Water Vapor Radiometer Subsystem: Design Description

020.45.00.00.00-0002-DSN

Status: **RELEASED**

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Change Record

Version	Date	Author	Affected Section(s)	Reason
0.1	2018-02-12	Ford	All	Initial draft, feedback on Sections 3 & 4
0.2	2018-05-01	Erickson	All	Content
1.0	2018-09-26	Erickson	All	Final
2.0	2019-04-30	Erickson	All	Minor revisions to prepare for IPT Lead review
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
A.01	2021-12-06	Hales	All	Major edit of all content.
A.02	2021-12-09	Hales	4.4.3, 4.4.12, 4.6, 4.8.3	Minor edits to voltages, regulator locations, and power budget.
A.03	2021-12-20	Hales	4.1, 4.8	Minor clarifications regarding interfaces.
A.04	2022-02-04	Hales	4.4.8, 4.4.13	Minor edits regarding noise diode timing.
B	2022-02-04	Lear	All	Formatting, copy edits; prepared PDF for signatures and release.
C	2022-05-31	Hales	4.1, 4.4.8, 4.4.10, 4.4.13, 4.4.14, 4.8.5, 4.8.6	Minor clarifications: timing, D502 cooling.

Table of Contents

1 Introduction

1.1 Purpose

The purpose of this document is to define the design of the ngVLA Water Vapor Radiometer (WVR) subsystem for the Conceptual Design phase of its development.

The design is driven by the requirements stated in [AD01] and the purpose of the design description is to define a design that can meet all the requirements stated in [AD01]. Compliance of the design to the requirements is defined in [AD02].

1.2 Scope

This design description is a holistic definition of the design, including performance, functional, mechanical, environmental, safety, reliability, availability and maintainability characteristics. This document also describes compliance with external interfaces in cases where they have a direct impact on the design.

This document does not include cost information; see [RD02].

2 Related Documents and Drawings

2.1 Applicable Documents

The following compliance documents are applicable to this document:

Ref. No.	Document Title	Rev/Doc. No.
AD01	Water Vapor Radiometer Subsystem: Technical Requirements	020.45.00.00.00-0001-REQ
AD02	Water Vapor Radiometer Subsystem: Compliance Matrix	TBD (needed for PDR/FDR)
AD03	ngVLA WVR Volume, Mass, and Location Requirements	020.45.00.00.00-0004-DWG

2.2 Applicable Interface Control Documents

The following interface compliance documents are applicable to this document:

Ref. No.	Document Title	Rev/Doc. No.
AD50	Antenna Electronics to ANT Subsystem ICD	020.10.40.05.00-0011-ICD

2.3 Reference Documents

The following reference documents are cited within the text and provide supporting context:

Ref. No.	Document Title	Rev/Doc. No.
RD01	ngVLA PBS	020.10.20.00.00-0004-DSN
RD02	ngVLA Cost Model	TBD
RD03	ngVLA N^2 Interface Control Diagram	020.10.40.00.00-0001-DWG
RD04	Survey of Previous 22 GHz WVRs for Radio Astronomy	020.45.01.00.00-0001-MEM
RD05	ngVLA WVR Feed and Optical Design Trade Study	020.45.01.00.00-0002-MEM
RD06	ngVLA WVR Receiver and Digital Processing Trade Study	020.45.01.00.00-0003-MEM
RD07	ngVLA WVR Switched Power Integration Time	020.45.01.00.00-0004-MEM
RD08	ngVLA WVR Tsys Measurement Model	020.45.01.00.00-0005-MEM
RD09	ngVLA Calibration Requirements	020.22.00.00.00-0001-REQ
RD10	ngVLA Antenna Electronics Block Diagram	020.20.00.00.00-0005-BLK
RD11	ngVLA Integrated Downconverters and Digitizers Design Description	020.30.15.00.00-0002-DSN
RD12	ngVLA M&C Hardware Interface Layer: Design Description	020.30.45.00.00-0004-DSN
RD13	ngVLA Power Supply Design Description	020.30.50.00.00-0002-DSN
RD14	ngVLA Digital Back End/Data Transmission System Design Description	020.30.25.00.00-0002-DSN

3 Subsystem Overview

3.1 Objective

The objective of the WVR subsystem is to reduce wavefront arrival time errors at ngVLA antennas by freezing the atmosphere on timescales faster than realistically accessible through calibrator fast switching.

3.2 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 noise contribution so that it may be subtracted from the science data. This is called fast switching, as the switching interval is much shorter than the science observation.

Fast switching is unable to correct for residual atmospheric phase noise that will corrupt the astronomical data on time scales faster than the switching period. Furthermore, for a given period in which science may be performed, fast switching reduces the available time-on-sky for the science data (observing efficiency) due to the need to slew to a calibrator, observe it, then slew back to the science target.

The purpose of water vapor radiometry is twofold: (1) to enable continuous tracking and correction of atmospheric phase noise between calibrator observations so as to minimize errors and improve the quality and utility of the corrected scientific data, and (2) to allow a dramatic increase in the calibrator switching timescale from tens of seconds without WVR to at least 5 minutes with WVR.

3.3 Operation

The WVR subsystem is responsible for measuring fluctuations in the brightness temperature of atmospheric water vapor in the main antenna astronomical beam using a water vapor radiometer. These data are used to infer changes in the column density of water vapor and, in turn, continuously solve for the variable propagation delay toward each antenna during periods between astronomical calibrator measurements.

A dedicated WVR antenna and receiver is used to constantly observe a band spanning 19.7 – 31.0 GHz, encompassing the pressure-broadened $6_{16} \rightarrow 5_{23}$ rotational transition of water vapor at 22.235 GHz. A wide band is accessed to account for the vertical structure and temperature of water vapor in the troposphere, and to distinguish corrupting spectral features such as contributions from water droplets in clouds. The band is channelized at 100 MHz resolution to provide tolerance to existing and future sources of RFI. The fixed WVR beam is aligned near-parallel to the main antenna beam, with appropriate overlap as a function of elevation for all applicable zenith angles.

At the start of an observation, an astronomical calibrator is observed to establish the absolute ratio between interferometer-observed delay fluctuations and WVR-observed brightness temperature fluctuations. By monitoring changes in the water vapor brightness temperature throughout an observation, estimates of change in antenna-dependent radio path delay can be applied to the science data. Periodically, but with a much larger interval than that of fast switching, the calibrator is re-observed to re-establish the absolute delay to temperature fluctuation ratio. For single dish astronomical observations (total power), periodic interferometric observations are required to calibrate this ratio; absolute radiometry is not supported. The WVR subsystem will not be utilized for phased array observations (near real-time data processing). The WVR receiver incorporates a switched noise diode to enable cancelation of gain fluctuations.

The WVR receiver and digitizer electronics operate at near-ambient temperature within an insulated and actively thermally controlled environment. Digitized data is passed to an independent WVR digital processing module for channelization. Offline software developed by the WVR subsystem and deployed and maintained by the Computing and Software (CSW) subsystem is used to process the channelized brightness temperature data, together with astronomical calibrator data and weather monitor data, to yield delay corrections to be applied to the astronomical science target data.

A WVR will be installed on each of the 244 x 18m antennas as well as 6 x dedicated tracking mounts situated within the footprint of the 6m antenna Short Baseline Array (SBA).

3.4 Context

22 GHz water vapor radiometry has been used successfully for scientific operations at several observatories, notably the Owens Valley Radio Observatory (OVRO; USA) 6-antenna interferometer from 1999, the NASA Goldstone (USA) tracking station from 2000 to support the Cassini spacecraft gravity wave experiment, the Plateau de Bure 6-antenna interferometer (PdBI; France) from 2001, and the Australia Telescope Compact Array (ATCA) 6-antenna interferometer from 2011. The successor to PdBI, the Northern Extended Millimeter Array (NOEMA) 12-antenna interferometer, is deploying updated WVRs in 2022.

The ngVLA will build and deploy several times more 22 GHz WVRs than developed for all previous astronomical observatories combined. [RD04] presents a review of previous 22 GHz WVRs.

4 WVR Subsystem Design

4.1 Subsystem Architecture

The WVR subsystem is a total power telescope with a dedicated antenna reflector, front end, receiver, digitizer, back end channelizer, and offline calibration software that is used to infer tropospheric delay calibration solutions and apply them to the science data to be delivered to ngVLA users.

Figure 1 presents an overview of the WVR subsystem including physical layout and a subset of interfaces with other ngVLA subsystems. A complete listing of interfaces with other subsystems is provided in Section 4.8.

