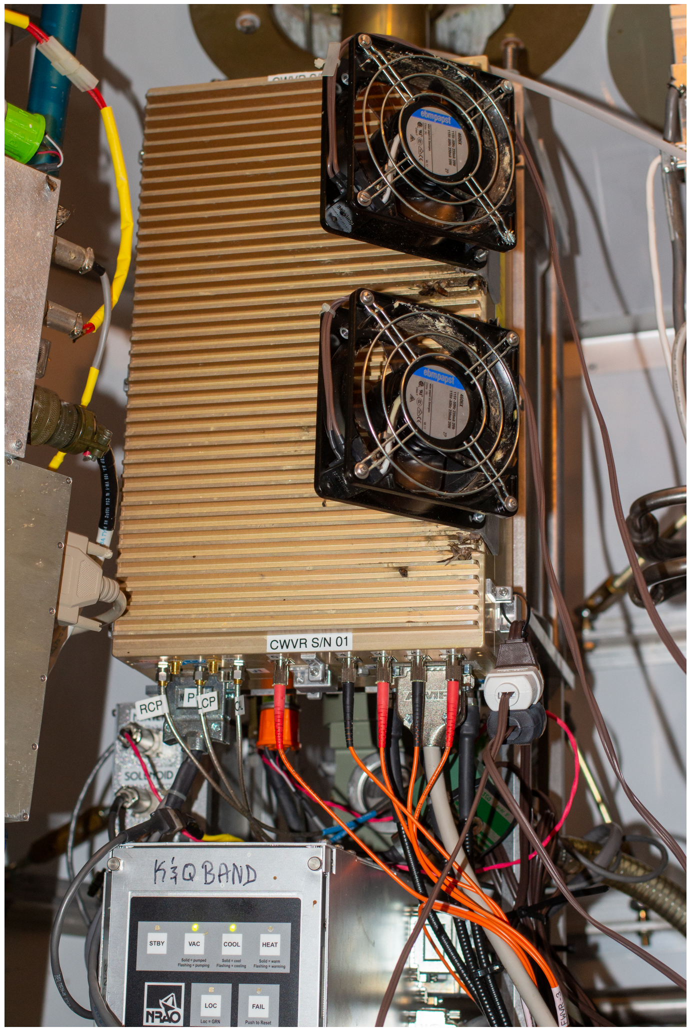

Figure 1. A nCWVR unit installed on a VLA K-band receiver. Fans are attached to the side of a large copper colored heat-sink. The unit is housed in an RFI tight clamshell style chassis. Radio frequency signal from the cold part of the receiver enters the nCWVR through SMA connectors (labeled RCP and LCP on the bottom left of the photograph). Five optical signals exit the box on fibers (the red and black connectors at the bottom of the photograph) corresponding to the five filters of the internal MMIC block.

based Compact Water Vapor Radiometer (CWVR) was proposed to be implemented on the EVLA (Chandler et al. 2004a). An initial version of the CWVR MMIC module was completed ∼ September 2004 (Morgan 2004). A full CWVR system was completed by 2010 (Willoughby 2010) and then characterized in 2017 (Gill et al. 2017). This characterization included channel isolation, gain stability and temperature dependence. Gill et al. (2017) concludes with the recommendation of a mechanical redesign and the production of the three to four CWVR systems. This redesign, dubbed nCWVR, was completed in 2018. Five nCWVR units were produced and four of them were installed on VLA antennas in 2019. The original CWVR was dismantled and its parts were used in the construction of the nCWVR units (see figure 1). Some limited demonstrations of the units were successful soon after installation (Towne 2020) however, significant smoothing was required to obtain coherent results. Subsequent attempts to perform phase correction with these units have been unsuccessful (Butler 2021) even with smoothing. Butler (2021) assessed the phase correction capabilities of the units

