Water Vapor Radiometer Design Description

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Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	2018-02-12	Ford	All	Initial draft, feedback on Section 3 & 4
0.2	2018-05-01	Erickson	All	Content
1.0	2018-09-26	Erickson	All	Final
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3.0	2019-05-31	Selina	3.1, 3.3	Minor edits for release.
A	2019-07-26	Lear	All	Prepared PDF for signatures and release

Table of Contents

1 Introduction

1.1 Purpose

This document provides a description for the Water Vapor Radiometer (WVR) subsystem reference design. It covers the design approach, functions, description of key components, interfaces, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the entire design of the WVR Subsystem, as part of the ngVLA Reference Design. It includes the subsystem's design, how it functions, and interfaces with the necessary hardware and software systems. It does not include specific technical requirements or budgetary information.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents may not be directly referenced herein but provide necessary context or supporting material.

Ref. No.	Document Title	Rev / Doc. No.
AD00	ngVLA WVR Subsystem Preliminary Requirements	020.45.00.00.00-0001-REQ
AD01	Fast Switching Calibration at the ngVLA Site	ngVLA Memo No. 1
AD02	Calibration Strategies for the ngVLA	ngVLA Memo No. 2
AD03	The Concept of A Reference Array for the ngVLA	ngVLA Memo No. 4
AD04	Considerations for a Water Vapor Radiometer System	ngVLA Memo No. 10
AD05	Results of Water Vapor Radiometry Tests at the VLA	EVLA Memo No. 73
AD06	A Study of the Compact Water Vapor Radiometer for Phase Calibration of the Karl G. Jansky Very Large Array	EVLA Memo No. 203

2.2 Reference Documents

The following documents are referenced within this text:

Ref. No.	Document Title	Rev / Doc. No.
RD01	Fast Switching Calibration at the ngVLA Site	ngVLA Memo No. 1

3 Subsystem Overview

3.1 Motivation

Relative phase across a pair of antennas (a baseline) is a key measurable of synthesis arrays. Noise in this signal is contributed by the electronics and by the atmosphere. Water vapor is the largest contributor to atmospheric phase noise. One way to reduce the influence of atmospheric phase noise is to slew all antennas to a calibrator source periodically throughout a science observation in order to calculate the atmospheric phase noise contribution so that it may be subtracted from the science data. This is called fast switching, as the switching interval is much smaller than the science observation.

For a given period in which science may be performed, fast switching reduces the available time-on-sky for the science data by the time necessary to slew to calibrator, observe the calibrator, and slew back to science. Worse, the switching interval decreases as observation frequency increases and also as atmospheric stability decreases. At the highest ngVLA observation frequencies and under normal atmospheric conditions, switching would occur at 30-second intervals [RD01].

It is the goal of the WVR to allow a dramatic increase in this switching interval, as well as reduce any residual atmospheric phase perturbations that corrupt the astronomical data between calibrator observations.

3.2 Operation

The WVR constantly observes an atmospheric water vapor emission line centered at 22 GHz in order to track changes in the column density of water vapor in the WVR beam. Before the observation, a calibrator is observed (as in switching) to establish an absolute phase offset between antennas and WVR-estimated column density is noted. By monitoring changes in the water vapor column density throughout an observation, estimates of change in phase can be applied to the science data. Periodically—but with a much larger interval than that of fast switching—the calibrator can be re-observed to re-establish absolute phase offset.

3.3 Construction

The WVR consists of a 1.2-meter antenna mounted to the main feed arm as shown in Figure 1 and Figure 2, in which the WVR dish is colored red.