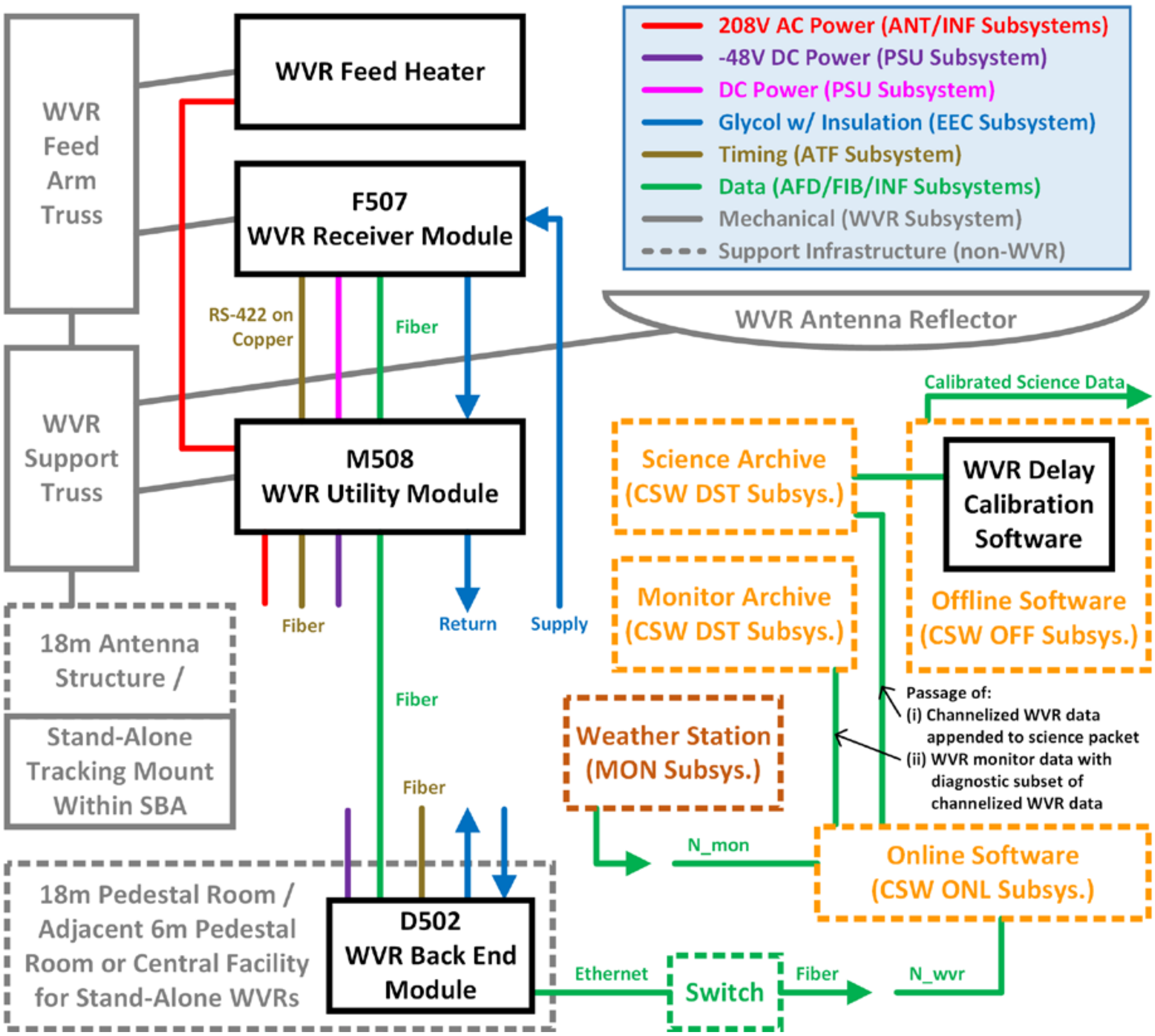

Figure 1: WVR subsystem overview and interfaces.

Selected aspects of the WVR subsystem design described in this document are displayed in the ngVLA Antenna Electronics Block Diagrams [RD10], specifically the sheets titled "Top Level," "Water Vapor Radiometer," and "Electronics Rack."

4.2 Key Features

The critical performance characteristics for a WVR are sensitivity, stability, and systematic error handling.

Key features of the WVR subsystem architecture and design are:

- 22 GHz water line selected because the 183 GHz line is too saturated at almost all ngVLA sites
- Empirical radiometric calibration approach tied to regular interferometric observations of an astronomical calibrator, designed to accurately measure small changes in wet delay through the troposphere rather than the total wet delay targeted by absolute radiometry
- Wide-band coverage from 19.7 – 31.0 GHz (wavelengths from 1 – 1.5 cm) with 100 MHz channel digital sampling for RFI tolerance and ability to discriminate spectral systematics arising from different meteorological conditions at the variety of ngVLA sites, including the continuum signature from water droplets in clouds
- Feedhorn, front end, receivers, and digitizers located within a compact module with 3 stages of active thermal control, utilizing 2 Peltier heat pumps and circulated glycol, to ensure high stability
- Feedhorn integrated within the innermost thermal regulation stage together with the LNA, with the feed located behind weather and infrared-shielding windows to support tight thermal control and improve performance during non-precision observing conditions with incident solar radiation
- Non-cryogenic front end to minimize power consumption and mass
- Single polarization to improve sensitivity and minimize mass
- Temperature-regulated noise diode for switched power determination of gain variations
- 8-bit digitizers to provide resilience within the emerging and future RFI landscape
- Digitized data is streamed via fiber to a dedicated back end digital processing module for channelization and subsequent transmission to central repositories over the M&C data stream
- Customized delay calibration software to be supplied to the Offline Software subsystem for open source release and integration within the ngVLA automated data processing pipelines
- Offset prime focus optics with unblocked aperture and low spillover to minimize systematic errors during antenna slews between calibrator and target
- Placement of power supplies and an M&C interface board under the WVR dish rather than at the focal point, to reduce complexity and mass of receiver module on feed arm
- SBA WVRs installed on standalone tracking mounts to simplify 6m antenna design
- No moving parts, with the exception of a low-maintenance az-el tracking system on the SBA standalone mounts, for improved reliability, low maintenance, and low life-cycle costs
- Commercial components where possible to minimize cost

4.3 WVR Locations

The ngVLA will comprise 244 x 18m antennas with baselines ranging from approximately 30m to 8860km, and 19 x 6m antennas in the SBA with baselines ranging from approximately 11m to 60m.

All 244 x 18m antennas will be outfitted with a WVR dish and associated F507, M508, and D502 Modules. The location of the WVR dish on an 18m antenna structure is illustrated in Figure 2. The WVR beam is installed with fixed orientation, aligned near-parallel with the main antenna beam. The optical axes intersect at 2.4 km fixed distance along the main boresight [AD01]. The D502 Module is located in an electronics rack in the pedestal room, where electronics for the main front ends are also located.

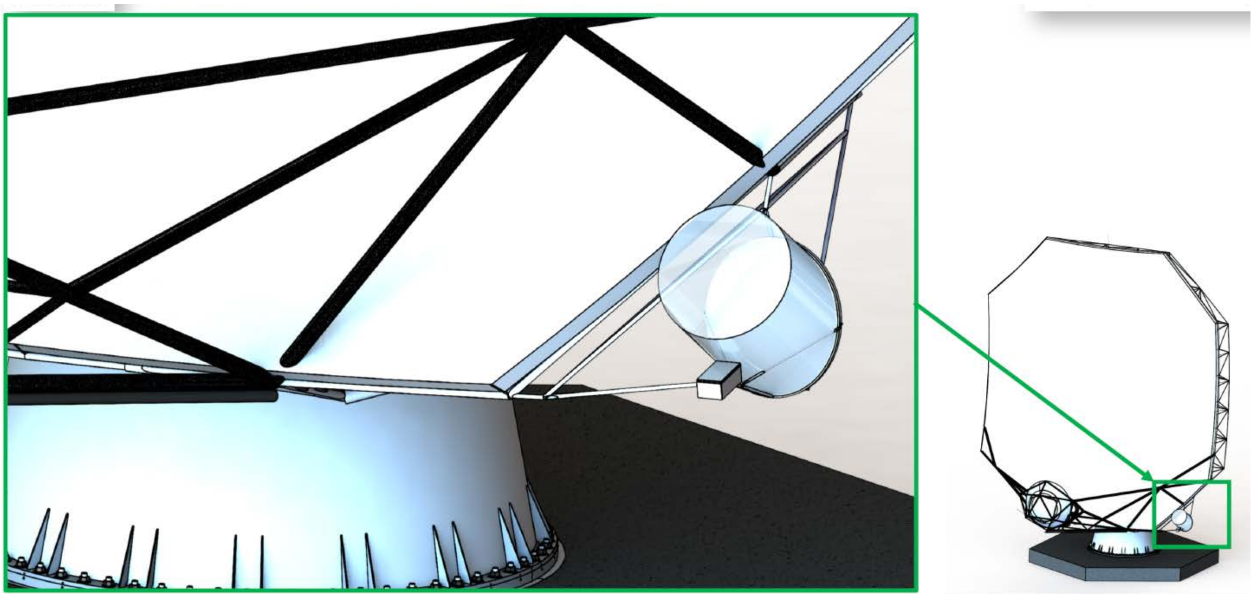

Figure 2: Location of WVR dish and F507 Module on main 18m antenna. The WVR optical beam is visualized.

To simplify design of the 19 x 6m antennas, WVR outfitting capability is not required. Instead, 6 dedicated standalone tracking mounts will be deployed, each alongside a nominated 6m antenna. Of these, 4 will be placed near the periphery of the SBA footprint and 2 will be placed near the center of the array. Each will be positioned to minimize shadowing by their assigned 6m antenna or nearby antennas, and to ensure that for any line of sight to the sky there will be at least 2 unobstructed WVR baselines. Only one of these unobstructed baselines is needed at any one time for calibration purposes; the second is provisioned for operational redundancy. (Having at least 3 baselines in the SBA WVR array will also enable phase closure testing.) Each tracking mount will be outfitted with a WVR dish, associated F507 and M508 Modules, and glycol heater/chiller unit. The D502 Modules will not be co-located at each tracking mount but will instead be placed within the pedestal rooms of their adjacent 6m antennas, or possibly in a central facility near the SBA footprint.

4.4 Subsystem Elements

4.4.1 Antenna with Support Trusses

The antenna is a commercial 1.45 m aperture parabolic dish (1.45 by 1.6 m) designed for prime focus, offset feed use. It is built by Sat-Lite Technologies (TX, USA) and targeted at the very-small-aperture terminal (VSAT) customer base as a vehicle-mounted satellite news gathering (SNG) antenna.

The commercial system is available with a Ka-band feed operating up to 31 GHz. The focal length is 116 cm (f/D of 0.8). The total mass is 71 kg, including the receiver system and a motorized az-el mount. The feed arm is capable of supporting an additional 45 kg of equipment. The commercial system is displayed in Figure 3 (next page). Only the dish is of interest for the ngVLA WVR.

Figure 3: Sat-Lite Technologies Model 1411 Peloris Class motorized 1.45 m vehicle-mount antenna.

The WVR antenna does not act 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 size of the antenna is determined by the requirement to achieve a 45' beam at 22.235 GHz, so as to sample the atmospheric water vapor present in the main beam of the hosting 18m antenna or nearby 6m antennas [see AD01 for details]. The offset between the main beam and WVR beam is sufficiently small [defined in AD01] to ensure suitable overlap as a function of altitude and elevation angle. The WVR antenna size is also determined by the need to deliver very low spillover with the feed described in Section 4.4.6, as this is important for minimizing delay measurement systematics across target-calibrator antenna slews.