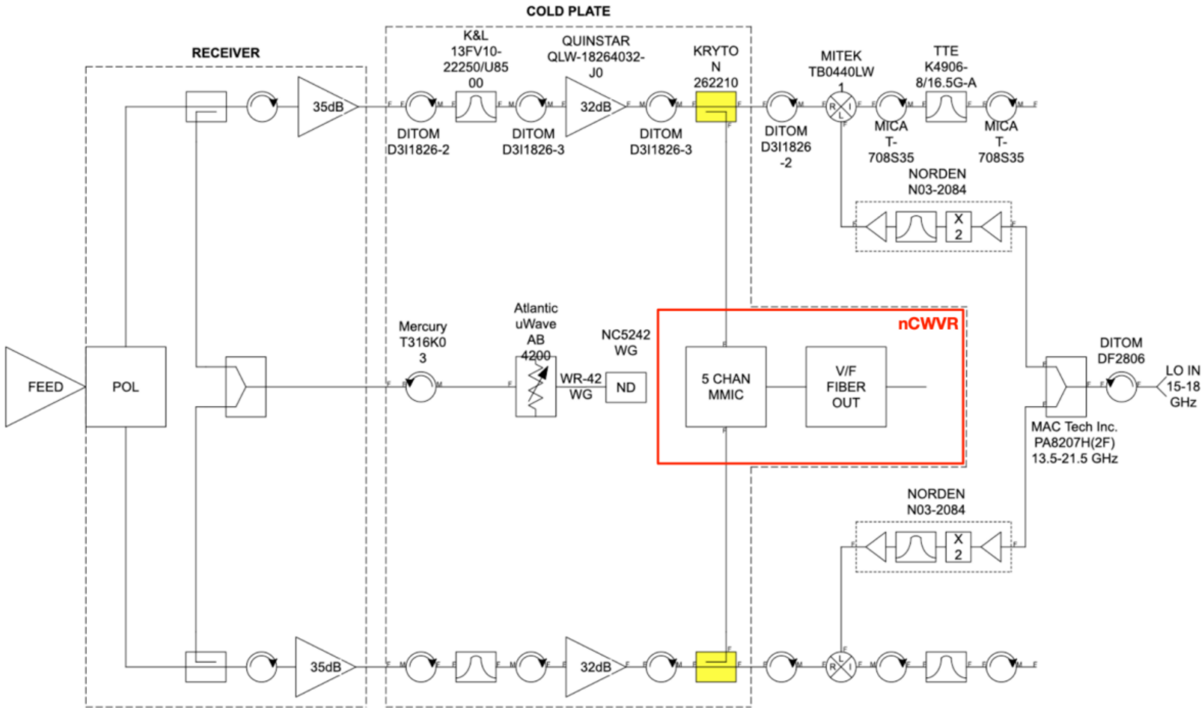

Figure 2. High-level block diagram of the nCWVR and how it fits into the VLA K-band signal chain. The red box labeled "nCWVR" and the yellow highlighted power splitter are the components that are specific to the nCWVR. The rest of the components are typical of the VLA K-band receiver. A single housing contains the nCWVR specific components and the general receiver room temperature RF and IF components.

approximately two years after install and found that the integrated systems were failing to perform basic radiometry. This is at odds with the successful test observation from 2019 (Towne 2020) and indicates that some changes occurred in the performance of the WVR units. Other than the parts of the nCWVR signal chain shared with the standard EVLA K-band and thus evaluated/maintained as a regular part of VLA operations, the 2021 results made the entire nCWVR signal suspect. In this memo, we take on the task of re-evaluating the performance metrics of the nCWVR units and assessing the current state of the program.

2. NCWVR DESIGN OVERVIEW

The nCWVR primarily does three things: (1) filters signal (2) detects filtered signal, (3) reads out the output of filters to fibers and (4) provides noise injection from temperature stabilized noise diodes for switched power calibration. The nCWVR is integrated into the signal path of the EVLA K-band receiver. After the postamps and filters, a power splitter divides the signal from the receiver between the nCWVR filter and the K-band intermediate frequency components (see figure 2). These RF components are installed on a temperature controlled plate (TCP) that has a Peltier thermo-electric cooler to reduce changes in temperature that would impact gain fluctuations. A temperature controller implements a PID control loop using internal thermometers. A double-hinged clam shell assembly houses the noise source for the receiver, the warm RF components, the nCWVR specific parts and the temperature control system. The TCP is separated from the IF section and controller by a piece of metal and insulating material. The two sides are connected by cabling, which must be

Table 1. Status of nCWVR units

Serial #	Install Date	Location	Status
001	2019-Jul-24	Storage	Decommissioned
002	2019-Jun-19	Storage	Tested, Insensitive, Decommissioned
003	2019-Sep-19	ea12	Untested
004	2019-Nov-13	ea07	Tested, Sensitive at hardware level
005	n/a	Storage	Decommissioned

disconnected to open the units. This design does not readily lend itself to debugging, fault diagnosis, and monitoring.