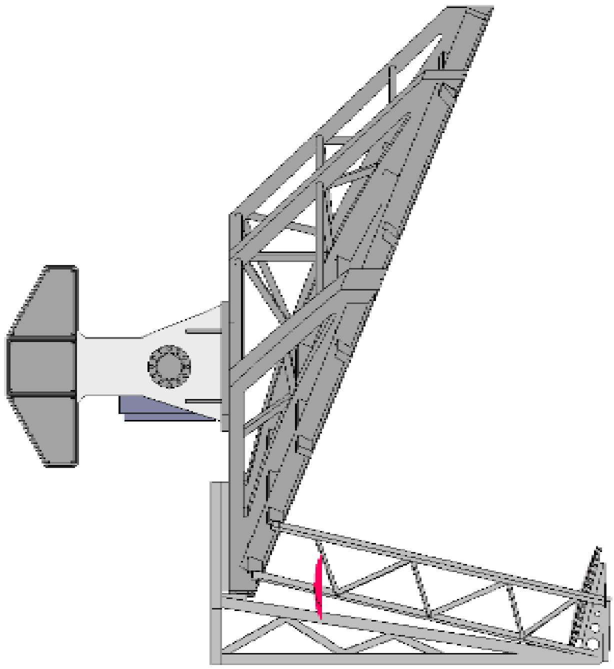

Figure 1 - Main and WVR dishes, side view. Antenna design shown is diagrammatic only.

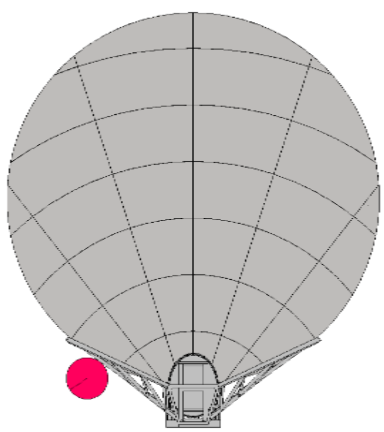

Figure 2 - Main and WVR dishes, front view. Antenna design shown is diagrammatic only.

The fixed WVR beam is aligned parallel to the main antenna beam. The WVR antenna architecture is Offset Prime Focus. The feed, receivers, digitizers, and support electronics are located in a module mounted to the main feed arm at the offset focal point. A mounting plate connected to the antenna's liquid cooling system provides a heat reservoir. Front End and receiver and digitizer electronics are thermally stabilized using Peltier heat pumps. A band from 18–32 GHz is digitized in the receiver module and digital data is streamed via fiber to the WVR processor in the pedestal room. Low-data-rate output is emitted into the Monitor and Control data stream.

4 Subsystem Design

4.1 Subsystem Block Diagram

Figure 3 shows the basic layout for the WVR subsystem.

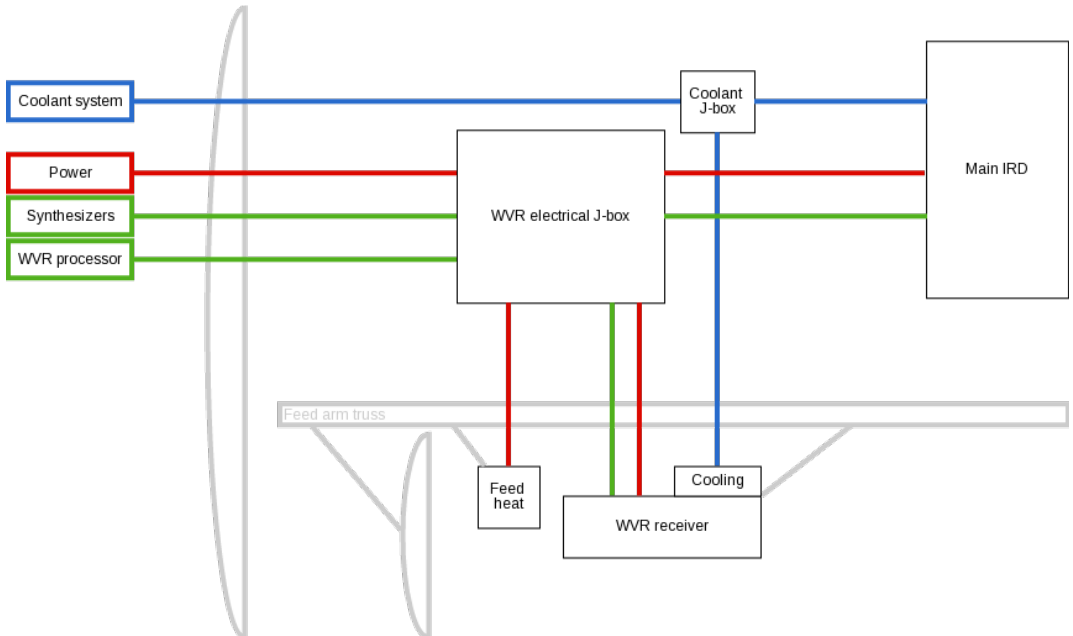

Figure 3 - WVR subsystem overview and interfaces.