The reflector is a single piece constructed from carbon fiber with typical surface accuracy ~0.3mm rms. It is rated for a working wind load of 20 m/s and survival to 35 m/s. The latter does not meet WVR subsystem requirements [AD01]. This limitation is addressed by affixing the reflector to a custom support truss.

The WVR reflector is mounted to a custom "support" truss with baseplate that is affixed, in turn, to the 18m antenna truss (Figure 2) or to the standalone tracking mount. Fine adjustment of the WVR antenna pointing is provided by adjustment bolts at the baseplate, or possibly using adjustment rods similar to those selected for the 18m antenna subreflector backup structure (BUS) interface. Adjustment is expected to be performed only during installation and major maintenance. Pointing adjustment will be performed 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 to maximize WVR receiver output. Adjustment bolts are locked with locking nuts and safety wire to prevent motion.

A second custom "feed arm" truss is used to position and accurately bolt the F507 Receiver Module at the offset prime focus in a feed low configuration (i.e. feed near horizon for a horizon pointing beam), noting that the feed will not be centered in the F507 module. The feed arm truss includes a fine-adjustment mechanism to allow the feed angle to be precisely aligned during pointing/alignment procedures described above. The adjustment bolts are locked as above to prevent motion.

The feed arm truss provides mounting points for cables and rigid piping for glycol lines. A lift (e.g. vehicle-mounted) is required to install the F507 on the 18m-hosted WVR truss (when the 18m main feed arm is oriented near the ground). The F507 on the standalone tracking mount is accessed directly when standing on the ground, for a zenith pointing dish. A safety bracket is provisioned to counter gravity for the F507 module during installation, where the feed will be pointing slightly above the horizon, so as to prevent injury or damage from falling objects or accidental release of glycol fluid.

The custom trusses and baseplate are manufactured from a combination of CFRP and steel, with insulation to protect against galvanic corrosion and thermal stress between carbon fiber and metal.

The feed described in Section 4.4.6 could be made slightly more compact by reducing the focal length. The option to procure a custom single-piece dish from Sat-Lite is available. As this is pursued, options to improve the wind rating using a stiffer dish, trading off truss mass, will be investigated. Similarly, conductor loss in a carbon fiber dish may be improved using a highly conductive coating, or by adding a copper mesh sublayer during fabrication of the dish.

Lightning protection is provisioned to ground the WVR structure to the 18m antenna or the standalone tracking mount. Two lightning rods are located on the WVR feed arm truss, behind the receiver module, pointing away from the WVR dish.

4.4.2 Tracking Mount in SBA

Six tracking mounts are provisioned within the footprint of the SBA, as described in Section 4.3.

Each mount is built using two commercial products: a pier and a tracking system. The antenna and trusses described in Section 4.4.1 are bolted to the tracking system, which is in turn installed on the pier affixed to the ground.

The base of the mount is a Radio2Space (R2S) C106-HEAVY pier, designed to be installed on a reinforced concrete base and fixed by high-strength bolts. It is built by PrimaLuceLab SpA (Italy) and targeted at the amateur and educational[1] communities to access professional radio astronomy and ground station technologies. The concrete base designs and complete installation instructions are supplied.

The mount head is a R2S GS-100 azimuth-elevation tracking system, also built by PrimaLuceLab SpA. It has a 100 kg load capacity, is weatherproof with reliability and performance in severe environments, and exhibits tracking precision that greatly exceeds the WVR requirements.

The R2S pier and tracking system are shown in the example in Figure 4 (next page). The tracker has az-el motion.

[1] A Radio2Space SPIDER 300A 3m telescope system is installed at the Etscorn Observatory at New Mexico Tech.

Figure 4: R2S SPIDER 300A 3m telescope with C106-HEAVY pier on concrete base and GS-100 tracker.

4.4.3 F507 Receiver Module

The F507 receiver module houses the WVR feedhorn, Front End, Integrated Receiver and Digitizer (IRD) modules, LO & Timing module, voltage regulators, and temperature controllers within a weather-resistant, thermally regulated, and RFI-shielded environment. The module bolts to the WVR feed arm truss at the correct point to place the feed phase center at the offset prime focus of the WVR antenna.

Figure 5 (next page) displays the signal path through the F507 and the degree of thermal regulation applied to the components. Figure 6 displays a complementary cross-section highlighting the layering used for thermal insulation and RFI shielding, heat transfer pathways between thermal stages, and an exaggerated depiction of venting considerations associated with the module lid.

The F507 module contains four thermally insulated stages. Three actively controlled inner thermal stages are situated within a passive outer environmental enclosure that acts as an external heat shield. All RF components are mounted to a plate within the innermost stage that is thermally stabilized to within 2 mK by a control system driving Peltier-effect heat pumps. The heat pump is thermally coupled to an intermediate stage plate that houses the IF electronics. The intermediate plate is regulated by a second Peltier heat pump that is, in-turn, coupled to the outermost actively regulated plate through which glycol is circulated. The glycol plate acts as the thermal dump for heat generated by the active components in the F507. A glycol ceiling plate is used to provide active thermal control across the upper surface area. All active components in the F507 operate continuously to encourage settling to stable temperatures and stable temperature gradients.

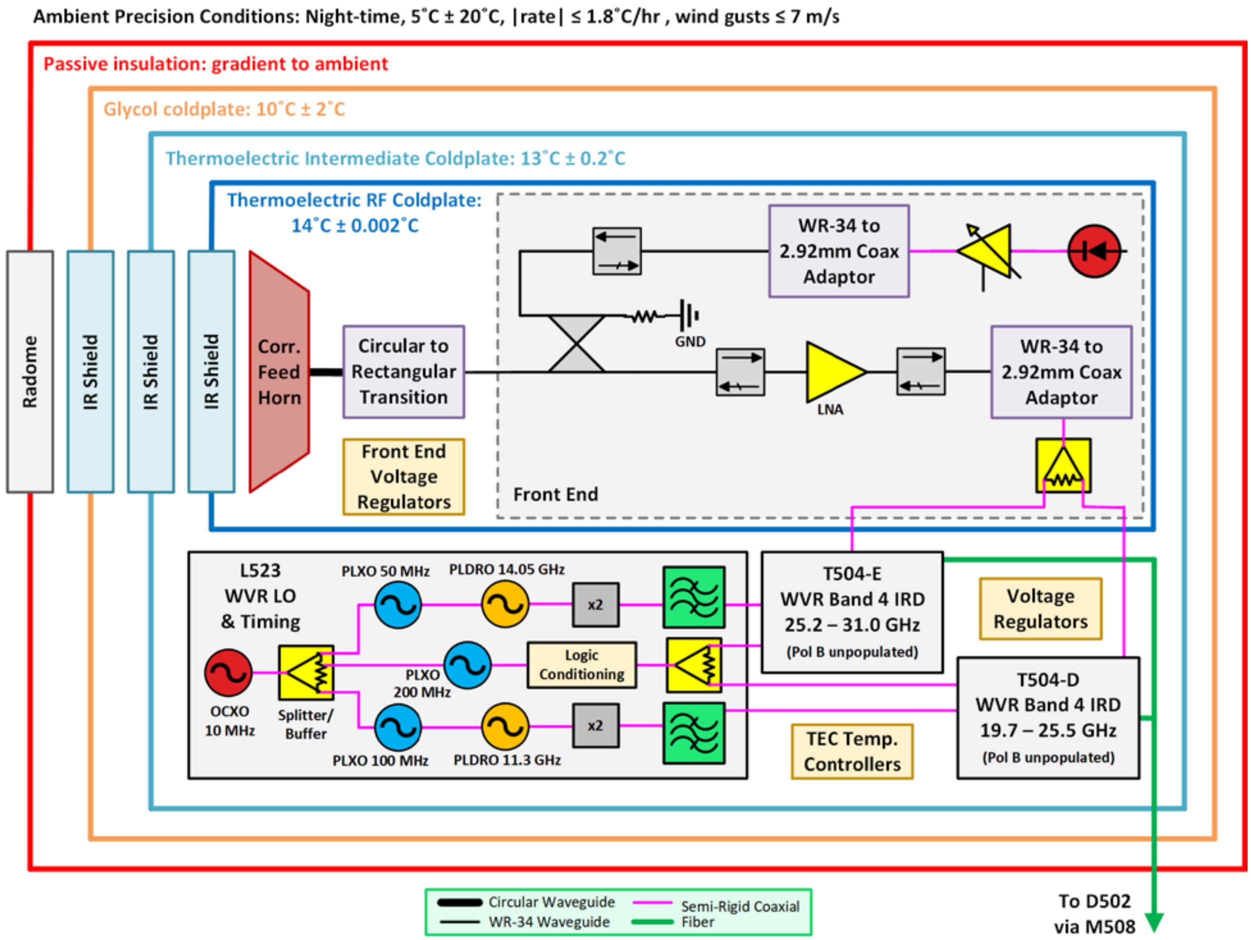

Figure 5: F507 WVR Receiver Module schematic, with approximate physical layout as viewed from the top.

The module is accessed for maintenance by opening a lid that contains the ceiling glycol coldplate. The lid and walls to the inner thermal stages incorporate small RFI-shielded low-flow vents to relieve barometric changes that will occur during module operation or as a result of ngVLA logistics and facility altitude differences. Such inevitable changes (even without the purposely-provisioned vent) will bring the likelihood of moisture entering the module. Changes in internal humidity will induce gain changes within the waveguide and coaxial components and cause condensation of water on the inner surfaces of the outer windows during cold weather[2]. Silica gel desiccant is placed in the vent airflow pathways to provide passive humidity control, with sufficient desiccant to maximize the replenishment maintenance timeframe to at least several years. Sealed armor cables are used to protect power, data, and glycol connections. Weather and RFI gaskets are provisioned.

The 100 MHz channels of the WVR are amplitude and bandpass calibrated in the field using two thermal sources — liquid nitrogen (LN_2) and an ambient-temperature source — as part of a standard "Y factor" calibration procedure. This procedure yields quasi[3]-absolutely calibrated Tsys, Tcal, and gain, after which

[2] The median dew temperature measured in 5 min intervals between 1977 - 2021 at the central ngVLA plains site where the 6m SBA and approximately 80% of 18m antennas are located is -2.6 C with MAD ±6.4 C.

[3] Continuum emission from water vapor frozen to the outside of the LN_2 styrofoam container will degrade the accuracy of the absolute calibration procedure.

the temperature-stabilized Tcal can be used in the field for switched power calculations to measure gain fluctuations during observations. This calibration procedure is performed for each F507 during installation/replacement on the WVR feed arm truss, but only after sufficient time (~1 hour) has passed to allow the internal electronics to thermally settle under active temperature regulation. This procedure is also performed earlier in the lab as part of quality control testing prior to packaging the module for storage. The F507 outer environmental enclosure contains a mounting bracket to support accurate placement of the hot/cold loads in front of the feedhorn radome.

The switched power system is unable to correct for gain variations arising ahead of the coupler, i.e. feedhorn, windows, and reflector. To compensate, the feedhorn is tightly thermally controlled with the front end, and standing waves are reduced through the use of isolators, feed windows that disperse reflected power, and off-axis optics (no reflector return path). This integration is also necessary to ensure stable characteristics for the calibration procedure described above, which will be performed in the field during a range of environmental conditions.

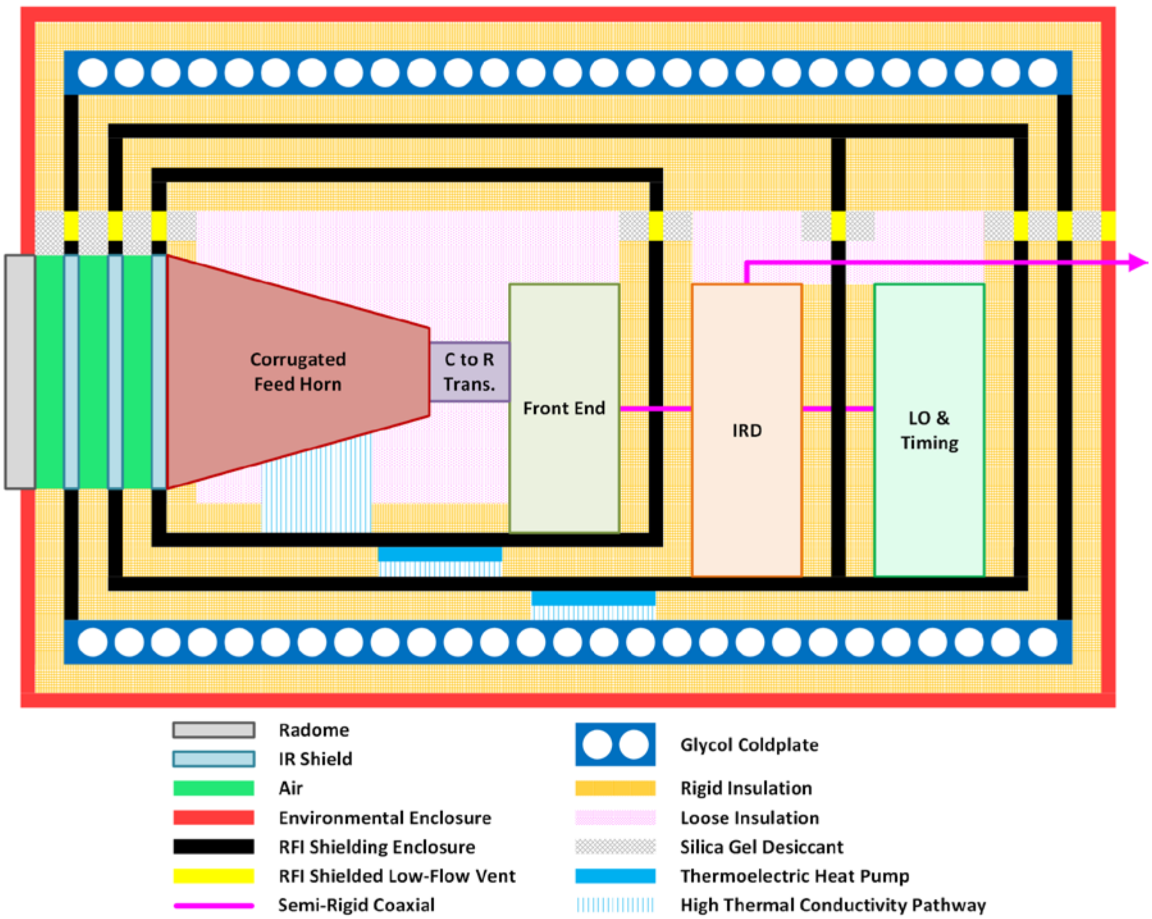

Figure 6: F507 WVR Receiver Module, with approximate physical layout as viewed from the side. For clarity in this diagram the IRD and LO & Timing Modules are displayed to the right of the Front End. Physically they will be placed alongside the inner thermal volume, as arranged in Figure 5 (i.e. overlapping in this view). Venting associated with the module lid is exaggerated in this diagram for clarity.

The calibration procedure described above does not require periodic Y factor calibration for deployed F507 Modules (equivalent of Dicke switching). Any slow degradation in the overall amplitude scale is accommodated within the empirical radiometry approach pursued by the WVR subsystem (see Section

4.4.15). Similarly, measurements of spillover temperature contribution are not required due to the low spillover design (note that sky dips are very difficult to perform to high accuracy due to atmospheric uncertainties).

To prevent degradation of module desiccant during transportation and potentially long-term storage, the F507 module will be enclosed in a storage case that contains additional desiccant that will be discarded upon F507 deployment.

The components of the F507 Receiver Module are described in more detail in the sections below.

4.4.4 Feed Heater

A radiant feed heater coil is mounted to the WVR feed arm truss, facing the feed but without obstructing the optics. The heater is a ceramic light bulb base with a circular heater element that screws in like a regular light bulb. The bulb is a quickly replaceable LRU. The supplied heat is sufficient to clear condensation from the radome without damaging the materials or adversely affecting the thermal/gain stability within the inner thermal envelopes in the F507.

AC power is supplied from a 208V outlet located in the 18m antenna apex or tracking mount. Current is supplied to the heater through a solid-state relay located within the environmental enclosure of the M508 Utility Module, but external to the inner RFI enclosure. Feed heat is commanded by the 18m antenna supervisor or, for the SBA-based units, a nearby 6m antenna (or entire SBA) supervisor. The supervisor also controls heaters for the main front ends and determines if heat is needed based on weather conditions. The M508 provides WVR override capability for feed heat for testing purposes.

4.4.5 Feed Windows

The feed is illuminated through 4 windows. The outer window, the radome, provides environmental protection for the inner windows and feed against ultraviolet radiation, moisture, and physical damage. The radome is made from HDPE foam (e.g. Propazote) with a pattern of v-grooves to reduce RF reflections and a thin outer layer of PTFE. The exterior PTFE surface is modified with an impressed cone shape to disperse reflected power away from the feedhorn. Three successive infrared (IR) filters are made from PTFE (e.g. Zitex) with impressed cone shapes. The IR filters are used to reduce thermal coupling from ambient conditions through to the strictly temperature-controlled inner volume in which the feed resides. Teflon brackets with low thermal conductivity are used to secure the windows. Air fills the narrow volumes between windows.

4.4.6 Feed

Radio emission from the dish is coupled to waveguide using a traditional radially corrugated feed horn (RCFH) with frequency coverage from 19 – 31.5 GHz, or 1.66:1 "waveguide" bandwidth ratio. It is compact and exhibits low spillover. For a prime offset optical configuration with approximately 87 cm focal length (f/D of 0.8) and 14.5 cm clearance from the reflector beam (c/D of 0.6), the following dimensions are estimated. The feed is 9 cm long with an opening diameter of 6 cm. It has a semi-flare angle of 14° that provides a high edge taper of -26 dB when subtending the 1.45m diameter reflector at a half-angle of 31°, and an aperture efficiency of 57%. The feed outputs dual orthogonal polarizations into 0.328" circular waveguide. The feed is to be prototyped by NRAO. It is relatively simple to fabricate with roughly quarter wavelength corrugations, making it suitable for mass production.

4.4.7 Circular to Rectangular Waveguide Transition

A transition from 0.328" circular waveguide to WR-34 rectangular waveguide is mounted to the output of the feed. The transition is continuous (rather than stacked plates), manufactured using standard electroforming techniques in which the mandrel is a set of tapered diagonal flats on four sides of a cylindrical dowel.

The transition effectively acts as an orthomode transducer with single linear polarization output. Circular and rectangular guides are both single-mode transmission lines over a limited bandwidth. A circular guide supports dual orthogonal polarizations. A rectangular guide only supports a single linear polarization orthogonal to the long dimension of the guide, assuming propagation of only the dominant (lowest frequency) mode.

4.4.8 Front End

The front end consists of discrete RF components. A switched noise diode source is coupled to the single polarization signal path from the transition. A low-noise amplifier (LNA) provides initial gain. A power divider splits the resulting signal to two IRD modules.

The noise diode is reverse-biased using current regulation for high stability. The diode is synchronized with sub-ms accuracy to network time (e.g. PTP) via the M508 Utility Module. The diode outputs analog white noise with a flat frequency response over a broad band and Gaussian amplitude distribution in the time domain. By periodically adding a noise reference, gain instabilities downstream from the coupler can be detected and calibrated. The injected noise temperature spectrum (Tcal), after passing through the electronics, is measured in the lab using hot/cold measurements and is temperature-stabilized during operation so that it is known during operation to within at most 0.6% error. This level of precision (but not necessarily absolute accuracy, due to the calibration approach described in Section 4.4.15) is necessary to ensure that gain drifts remain within the required 5 mK over 3° antenna slews (with maximum 0.8 K change in system temperature in precision operating conditions) between sightlines toward the astronomical calibrator and target [RD08] (calculated assuming the system temperature model described in Section 7.1.9 of [AD01]).

The ratio between injected noise temperature and system temperature must be 1:1 to track gain fluctuations to within the demanded 0.012% within a bandwidth of 1.45 GHz (set to half the 2.9 GHz sideband) in 1 sec, assuming a diode duty cycle[4] of 25% [RD07]. These values will also be sufficient to yield sensitivity within the required 50 mK in a 100 MHz channel within 1 sec[5], assuming a maximum system temperature of 420 K in precision operating conditions (see Section 4.5), and to track gain drifts to better than 0.05/420 = 0.0012% within a 100 MHz channel over 5 mins. To achieve this, variable gain is included in the diode path, i.e. an amplifier followed by a variable attenuator. It is expected that these additional components will be necessary to produce a noise temperature equal to the 420 K system temperature. The attenuator will be initially set to an appropriate level then remain fixed throughout operations.

Small reflections and associated standing waves are inevitable along the antenna signal path. The magnitude and phase of these reflections, and any instabilities in the standing waves (e.g. reflections off the radome, which is exposed to ambient temperature fluctuations), have the potential to corrupt the utility of the noise diodes for accurate gain calibration. Isolators are placed ahead and behind the LNA to minimize impedance mismatches and resulting standing waves. An isolator is also placed between the coupler and

[4] This calculation is independent of switching frequency. However, short pulses are desirable to minimize thermal cycling. To restrict diode firing time to <2 ms with 25% duty cycle, the switching frequency must be >125 Hz.
[5] This accounts for the firing duty cycle; i.e. the integration time, free of Tcal, is only 0.75 sec.

noise diode. A broadwall coupler with high (35 dB) directionality provides attenuation of the noise diode signal toward the feed. The feed windows are designed to minimize reflections (see Section 4.4.5).

To minimize losses, WR-34 waveguide components and transmissions lines are selected until after the LNA, before the splitter. WR-34 is formally rated between 22 – 33 GHz. While capable of operating close to the cutoff frequency at 17.3 GHz, increasingly significant performance degradation below the optimal 22 GHz lower edge suggests a practical limit near 19 GHz. The WVR subsystem will operate[6] down to 19.7 GHz. Coaxial 2.92mm (K) connectors are rated up to 40 GHz.

4.4.9 Integrated Receiver and Digitizer

The F507 Receiver Module will incorporate two minimally-modified ngVLA Band 4 IRD modules to further amplify, downconvert, filter, and digitize the signals from the Front End. Re-use of IRD modules designed for the main antenna signal path will yield significantly reduced design/development/production costs and risks with important benefits of minimized volume/mass/power and operational simplification for maintenance and spares inventory.

Each unmodified Band 4 IRD [see RD11] contains two sideband separating (2SB) receivers with shared LO input to facilitate dual polarization, RF tuning range between 20.5 – 34 GHz, instantaneous bandwidth of 5.8 GHz (2.9 GHz per sideband), and 8 bit interleaved Serial ADCs with quadrature sampling per polarization that provide direct-to-baseband downconversion. Unformatted data is output is via fiber-optic transceivers.

To avoid eroding the benefits of using an "already designed" module, two modifications with minimal overheads are pursued for application in the WVR subsystem.

First, only a single polarization channel will be utilized in each IRD. As a result, 2 IRD modules with independent LOs are required to provide continuous RF sampling from 19.7 – 31.0 GHz, with 300 MHz overlap to facilitate precise calibration while accounting for the IRD's IF anti-alias filter edges. To minimize redesign effort, unnecessary components for the second channel may be deleted, but the power supply, M&C, and IF circuit board will retain their dual-channel layouts with the superfluous elements unpopulated or dormant. The modified IRD will therefore be cheaper than a dual-channel module and consume less power. Testing is needed to verify performance below 20 GHz (the lowest frequency currently tested), where the gain slope of the RF amplifier is dropping off at approximately 4 dB/GHz. However, this is not anticipated to be of significant concern for the WVR use case. Should performance be degraded to an unacceptable level, the lower edge can be instead fixed at 20 GHz. (Alternatively, testing may reveal sufficient performance down to 19 GHz, in which this cutoff will be pursued.)

Second, fixed LO frequencies at 22.6 GHz and 28.1 GHz will be utilized. These are different to the fixed LO frequencies needed for the main antenna Band 4 signal path at 23.2 GHz and 29.0 GHz. This change is not anticipated to require any changes to IRD design, though lab calibration and testing for the modified IRDs will of course differ slightly.

4.4.10 Local Oscillator & Timing for IRDs

The IRDs require fixed frequency LO sources at 22.6 GHz and 28.1 GHz, and a 200 MHz reference clock for the digitizers. Phase-locked dielectric resonator oscillators (PLDROs) are selected as these will provide sufficiently stable frequency and amplitude. To facilitate rapid diode switching and the calibration approach described in Section 4.4.15, WVR data must be sampled in the F507 Receiver Module and D502 Back End

[6] For reference, the main ngVLA Band 4 front end is planning to utilize WR-34 waveguide over 20.5 – 34 GHz.

Module synchronously with the main antenna/science data stream. However, to prevent generating RFI that would otherwise coherently affect the main science data stream, the WVR clock and LO are designed to be free-running (i.e. not phase-locked to the rest of the system) but with sufficiently accurate/synchronous timing to facilitate diode switching and calibration.

The WVR frequency sources are synchronized to an independent oven-controlled crystal oscillator (OCXO). The OXCO output is multiplied to obtain the LO for the IQ mixers and the digitizer clock. A frequency doubler is selected for the final stage of the PLDRO, as is typical for frequencies above approximately 20 GHz. The 200 MHz reference for the digitizers is generated by phase-locked crystal oscillators (PLXOs) referenced to the same 10 MHz OCXO, as shown in Figure 5.

4.4.11 F507 Voltage Regulators

The F507 Receiver Module contains linear voltage regulators that accept DC voltages from the M508 Utility Module (described in 4.4.13) and supply stable voltages to the F507 electronics. Regulators situated within the inner thermally controlled volume are used to supply +28V, +12V, +3.3V, +1.6V, and +0.15V DC the front end electronics (LNA, noise diode). Regulators situated on the intermediate coldplate are used to supply ±15V, +12V, ±5V, and +3.3V DC to the remaining electronics (IRD Modules, LO & Timing Module, TECs, temperature controllers). The regulators are enclosed within RFI shielding.

4.4.12 F507 Thermal Control

The front end electronics, particularly the noise diode and LNA, must be thermally stabilized in order to satisfy the gain drift requirement of 0.001% over 5 min. The most temperature sensitive component is the LNA with gain stability of 0.02 dB/K (0.5% per K). As a result, the RF components are mounted to a thermal mass – the "RF coldplate" – which is stabilized[7] to within 2 mK. To minimize thermal gradients and fluctuations, the feedhorn is also thermally coupled to the RF coldplate and is co-located with the front end, and regulators necessary for the front end, within an insulated inner thermal stage.

The RF coldplate is thermally coupled to a solid-state thermoelectric cooler (TEC) that can pump heat through itself in either direction based on supplied electrical current. The base of the TEC is thermally coupled to an "intermediate coldplate". The IRD and LO & Timing modules also mounted to the intermediate coldplate. This coldplate is then thermally coupled to a larger "primary" TEC and, in-turn, to a "glycol base coldplate". The side walls and ceilings of each thermal enclosure are passively thermally coupled to their respective coldplate, with the exception of a "glycol ceiling coldplate" that provides coarse active thermal control across the upper surface area of the F507 Module as illustrated in Figure 6. The TECs are positioned (from the underside) centrally between active components, with the active components positioned to minimize significant conductive heat flows from transiting other active components.

The three actively controlled thermal stages are situated within a passive outer environmental enclosure that is coated with IR-reflective paint. The feed windows reflect and attenuate IR radiation incident on the feed, as described in Section 4.4.5, enabling tight thermal control of the innermost stage.

Insulation is used to minimize radiative and convective heat transfer between active components, resulting in dampened random temperature fluctuations. All active components in the F507 operate continuously

[7] While the noise diode is less sensitive to temperature (0.2% per K) and could be used to correct for LNA gain fluctuations, provided that the stability is within 5 mK at the diode position on the RF coldplate, the 2 mK constraint is selected for the RF plate control point to provide overhead for any fluctuations in thermal gradients.

to encourage settling to stable temperatures, including the switched noise diode when operated as described in Section 4.4.8. This also encourages the formation of stable thermal gradients between components. Rigid insulation is provisioned between each thermal stage using silica aerogel sheets. PTFE brackets are used throughout to minimize conduction across structural mounts between thermal stages. Remaining cavities are filled with loose aerogel beads to dampen air sloshing during calibrator-target antenna slews. The durable beads can be easily removed for maintenance access.

The coldplates are manufactured from aluminum, selected for high thermal conductivity and low density. Aluminum load plates are used to thermally couple the coldplates to the TECs. The glycol coldplates have "crossflow" channels for circulating fluid (fluid flow perpendicular to heat flux). Glycol at temperature[8] 10 C is pumped from a heater/chiller through insulated piping to the F507 Module, where it is delivered into the glycol coldplate within a variability bound of ±2 C. The supply line is split outside the module into 2 lines that feed the glycol coldplates, sized to preference the base coldplate to which the primary TEC is thermally coupled. The exit lines are joined outside the F507 and fed to the M508 Utility Module. Fluid connections are high-reliability drip-free quick-connects and fluid lines are nitrile-based hydraulic hoses protected by steel armor cable. On an 18m antenna, the glycol heater/chiller is located in the turnhead. A small dedicated heater/chiller is provisioned for each standalone WVR mount within the SBA, located in a stationary location below the turnhead.

Digital I^2C thermometers are distributed throughout the F507 Module, including at several locations on each coldplate to sample thermal gradients. The temperature resolution of the sensors is 0.8 mK. Calibrated accuracies are within ±0.2 C. Alignment of absolute temperature points between sensors is not needed. A control point thermometer for each TEC is placed on the opposite side of each respective coldplate. For the RF and intermediate thermal stages, the control point sensor and TEC are connected to a compact chassis-mount digital temperature controller that maintains the coldplate at the specified temperature. The temperature controller for each coldplate is located on the inner side wall of the intermediate thermal stage. While the digital controllers do not require temperature stabilization, co-locating them within the F507 is preferred to minimize connection lengths to the thermometers and TECs.

The temperature setpoints for the RF and intermediate coldplates are 14 C and 13 C, respectively. These temperatures provide sufficient clearance above the glycol coldplate variability range (up to 12 C) while avoiding the non-crystalline "PTFE knee," where room-temperature phase transitions may give rise to instabilities when operating at a fixed temperature. Commercial 18 W and 120 W TECs are used to thermally stabilize the RF and intermediate coldplates, respectively. The thermometer resolution and control parameters for the intermediate coldplate are tuned to minimize sensitivity and reactivity to thermal variations finer than ±0.2 C, to ensure that the intermediate coldplate acts as a sink for RF coldplate fluctuations without destabilizing the RF TEC.

4.4.13 M508 Utility Module

The M508 module provides monitor & control (M&C), DC power, antenna timing over copper (RS-422), and fiber to the F507 Receiver Module, and a relay for supplying AC power to the WVR feed heater.

The M508 resides under the WVR reflector, affixed to the reflector support truss. It contains an outer environmental enclosure within which resides a relay for controlling AC power to the WVR feed heater, a fiber splice tray, and an inner RFI-shielded enclosure.

[8] Approximate median temperature measured in 5 min intervals between 1977 - 2021 at the central ngVLA plains site where the 6m SBA and approximately 80% of 18m antennas are located.

The RFI-shielded enclosure contains a glycol coldplate that hosts a M&C Module and a DC-DC Power Supply Module. The coldplate is fed by the return glycol line from the F507 Receiver Module. The hollow volume between the inner RFI enclosure and the outer environmental enclosure is thermally insulated using rigid Garolite G-10, a fiberglass-epoxy laminate that is typically used in NRAO front ends.

The M&C Module [RD12] is connected to the 18m antenna M&C fiber network. Each SBA standalone unit connects via their adjacent 6m antenna (where their D502 Module is located). The M&C board provides control over the feed heater and almost all electronics in the F507 and M508 modules; the exception is control of the TECs in the F507 Module, which are managed by temperature controllers located within the F507. All sensors, including coldplate temperatures, system voltages, and system currents, are read by the M&C board and reported to the M&C network. The antenna supervisor in the 18m pedestal room, or a nearby 6m antenna (or entire SBA) supervisor, analyzes conditions at the location of the F507 module and elsewhere and provides control over F507 power-up, operation, and safe shutdown. WVR feed heat is commanded as described in Section 4.4.4. The M&C Module supplies a network time reference (e.g. PTP) to switch the diode in the F507, facilitating synchronous sampling in the D502 and with the main antenna signal path (to support calibration, described in Section 4.4.15).

The DC–DC Power Supply Module [RD13] receives –48V DC from the P500 Module in the 18m or 6m antenna pedestal. The module contains Vicor DC–DC converters that supply +32V, ±17.5V, ±7.5V, and +5V DC to the F507 module. Each converter has M&C and temperature sensors so they can be shut down for over-current or over-temperature conditions.

A fiber splice tray is located within the M508 environmental enclosure but outside the RFI enclosure. This is used to collect fiber from the M508 RFI enclosure and from the F507 Receiver Module, for passage through via the 18m or 6m antenna elevation and azimuth wraps.

A solid-state relay is located within the M508 environmental enclosure but outside the RFI enclosure. The relay is used to control AC power to the feed heater.

4.4.14 D502 Back End Module

The D502 module is a modified version of the D501 Digital Back End (DBE) module; see details in [RD14]. Like the D501, the D502 electronics are air-cooled within an RFI-shielded enclosure. Further shielding is provided by the electronics rack in which the D502 is situated. The locations of the D502 modules are described in Section 4.3.

The D502 receives unformatted optical data from the two IRDs in the F507 Receiver Module, performs sideband separation, polyphase filter channelization, and integration of the data using FPGAs, and packages the resulting data in Ethernet format for transmission across private and public telecommunications infrastructure managed by the Central Fiber Infrastructure (FIB) subsystem. These data are accessed by the Computing and Software (CSW) Online (ONL) subsystem as indicated in Figure 1.

The D502 generates 58 x 100 MHz channels per IRD data stream, sampling synchronously with the switched power at a base rate of 125 Hz (see Section 4.4.8). The spectra are real-valued (unlike visibilities). The data are bandpass corrected using templates from lab hot/cold measurements, and accounting for offset, gain, timing, and bandwidth mismatches introduced by the interleaved IRD samplers. Integration of the samples free of Tcal (i.e. 75% of samples per unit time, assuming a diode duty cycle of 25%) is performed with output at 1 Hz per channel. The switched power data (on and adjacent off sample only) are averaged over 15 x 100 MHz channels (i.e. per half-sideband, involving one overlapping channel; see Section 4.4.8) at 1 Hz and used to correct for gain fluctuations on this timescale. Similarly, the switched power data are averaged over 5 min per 100 MHz channel and used to correction for gain drifts. The gain correction calculations include algorithms to exclude switched power data affected by RFI. The brightness temperature spectra in the overlapping 3 x 100 MHz channels between IRD data streams are synchronously aligned in order to normalize the bandpass and provide a consistent amplitude scale across the full 19.7 – 31.0 GHz observing band. The gain corrections and a diagnostic subset of the switched power and flag data are included in the transmitted data packets.

4.4.15 Delay Calibration Software

The WVR subsystem will develop delay calibration software to be deployed and maintained within the CSW Offline Software (OFF) subsystem. When initiated as part of automated (or manual) offline science data processing, the WVR delay calibration software will flag and exclude WVR data corrupted by RFI, process these data together with astronomical calibrator interferometric data and weather station data to calculate delay corrections, and save the solutions to a calibration table appended to the science data packet. Ultimately the OFF subsystem will apply the corrections to the science data and deliver the calibrated data to the end user. These steps are summarized in Figure 1. The ngVLA will not use WVR for online calibration (i.e. near real-time).

The WVR subsystem is designed to accurately measure small changes in wet delay (50 μm pwv per second) rather than the absolute wet delay (tens to hundreds of mm pwv). As a result, complicated time-dependent meteorological models to support absolute radiometry are not necessary. Instead, a more empirical approach can be utilized to measure the scaling relationship between fluctuations in WVR-observed brightness temperature and those in interferometer-observed delay when observing an astronomical calibrator. The WVR data alone can then be used to measure delay corrections when the interferometer observes a target, bracketed between calibrator observations with cycle time no faster than 5 mins to maintain the WVR-interferometer scaling reference frame.

The total zenith atmospheric opacity near the 22 GHz water line is the sum of 5 principal components, as described in Section 7.1.9 in [AD01]. These can be approximately modeled using 4 frequency-dependent opacity contributions: a temporally stable dry term, a fluctuating dry term, a temporally stable wet term, and a fluctuating wet term. The fluctuating wet term arises from the 22 GHz water vapor line of interest. The other terms contribute to the total delay, but are systematics from the viewpoint of WVR operation. It should be noted that the "stable" and "fluctuating" contributions in this model are in fact drawn from a common power spectrum of fluctuations. Provided that the ratio between "slow" and "fast" sampling rates is not too large (e.g. seconds and minutes, respectively), and that the power spectrum is non-flat on these timescales, then the contributions can be separated as above. For the text below, it is assumed that any "fast" dry terms contribute on timescales that are at most slowly-varying over the wet "slow" rate. (Put another way, the calibrator switching rate sets the Nyquist rate for dry contributions and any residual aliasing is expected to be negligible.) Therefore, the only true "fast" contribution is from water vapor.

To distinguish changes caused by fluctuating water vapor from the other contributions to the total delay, the latter of which will also include residual gain errors (though designed here to be below detrimental thresholds) and spillover (same), the multi-channel wide-band data are used isolate the contribution from the known, and differing, spectral shape of the pressure-broadened water line. The objective is to use the WVR to infer changes in the excess path arising from the "fluctuating" water vapor contribution, then add these to the other slower-varying delay contributions to obtain the total delay. The total tropospheric delay across a baseline between antennas i and j is given by

$$\begin{aligned} L_{tropo,i} - L_{tropo,j} &= \left(L_{fwv,i} + L_{other,i}\right) - \left(L_{fwv,i} + L_{other,j}\right) \\ &= \sum \left(a_{i,c} + b_{i,c}\right) T_{i,c} - \sum \left(a_{j,c} + b_{j,c}\right) T_{j,c} \end{aligned}$$

where T_c are calibrated system temperatures per WVR frequency channel c (Tcal-scaled, but free of Tcal), a_c and b_c are channel weights used to combine these measurements, the top right side indicates the total delay arising from fluctuating water vapor and the sum of all other contributions, and a and b are associated with L_{fwv} and L_{other}, respectively. The objective for the WVR delay calibration software is to fit for the per-WVR weights when comparing with per-baseline interferometric delay measurements on a calibrator, so that corrections to the per-antenna interferometric delays on the left side of the equation can be predicted during periods between calibrator measurements.

Prior to initiation of the delay calibration software in the offline data processing, it is assumed that standard interferometric delay calibration will have been performed on the calibrator scans, generating antenna-based tropospheric delay solutions (i.e. separated from ionospheric delay solutions, relevant in Bands 1 and 2) on at least two timescales: per second, and per scan. The latter is assumed to be 16 sec, which for a worst-case slew time of 7 sec to a calibrator located up to 3° away will result in 90% observing efficiency over a minimum calibrator-target-calibrator cycle time of 5 minutes. The result will be the availability of interferometrically-derived antenna-based delays with errors[9] for 18m antennas within 1 psec per 1 sec integration, and within 0.1 psec per 16 sec integration, where these are estimated conservatively assuming dual-polarization observations of a point source with minimum flux density 0.5 Jy using only 10 contributing antennas in any of Bands 2-6. To satisfy the 1 psec delay error limit in Band 1, the minimum flux density must be 0.7 Jy (acceptable). To satisfy the 0.1 psec limit in Band 1, a 1.4 Jy point source and 15 antennas are required (likely acceptable). For 6m antennas, to satisfy the errors above, there must be 15 contributing antennas, the flux density must be 0.8 Jy for the 1 sec solutions and as strong as 1.9 Jy for the 16 sec solutions in Band 2, and Band 1 is excluded. Longer integration times are acceptable for the SBA.