The core nCWVR component is a MMIC housing switches, variable attenuators, amplifiers, multiplexer, and tunnel diode detectors. The circuit is housed in a block with two SMA connectors, for the LCP and RCP signal from the receiver, and a single D-sub connector which includes power input, controls (such as switch positions) and signal output (Gill et al. 2017). The detector voltage from each filter is sent to a voltage to frequency converter (VFC) board which outputs pulses. The frequency of the pulses maps the output of the detectors (nominally expected to be 0-10 V but found to be actually negative relative to receiver ground) to 0-2 MHz. The pulses, on fiber optic cables, are counted by an F318 module.

3. PROJECT STATUS

At this time, only two nCWVR units remain in operation. Unit 001 was decommissioned circa 2024. This was due to repairs needing to be undertaken for the unit's host receiver and there being no established procedure for the recharacterization of an nCWVR after changes have been made in its signal path. Unit 002 was taken into the lab for testing in late 2025 and found to be unresponsive to hot/cold load tests and subsequently decommissioned. Unit 003 remains on antenna 12 and in operation, however its hardware level performance has not been reassessed since installation. Unit 004 was originally installed on antenna 25, however it was taken off the array in late 2025 and underwent hardware level lab testing. It was then re-installed on antenna 7 where it is currently in operation. Unit 005 was never installed on the array. A summary of the status of each unit is give in table 1.

4. TESTING

Here we outline some of the hardware level tests done to investigate the problems with the still existing nCWVR units. The goal of these tests was to determine if there was a clear hardware failure that could explain the results of Butler (2021).

4.1. *Channel Isolation*

Channel isolation was tested using an engineering testbed version of the nCWVR system. This testbed was constructed using primarily spare parts from the already decommissioned unit 001. The bed allowed us to test components in isolation and precisely control input signals. The testbed

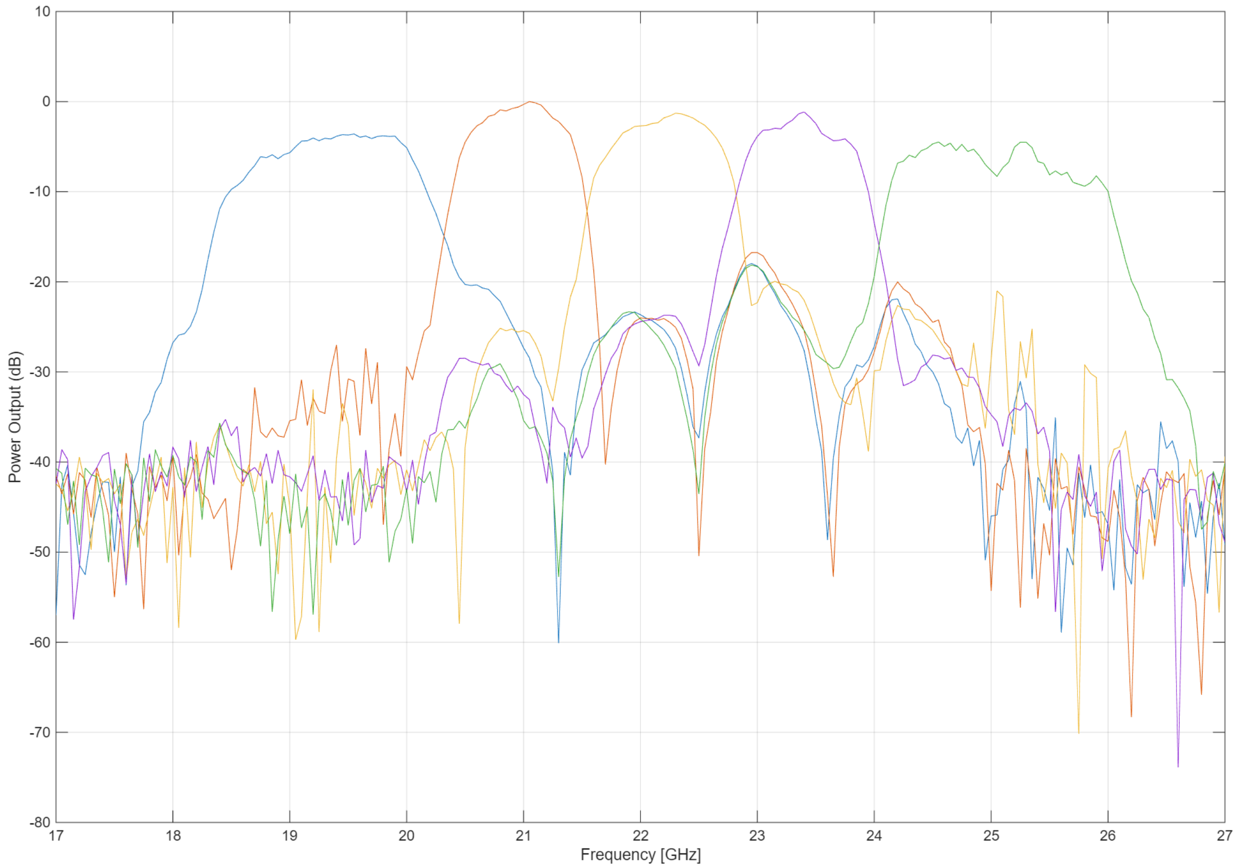

Figure 3. Passbands of nCWVR 001 MMIC block five channels measured on 7/14/2025. Power is normalized to maximum voltage response of detectors with -55 dBm power at input to testbed.

included all non-cryogenic signal chain components of the K-band receiver including the RF post-amps and IF components. This setup lacks any active thermal stabilization, so it is not well suited for noise or sensitivity measurements. In this test the VFC was excluded allowing us to better isolate the performance of the filters.

The input from the cold receiver is emulated by a signal generator. To emulate observing conditions the mixer in the IF section of the signal chain was provided with a nominal LO from a second signal generator. This ensures that any power reflected from the mixer or any leakage from the LO to the RF port of the mixer matches what would be seen in the observing setup. The detector voltages were captured using a Keysight U3402A multimeter. Only one channel was tested at a time and the channels not under test were grounded through a resistor matching the impedance of the digital multimeter (DMM). All grounds were tied together including the case ground on the MMIC block. The LO was set at a constant 15 GHz at 0 dBm (Hewlett Packard 83624A). A sweeping test signal is introduced at what would be the output of the cold receiver, the first component in the chain after the signal generator being a DITOM D3I1826-1 (see nCWVR block diagram, Figure 2). We use an Agilent 83630B signal generator in flat power mode (a feedback to a spectrum analyzer is setup to ensure this) to sweep a 17 - 27 GHz signal in 50 MHz steps at -55 dBm through the system. It should be noted that -55 dBm would be the output power at the generator and we expect some loss in the cable before the signal reaches the nCWVR test bed. A control computer is used to sync the signal sweeping with the read commands of the DMM. For each step in frequency, the voltage was taken

Table 2. Sensitivity of the five channels, unswitched, of the unit 004 nCWVR at the detector and the channel bandwidths.

	CH1	CH2	CH3	CH4	CH5
NET [$mK\sqrt{s}$]	88.4	101.5	93.9	93.2	95.7
$\Delta\nu$ [GHz]	1.5	0.75	1.0	0.75	1.5

with the signal generator in the on and off state and the difference was treated as the response by the detector from the input signal. The results for the nCWVR 001 MMIC block are presented in figure 3. The level of leakage differs from channel to channel but generally peak at the level of ∼20dB or 1%. These findings are consistent Gill et al. (2017) and Towne (2020).

4.2. *Sensitivity*

The sensitivity of unit 004 was determined with the full nCWVR production assembly including a science ready K-band receiver in the lab. This was done because the sensitivity of the WVR will depend on both the receiver performance and the performance of the thermal control system. The VFC was again excluded, so the sensitivity is tested coming out of the detector. To accomplish this while still having the nCWVR in a nominal state (i.e. the same level of thermal isolation/stability the unit would have deployed to an antenna), a test cable was plugged into the internal wiring harness that connects the VFC to the MMIC block. We then removed one of the case mounted fiber couplers from the nCWVR and threaded the test cable to the exterior where we could connect it to a bread board for testing. An Agilent 34401A DMM was used to read the voltages (relative to receiver ground) of the channels (one channel at a time). This DMM can sample voltage at 5.5 digits of resolution at 60 Hz with normal mode rejection of noise on the AC power line. The expected quantization noise is on the order of 10 μV, well below the noise level measured on the detectors. Channels not under test were grounded through a resistor matching the impedance of the DMM.

To measure the sensitivity of the unit we compared the voltage response of the system with a room temperature load and a load at the temperature of boiling LN2. The VLA science receivers are characterized after any repairs using approximate black body loads at different temperatures. These loads are placed in front of the receiver window to fill the beam. We performed this procedure taking data for several minutes with each load filling the beam. Then we fit a linear function to map voltage to temperature by using the known temperatures of each load. The appropriate adjustment was made for the LN2 load temperature to account for elevation. We then measured the RMS in units of temperature for each channel while looking at the room temperature load to give the noise equivalent temperature (NET). The RMS was based on approximately 30 minutes of data for each channel. By accounting for the sampling rate of the DMM (60 Hz in this case) we can then give the NET as the temperature of the noise at a sampling rate of 1 Hz. $NET = \sigma_T/\sqrt{f}_s$ where σ_T is the RMS of the detector in temperature units and f_s is the number of samples per second, is used to define noise equivalent temperature here. The 60 Hz sampling rate will slightly under sample the signal. In section 4.3 we show that rise time of detector is 10 ms, therefore Nyquist sampling is achieved at

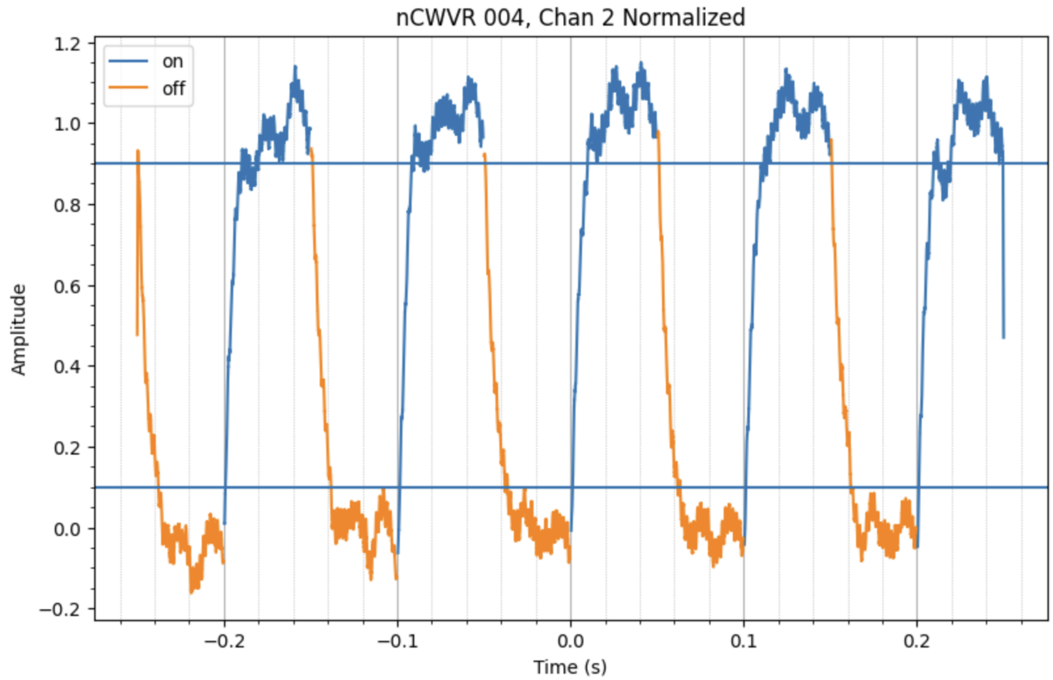

Figure 4. Normalized detector output of channel 2 on nCWVR unit 004 while installed on VLA antenna 7. The calibration noise source is switching at 10 Hz and the calibration states of the detector have been segmented. 10% and 90% of the amplitude of the ON state are indicated by horizontal lines. 60 Hz RFI was being picked up on the oscilloscope voltage probe.

70 Hz. The sensitivity results for unit 004 as an un-switched system at the detector are reported in table 2. The sensitivity of the channels is independent of bandwidth demonstrating the noise is not thermally limited. Past work had measured the sensitivity of the units directly following construction but only of the fully integrated system (including the VFC based readout). Towne (2019) found the per channel sensitivity of the first production unit in the lab of 1.3 - 5.8 K$\sqrt{s}$. There is an order of magnitude discrepancy between level of sensitivity found at the detector in this work and the sensitivity found for the full system in past work. This work is the first published measurement of the nCWVR sensitivity at the detector. We will go into the importance of these result in section 5.

4.3. *Detector Rise Time*

As a part of normal science operation, the receiver gain is calibrated by a 10 Hz switched noise source. In the WVR equipped receivers the noise source is located on the WVR temperature controlled plate (see figure 2). The calibration signal is coupled into the cold part of the receiver. The WVR effectively chops between Tsys (which includes contributions from the amplifiers and the sky) and Tsys + Tcal. Tcal is 3-5 K and is measured as a function of frequency in the lab at the end of each receiver maintenance cycle. We measured the rise time of the nCWVR detectors by comparing the voltage driving the noise source and the detector voltage relative to receiver ground. nCWVR unit 004 was tested while installed in VLA antenna 7. A spliced testing cable was used to probe the calibrator driving voltage. The detector voltage was accessed with a test cable in the same way described in section 4.2). A Keysight InfiniiVision DSOX3034T oscilloscope was used to simultaneously sample the calibrator voltage and a single detector at 200 MSa/s. We then de-convolved the two calibration states of the nCWVR detectors, segmenting the signal in time by its calibration state. The rise time is defined as the time it takes the detector to go from 10% to 90% of its on state amplitude. We find that the detector rise time for unit 004 is ∼10 ms. An example channel is shown in figure 4. We note that 60 Hz RFI was being picked up by the voltage probe on the oscilloscope during the test.

5. DISCUSSION

During the initial production run (circa 2019) of the five nCWVR units, the achieved sensitivity was at least an order of magnitude worse than what was expected by the design (Towne 2019). Rather than searching for a hardware issue to explain this loss of sensitivity, the project adopted a smoothing strategy. This smoothing strategy was successful in tracking phase changes due to the atmosphere in at least one test observation (Towne 2020). However, this observation required a great deal of unit specific coefficients and data analysis to be successful, including: the right level of smoothing, measuring the switched power mixing factor, determining the noise/Tcal for each channel in the lab and channel weighting based on atmospheric modeling. The lab determined coefficients are likely to change over time and are guaranteed to change any time normal maintenance is conducted on the WVR host K-band receiver. Procedures were not established to remeasure these coefficients and update the software handling retrieval from the channel voltages. As such, the results from the 2020 memo have not been replicable.

The testing in this work establishes evidence that the nCWVRs still in operation are successfully filtering emission and are sensitive at the detector. There must be a significant hardware failure downstream of the detector to explain the loss in sensitivity in the integrated units. This points to an issue with the readout system which consists of the VFC module in the WVR and the on-fiber signal receiver in the F318. There are a number of possible explanations for this including but not limited to: the output power of the detector falling outside the linear range of the VFC chip, improperly handled pulse counting, and noise in the reference voltage. The VFC modules are custom boards designed at NRAO based on the Texas Instruments VFC110 chip. Replacing or repairing this readout system would be necessary for the nCWVR project to continue.

5.1. *Caveats*

On the channel isolation test, only one MMIC block (the nCWVR 001) was retested for channel isolation in this work. However, channel leakage does not appear to be core to the issue preventing the nCWVR units from working. A more robust channel isolation measurement can be derived by combining sweeps at multiple power levels (as shown in Gill et al. 2017), however we deemed that unnecessary for this assessment. We found definitively that in the case of nCWVR 001, channel leakage is within expected levels at input power levels of -55 dBm and below. The channels were found to saturate for a significant percentage of their passbands with an input power of -43.5 dBm and above. If channel isolation tests are deemed necessary for other nCWVR units, we recommend sweeping with an input power in between -55 and -43.5 dBm. It should be noted that the design goal for nCWVR was ∼30dB channel isolation, which was never achieved. Studies have not been conducted to determine how the ∼1% channel leakage affects retrieval. Of particular concern is the wing channels (1 and 5) which seem to receive more than 1% of the power close to the center of the covered spectrum (near 23 GHz) where atmospheric emission is expected to be higher than in the part of the spectrum the wing channels are centered on. To study the independence of the channels and how the leakage affects retrieval, the channels pass bands should be convolved with atmospheric emission models based on the VLA site.

Something relevant to all the testing is the voltage output of the detector relative to ground which was found to be negative across all tested units. The previous documentation from this project does not indicate that the MMIC block detectors are setup in this way or why this design decision was made.

Only two units were tested for overall sensitivity at the detector in this work. Unit 002 was found to be unresponsive to hot/cold load testing so quantitative sensitivity measurements were abandoned for that unit. Unit 004 was found to be sensitive and the results are reported in section 4.2. If continued operation of the nCWVR project is expected, this test should be repeated with unit 003. We also recommend future tests of the nCWVR sensitivity use instruments with a sampling rate of 70 Hz or better to achieve Nyquist sampling. Some high frequency noise will not be detected with the existing test setup. The calibration switching performance test should be repeated with shielded cabling for both units.

6. RECOMMENDATIONS

We recommend that the nCWVR project be recovered by replacing the readout and recording stages of the system. A functional WVR system at the VLA site is a critical pathfinder for the ngVLA, as such, either the nCWVR project needs to be recovered or two prototypes of the proposed digital backend based ngVLA WVR (Duverneay et al. 2022) need to be produced. nCWVR recovery can be accomplished faster than prototyping and building two entirely new systems (barring unforeseen hardware issues). Here we outline what would be required to recover the two nCWVR units.

The most direct way to recover the nCWVR would be to replace the existing VFC-based readout system with a direct analog-to-digital conversion (ADC) based readout. This could be accomplished by building a custom ADC board for the nCWVR or by using a COTS data acquisition system. In any case, we recommend the following be adopted as requirements for the readout stage:

- Simultaneous sampling of five channels
- Enough bits for digitization noise to be negligible in the overall noise budget (exact amount will depend on a number of factors, but we expect 16 bits to be sufficient)
- A minimum of 200 Hz per channel sampling rate

The sampling rate is intended to give a reasonable time resolution of the 10 Hz calibration signal. A sampling rate of 1 kHz or better per channel would improve noise rejection. There are a number of commercially available ADC chips that could meet these requirements in a custom readout setup such as the Analog Devices AD7606C-16. There are also commercially available complete data acquisition systems such as the LabJack T8, that could meet these requirements. We will need to evaluate what solution can be implemented while meeting the VLA's RFI restrictions.

Once a working readout and recording stage has been implemented for units 003 and 004, we further recommend that another nCWVR unit be constructed based on the existing parts from the decommissioned units. As a minimum of two units are needed to track phase error across a baseline, only having two units available creates a single point of failure. Having 3 units would also allow us to experiment with phase closure using the radiometers. As the MMIC block from unit 001 was successfully tested in this work, we recommend using that block for the new unit.

7. LESSONS LEARNED

There were a number of early design decisions made with the nCWVR that have made it difficult to maintain and repair. As operational robustness is an implicit requirement of the ngVLA WVR subsystem it is worth discussing how these challenges can be avoided in the future. All of the issues outlined below would have been mitigated by thorough documentation and continuity of expertise.

7.1. *Technical*

Accessing the interior of the units is non-trivial as the connections between the two halves of the clam shell must be broken to open the unit. Two SMA lines run between the cold plate and IF section of the unit with minimal slack, requiring angled wrenches and prior knowledge of the device's peculiarities to access. There is no external access to the temperature control plate system or thermometers. In a system where thermal stability directly impacts performance, this makes diagnosing issues with the units challenging. Future designs will have to prioritize accessibility to the internal components as well as access to information on the health of the device.

7.2. *Operational*

The are significant differences between five production units of the nCWVR that were not well documented. These differences include cabling, insulation, and casing. As such there was a great degree of difference between how the units performed. Each unit requires a highly individual calibration. The main purpose of the nCWVR is to make relative measurements of the atmosphere, as such making the units as similar as possible should have been a higher priority. The design should have been fixed early in production or updates should have been backported to the units earlier in the production run. A more critical failure was the lack of established protocols for recalibrating the units on a regular basis. Multiple units were decommissioned because they were deemed uncalibrated. Future projects will need to establish regular procedures for evaluating units and updating the coefficients that are key to channel interpretation.

8. CONCLUSION

22 GHz WVR for tropospheric phase correction is a viable strategy but it has yet to be demonstrated at scale at the VLA. The nCWVR at its core is a sensitive instrument design but a failure to properly implement VFC based readout has meant that almost no usable data has come from the project. If a replacement readout system can be made without significant investment then nCWVR could still be a useful tool for ngVLA. We are assessing the options available to replace the readout system. If the nCWVR still requires significant investment to become viable, then it is reasonable to move resources to other projects.

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