4.2 Subsystem Components

4.2.1 Antenna

The antenna is a 1.2 by 1.4 m parabolic dish designed for offset prime focus use, built by General Dynamics and targeted at the Very Small Aperture Terminal (VSAT) customer base. It is constructed of glass fiber reinforced polyester and is rated for a working wind load of 50 mph and survival to 125 mph. Note that the WVR antenna is not acting as a power collector, but rather as a view-limiting device to ensure that atmospheric conditions in the main antenna beam are accurately sampled. The minimum size of the antenna was calculated to achieve a WVR beam diameter at 22 GHz that is close to the beam diameter of the main antenna beam at 2 km altitude, under which most water vapor turbulence has been observed.

The antenna is mounted via truss to the starboard side of the main antenna truss. The WVR side of the truss supports a connection plate, to which an antenna mounting plate is attached via three adjustment bolts. The antenna mounts directly to the antenna mounting plate. Fine adjustment of antenna pointing is provided by the three adjustment bolts. Adjustment is expected to be performed only during installation and major maintenance. Pointing adjustment will be performed by using a software pointing calibration routine to center the main beam on a geostationary satellite with a K-band downlink, then manually adjusting the adjustment bolts on the antenna mounting plate to maximize WVR receiver output. Adjustment bolts are locked with locking nuts and safety wire to prevent motion.

4.2.2 Receiver Module

Figure 4 shows the basic WVR receiver module design.