The delay calibration software performs several steps, summarized as follows:

1. Integrate the T_c spectrum over each calibrator scan (e.g. 16 sec each). Use these data and the interferometrically-determined L_{tropo} solutions to solve for the b_c weights per scan, assuming L_{fwv} and a_c are zero. In the most simplistic case (pure empirical approach), assume the b_c weights conform to a standard spectral template in which the contributions from the 5 principal opacity components are modeled without any supplied weather monitor data (e.g. using template values for pressure broadening as a function of site altitude above sea level). However, the preferred approach is to utilize weather monitor data (hybrid[10] absolute-empirical approach) to optimize the weights, for example by incorporating surface pressure and temperature data to factor prevailing pressure broadening and if possible vertical (altitude) structure into the solutions. These are the "slow" b_c contributions to the total delay.
2. Interpolate the "slow" b_c solutions to obtain a smooth time series with 1 sec sampling throughout the entire science observation (or fraction relevant to the calibrator and target of interest). For the hybrid approach, perform smoothing over the underlying variables such as temperature, pressure, and inferred altitude structure, and calculate the resulting time series for the b_c weights.
3. Calculate the time series for L_{other} at 1 sec sampling using the interpolated 1 sec b_c weights and the 1 sec T_c data. Subtract this time series from the interferometric L_{tropo} solutions measured per second to obtain a time series of L_{fwv} with 1 sec sampling throughout the entire observation.

[9] This calculation uses the equation for delay measurement error cited in Section 5.3.1.1 of [RD09] together with the anticipated ngVLA interferometric sensitivities cited in Section 5.1 of [RD09].
[10] Note that a pure absolute approach would require measurement of absolutely-calibrated Tsys, and ideally real-time three-dimensional meteorological data, so as to predict the delay using theoretical scaling.

4. Perform the equivalent of step 1 to solve for the a_c weights using the L_{fwv} time series; i.e. assume $L_{tropo} = L_{fwv}$ per antenna and that L_{other} and b_c are zero in the version of the equation shown above. These are the "fast" a_c contributions to the total delay.
5. Using the 1 sec data, sum the a_c and interpolated b_c weights and multiply by T_c to obtain L_{tropo} per antenna (relative to the reference antenna where delays are set to zero) with 1 sec sampling throughout the observation. These solutions should be used for subsequent data processing in the OFF subsystem, rather than the prior interferometric-only tropospheric antenna-based delay solutions.

If atmospheric conditions lead to Tsys fluctuations that are below the noise level of the WVR, delay corrections may not be necessary to yield high quality science data.

To support the SBA-based WVRs with locations described in Section 4.3, the delay calibration software will include logic to select the appropriate valid baseline(s) to avoid shadowing and to propagate solutions to all 6m antennas.

Two options that are not anticipated to be necessary, but are worth highlighting, as described as follows.

The strategy for observing calibrators during a science observation will influence options available in the WVR delay calibration software. Rather than interleave the target with observations of a single calibrator, it may be advantageous to observe 2 nearby calibrators that approximately linearly bisect the target on the sky. Both calibrators would not necessarily need to be observed each calibration cycle. If this approach is pursued, then the approach described above could be modified accordingly.

Another option to be explored is whether the approach described in this section can be improved by using several nearby WVR units to optimize the spectral modeling. The antenna-dependent WVR delay calibration approach described above may therefore benefit from expanding to a multi-antenna solver in which a simple distributed atmospheric model is constructed and used to improve solution accuracy.

4.5 Noise Budget

Table 1 presents a noise cascade estimate for the WVR Receiver Module, calculated using the Friis formula. Input cells are white, calculated cells are yellow. The noise figures (NFs; units of dB) assume a 25 C upper limit to precision ambient temperature and worst-case losses across a band from 19 – 31 GHz. For reference, $T_{noise} = T_{phys}(F-1)$ where the noise figure F (linear) is given by $F = 10^{NF/10}$. The cascaded noise is within the requirement of 480 K.

Component	Gain (dB)	Noise Figure (dB)	Physical Temp. (C)	Cascaded Gain (dB)	Cascaded Noise Figure (dB)	Noise Temp. (K)	Cascaded Noise Temp. (K)	Notes
Antenna Reflector	-0.03	0.03	25	-0.03	0.03	2.1	2.1	Ohmic, spillover; JPL AWVR low edge illum. -25 dB, spill <0.3% [Tanner+2001 in RD05].
Radome	-0.04	0.04	25	-0.07	0.07	2.8	4.8	From Band 4 estimate [020.30.05.00.00-0004-GEN].
Infrared Windows	-0.05	0.05	25	-0.12	0.12	3.5	8.4	Scale Band 4 Teflon 2->3 layers. Upper limit temp.
Corrugated Feed Horn	-0.05	0.05	12	-0.17	0.17	3.3	11.7	From Band 4 estimate for custom feed.
Circ. to Rect. WG Trans.	-0.05	0.05	12	-0.22	0.22	3.3	15.2	e.g. Eravant SWT-34328-SA
Coupler	-0.50	0.50	12	-0.72	0.72	34.8	51.8	e.g. Eravant SWD for WR-34
Isolator	-1.30	1.30	12	-2.02	2.02	99.5	169.2	e.g. Eravant STF-34-S1
LNA	31.00	1.73	12	28.98	3.75	139.5	391.4	e.g. LNF-LNR19-34WA
Isolator	-1.30	1.30	12	27.68	3.75	99.5	391.5	e.g. Eravant STF-34-S1
WR-34 to 2.92mm Coax	-0.35	0.35	12	27.33	3.75	23.9	391.6	e.g. Eravant SWC-34KF-E1
Splitter	-5.00	5.00	12	22.33	3.76	616.6	392.7	e.g. Pasternack PE2078
IRD	60.00	6.50	12	82.33	3.80	988.6	398.5	NF <1000K @ 290K (requirement IRD0505)

Table 1: Noise cascade for WVR signal path.

The system temperature is obtained by adding 3 K from the cosmic microwave background and upper limits between 15 K (precision conditions) to 65 K (normal conditions) for slant atmospheric opacity (both wet and dry components), yielding respective upper limits between approximately 420 K to 470 K.

4.6 Power and Thermal Budget

Table 2 presents a preliminary power and thermal management budget for modules in the WVR subsystem. Rows that only contribute to the thermal totals are indicated in parentheses.

Module	Component	Power per Device (W)	Quantity	Power (W)
F507	Front End (+28V, +12V, +3.3V, +1.6V, +0.15V)	1.2	1	1.2
F507	RF Coldplate Voltage Regulators (+28, +12, +3.3, +1.6, +0.15; dissipation only)	(0.07)	5	(0.4)
F507	RF TEC (e.g. TE-127-1.0-2.5) (+3.3V)	5.6	1	5.6
F507	T504-D/E IRD Module (±15V, ±5V, +3.3V)	12	2	24
F507	L523 LO & Timing Module (+12V, +5V)	12	1	12
F507	RF TEC Temp. Controller (+5V)	0.8	1	0.8
F507	Primary TEC Temp. Controller (+5V)	1.1	1	1.1
F507	Intermediate Coldplate Voltage Regulators (±15, +12, ±5, +3.3; dissipation only)	(2.6)	6	(15.6)
F507	Primary TEC (e.g. HP-199-1.4-1.15**)** (+3.3V)	8.5	1	8.5
TOTAL Power (Thermal) for F507 WVR Receiver Module				**53 (69)**
-	Feed Heater (AC)	500	1	500
F507	As above (DC)	53	1	53
M508	Vicor DC-DC Bricks (+32V, ±17.5V, ±7.5V, +5V; dissipation only)	(3)	5	(16)
M508	M&C Board (DC)	40	1	40
TOTAL Power (Thermal) for M508 WVR Utility Module				**593 (56)**
D502	FPGA-based processor (DC)	400	1	400
TOTAL Power/Thermal for D502 WVR Back End Module				**400**

Table 2: Preliminary power and thermal management budget for the WVR subsystem.

Heat exchange associated with the glycol coldplates in the F507 Module will be greater than the indicated 69 W due to additional transfer with the ambient environment. For example, solar radiation will impart ~1100 W/m^2, or approximately 330 W, over the sun-lit surface of the F507 (using sizing presented in Section 4.7, modulo IR-reflective paint). Heating capability will be needed during cold ambient conditions.

The heat to be removed by the glycol coldplate in the M508 Module is only 56 W, due to the pass-through supplies for AC to the feed heater and DC to the F507 Module.

4.7 Mass and Volume Budget

Table 3 presents a preliminary mass and volume budget for the WVR equipment to be mounted on the 18m antenna truss or on the SBA standalone az-el tracker.

Module	Component	Mass (kg)	Quantity	Mass Subtotal (kg)	QTY1 Dimensions (in.)
F507	All structure incl. 2 x glycol coldplate	12	1	12	29 x 14 x 10
F507	Feedhorn	0.5	1	0.5	3.5 x 2.5 dia
F507	Circ. To Rect. WG Transition	0.02	1	0.02	2 x 1 x 1
F507	Broadwall Coupler	0.1	1	0.1	7.5 x 1.4 x 1
F507	Isolator	0.15	3	0.45	3 x 1.3 dia.
F507	Splitter	0.02	1	0.02	1 x 1 x 0.5
F507	WR-34 2.92mm Coax Adaptor	0.1	2	0.2	1.5 x 1.5 dia.
F507	T504-D/E IRD Module	1.5	2	3	6 x 3 x 2
F507	L523 LO & Timing Module	0.75	1	0.75	6 x 3 x 2
F507	Electronics incl. Temp. Ctrl., Cabling	0.5	1	0.5	mixed
TOTAL for F507 WVR Receiver Module				**17.5**	**L29 x W14 x H10**
M508	All structure incl. 1 x glycol coldplate	8	1	8	20 x 8 x 4
M508	Vicor DC-DC Bricks	0.1	5	0.5	3 x 2 x 0.5
M508	Electronics incl. M&C Board, Cabling	1	1	1	mixed
TOTAL for M508 WVR Utility Module				**9.5**	**20 x 8 x 4**
F507	Total from above	17.5	1	17.5	as above
M508	Total from above	9.5	1	9.5	as above
-	Feed Heater	2	1	2	8 x 5 dia.
-	Cables, Glycol Piping to F507, M508	5	1	5	mixed
-	Feed Arm Truss	20	1	20	32 x 40 x 70
-	Support Truss w/ Mount Baseplate	30	1	30	63 x 57 x 56
-	Antenna Reflector	14	1	14	57 x 57 x 26
TOTAL for equipped WVR down to baseplate of support truss				**98.0**	**L89 x W57 x H100 (zenith pointing)**

Table 3: Preliminary mass and volume budget for WVR equipment to be installed on a sky-tracking structure.