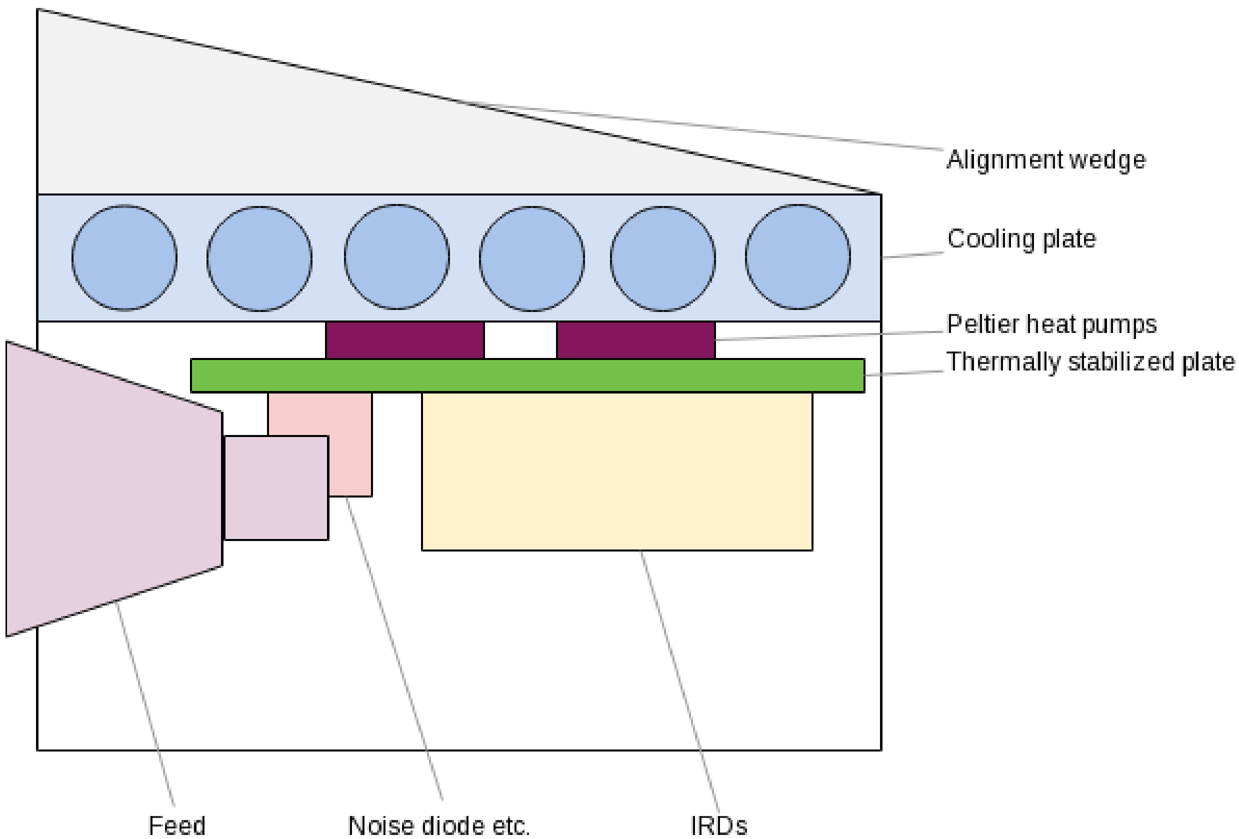

Figure 4 - WVR receiver module layout.

The module contains the feed, receiver, and all digitizing and processing electronics for the WVR. It is an aluminum enclosure with both weather and RFI gasket seals, and a sealed armor cable to protect power and data connections. The module mounts via cooling plate and offset wedge to the main feed arm truss at the correct point to place the feed phase center at the focal point of the WVR antenna.

Inside the module (Figure 5), RFI-tight compartments separate the feed, LNA, switched-power system, and receivers from the power supplies and thermal control boards. All RF components are mounted to a thermally stable plate that is kept at 30.00°C +/– 0.01°C by a control system driving Peltier-effect heat pumps. The heat pumps are thermally connected to the module wall that is thermally connected to the antenna cooling system. Thermal insulation around the thermal plate reduces thermal transfer from the enclosure walls, and an external heat shield reduces solar heating on the exposed module walls.

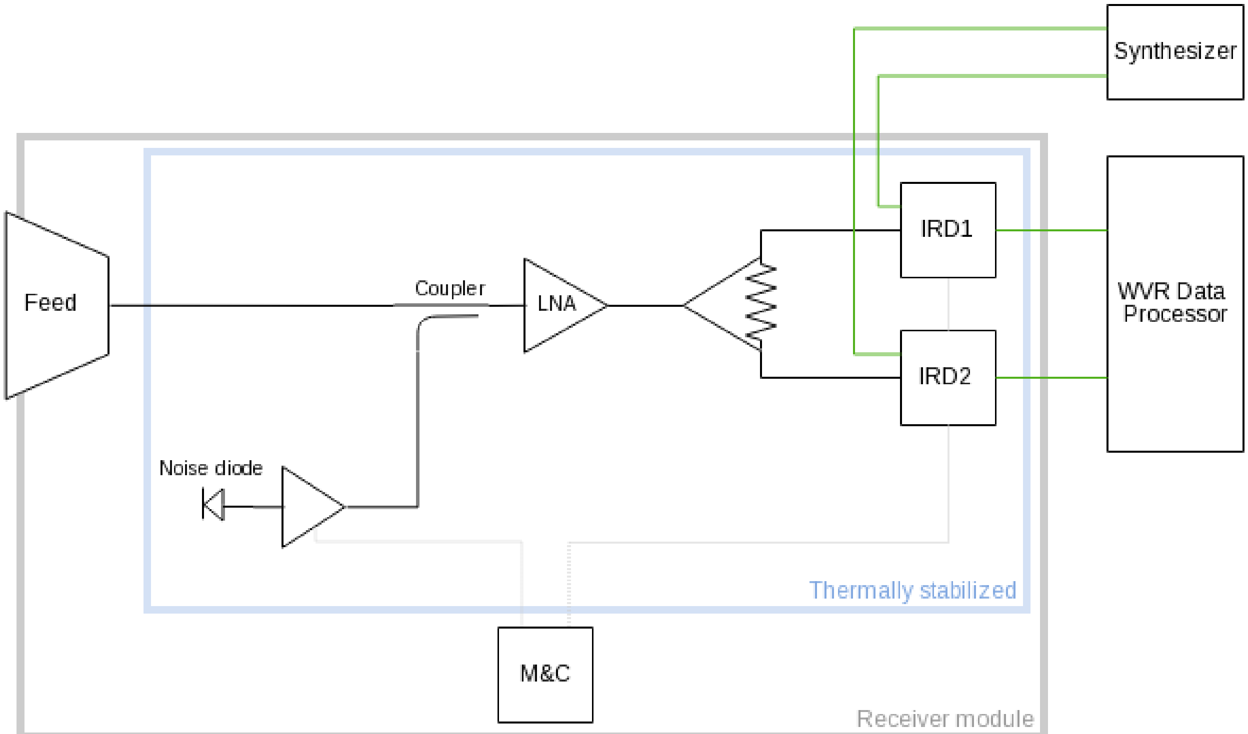

Figure 5 - WVR receiver module schematic.

4.2.3 WVR Junction Box

WVR power and fiber are connected at the WVR junction box located inside the main feed arm truss along the electrical conduit leading from the Pedestal Room to the IRD module. The junction box is a commercial weather-sealed electrical box specified for all-angle exposure. Sealed armor cable is used to convey –48 V power and M&C fiber to the WVR.

4.2.4 Alignment Wedge

A manually adjustable hinged wedge is mounted to the main antenna feed arm truss, and provides the mounting point for the cooling plate and WVR electronics module. The wedge provides the necessary feed angle relative to the WVR antenna in order to allow adjustment of the WVR beam to be parallel to the main antenna beam. The wedge contains a fine-adjustment mechanism to allow the feed angle to be precisely aligned during the WVR pointing/alignment procedure performed during installation and major maintenance. Adjustment bolts are locked after alignment with safety wire.

4.2.5 Cooling Plate

The WVR cooling plate is similar to the main IRD module cooling plate. Fluid cooled by refrigerators on the antenna pedestal is circulated through lines leading to the cooling plate, through channels in the cooling plate, and back to the pedestal room. Coolant temperature is maintained at 20°C +/– 5°C by a control system in the pedestal room. The WVR cooling plate contains channels for circulating fluid, and is removable for maintenance. Mounting holes allow attachment to the alignment wedge on one side and of the electronics module on the other.

Thermal transfer to the module is facilitated by flat-machined surfaces and silicone thermal-transfer gasket. Fluid connections are high-reliability drip-free quick-connects and fluid lines are nitrile-based hydraulic hoses protected by steel armor cable.

4.2.6 Feed

The wide-band feed is an mWave FPP1-222-S linear feed for K band 18.0–26.5 GHz. It is flange-mounted to the aft end of the receiver module with RFI and environmental gaskets. The feed terminates in an SMA-K female connector, and is protected from ultraviolet radiation and physical damage by a PTFE window.

4.2.7 Feed Heater

A radiant feed heater coil is mounted to the main feed arm aft of the feed and facing it. Power connections to the feed heater are supplied from the WVR junction box. Current is supplied to the heater through a solid-state relay in the WVR junction box which is controlled by the WVR processing module in the pedestal room. Feed heat is commanded by the antenna supervisor, which determines if conditions are necessary for feed heat based on weather data, feed temperature, and WVR data output. The supplied heat is sufficient to clear condensation from the window without damaging the window material.

4.2.8 Front End

A single polarization is taken from the K-band feed. A switched noise diode source is coupled to the feed signal, and a low-noise amplifier provides initial gain. A power divider provides the signal to the two Integrated Receiver/Digitizer modules, which amplify and filter, downconvert, and digitize the signals.

4.2.9 Integrated Receiver/Digitizer

The NRAO CDL has developed an Integrated Receiver/Digitizer (IRD) module to be used for ngVLA. The WVR will use two IRD modules, each of which consists of two independent receivers and digitizers. In total, four subbands covering K band will be sampled, with 32 100 MHz channels for each subband being produced by the WVR processing module.