4.8 Interfaces with Other subsystems

This section describes interfaces between the WVR subsystem other ngVLA subsystems. These are managed according to the ngVLA N^2 Interface Control Diagram [RD03]. See [AD01] for a graphical summary of WVR subsystem interfaces and information regarding ICDs.

The T504-D/E IRD Modules and the L523 LO & Timing Module in the F507 WVR Receiver Module are considered part of the WVR subsystem and not of the IRD subsystem or Antenna Time and Frequency (ATF) subsystem, respectively.

4.8.1 ANT Subsystem

The WVR support truss supports the M508 Utility Module, antenna reflector, feed arm truss, feed heater, and F507 Receiver Module. The WVR support truss mounts to the 18m antenna truss provisioned by the Antenna (ANT) subsystem.

The ANT subsystem provisions 500 W AC power (Section 4.6) to the WVR feed heater via the M508 WVR Utility Module. This involves mechanical fastening to the WVR support and feed arm trusses.

The 18m antenna must be capable of performing a pointing calibration routine to center the WVR beam on a geostationary satellite (Section 4.4.1). This is similar to the antenna motion required for main beam pointing calibration, but now with a pointing offset to ensure that the WVR beam is aimed correctly.

4.8.2 INF Subsystem

The standalone WVR pedestals are situated within the SBA footprint interface with foundations, electrical distribution, and fiber distribution provisioned by the Array Infrastructure (INF) subsystem.

4.8.3 PSU Subsystem

The M508 WVR Utility module and D502 WVR Back End module interface with the -48V DC power supply provisioned by the Power Supplies and Distribution (PSU) subsystem. The M508 consumes approximately 600 W, including the power supplied to the F507 Module and feed heater, as estimated in Section 4.6.

The PSU subsystem also provisions DC power cabling between the M508 WVR Utility Module and the F507 WVR Receiver Module. This involves mechanical fastening to the WVR support and feed arm trusses.

4.8.4 BMR Subsystem

The F507, M508, and D502 electronics are housed within RFI-shielded enclosures provisioned by the Bins, Modules, and Racks (BMR) subsystem. The D502 Back End Module is located within an electronics rack provisioned by the BMR subsystem at the locations described in Section 4.3.

4.8.5 EEC Subsystem

The F507 and M508 electronics and RFI-shielded enclosures are housed within weather-resistant environmental enclosures provisioned by the Antenna Electronics Environmental Control (EEC) subsystem.

The EEC subsystem supplies glycol in a loop first to the F507 Receiver Module, then the M508 Utility Module, followed by return to the heater/chiller. This involves mechanical fastening to the WVR support and feed arm trusses. The glycol flow rate is sufficient to provide necessary heating/cooling for the module electronics (see Section 4.6), as well as the heat transfer associated with hot/cold weather and solar loading. Chiller locations are described in Section 4.4.12.

The EEC subsystem also supplies air cooling to regulate the D502 Back End Module located in the electronics rack of the 18m or adjacent 6m antenna (Section 4.3).

4.8.6 HIL Subsystem

The M&C board in the M508 WVR Utility Module is provisioned by the M&C Hardware Interface Layer (HIL) subsystem. The M&C Board only handles M&C data for the F507 and M508 Modules and the feed heater relay. The M&C Board does not handle WVR measurement data produced by the IRDs in the F507, which is routed separately via the fiber splice tray located in the M508 Module. The M&C board routes the network time reference (e.g. PTP) to the switched diode in the F507.

4.8.7 AFD Subsystem

Fiber is provisioned to the M508 and D502 Modules, and between the M508 and F507 Modules, by the Antenna Fiber Distribution (AFD) subsystem. This involves mechanical fastening to the WVR support and feed arm trusses.

For standalone WVR units situated within the SBA footprint, the AFD subsystem passes fiber from the M508 Module to the INF subsystem for underground fiber distribution, then the AFD subsystem carries this fiber to a D502 WVR Back End Module located as described in Section 4.3.

4.8.8 MCL Subsystem

M&C data from the F507, M508, and D502 modules are sent over the M&C network provisioned by the Monitor and Control (MCL) subsystem. This includes a diagnostic subset of channelized WVR measurement data from the D502.

The MCL subsystem facilitates the connection between the feed heat supervisor for the 18m or adjacent 6m antenna (or entire SBA supervisor, if applicable) and the WVR feed heat relay managed via the M&C board located in the M508 WVR Utility Module.

Similarly, the MCL subsystem facilitates the connection between the SBA-based WVR tracker pointing and the 6m array target pointing. (This assumes that the SBA does not operate using subarrays.)

4.8.9 ATF Subsystem

The Antenna Time and Frequency (ATF) subsystem supplies timing to the D502 WVR Back End Modules at the locations described in Section 4.3.

4.8.10 MON Subsystem

The WVR delay calibration software described in Section 4.4.15 utilizes surface pressure and temperature data provisioned by the Environmental Monitoring and Characterization (MON) subsystem. The demands placed on weather station locations by the WVR subsystem are described in [AD01].

4.8.11 ONL Subsystem

The channelized WVR measurement data delivered from the D502 WVR Back End Modules is collated and appended to the main antenna science data packet by the Online Software (ONL) subsystem and transmitted for storage in the Observatory Science Data Archive. The ONL subsystem also appends weather station surface temperature and pressure data provisioned by the MON subsystem to the science data packet.

The ONL subsystem accesses the WVR M&C data transmitted over the M&C network and transmits it for storage in the Observatory Monitor Database and, where relevant (e.g. tracking and status data for WVR subsystem modules), in the Observatory Quality Control Database.

4.8.12 OFF Subsystem

The WVR delay calibration software described in Section 4.4.15 is deployed and maintained within the Offline Software (OFF) subsystem, where it is applied to the combined data packet (WVR, MON, and science data) retrieved from the Observatory Science Data Archive.

The WVR delay calibration software is included in the automated calibration pipeline for Standard Observing Modes, and made available to the community to foster algorithm development and non-standard applications (e.g. atmospheric research).

4.8.13 MSS Subsystem

The WVR subsystem is included in software provisioned by the Maintenance and Support (MSS) subsystem that is tailored to supporting maintenance activities, including tools to query M&C data and the display of M&C data in engineering dashboards.

4.8.14 DST Subsystem

The Datastores (DST) subsystem ensures that all applicable data products from the WVR subsystem are archived for the life of the facility, including the Observatory Monitor Database, Observatory Quality Control Database, and Observatory Science Data Archive.

4.8.15 FIB Subsystem

All WVR measurement and M&C data is transmitted across private and public telecommunications infrastructure managed by the Central Fiber Infrastructure (FIB) subsystem to be processed by the Online Software (ONL) subsystem.

5 Appendix A: Trade Studies

The following trade studies contributed to the conceptual design selected for presented in this document:

- ngVLA WVR Feed and Optical Design Trade Study [RD05]
- ngVLA WVR Receiver and Digital Processing Trade Study [RD06]

6 Appendix B: Abbreviations and Acronyms

Acronym	Description
AC	Alternating Current
AD	Applicable Document
AFD	Antenna Fiber Distribution
ANT	Antenna
ATCA	Australia Telescope Compact Array
ATF	Antenna Time and Frequency
BMR	Bins, Modules, and Racks
BUS	Backup Structure
CoDR	Conceptual Design Review
CFRP	Carbon-Fiber-Reinforced Polymer
CSW	Computing and Software
DBE	Digital Back End
DC	Direct Current
DST	Datastores
EEC	Antenna Electronics Environmental Control
EMI	Electromagnetic Interference
FDR	Final Design Review
FIB	Central Fiber Infrastructure
FPGA	Field-Programmable Gate Array
HDPE	High-Density Polyethylene
HIL	Hardware Interface Layer
ICD	Interface Control Document
IF	Intermediate Frequency
INF	Array Infrastructure
IPT	Integrated Product Team
IR	Infrared
IRD	Integrated Receiver and Digitizer
LN_2	Liquid Nitrogen
LNA	Low Noise Amplifier
LO	Local Oscillator
LRU	Line Replaceable Unit
MAD	Median Absolute Deviation
MON	Environmental Monitoring and Characterization
ngVLA	Next Generation Very Large Array
NASA	National Aeronautics and Space Administration
NF	Noise Figure

Acronym	Description
NOEMA	Northern Extended Millimeter Array
NRAO	National Radio Astronomy Observatory
M&C	Monitor and Control
MAD	Median Absolute Deviation
MCL	Monitor and Control
MSS	Maintenance and Support
OFF	Offline Software
ONL	Online Software
OVRO	Owens Valley Radio Observatory
OCXO	Oven-Controlled Crystal Oscillator
PBS	Product Breakdown Structure
PdBI	Plateau de Bure Interferometer
PDR	Preliminary Design Review
PLDRO	Phase-Locked Dielectric Resonator Oscillator
PLXO	Phase-Locked Crystal Oscillator
PSU	Power Supplies and Distribution
PTFE	Polytetrafluoroethylene
PTP	Precision Timing Protocol
pwv	Precipitable Water Vapor
R2S	Radio2Space
RCFH	Radially Corrugated Feed Horn
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
SADC	Serial Analog-to-Digital Converter
SBA	Short Baseline Array
SNG	Satellite News Gathering
TBD	To Be Determined
Tcal	Calibration Noise Temperature
TEC	Thermoelectric Cooler
Tsys	System Noise Temperature
TX	Texas
USA	United States of America
VSAT	Very-Small-Aperture Terminal
WG	Waveguide
WVR	Water Vapor Radiometer

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