To ensure precise calibration, one channel of each subband will overlap one channel of the neighboring subbands. The IRD digitizers will be configured to provide 8-bit samples to better handle RFI, an increase in which is expected over the array lifetime. Data is streamed over a custom transmit-only fiber link using QSFP28 transceivers directly to the processing module in the pedestal room.

4.2.10 Monitor and Control

Monitor and control in the receiver module is provided by a standard ngVLA M&C board. The board is connected to the M&C fiber network and provides control over the IRDs, switching diode, feed heaters, and all other electronics. All sensors, including feed and cold plate temperatures, system voltages, and system currents, are read by the M&C board and reported to the M&C network. The antenna supervisor software in the pedestal room analyzes conditions in the WVR and elsewhere and provides control over WVR power-up, operation, and safe shutdown.

4.2.11 Thermal Stabilizer

To determine water vapor column density, the amplitude of each spectral channel must be determined with an accuracy of about one part in 10,000. Fluctuations in gain and other parameters of the Front End electronics make this specification impossible to meet unless thermal stability is maintained to within about 0.01°C. To achieve this stability, the RF components and the digitizers are mounted to a thermal mass—the “cold plate”—which is maintained at a specified temperature to that accuracy.

The cold plate is manufactured out of 6063 aluminum, picked for its superior thermal conductivity. Through aluminum load plates, the cold plate is thermally connected to Peltier effect devices, which can pump heat through themselves in either direction based on supplied electrical current. The Peltier devices are thermally connected to the enclosure, then to the antenna cooling plate. The cold plate has thermal sensors mounted to it. The processor on the Monitor and Control board (details below) implements a control system to maintain the cold plate at the specified temperature.

4.2.12 Processing Module

The processing module is a Dell PowerEdge C4130 1U rack-mount server located in the pedestal room electronics rack, hosting a Bittware XUSP3S processing card. Four QSFP28 modules accept fiber data from the WVR receiver module. This server is also the host for the antenna supervisor processing board. RFI Shielding is provided by the pedestal rack.

4.2.13 Firmware

Data from the two IRDs is received via the QSFP link and read by the FPGA logic. A 32-channel polyphase filter (PPF) channelizes the data from the four subbands. Integration of 100–1000 ms is performed per-channel. Detection algorithms flag channels affected by RFI. Calibration routines join the subbands and normalize the bandpass. An ARM processor soft-core is then triggered to process the channel data to determine the water vapor column density in the WVR beam, and the data is emitted onto the M&C network. The processor board also networks M&C data for itself, IRDs, temperature controller, power supplies, and all other electronics in the module.

4.3 WVR Locations

All 18-meter antennas in the array will be equipped with a WVR.

4.4 Interfaces with other Subsystems

4.4.1 Antenna Feed Arm Truss

The antenna will mount to the feed arm truss, and therefore must induce no undue loads from wind or thermal stress.

4.4.2 Antenna Liquid Cooling

The WVR receiver will use 20 W of cooling from the antenna cooling system, and will require one line each for outbound and return cooling fluid.

4.4.3 Antenna Air Cooling

The WVR processor will use 100 W of cooling, supplied by the common rack cooling air.

4.4.4 Local Oscillator

Four LO clocks are provided to the WVR electronics module via fiber from clock synthesizers in the pedestal room.

4.4.5 Time

Accurate observation time will be provided to the data processing module by the array's Time Distribution System.

4.4.6 Monitor and Control

The WVR processor will use 100 kB/s on the M&C Ethernet over a single fiber connection.

4.4.7 Power

The WVR receiver will consume 20 W of power from the antenna supply. The WVR processor will use 100 W of power from the common pedestal rack supply.

5 Appendix

5.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
CDL	Central Development Laboratory, NRAO
DBE	Digital Back End
DTS	Data Transmission System
IF	Intermediate Frequency
LNA	Low-Noise Amplifier
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NSF	National Science Foundation
PLL	Phase Locked Loop
PFB	Polyphase Filter Bank
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
TBD	To Be Determined
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer