Water Vapor Radiometer Subsystem: Technical Requirements

020.45.00.00.00-0001-REQ

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
C. Hales	Electronics Division, NRAO	2022-01-18

APPROVALS	**ORGANIZATION**	**SIGNATURES**
S. Durand, Ant. Elec. IPT Lead	Electronics Division, NRAO	Steven Durand Steven Durand (Jan 19, 2022 14:42 MST)
R. Selina, Project Engineer	Electronics Division, NRAO	R. Selina R. Selina (Jan 23, 2022 15:45 MST)
T. Küsel, System Engineer	Program Mgmt. Dept., NRAO	Thomas Kusel Thomas Kusel (Jan 24, 2022 08:53 EST)
W. Esterhuyse, Antenna Project Manager	Program Mgmt. Dept., NRAO	

RELEASED BY	**ORGANIZATION**	**SIGNATURE**
W. Esterhuyse, Antenna Project Manager	Program Mgmt. Dept., NRAO	

Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-09-27	Erickson	All	Final 01
02	2018-12-20	Erickson	All	Address RIDs
03	2019-04-30	Erickson	All	Final review
04	2019-05-30	Selina	2.1, 4, 11	Minor edits for release. Updated traceability.
A	2019-07-26	Lear	All	Prepared PDF for signatures and release.
A.01	2020-10-06	Hales	All	Major revision of all content including title. Removed WVR1001 and WVR0101. Moved WVR1013 to WVR7901.
A.02	2021-03-09	Hales	Many	Updated after internal informal review. Added RFI & EMC requirements. Revised flow-down from calibration requirements. Removed WVR0012.
A.03	2021-05-10	Hales	Many	Clarifications throughout following SRR feedback.
A.04	2021-05-11	Lear	All	Prepared PDF for approvals & release.
B.01	2021-12-20	Hales	2.2, 3.2, 3.3, 6, 7, 9.1.1, 9.1.4, 9.2, 10.1	Minor edits to align with updated [RD08] and close ECN0001. Edited all subsections in Section 7.2, including wording for several interface assumptions and modification of the ICD title for [AD13]. Edited WVR-prefixed requirements as follows. Updated: 0003-0005, 0008-0009, 0201, 0350, 0500, 0502, 0600-0602, 0604, 0606, 1003, 1070, 1072-1073, 1170-1171, 1175-1178, 1303-1304, 2001-2002, 7102-7106; Added: 1074; Removed: 0552, 0906, 1172, 7553–7558. Resolved ECN0001 as follows: Updated WVR1500; Added WVR7118 and WVR7593–7602.
C	2022-01-19	Lear	All	Minor formatting and copy edits. Prepared PDF for signatures & release.

Table of Contents

1 Introduction

1.1 Purpose

This document presents the complete set of Level 2 subsystem requirements to guide the design and development of the Water Vapor Radiometer (WVR) subsystem.

Requirements described in this document are derived from applicable ngVLA System Requirements [AD01] and system-level requirement specification documents [AD02–AD07]. The overall requirements hierarchy and management strategy are outlined in [RD01] and [RD02].

The content of these requirements is at the subsystem level, conforming to the system architecture [RD03], but aims to be implementation agnostic within the subsystem boundaries. Some assumptions about the subsystem may be given, but only to the degree necessary to unambiguously define the subsystem requirements.

1.2 Scope

The scope of this document is the Water Vapor Radiometer Subsystem. This includes the following:

- Hardware and software subsystem requirements that satisfy functional and nonfunctional System Requirements [AD01].
- Software and control systems required to monitor and operate the subsystem.
- Nonfunctional requirements unique to this subsystem (e.g., safety, quality, reliability, maintainability).
- Interface Requirements (I/F) necessary to integrate with other Systems and Subsystems.
- Enumeration of requirements, each with a unique identifier, as well as other attributes as described in [RD02], and any other attributes needed for particular subsystems as determined by agreement between the Project Office Engineers and the Integrated Product Team (IPT) leads.
- Key Performance Parameters (KPPs).
- Requirements specified for the complete lifecycle of the subsystem, including any requirements that are applicable for operations, maintenance, decommissioning, and disposal.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents apply to this Requirements Specification to the extent specified. In the event of a conflict between the documents referenced herein and the content of this Requirements Specification, the content of the *highest*-level specification (in the requirements flow-down) shall be considered the superseding requirement for design elaboration and verification.

Ref. No.	Document Title	Doc. No.
AD01	ngVLA System Requirements (SYS)	020.10.15.10.00-0003-REQ
AD02	ngVLA System Environmental Specifications (ENV)	020.10.15.10.00-0001-SPE
AD03	ngVLA System EM Compatibility and RFI Mitigation Requirements (EMC)	020.10.15.10.00-0002-REQ
AD04	ngVLA L1 Safety Requirements (SAF)	020.80.00.00.00-0001-REQ
AD05	ngVLA L1 Security Requirements (SEC)	(In Prep.)

Ref. No.	Document Title	Doc. No.
AD06	ngVLA Electronics Specifications (ETR)	020.10.15.10.00-0008-REQ
AD07	ngVLA Calibration Requirements (CAL)	020.22.00.00.00-0001-REQ
AD08	International Standard: Protection Against Lightning	IEC 62305:2010
AD09	Environmental Engineering Considerations and Laboratory Tests	MIL-STD-810H
AD10	NRAO-NM Environment, Safety, and Security Manual	https://info.nrao.edu/oas/safety/nrao-safety-manuals
AD11	USGS Coterminous US Seismic Hazard Map – PGA 2% in 50 Years	ftp://hazards.cr.usgs.gov/web/nshm/conterminous/2014/2014pga2pct.pdf
AD21	ngVLA WVR Volume, Mass, and Location Requirements	020.45.00.00.00-0004-DWG

2.2 Applicable Interface Control Documents

The following ICDs contribute to the definition of the external boundary of this subsystem and are applicable to its specification:

Ref. No.	Document Title	Doc. No.
AD12	Antenna Electronics to ANT Subsystem ICD	020.10.40.05.00-0011-ICD
AD13	WVR Subsystem to INF Subsystem ICD	020.10.40.05.00-0021-ICD
AD14	WVR Subsystem to PSU Subsystem ICD	020.10.40.05.00-0022-ICD
AD15	WVR Subsystem to BMR Subsystem ICD	020.10.40.05.00-0023-ICD
AD16	WVR Subsystem to EEC Subsystem ICD	020.10.40.05.00-0024-ICD
AD17	WVR Subsystem to HIL Subsystem ICD	020.10.40.05.00-0025-ICD
AD18	WVR Subsystem to AFD Subsystem ICD	020.10.40.05.00-0026-ICD
AD19	WVR Subsystem to MCL Subsystem ICD	020.10.40.05.00-0027-ICD
AD20	WVR Subsystem to ATF Subsystem ICD	020.10.40.05.00-0028-ICD

2.3 Reference Documents

The following documents are referenced within this text or provide supporting context:

Ref. No.	Document Title	Doc. No.
RD01	ngVLA Systems Engineering Management Plan	020.10.00.00.00-0001-PLA
RD02	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
RD03	ngVLA System Architecture	020.10.20.00.00-0002-DWG
RD04	Interferometry and Synthesis in Radio Astronomy	Thompson, Moran & Swenson, 2017, Springer, 3rd Ed.
RD05	A Study of the Compact Water Vapor Radiometer for Phase Calibration of the Karl G. Jansky Very Large Array	EVLA Memo No. 203
RD06	Considerations for a Water Vapor Radiometer System	ngVLA Memo No. 10
RD07	Temporal and Spatial Tropospheric Phase Fluctuations at the VLA (and Beyond) and Implications for Phase Calibration	ngVLA Memo No. 61

Ref. No.	Document Title	Doc. No.
RD08	ngVLA Water Vapor Radiometer Subsystem: Design Description	020.45.00.00.00-0002-DSN
RD09	Reliability Prediction of Electronic Equipment	MIL-HDBK-217F
RD10	Non-Electronic Parts Reliability Data	NPRD
RD11	Some Issues for Water Vapor Radiometry at the VLA	VLA Sci. Memo No. 177
RD12	Radiometric profiling of temperature, water vapor and cloud liquid water using various inversion methods	https://www.researchgate.net/publication/288824283_Radiometric_profiling_of_temperature_water_vapor_and_cloud_liquid_water_using_various_inversion_methods (similar version published as Solheim et al., 1998, Radio Science, 33, 393)
RD13	On Determining Visibilities from Correlation Products	EVLA Memo No. 145
RD14	Resolving the Radio Source Background: Deeper Understanding through Confusion	Condon et al., 2012, ApJ, 758, 23
RD15	Deriving the tropospheric integrated water vapor from tipping curve–derived opacity near 22 GHz	Deuber et al., 2005, Radio Science, 40, RS5011
RD16	Absorption and Emission by Atmospheric Gases	Waters, 1976, Methods in Experimental Physics, Vol. 12, Part B (Astrophysics: Radio Telescopes; Academic Press, NY), RD18142
RD17	Improving the frequency resolution of the default atmospheric opacity model	EVLA Memo No. 143
RD18	Radiometric monitoring of atmospheric water vapor as it pertains to phase correction in millimeter interferometry	Sutton & Hueckstaedt, 1996, A&AS, 119, 559
RD19	An updated model for millimeter wave propagation in moist air	Liebe, 1985, Radio Science, 20, 1069
RD20	Results of Water Vapor Radiometry Tests at the VLA	EVLA Memo No. 73
RD21	Synthesis of Optimal Estimators for Water Vapor Radiometry	ngVLA Memo No. 79
RD22	Requirements for Subreflector and Feed Positioning for ALMA Antennas	ALMA Memo No. 479
RD23	Water Vapour Radiometers for the Australia Telescope Compact Array	Indermuehle et al., 2013, PASA, 30, e035
RD24	ngVLA N^2 Interface Control Diagram	020.10.40.00.00-0001-DWG
RD25	ngVLA Notional Reference Observing Program	020.10.15.05.10-0001-REP
RD26	ngVLA Notional Envelope Observing Program	020.10.15.05.10-0002-REP
RD27	ngVLA Antenna Technical Requirements	020.25.00.00.00-0001-REQ
RD28	ngVLA System Technical Budgets	020.10.25.00.00-0002-DSN

3 Overview of Subsystem Requirements

3.1 Document Outline

This document presents the technical requirements for the Water Vapor Radiometer (WVR) subsystem. These parameters determine the overall performance of the subsystem and the functional requirements necessary to enable its operation and maintenance.

The Level 2 Subsystem Requirements and detailed explanatory notes are found in Section 7. The notes contain elaborations regarding the meaning, intent, and scope of the requirements. These notes form an important part of the definition of the requirement and should guide the verification procedures.

In many cases, the notes contain an explanation or an analysis of how the numeric values of requirements were derived. Where numbers have a degree of ambiguity or are insufficiently substantiated, this is also documented in the notes. In this way, the trade space available is apparent to scientists and engineers who will guide the evolution of the ngVLA concept.

3.2 Subsystem General Description

The WVR subsystem is a total power telescope that is responsible for measuring the brightness temperature of atmospheric water vapor in the antenna main beam using a water vapor radiometer. Fluctuations in these data will be used to continuously solve for the variable propagation delay toward each antenna during periods between astronomical calibrator measurements [RD04–RD07].

A summary of the WVR subsystem design is presented below to assist interpretation of the requirements and interfaces described in this document. This summary is implementation-agnostic where possible. See the WVR Subsystem Design Description [RD08] for details regarding the selected design. Revisions to this document and the WVR Subsystem Design Description will occur as the subsystem concept matures.

The WVR subsystem is designed for continuous automated operation, with the ability to be fully remotely controlled, and with only minimal human interaction during preventive and corrective maintenance activities at the antenna.

The WVR subsystem comprises seven line-replaceable units (LRUs): a WVR Antenna Module (WAM), a WVR Feed Heater Module (WHM), a WVR Receiver Module (WRM), a WVR Utility Module (WUM), a WVR Digital Processor Module (WDM), and 2 remaining LRUs described below. Each LRU is replaceable at the operational location. The five LRUs identified above will be installed on every 18m antenna, and on at least three dedicated stand-alone tracking mounts located within the footprint of the 6m antenna Short Baseline Array (SBA). These modules will not be installed on any 6m antennas. The SBA-based WVRs include two additional LRUs: a WVR Pier Module (WPM), and a WVR Tracker Module (WTM).

Figure 1 (next page) presents an overview of the WVR subsystem focusing on the modules identified above and interfaces with external subsystems, when mounting on an 18m antenna. Figure 2 presents an equivalent overview for the WVR units installed on stand-alone tracking mounts within the footprint of the SBA.

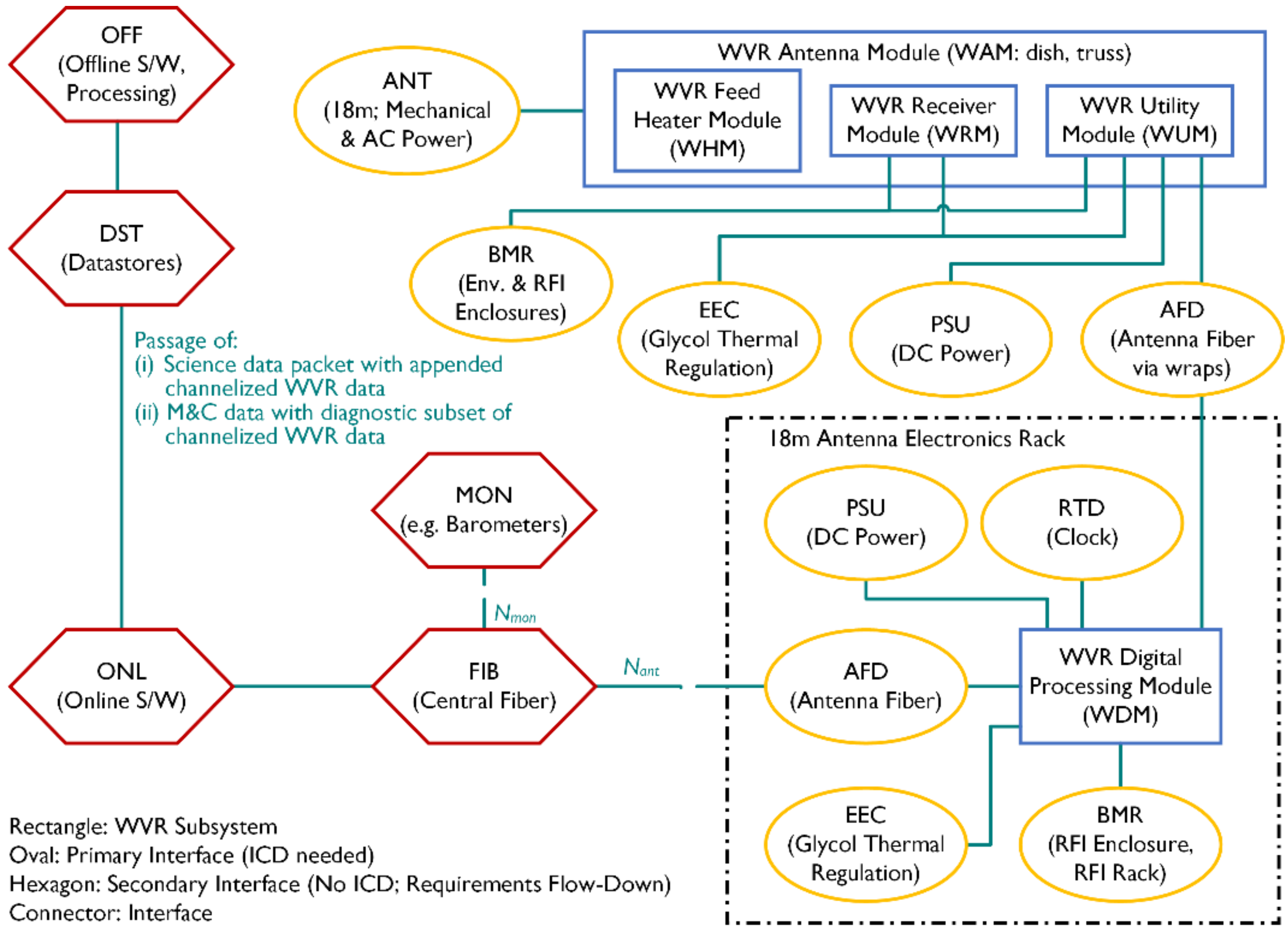

Figure 1: Overview of the Water Vapor Radiometer subsystem and interfaces with other subsystems, when mounting the WAM on an 18m antenna. For clarity, some subsystems are displayed twice, and not all interfaces are explicitly drawn. The WRM is DC powered and networked via the WUM. The WHM is AC powered through an interface with the ANT subsystem via a relay in the WUM. The MCL and HIL subsystems (monitor & control software and hardware layers, respectively) are not displayed; a primary interface exists between the HIL subsystem and the WUM. Interfaces representing the storage of configuration monitoring data, test and repair data, failure and anomaly reports for each WVR module, and scientific data in databases provisioned by the DST subsystem are implicitly assumed.

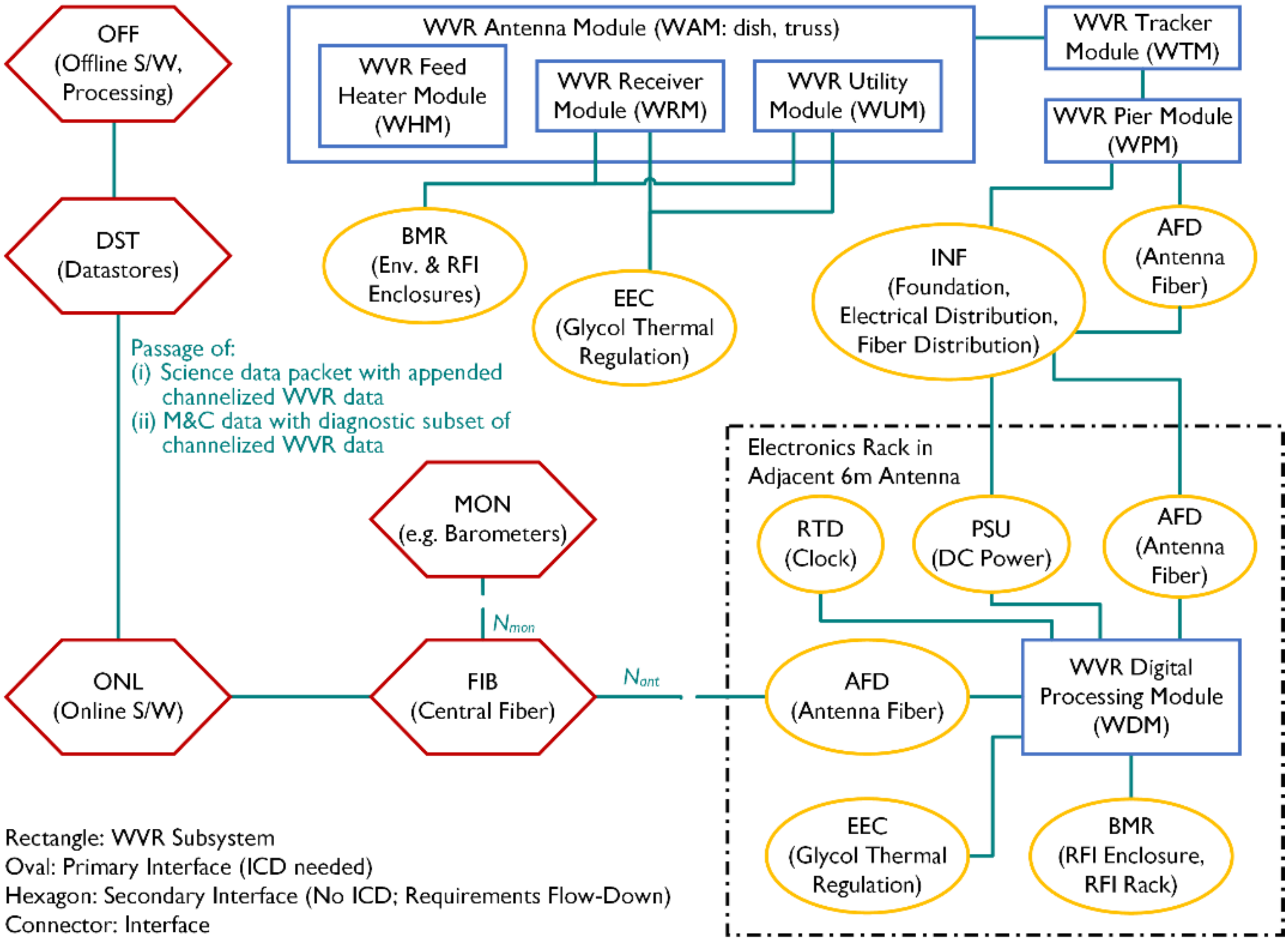

Figure 2: Equivalent to Figure 1 but where the WAM is situated on a tracking mount in the SBA footprint.

The WAM contains a dedicated WVR reflector dish, a support truss that affixes to the main 18m antenna structure or SBA-based WTM, and a truss to mount the WRM. The reflector is located at the edge of the main 18m dish to avoid blocking the main beam, and mounted in a fixed orientation without active positioning such that the optical axis intersects that of the zenith-pointing main beam at an altitude of 2400 m above ground level (AGL; i.e. the intersection is at a fixed distance along the main beam axis). The receiver mount accepts the WRM with mating surfaces designed to support accurate placement of the feed at the focal point.

The WRM contains a feed with environmental protection window, an external window heater, a receiver and digitizer contained within an RFI-shielded enclosure, temperature stabilized plates on which the electronics are situated, and an outer environmental protection enclosure with alignment structures. The receiver amplifies and down-converts a multi-GHz bandwidth encompassing the $6_{16} \rightarrow 5_{23}$ rotational transition of water vapor at 22.235 GHz. The receiver includes a switched noise diode to enable cancelation of gain drifts. The diode is coupled upstream from a low noise amplifier (LNA). All RF components and the digitizer are mounted to plates that are maintained at a fixed near-ambient temperature. Thermoelectric devices are affixed beneath the plates to provide fine temperature regulation. The RFI enclosure incorporates a heat exchange plate through which liquid glycol is circulated for coarse temperature regulation. The Antenna Electronics Environmental Control (EEC) subsystem is responsible for the glycol thermal control network including the heat exchanger plate. The Bins, Modules, and Racks (BMR) subsystem is responsible for the environmental and RFI enclosures. Power supplies provisioned by the Power Supplies and Distribution (PSU) subsystem, and a Monitor and Control (M&C) board provisioned by the Hardware Interface Layer (HIL) subsystem, are located within the WUM to support the WHM and WRM. The WUM is located under the reflector to reduce the complexity and mass of the WRM.

The WDM contains a dedicated FPGA-based processor housed within an RFI shielded enclosure (supplied by the BMR subsystem), to be located within an RFI-shielded electronics rack. The WDM is independent from the Digital Back End (DBE) that supports the main antenna signal path. The WDM ingests digitized data from the WRM, sent over dedicated fiber through the 18m antenna wrap provided by the Antenna Fiber Distribution (AFD) subsystem. The WDM performs antenna-based digital processing including channelization, after which it prepares the processed data and injects it via the HIL subsystem to the antenna M&C data stream provisioned by the Computing and Software (CSW) Monitor and Control (MCL) subsystem. These data then pass through the AFD subsystem and are subsequently transmitted across private and public telecommunications infrastructure managed by the Central Fiber Infrastructure (FIB) subsystem. The Antenna Time and Frequency (ATF) subsystem is responsible for delivering a timing reference to the WDM.

For SBA-based WVRs, the WDM is located in the electronics rack of an adjacent 6m antenna. Electrical power and fiber are passed under-ground between the 6m antenna and the stand-alone mount via the Array Infrastructure (INF) subsystem.

DC power is supplied to the WRM, WUM, and WDM by the PSU subsystem. AC power is supplied to the WHM by the 18m Antenna (ANT) subsystem or, for the SBA-based units, the INF subsystem.

The WRM, WUM, and WDM pass conventional M&C data across the AFD and FIB subsystems. The CSW Maintenance & Support Software (MSS) subsystem is responsible for provisioning software tailored to supporting maintenance activities, including tools to query M&C data and the display of M&C data in engineering dashboards.

The channelized WVR data from each of N_{ant} antennas are separated from the WVR M&C data stream by software in the CSW Online Software (ONL) subsystem. The ONL subsystem saves these data to the science data package together with other relevant monitor data (e.g. barometric pressures) reported by multiple (N_{mon}) weather stations provisioned by the Environmental Monitoring & Characterization (MON) subsystem. The ONL subsystem then passes the appended science data package to the CSW Datastores (DST) subsystem for storage in the science data archive. The ONL subsystem passes the remaining WVR M&C data and a diagnostic subset of the channelized WVR data for storage in an M&C database provided by the DST subsystem.

Dedicated software within the CSW Offline Software (OFF) subsystem accesses the WVR and related data in the science data package, identifies corrupted data to be flagged and excluded from subsequent processing, calculates delay corrections, saves these solutions to calibration tables, and appends these tables to the science data package.

The WVR subsystem defines low-level data as M&C data together with a diagnostic subset of the channelized WVR data. High-level data is defined as calibration solutions derived in the OFF subsystem. Note that high-level data from the WVR subsystem perspective corresponds to "low-level" data from a system-level perspective.

Spare LRUs will be stored at the Maintenance Center and at Remote Support Stations, both provided by the Operations Buildings (OPS) subsystem. Repair of a deployed LRU will involve transportation of a spare to the antenna site, swapping in the spare LRU and return of the WVR subsystem to operational status, transportation of the removed LRU to a separate Repair Center provisioned by the OPS subsystem, and, if appropriate, subsequent shipping to the Maintenance Center or a Remote Service Station facility for storage prior to future redeployment.

Configuration monitoring data, test and repair data, and failure and anomaly reports for each LRU will be recorded in databases provided by the DST subsystem.

3.3 Key Requirements Summary

The following table provides a summary of the major subsystem requirements in order to provide the reader with a high-level view of the desired subsystem.

Parameter	Summary of Requirement	Reference Requirements
LRU MTBM	The WVR subsystem shall be designed to deliver a MTBM of no less than 35,000 hours per antenna [RD28], excluding components that can be reasonably deemed ancillary to operation (e.g. non-critical monitor point sensors).	WVR1003
Automated Re-Configuration	WVR subsystem hardware and software shall automatically self-configure to an operationally-ready state after a maintenance hot swap or a power interruption (including an intentional power cycle), with minimal post-connection interaction from site personnel and remote operators.	WVR0502
Provision of Diagnostic Tools	Automated (and manual where necessary) tools shall be provided for engineers and technicians to monitor the real-time health and historical trends of the WVR subsystem and to remotely diagnose failures and behavior anomalies.	WVR0504
Precipitable Water Vapor: Precision Operation	The WVR subsystem shall be capable of precision performance for PWV path lengths between 1–6 mm, with median of 4 mm.	WVR1027
Delay Measurement Noise: Precision Performance	The WVR subsystem shall contribute delay measurement noise within 1 ps per 1 sec integration (or radiometer-scaled equivalent) during Precision Operation conditions.	WVR0001
Delay Measurement Drift: Precision Performance	The WVR subsystem shall contribute delay measurement drift within 0.1 ps over 5 min during Precision Operation conditions.	WVR0901
Tropospheric Sampling Rate	The WVR subsystem shall be capable of sampling the brightness temperature of the troposphere at a rate up to 1 Hz (1 sec integration time).	WVR0002
Processed Frequency Range	The WVR subsystem shall process the frequency range from 20 GHz to 30 GHz (goal: 17 GHz to 32 GHz).	WVR0005
Spectral Resolution	The WVR subsystem spectral resolution shall be no coarser than 200 MHz/channel.	WVR0008
System Noise Temperature: Precision Performance	The WVR subsystem shall satisfy $T_{sys} \leq 500$ K during Precision Operation conditions.	WVR0009

Parameter	Summary of Requirement	Reference Requirements
Antenna and Receiver Noise Temperature (T_{ant}+T_{rx})	The combined antenna and receiver temperature contributions to Tsys for the WVR subsystem shall not exceed 480 K, excluding atmospheric and sky emission.	WVR1171
Atmospheric Temperature Measurement Error: Precision Performance	The WVR subsystem shall measure atmospheric brightness temperatures within 50 mK rms in 1 sec during Precision Operation conditions.	WVR0010
Atmospheric Temperature Measurement Drift: Precision Performance	The WVR subsystem shall measure atmospheric brightness temperatures within 5 mK drift over 5 min during Precision Operation conditions.	WVR0011
Gain stability: Precision Performance	The WVR subsystem shall exhibit gain stability $\Delta G/G$ within $50\ mK/500\ K = 1 \times 10^{-4}$, or equivalent for design Tsys, for timescales ranging between 1 sec to 5 min under Precision Operation conditions.	WVR1175
Gain Drift: Precision Performance	The WVR subsystem shall exhibit gain drift $\Delta G/G$ within $5\ mK/500\ K = 1 \times 10^{-5}$, or equivalent for design Tsys, over 5 min under Precision Operation conditions.	WVR1177
Receiver Physical Temperature Stability: Precision Performance	The WVR subsystem shall thermally stabilize the receiver electronics to ensure noise temperature stability within 5 mK over 5 minutes during Precision Operation conditions.	WVR0006
Boresight Intersection Distance	The WVR subsystem optical axis shall intersect at 2.4 km fixed distance along the main beam axis.	WVR1300
Antenna HPBW	The WVR subsystem antenna HPBW shall be 45 arcmin at 22.235 GHz.	WVR0003
Total Pointing Accuracy	The WVR subsystem antenna and feed shall be mounted and maintain pointing toward the unperturbed beam intersection point within 6 arcmin rms under Precision and Normal Operation conditions at all main antenna sky pointing vectors.	WVR0004
WVR Antenna Pointing Accuracy	The WVR subsystem antenna and feed shall maintain pointing accuracy within 5 arcmin rms when mounted to a fixed surface under Precision and Normal Operation conditions, at all relevant mounting orientation angles.	WVR1302

4 Requirements Management

4.1 Requirements Definitions

Consistent with the Requirements Management Plan [RD02], the following definitions of requirement "levels" are used in the ngVLA program. The requirements in this document are at the L2 subsystem level.

Requirement Level	Definition
L0	User requirements expressed in terms applicable to their needs or use cases (Science Requirements or Stakeholder Requirements)
L1	Requirements expressed in technical functional or performance terms, but still implementation agnostic (System Level Requirements)
L2	Requirements that define a specification for an element of the system, presuming a system architecture (Subsystem Requirements)

4.2 Requirements Flow Down

Figure 3 (next page) displays the relationships between the various requirements and concept documents that flow down to the Water Vapor Radiometer subsystem. Requirement prefixes displayed in the traceability column of this document are drawn from the applicable documents as indicated in Section 2.1.

Individual subsystem specifications (Level 2) flow from the Level 1 requirements, and may not always be directly attributable to a single system requirement. For example, phase drift specifications at the system level may be apportioned to multiple subsystems, or a subsystem spec may be in support of multiple higher-level requirements. Completeness of the Level 2 requirements is assessed at the requirements review of each subsystem.

While this is a top-down design process, the process is still iterative rather than a waterfall or linear process. The feasibility and cost of requirements implementation lead to trade-offs that feedback to higher-level requirements. The end goal is to build the most generally capable system that will support the Key Science Goals within the programmatic constraints of cost and schedule.

Maintaining enumerated and traceable science requirements, system requirements, and subsystem specifications ensures this trade-off process is complete and well understood by the project team. The effect of a change in a subsystem specification can be analyzed at the system level, and thereafter the impact on a specific scientific program can be ascertained.

Requirement IDs are static once assigned and therefore not always in sequential order due to subsequent revisions of the associated documents.

4.3 Verb Convention

This document uses "shall" to denote a requirement. The verbs "should" and "may" denote desired but not strictly required parameters. "Will" denotes a future happening. Desired but not required features are noted as "desirable" or "goals."

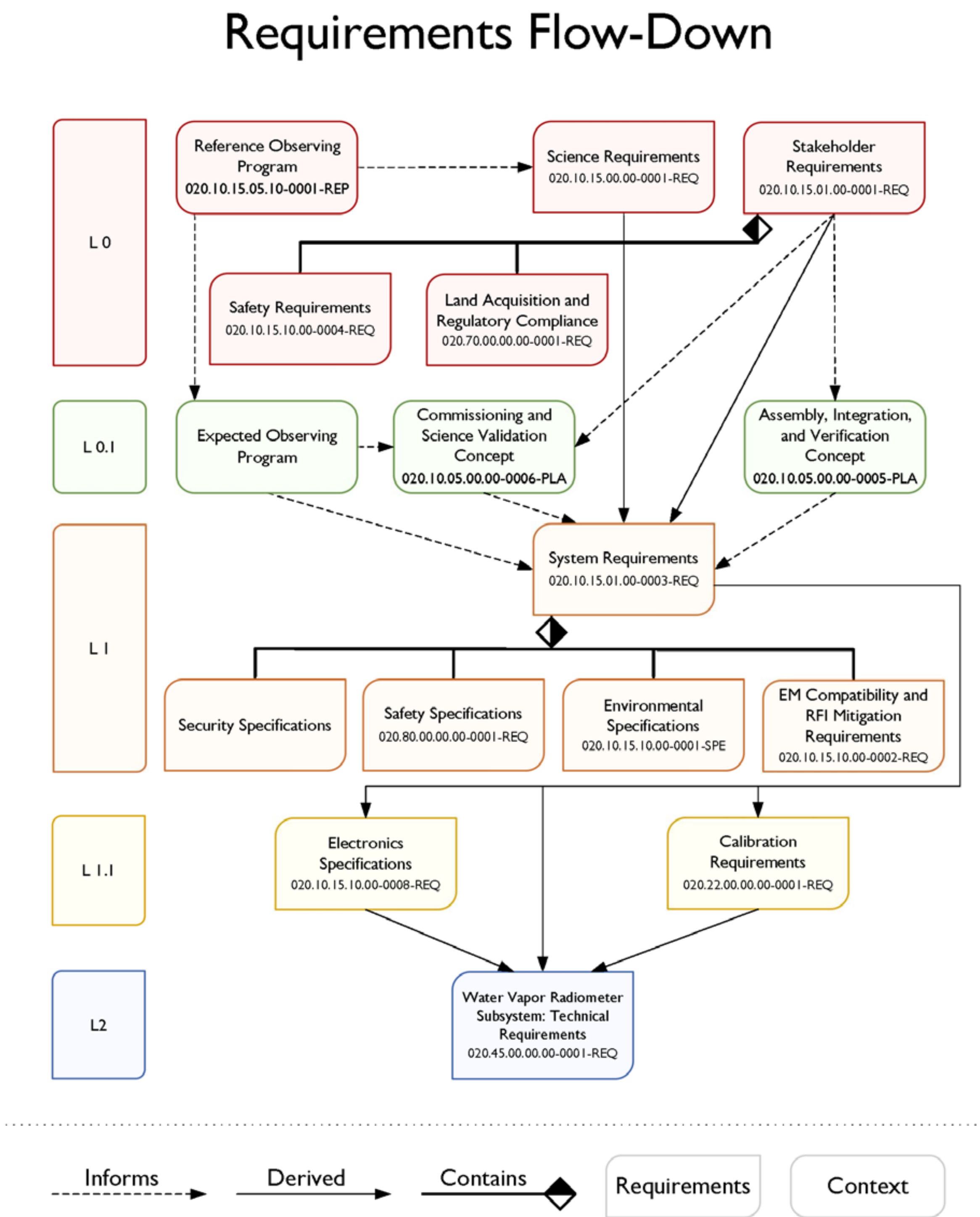

Figure 3: Requirements flow-down to the Water Vapor Radiometer Subsystem.

5 Assumptions

The following assumptions are made in the definition of these subsystem requirements:

- Subsystem requirements apply to performance before any operational calibration corrections are applied unless explicitly stated otherwise.
- Hardware requirements apply to a properly functioning system under the precision operating environmental conditions unless explicitly stated otherwise.
- Hardware requirements assume that all system parts that would normally be in place during observations are working within their respective specifications (e.g., glycol system) unless explicitly stated otherwise.
- Survival conditions may be encountered when the antenna is not (yet) in its stow-survival orientation.
- The general architecture and interface boundaries of the WVR subsystem conform to the description provided in Section 3.2.

6 Environmental Conditions

The WAM and affixed modules of the WVR subsystem are exposed directly to the outside environment. These modules shall satisfy the environmental requirements traced from the ngVLA System Environmental Specifications [AD02] presented in Section 7.1.1.

Similarly, the WAM and affixed modules shall satisfy the requirements traced from the ngVLA System EM Compatibility and RFI Mitigation Requirements [AD03] presented in Section 7.1.2. The WDM shall also satisfy the EMC/RFI requirements but with allowed overheads to be offset by shielding provided by the electronics rack.

The WVR subsystem hardware shall operate under the Precision, Normal, and Limiting (antenna stow-inducing) Operating Conditions as defined in [AD02]. Significantly, the WVR subsystem shall continue to operate safely within the broader limits set by the Standby Conditions to ensure the ability to resume operation within 5 minutes as specified in [AD02]. A standby mode, in which electronics may be turned off but with the ability to resume operations within 5 minutes after power-up, therefore does not exist for the WVR subsystem.

This is also the case with the liquid glycol thermal control network supplied by the Antenna Electronics Environmental Control (EEC) subsystem. If the operating conditions exceed the constraints set by the Standby Conditions, the liquid lines may need to automatically shut down. If this occurs, the WRM will also need to shut down to protect its components including thermoelectric devices. Once shut down, the electronic components will begin to equilibrate with the ambient temperature. The WRM, and therefore the WVR subsystem, shall not return to operating conditions until the EEC subsystem is operating within the acceptable constraints presented in Section 7.1.1, even if this occurs after the environment has returned to within the limits of the Standby Conditions. It is understood that the EEC subsystem could take longer than 5 minutes to resume operation after a shutdown. Note that while the WDM may be capable of returning to an operational status within 5 mins following power-up, the limiting constraint on returning the WVR subsystem as a whole to operational status rests with the WRM.

Environmental conditions for storage and transportation of WVR subsystem elements shall not exceed the constraints specified by the equipment manufacturers (such as vibration and temperature levels).

7 Subsystem Requirements

7.1 Functional and Performance Requirements

7.1.1 Environmental Requirements

Parameter	Req. #	Value	Traceability
Altitude Range	WVR1005	The WVR subsystem shall be capable of operation and survival at altitudes ranging from sea level to 2500m.	ENV0351
Solar Thermal Load: Precision Operation	WVR1019	The WVR subsystem shall be capable of precision performance at nighttime (no solar thermal load within last 2 hours).	ENV0311
Solar Thermal Load: Normal Operation	WVR1020	The WVR subsystem shall be capable of normal performance when exposed to full sun (up to 1200W/m^2 from 0.3–60 μm).	ENV0321, ENV0561
Temperature: Precision Operation	WVR1014	The WVR subsystem shall be capable of precision performance in temperatures –15°C ≤ T ≤ 25°C.	ENV0313
Temperature: Normal Operation	WVR1021	The WVR subsystem shall be capable of delivering normal performance in temperatures –15°C ≤ T ≤ 35°C.	ENV0323
Temperature: Limited Operation	WVR1016	The WVR subsystem shall be capable of limited performance in temperatures –25°C ≤ T ≤ 45°C.	ENV0362
Temperature Rate of Change: Precision Operation	WVR1015	The WVR subsystem shall be capable of precision performance for rates of change of ambient temperature up to 1.8°C/hr.	ENV0314
Temperature Rate of Change: Normal Operation	WVR1022	The WVR subsystem shall be capable of normal performance for rates of change of ambient temperature up to 3.6°C/hr.	ENV0324
Precipitation: Precision Operation	WVR1023	The WVR subsystem shall be capable of precision performance when there is no precipitation.	ENV0315
Precipitation: Normal Operation	WVR1024	The WVR subsystem shall be capable of normal performance when there is no precipitation.	ENV0325
Precipitation: Limited Operation	WVR1025	The WVR subsystem shall be capable of limited performance for rainfall up to 5 cm/hr over 10 mins.	ENV0363
Ice Accumulation: Limited Operation	WVR1026	The WVR subsystem shall be capable of limited performance when there is ice accumulation equivalent to 2.5 mm radial.	ENV0334, ENV0364
Precipitable Water Vapor: Precision Operation	WVR1027	The WVR subsystem shall be capable of precision performance for PWV path lengths between 1–6 mm, with median of 4 mm.	ENV0316
Precipitable Water Vapor: Normal Operation	WVR1028	The WVR subsystem shall be capable of normal performance for PWV path lengths between 1–26 mm, with median of 18 mm.	ENV0326

Parameter	Req. #	Value	Traceability
Wind: Precision Operation	WVR1029	The WVR subsystem shall be capable of precision performance for wind speeds up to 5 m/s average over 10 mins with peak gusts up to 7 m/s.	ENV0312
Wind: Normal Operation	WVR1030	The WVR subsystem shall be capable of normal performance for wind speeds up to 7 m/s average over 10 mins with peak gusts up to 10 m/s.	ENV0322
Wind: Limited Operation	WVR1031	The WVR subsystem shall be capable of limited performance for wind speeds up to 30 m/s average over 10 mins.	ENV0361
Relative Humidity: Limited Operation	WVR1047	The WVR subsystem shall be capable of limited performance for relative humidity $0\% \leq RH \leq 100\%$ with condensation permitted.	ENV0365
Survival: Wind	WVR1032	The WVR subsystem shall survive without damage winds up to 50 m/s average.	ENV0341
Survival: Temperature	WVR1017	The WVR subsystem shall survive without damage temperatures in the range $-30°C \leq T \leq 50°C$.	ENV0342
Survival: Radial Ice	WVR1033	The WVR subsystem shall survive without damage radial ice up to 2.5 cm.	ENV0343
Survival: Water Infiltration	WVR1034	The WVR subsystem shall survive without damage rainfall intensity of 16 cm/hr over 10 mins, with droplets sized 0.5 to 4.5mm, at wind velocity of 15 m/s in any direction.	ENV0344, ENV0571
Survival: Snow Load Depth	WVR1035	The WVR subsystem shall survive without damage snow depths up to 25 cm.	ENV0345
Survival: Snow Load Pressure	WVR1036	The WVR subsystem shall survive without damage pressures equivalent to 100 kg/m^2 on horizontal surfaces.	ENV0346
Survival: Hail Stones	WVR1037	The WVR subsystem shall survive without residual performance degradation hail up to 2.0 cm in diameter.	ENV0347
Lightning Protection of Structures and Housings	WVR1050	WVR subsystem structures and housings shall be protected from both direct and nearby lightning strikes, achieving Protection Level 1 as defined in IEC 62305-1/3 [AD08].	ETR0824
Lightning Protection of Electronics	WVR1006	WVR subsystem electronics shall be protected against Lightning Electromagnetic Impulse (LEMP) in accordance with IEC 62305-4 [AD08].	ENV0512, ETR0825
Seismic Protection	WVR1038	The WVR subsystem shall withstand a low-probability [AD11] earthquake with up to 0.2g peak acceleration in any orientation.	ENV0521

Parameter	Req. #	Value	Traceability
General Vibration Protection	WVR1039	The WVR subsystem shall withstand without damage persistent vibration with a power spectral density defined in Figure 1 from [AD02]. LRUs shall be tested to this vibration specification along all three axes as defined in the MIL-STD-810H [AD09] Method 514.8 Procedure I for General Vibration, for a period of 60 mins.	ENV0531
Mechanical Shock Protection	WVR1010	The WVR subsystem equipment and packaging of LRUs shall withstand without damage mechanical shock levels from handling as defined in the MIL-STD-810H [AD09] Method 516.8 Logistic Transit Drop Test, modified to use the drop heights specified in Table 1 from [AD02].	ENV0582, ETR1179
Dust Protection	WVR1007	The WVR subsystem shall be protected against windblown dust, ashes, and grit.	ENV0541
Rodent Protection	WVR1008	The WVR subsystem shall be protected against rodent damage to exposed equipment.	ENV0551
Solar Radiation Protection: UV	WVR1040	The WVR subsystem shall be designed for a daily UV flux of 100 W/m^2 from 280–400 nm.	ENV0562
Corrosion Protection	WVR1041	The WVR subsystem shall be designed to prevent corrosion to exposed equipment that may impact performance or structural integrity over the design life.	ENV0591
ESD Protection	WVR1042 –1046	Every WVR subsystem LRU and subassembly shall comply with ETR0501, ETR0503, ETR0504, ETR0505, and ETR0506.	ETR0501, ETR0503, ETR0504, ETR0505, ETR0506
Storage: Temperature	WVR1018	WVR subsystem LRUs shall survive without damage temperatures in the range 0°C ≤ T ≤ 30°C when disconnected and packaged for storage.	ENV0373
Storage: Relative Humidity	WVR1048	WVR subsystem LRUs shall survive without damage relative humidity in the range 10% ≤ RH ≤ 90% when disconnected and packaged for storage.	ENV0372
Transportation: Temperature	WVR1049	WVR subsystem LRUs shall survive without damage temperatures in the range –30°C ≤ T ≤ 60°C during transportation when disconnected and packaged for shipping.	ENV0382

The Precision, Normal, and Limited Operation requirements presented above define the conditions under which the subsystem shall meet the Precision, Normal, and Limited Performance requirements presented in Section 7.1.7.

The Precision Operation requirements define the conditions under which the subsystem shall provide optimal performance.

The Normal Operation requirements define the conditions under which the performance requirements are relaxed but shall still deliver adequate performance for science observations below 50 GHz.

The Limited Operation requirements define a boundary zone beyond the Normal Operation constraints within which the subsystem shall be capable of safe operation but without any performance guarantees. The subsystem may automatically shut down once the environment exceeds the limited operation constraints. Recall from Section 6 that the WVR subsystem does not have a Standby Operation mode.

The Survival requirements define the environmental conditions that the subsystem shall withstand without functional damage when all subsystem elements are placed in their least-vulnerable states, but without assuming that the 18m or 6m antennas are placed in their stow-survival orientations.

7.1.2 RFI & EMC Requirements

The WVR subsystem electronics shall be shielded to avoid radio frequency interference (RFI) being received by the Front End electronics. All ngVLA equipment shall exhibit complete electromagnetic compatibility (EMC) among components, demanding prevention of electromagnetic interference (EMI) within and between subsystems.

Software requirements for identifying and flagging RFI are presented in Section 7.2.12.

Parameter	Req. #	Value	Traceability
Spurious Signal Level	WVR0350	The WVR subsystem shall comply with EMC0310 regarding spurious signal levels.	EMC0310
Emission Verification Frequencies	WVR1012	The WVR subsystem shall comply with EMC0311 regarding test verification of spurious signal emission levels.	EMC0311
Low Frequency Emission	WVR0351	The WVR subsystem shall comply with EMC0312 regarding test quantification of spurious signal emission levels at low frequency.	EMC0312
Relay Contact Arcing	WVR0352	All WVR subsystem relay contacts and actuators shall be properly bypassed with snubber circuits, shielded, and/or filtered.	EMC0321
Amplifiers & Oscillators	WVR0353	All WVR subsystem amplifiers and oscillators shall be mounted in shielded enclosures that will provide effective shielding of radio frequency energy.	EMC0322
Silicon Controlled Rectifiers	WVR0354	Silicon-controlled rectifier switching devices shall not be used in the WVR subsystem unless phase controlled and zero current crossing switching techniques are used.	EMC0323
Gaseous Discharge Devices	WVR0355	No gaseous discharge devices shall be employed in WVR subsystem active circuits, except as noise sources for test and calibration. Use of such devices for lightning and ESD protection is permitted.	EMC0324
Static Discharge Mitigation	WVR0356	The WVR subsystem shall employ means to reduce static electricity and the consequent radio frequency noise generated in any rotating machinery.	EMC0325

Parameter	Req. #	Value	Traceability
Display Shielding	WVR0357	All WVR subsystem displays (LCD, plasma, LED, CRT) shall have fully enclosed RFI shields, including an RFI shield in front of the display. This requirement may be waived if the screen is powered off during typical operation and is used for maintenance purposes only. It must be possible to monitor and turn off such emitting devices remotely (via the M&C subsystem).	EMC0326
Digital Equipment Shielding	WVR1011	All WVR subsystem digital equipment, whether a simple logic circuit, embedded CPU, or rack mounted PC shall be shielded and have its AC or DC power line and communication line(s) filtered at the chassis.	EMC0327
COTS Immunity Standards	WVR0358 –0359	The WVR subsystem shall comply with EMC0401 and ETR0402 regarding electromagnetic immunity and certification of Commercial Off-the-Shelf equipment.	EMC0401, EMC0402
Step Voltage Fluctuations	WVR0360 –0361	The WVR subsystem shall comply with EMC0411 and EMC0412 regarding AC and DC supply step fluctuations.	EMC0411, EMC0412
Voltage Dips	WVR0362 –0365	The WVR subsystem shall comply with EMC0421–EMC0424 regarding AC and DC voltage dips.	EMC0421, EMC0422, EMC0423, EMC0424
Voltage Interruptions	WVR0366 –0367	The WVR subsystem shall comply with EMC0431 and EMC0432 regarding AC and DC voltage interruptions.	EMC0431, EMC0432
Voltage Surges and Bursts	WVR0368 –0369	The WVR subsystem shall comply with EMC0451 and EMC0452 regarding AC and DC supply burst immunity.	EMC0451, EMC0452
Conducted Noise	WVR0370 –0371	The WVR subsystem shall comply with EMC0461 and EMC0462 regarding AC and DC conducted noise immunity.	EMC0451, EMC0452
ESD Thresholds	WVR0372 –0374	The WVR subsystem shall comply with EMC0471–EMC0473 regarding electrostatic discharge thresholds.	EMC0471, EMC0472, EMC0473
Input Dynamic Range	WVR0375	The WVR subsystem shall comply with SYS1203 regarding analog headroom to mitigate against the impacts of solar observing and RFI.	SYS1203
Input Protection	WVR0376	The WVR subsystem shall survive exposure to input signal power of up to 10 dBm, integrated over the receiver bandwidth, with no damage to the receiving elements.	SYS1204
Instantaneous Dynamic Range	WVR0377	The WVR subsystem shall comply with SYS1201 regarding instantaneous dynamic range.	SYS1201

7.1.3 Lifecycle Requirements

Parameter	Req. #	Value	Traceability
Design Life	WVR0301	The WVR subsystem shall be designed for an expected operational life no less than 20 years, where the operational life is defined to start at the full operations milestone that occurs at the close-out of the construction project.	SYS2801
Lifecycle Cost Optimization	WVR0302	The WVR subsystem design shall minimize total lifecycle costs over the projected design life, including manufacturing, transportation, construction/assembly, operation, and decommissioning.	SYS2802
Part Selection for Maintainability	WVR0303	All WVR subsystem components shall have projected continuity of support or interchangeable equivalents over the subsystem design life.	SYS2805
Critical Spares	WVR0304	Critical spares for the WVR subsystem shall be identified and provided with sufficient inventory to support the subsystem for its design life.	SYS2812

Critical spares are defined as parts that are likely to become obsolete over the operating life, are unlikely to have market substitutes, or cannot be produced/ordered in small volumes.

7.1.4 Maintenance and Reliability Requirements

Parameter	Req. #	Value	Traceability
Modularization	WVR1004	The WVR subsystem shall be modularized into LRUs to facilitate site maintenance.	SYS2403
Interchangeable LRU	WVR0500	Any WVR subsystem LRU shall be swappable at the antenna by at most 2 people within 3 hours.	SYS3230, SYS3231, SYS2611
LRU easy removal and replacement	WVR0501	WVR subsystem LRUs shall provide guides where relevant to facilitate LRU mounting without special alignment procedures.	SYS2403
LRU MTBM	WVR1003	The WVR subsystem shall be designed to deliver a MTBM of no less than 35,000 hours per antenna [RD28], excluding components that can be reasonably deemed ancillary to operation (e.g. non-critical monitor point sensors).	SYS2610
Automated Re-Configuration	WVR0502	WVR subsystem hardware and software shall automatically self-configure to an operationally-ready state after a maintenance hot swap or a power interruption (including an intentional power cycle), with minimal post-connection interaction from site personnel and remote operators.	SYS2304, SYS3111, SYS3114, SYS3232

Parameter	Req. #	Value	Traceability
Preventive Maintenance Interval	WVR1002	The WVR subsystem shall be designed with a preventive maintenance interval no shorter than 1 year (goal: no preventive maintenance).	SYS3200
Provision of Predictive Tools	WVR0503	Automated tools shall be provided to predict the location and nature of WVR subsystem failures in support of maintenance scheduling.	SYS3221
Provision of Diagnostic Tools	WVR0504	Automated (and manual where necessary) tools shall be provided for engineers and technicians to monitor the real-time health and historical trends of the WVR subsystem and to remotely diagnose failures and behavior anomalies.	SYS2405, SYS3220, SYS3110, SYS3113
Engineering Console	WVR0505	The WVR subsystem shall include an engineering console to communicate the status of the subsystem and all LRUs deployed in the array, with the ability to focus on any individual LRU to assist in real-time diagnosis.	SYS2407
Criteria for Scheduling Maintenance	WVR0506	Preventive and corrective maintenance scheduling for the WVR subsystem shall be automated based on a combination of the severity of existing issues, required preventive maintenance, and predictions of pending problems.	SYS3203
Use of Failure Analysis in Spares Planning	WVR0507	Failure analysis shall be used in planning the WVR subsystem spares inventory. Factors considered shall include the projected availability for spares, the time required to repair the failure, viability of critical vendors, and shelf life.	SYS3204
LRU Storage	WVR0508	WVR subsystem LRUs shall be stored in shipping-ready packaging that provides protection from any damage or deterioration over the shelf life.	SYS2821
Maintenance Tiers	WVR0510	Maintenance tasks for the WVR subsystem shall be classified in tiers to assign the level of skill or maintenance visit required. It is a goal that site-based maintenance be limited to lower levels, with high-skill work generally performed at the Repair Center by specialized staff and equipment under a higher degree of environmental and process control.	SYS3201
Optimization for Maintenance	WVR0511	Design of the WVR subsystem and all tools required for its maintenance and repair shall be optimized to maximize the efficiency of time spent on antenna visits and repair of equipment.	SYS3202
Transportation Protection	WVR1009	Shipping cases and packaging for WVR subsystem LRUs shall be provided with ESD protection and mechanical shock absorption consistent with the equipment specifications.	SYS3904

Parameter	Req. #	Value	Traceability
Battery Use	WVR0517	Batteries shall not be used in the WVR subsystem.	ETR0817
Memory	WVR0518	The WVR subsystem shall use non-volatile memory where possible.	ETR0817
Local Firmware	WVR0519	All WVR subsystem programmable devices shall have local copies of their firmware at the antenna site (i.e. devices shall not depend on M&C to become operational). Firmware that is for basic functional & diagnostic purposes, but may be configured remotely for normal operation, satisfies this requirement.	ETR0906
Firmware Updates	WVR0520	All WVR subsystem devices containing firmware shall be upgradeable remotely (i.e. without visiting the antenna site).	ETR0907
Electronic Test and Measurement Equipment – Maintenance & Calibration	WVR0521	All electronic test equipment used in the development and maintenance of WVR subsystem electronics shall be maintained and calibrated to traceable external standards on an annual basis or as recommended by the equipment manufacturer (whichever is shorter).	ETR0913

7.1.5 Monitor and Control Requirements

Parameter	Req. #	Value	Traceability
LRU Monitoring	WVR0201	WVR subsystem LRUs shall stream monitor data on short timescales (0.1 sec to 10 min) for use by diagnostic and predictive maintenance programs and for direct inspection by engineers and technicians.	SYS2408, SYS3101
LRU Alerts	WVR0600	WVR subsystem LRUs shall report a prioritized alert when out of specification for processing by the operator and maintenance scheduler.	SYS3102
Fast Read-Out Modes	WVR0601	WVR subsystem LRUs shall provision fast read-out modes for remote engineering diagnostics (e.g. RF inputs, LO input, regulated power supply levels).	SYS3105
Intelligent LRUs	WVR0602	WVR subsystem LRUs shall be smart devices with on-board advanced diagnostics that can be accessed remotely for troubleshooting (e.g. power detectors).	SYS3112, ETR0911
Watchdogs	WVR0603	All WVR subsystem programmable devices shall utilize watchdog timers and power supervisors to detect lockups and attempt self-recovery.	ETR0908

Parameter	Req. #	Value	Traceability
M&C Commanded Reset for DC Powered Devices	WVR0604	All DC powered WVR subsystem LRUs and complex programmable devices shall be provided with a physical reset line connected to a local M&C device to allow remote reset commands to be sent. This could be implemented as a ganged reset to all devices in an LRU or as individual lines to each device (or group of devices) as determined by the designer.	ETR0909
M&C Commanded Reset for AC Powered Devices	WVR0605	All AC powered WVR subsystem LRUs shall be connected to a remotely controllable Power Distribution Unit (PDU) or similar device that can be remotely commanded via the M&C system to power cycle each individual device.	ETR0912
Periodic Self-Tests	WVR0606	All WVR subsystem devices with M&C connection shall perform and report results from self-tests at power on and on a periodic basis.	ETR0910
Self-Monitoring	WVR0607	The WVR subsystem shall automatically monitor its health and prohibit actions likely to cause damage, or shut down to prevent damage.	SYS2701

7.1.6 Configuration Management

Parameter	Req. #	Value	Traceability
LRU Physical and Online Identification	WVR0700 –0704	All WVR subsystem LRUs shall comply with ETR0401–0404 and ETR0409 to facilitate configuration monitoring and tracking.	ETR0401, ETR0402, ETR0403, ETR0404, ETR0409
Configuration Monitoring	WVR0705	Tracking and status data for every WVR subsystem LRU shall be recorded in the Quality Control Database, including LRUs out of service (e.g. in transit, in storage, under repair).	SYS2406, SYS3404
Version Control	WVR0706	WVR subsystem software and firmware shall be version controlled via a configuration management process.	SYS3602

7.1.7 Performance Requirements

Parameter	Req. #	Value	Traceability
Delay Measurement Noise: Precision Performance	WVR0001	The WVR subsystem shall contribute delay measurement noise within 1 ps per 1 sec integration (or radiometer-scaled equivalent) during Precision Operation conditions.	CAL0303
Delay Measurement Noise: Normal Performance	WVR0900	The WVR subsystem shall contribute delay measurement noise within 3 ps per 1 sec integration (or radiometer-scaled equivalent) during Normal Operation conditions.	CAL0303

Parameter	Req. #	Value	Traceability
Delay Measurement Drift: Precision Performance	WVR0901	The WVR subsystem shall contribute delay measurement drift within 0.1 ps over 5 min during Precision Operation conditions.	CAL0303
Delay Measurement Drift: Normal Performance	WVR0902	The WVR subsystem shall contribute delay measurement drift within 0.6 ps over 20 min during Normal Operation conditions.	CAL0303
Slew Drift: Precision Performance	WVR0903	The WVR subsystem shall satisfy WVR0901 during antenna slews over 3˚ on the sky.	CAL0303, SYS1104
Slew Drift: Normal Performance	WVR0904	The WVR subsystem shall satisfy WVR0902 during antenna slews over 3˚ on the sky.	CAL0303, SYS1104
Limited Performance	WVR0905	The WVR subsystem shall be capable of safe operation under Limited Operation conditions, but without any performance guarantees. (Goal: achieve Normal Performance under Limited Operation conditions.)	SYS2701
Tropospheric Sampling Rate	WVR0002	The WVR subsystem shall be capable of sampling the brightness temperature of the troposphere at a rate up to 1 Hz (1 sec integration time).	CAL0303
Accessible Field of View: Precision Performance	WVR0907	The WVR subsystem shall be capable of Precision Performance under Precision Operation conditions when observing at main antenna elevations between 35° to 88°, relative to the local horizon.	SYS1102, CAL0303
Accessible Field of View: Normal Performance	WVR0908	The WVR subsystem shall be capable of Normal Performance under Normal Operation conditions when observing at main antenna elevations between 12° to 88°, relative to the local horizon.	SYS1102
Solar Observing Performance	WVR0909	The WVR subsystem shall be capable of Limited Performance when observing the sun (i.e. no damage and without performance guarantees).	SYS1203

Precision, Normal, and Limited Operation requirements and their relationships with Precision, Normal, and Limited Performance requirements are explained in Sections 6 and 7.1.1.

Measurements of tropospheric delay will be affected by three types of errors:

1. The first arises from natural fluctuations in the troposphere. Natural fluctuations do not exhibit radiometer noise scaling. Instead, these fluctuations are characterized by the temporal structure function relationship presented in [RD07]. CAL0303 specifies the allowable level of natural delay fluctuations and in-turn the sampling rate necessary to remove (i.e. calibrate) fluctuations that occur above this level. CAL0303 requires 1 ps in 8 sec with a goal of 180 fs in 1 sec.
2. The second arises from the measurement process due to inherent thermal noise and drift in the WVR subsystem equipment. This noise will ideally exhibit radiometer scaling. To ensure that measurement errors do not contribute more than approximately 10% to the combined total with natural tropospheric fluctuations, measurement errors must be within approximately half of the total noise requirement specified by CAL0303. This yields a requirement for measurement noise of 0.5 ps per 8 sec integration, or conservatively 1 ps per 1 sec integration assuming ideal

radiometer scaling. CAL0303 also specifies that any systematic measurement drifts must be within 0.1 ps over 5 min. Equivalent values in units of electrical path length are obtained by multiplying by the speed of light. Equivalent values in units of precipitable water vapor (PWV) column w (i.e. integrated water vapor density) are obtained by dividing the electrical path length by factor 6.3 (assuming an isothermal atmosphere at 280 K; [RD04] Eq. 13.19), yielding 50 μm noise in 1 sec and 5 μm drift over 5 min. These values define Precision Performance. (For comparison, and as an informal goal for WVR0001, note that measurement noise would need to be 180 fs or 9 μm PWV in 1 sec in order to equal the natural level of fluctuations expected from the troposphere on this timescale.)

3. A third type of error arises from delay inference from the measured data. This is assumed to be Gaussian, incorporated into the measurement error constraints derived above, and (likely) negligible.

For comparison, test results obtained in September 2019 for a single JVLA baseline outfitted with Compact Water Vapor Radiometers (CWVRs) demonstrate residual delay calibration errors of 2 ps, with expected future improvement when known instrumental issues are corrected [RD21].

Requirements for Normal Performance are derived following the calculations presented for CAL0303 in [AD07], but with a reduced image dynamic range target of 35 dB at 8 GHz (rather than 45 dB). Antenna-based tropospheric delay fluctuations must be within 5 ps noise at 1 min cadence. Taking half this value yields a requirement for measurement noise of 2.5 ps per 1 min integration. This is conservatively translated to 3 ps in 1 sec (rather than 40 ps per 1 sec integration assuming ideal radiometer scaling) so that phase noise remains within 120˚ at 116 GHz (note from [RD07] that the atmospheric coherence time for 120˚ noise at 116 GHz is 30 sec, in which case sampling at 1 sec cadence will facilitate some imaging science under Normal Operation conditions due to the ability to reduce the standard error in the mean within each 30 sec window). The drift requirement is also calculated as above, yielding 0.6 ps over a lengthened timescale of 20 min (rather than 5 min). Equivalent values in units of PWV are 140 μm noise in 1 sec and 30 μm drift over 20 min.

Delay measurement drift requirements are specified over 3˚ motions on the sky, corresponding to the maximum anticipated separation between a target and a nearby suitable astronomical calibrator. SYS1104 requires the capability to track objects and map an area of sky at 10x sidereal speeds (12.5˚ over 5 min, or 50˚ over 20 min) when under 70˚ elevation. This is supported by the drift requirements in this document, as several nearby calibrators will be observed during fast tracking or wide-area mapping, each no more than 3˚ from the target regions in between (i.e. the time between calibrator observations will be less than 5 min or 20 min).

A sampling rate up to 1 Hz shall be supported, as incorporated above, so as to (i) provide headroom for Nyquist sampling of atmospheric advection speeds faster than the typically assumed value of 10 m/s and (ii) enable integration over multiple samples for engineering diagnostics (e.g. noise scaling tests).

The minimum antenna elevation angle for Precision Performance (WVR0907) is derived in Section 7.1.11. A cutoff at 35˚ is consistent with the Notional Reference Observing Program [RD25] and the Notional Envelope Observing Program [RD26], and will avoid difficulties for Precision Performance at large airmass.

7.1.8 Spectral Requirements

Parameter	Req. #	Value	Traceability
Processed Frequency Range	WVR0005	The WVR subsystem shall process the frequency range from 20 GHz to 30 GHz (goal: 17 GHz to 32 GHz).	WVR0001, WVR0901, WVR0903, WVR0907
Gaps in Frequency Coverage	WVR1070	Any bandwidth divisions for transmission and processing in the WVR subsystem shall not create gaps in frequency coverage.	WVR0001, WVR0901, WVR0903, WVR0907
Spectral Resolution	WVR0008	The WVR subsystem spectral resolution shall be no coarser than 200 MHz/channel.	WVR0001, WVR0901, WVR0903, WVR0907
Sampled Polarizations	WVR1071	It is a goal for the WVR subsystem to sample two independent polarization streams simultaneously.	SYS4100
Bandpass Stability: Precision Performance	WVR1072	The WVR subsystem shall deliver channel-averaged bandpass amplitude stability within the drift stability defined in WVR1177.	WVR1177
Bandpass Stability: Normal Performance	WVR1073	The WVR subsystem shall deliver channel-averaged bandpass amplitude stability within the drift stability defined in WVR1178.	WVR1178
Local Oscillator Stability	WVR1074	The frequency stability $\Delta f/f$ of the local oscillator signal supplied to the WVR subsystem receiver shall be within 10^{-5} on timescales up to 5 min (goal: 12 hours).	WVR0008, WVR0011, WVR0005

- *Processed Frequency Range:* A wide band is needed to facilitate accurate separation of water vapor fluctuations from superimposed spectral features arising from infrared water vapor line-wing emission, liquid water continuum emission, oxygen line-wing emission, dry air, and fluctuations in ground pickup. As the bandwidth is decreased, component separation degeneracies are increased, leading to increased delay measurement errors. The band must encompass at least several GHz from both shoulders of the broad water vapor spectral line centered at 22.2 GHz so that pressure broadening can be detected and used to constrain the variable distribution of water vapor with height. The band must extend down to at least 20 GHz, including the 20.6 GHz hinge point where absorption is approximately invariant with pressure and is therefore a useful frequency for calibration, and ideally down to 17 GHz. The band must extend up to at least 30 GHz to best constrain the liquid water contribution arising from fog and clouds [RD04 Sec. 13.3.2]. The brightness temperature at 31.5 GHz is dominated (~70%) by liquid continuum [RD19].
- *Gaps in Frequency Coverage:* Complete frequency coverage is required to minimize systematics over the wide band and minimize delay measurement errors in the presence of RFI, where data in affected spectral spans may need to be flagged.
- *Spectral Resolution:* Delay measurement errors increase with increasing channel bandwidth due to averaging over spectral features of interest. The spectral resolution is required to be no coarser than 200 MHz/channel. Narrow channels are advantageous for RFI identification and for minimizing the

number of RFI-corrupted channels (flagged channels lead to loss in sensitivity and loss in spectral coverage, both of which impact delay measurement error).

- *Sampled Polarizations:* Simultaneous dual sampling is advantageous for reasons of RFI resilience, resilience against polarization-dependent systematics [e.g. RD21 Sec. A.2], and redundancy (reduced site maintenance burden).
- *Bandpass Stability:* Drift requirements for bandpass amplitude stability per polarization, averaged over all channels, are derived from gain stability requirements described in Section 7.1.9.
- *Local Oscillator Stability:* The change in atmospheric brightness temperature with frequency is maximized near 21.5 GHz, with a gradient of approximately 6 mK per 1 MHz. To satisfy the brightness temperature drift requirement of 5 mK (WVR0011) within a channel no broader than 200 MHz (WVR0008) so that the slope remains approximately linear, the frequency must be stable to within $\Delta f < 5\,mK\ /\ (0.5 \times 6\,mK) \approx 1\,MHz$. Conservatively, assuming this must be satisfied at 30 GHz (WVR0005), the required frequency stability is $\Delta f/f < 10^{-5}$. This must be satisfied over the precision gain timescale of 5 min, but preferably over a timespan that exceeds the length of any observation scheduling block. This is applicable to both precision and normal operation conditions.

7.1.9 Sensitivity Requirements

Parameter	Req. #	Value	Traceability
System Noise Temperature: Precision Performance	WVR0009	The WVR subsystem shall satisfy $T_{sys} \leq 500$ K during Precision Operation conditions.	WVR1027, WVR0907, WVR1014
System Noise Temperature: Normal Performance	WVR1170	The WVR subsystem shall satisfy $T_{sys} \leq 550$ K during Normal Operation conditions.	WVR1028, WVR0908, WVR1021
Antenna and Receiver Noise Temperature (T_{ant}+T_{rx})	WVR1171	The combined antenna and receiver temperature contribution to T_{sys} for the WVR subsystem shall not exceed 480 K, excluding atmospheric and sky emission.	WVR0009
Atmospheric Temperature Measurement Error: Precision Performance	WVR0010	The WVR subsystem shall measure atmospheric brightness temperatures within 50 mK rms in 1 sec during Precision Operation conditions.	WVR0001
Atmospheric Temperature Measurement Error: Normal Performance	WVR1173	The WVR subsystem shall measure atmospheric brightness temperatures within 140 mK rms in 1 sec during Normal Operation conditions.	WVR0900
Atmospheric Temperature Measurement Drift: Precision Performance	WVR0011	The WVR subsystem shall measure atmospheric brightness temperatures within 5 mK drift over 5 min during Precision Operation conditions.	WVR0901
Atmospheric Temperature Measurement Drift: Normal Performance	WVR1174	The WVR subsystem shall measure atmospheric brightness temperatures within 30 mK drift over 20 min during Normal Operation conditions.	WVR0902

Parameter	Req. #	Value	Traceability
Gain Stability: Precision Performance	WVR1175	The WVR subsystem shall exhibit gain stability $\Delta G/G$ within $50\ mK/500\ K = 1\times10^{-4}$, or equivalent for design Tsys, for timescales ranging between 1 sec to 5 min under Precision Operation conditions.	WVR0010, WVR0009, WVR0907
Gain Stability: Normal Performance	WVR1176	The WVR subsystem shall exhibit gain stability $\Delta G/G$ within $140\ mK/550\ K = 2.5\times10^{-4}$, or equivalent for design Tsys, for timescales ranging between 1 sec to 20 min under Normal Operation conditions.	WVR1173, WVR1170
Gain Drift: Precision Performance	WVR1177	The WVR subsystem shall exhibit gain drift $\Delta G/G$ within $5\ mK/500\ K = 1\times10^{-5}$, or equivalent for design Tsys, over 5 min under Precision Operation conditions.	WVR0011, WVR0009
Gain Drift: Normal Performance	WVR1178	The WVR subsystem shall exhibit gain drift $\Delta G/G$ within $30\ mK/550\ K = 5\times10^{-5}$, or equivalent for design Tsys, over 20 min under Normal Operation conditions.	WVR1174, WVR1170

The system noise temperature measured by a switched radiometer is (e.g. [RD13])

$$T_{sys} \approx T_{atm}^{0,w}(1-\exp[-A\tau^{0,w}]) + T_{cmb}\exp(-A\tau^{0,w}) + T_{ant} + T_{rx}$$

where z is zenith angle, $A \approx \sec z$ is airmass assuming a plane-parallel atmosphere, and superscripts $0, w$ indicate a zenith (0) PWV-dependent (w) value. The noise diode is only used for tracking gain fluctuations and does not contribute to the equation above (it is off) for WVR measurements. The temperature contributions are identified below, together with estimated upper limits in order to derive requirements below for system temperature and gain stability.

The zenith atmospheric opacity[1] $\tau^{0,w}$ near 22 GHz arises from the sum of 5 principal components:

1. Pressure-broadened emission from the 22.235 GHz water vapor line [RD15]; also [RD16], [RD17]
2. Far-wing emission from very strong water vapor lines at infrared wavelengths, which appear as a continuum near 22 GHz (the origin of this "excess" water vapor absorption was uncertain for several decades) [RD18; also RD16, RD19, RD04 Sec. 13.1.4]
3. Continuum emission from liquid water droplets and ice crystals suspended in fog and clouds (hydrosols) [RD04 Sec. 13.3]
4. Wing emission from very strong molecular oxygen lines near 60 GHz, which appear as a continuum near 22 GHz [RD06 Fig. 6]
5. Continuum emission arising from viscous damping of dry air [RD19 Fig. 5].

Summing estimates for each of these components (see references above), but excluding an explicit term for component 2 because it is factored into the empirical Gaut-Reifenstein expression for component 1, and assuming a very wet cumulus cloud for component 3 and conservative upper limits for components 4 and 5, yields an upper limit for zenith opacity given by

[1] Optical depth is the product of zenith opacity and airmass. An optically thin medium is one in which the optical depth is less than unity, where photons will traverse the line of sight without absorption. Optically thick media absorb photons. The 22 GHz water line remains unsaturated (i.e. optically thin) for $z < 78°$ when $w \lesssim 23$ mm.

$$\tau^{0,w} < k\frac{w(mm)+3.5}{177} + 0.07 + 0.01 + 0.01\,.$$

The correction factor $k = p_{0.55km}/p_{2.5km} \approx 1.36$ accounts for pressure broadening [RD04 Sec. 13.3.2] between an altitude of 550 m and 2.5 km, the former altitude set by the apparatus described in [RD15] to derive the PWV relationship for component 1, and the latter set by WVR1005.

The zenith atmospheric brightness temperature $T_{atm}^{0,w}$ is then given by

$$T_{atm}^{0,w} < T_h(1 - \exp[-\tau^{0,w}])$$

where T_h is the physical temperature at height h above the surface. Assuming a scale height for water vapor of 2 km, a surface temperature of 35°C, a vertical lapse rate of approximately 7°C/km, and neglecting differences in vertical structure between the opacity contributions for this conservative calculation, the temperature aloft is $T_h \approx 290\ K$ [RD04 Sec. 13.2.1].

Assuming negligible sources of diffuse astrophysical emission (e.g. Galactic plane), the unresolved astrophysical background is dominated by the cosmic microwave background (cmb) given by

$$T_{cmb} < 3\ K\,.$$

It is assumed that temperature contributions from resolved astrophysical sources are negligible, whether from the distribution of extragalactic sources (6×10^{-5} K at 22 GHz; [RD14]) or from individual sources.

The sum $T_{ant} + T_{rx}$ must be less than 480 K to avoid placing strenuous demands ($<10^{-4}$) on gain stability under precision operating conditions (below).

The antenna temperature T_{ant} term includes contributions from reflector surface ohmic losses and sensitivity to ground emission T_{gnd} (spillover and scattering). Note that, as defined in the equation for system temperature above, T_{ant} excludes atmospheric and sky temperature contributions. Certain designs may render the spillover and scattering contributions negligible over relevant changes in zenith angle (WVR0903). As an upper limit to constrain the calculation below, spillover and scattering are assumed to arise from soil at temperature $T_{gnd} = 310\ K$ with fractional backlobe[2] solid angle $\epsilon_{bl} = \Omega_{bl}/\Omega_{4\pi} = 5\%$, where $\Omega_{bl} = 1 - \Omega_{fl}$ is the effective solid angle of the backlobes of the antenna power pattern, Ω_{fl} is the effective solid angle of the main beam and its near sidelobes, and $\Omega_{4\pi}$ is the all-sky integral of the power pattern. For illustration, accommodating surface losses within the above conservative upper limit for spillover and scattering ($\epsilon_{bl}T_{gnd}$), the antenna temperature must satisfy

$$T_{ant} < 20\ K\,.$$

The final contribution is from the receiver electronics which will be thermally stabilized (Section 7.2.5). The reliability of components typically decreases with increasing temperature. At ambient temperature, the upper limit to the noise temperature of the receiver electronics (dominated by the LNA), averaged across the band, is therefore

$$T_{rx} < 460\ K\,.$$

Note that quantum corrections are not needed when converting between physical to noise temperatures for non-cryogenic equipment [e.g. RD04 Sec. 7.1.2]. Note also that ohmic losses arising from passive components are assumed to be accommodated within the conservative upper limits presented above. These losses include feed surfaces and the feed window that contribute to T_{rx}.

[2] Note that in reality the atmospheric and cmb temperature contributions need to be multiplied by a forward beam efficiency factor $\epsilon_{fl} = \Omega_{fl}/\Omega_{4\pi}$, but this is neglected for the conservative calculations presented here.

Figure 4 presents resulting estimates of system temperature for zenith angles up to 78° and zenith PWV columns ranging between 1–26 mm (from WVR1027 and WVR1028). Note that opacity of the 22 GHz water line rarely exceeds 0.2 in the zenith direction, corresponding to approximately 23 mm PWV.

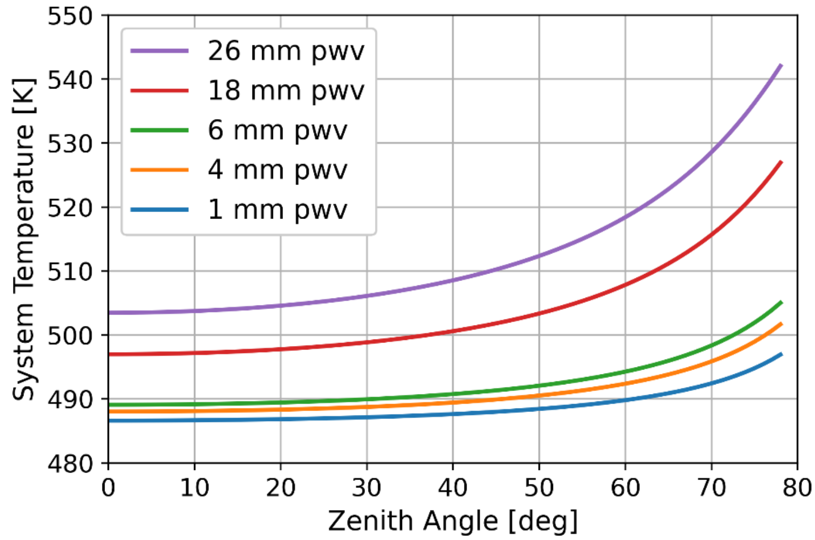

Figure 4: System temperature upper limits as functions of PWV column and zenith angle.

From these curves, requirements for system temperature upper limits are set at 500 K under Precision Operation conditions within 55° zenith angle (WVR0907), and 550 K under Normal Operation conditions.

Requirements for measurement errors are expressed in terms of atmospheric brightness temperature as the target observable, not system temperature. The distinction is that the frequency-dependent system temperature measurement data will be processed to infer changes in atmospheric brightness temperature (and, in-turn, tropospheric delay), resulting in an additional source of error (identified as the third error listed in Section 7.1.7). To illustrate accommodation of this additional error contribution, the atmospheric brightness temperature requirements may be conservatively interpreted as system temperature measurement error requirements for an individual channel at line-center (and therefore effectively for all channels). This will ensure that errors resulting from the combination of multi-channel system temperature data will satisfy the atmospheric brightness temperature error requirements.

Simulations can be used to determine the brightness temperature sensitivity per unit PWV column for a given antenna altitude and spectral weighting scheme. This document will conservatively assume ΔT_{rms} / Δw_{rms} ≈ 1 K/mm following [RD11]. This is a worst-case scaling arising from the particular (un-optimized) spectral sampling investigated by [RD11].

For comparison, the best-case sensitivity at line center is approximately 2 K/mm [RD04 Table 13.5]. Following Section 7.1.7, requirements for Precision delay measurement errors in units of PWV column are 50 µm noise in 1 sec and 5 µm drift over 5 min. Using the scaling above, these convert to 50 mK and 5 mK, respectively. Requirements for Normal delay measurement errors are 140 µm noise in 1 sec and 30 µm drift over 20 min. These convert to 140 mK and 30 mK, respectively.

Note that these calculations assume perfect accounting of continuum contributions from water vapor, hydrosols, oxygen, and dry air. This should be approximately correct for a wide-bandwidth design. Note also that the theoretical sensitivity limit for a radiometer is given by $T_{sys}/\sqrt{BT}$ for bandwidth B and integration time T. This yields 17 mK assuming a system temperature of at most 550 K, 1 sec integrations, and a conservative bandwidth of 1 GHz. This is comfortably within the sensitivity requirements above, and where in reality a wider bandwidth is anticipated.

Requirements for gain stability $\Delta G/G$ are then calculated as $50\,mK/500\,K = 1\times10^{-4}$ for Precision Performance and $140\,mK/550\,K = 2.5\times10^{-4}$ for Normal Performance. Corresponding gain drift requirements are $5\,mK/500\,K = 1\times10^{-5}$ for Precision Performance and $30\,mK/550\,K = 5\times10^{-5}$ for Normal Performance. Accurate temperature control of the RF electronics will be needed to minimize gain drift.

7.1.10 Thermal Stability Requirements

Parameter	Req. #	Value	Traceability
Receiver Physical Temperature Stability: Precision Performance	WVR0006	The WVR subsystem shall thermally stabilize the receiver electronics to ensure noise temperature stability within 5 mK over 5 minutes during Precision Operation conditions.	WVR0011
Receiver Physical Temperature Stability: Normal Performance	WVR1200	The WVR subsystem shall thermally stabilize the receiver electronics to ensure noise temperature stability within 30 mK over 20 minutes during Normal Operation conditions.	WVR1174

Receiver Temperature Stability: Quantum corrections are applied when tracing the noise temperature requirements from Section 7.1.9 to those presented here in units of physical temperature, because the WVR subsystem receiver is non-cryogenic [RD04 Sec. 7.1.2].

7.1.11 Antenna Requirements

Parameter	Req. #	Value	Traceability
Boresight Intersection Distance	WVR1300	The WVR subsystem optical axis shall intersect at 2.4 km fixed distance along the main beam axis.	CAL0303
Antenna HPBW	WVR0003	The WVR subsystem antenna HPBW shall be 45 arcmin at 22.235 GHz.	CAL0303
Total Pointing Accuracy	WVR0004	The WVR subsystem antenna and feed shall be mounted and maintain pointing toward the unperturbed beam intersection point within 6 arcmin rms under Precision and Normal Operation conditions at all main antenna sky pointing vectors.	CAL0303, WVR1300, WVR0003
WVR Antenna Pointing Accuracy	WVR1302	The WVR subsystem antenna and feed shall maintain pointing accuracy within 5 arcmin rms when mounted to a fixed surface under Precision and Normal Operation conditions, at all relevant mounting orientation angles.	WVR0004

Parameter	Req. #	Value	Traceability
Feed Position Accuracy: Precision Performance	WVR1303	Gain fluctuations resulting from WVR subsystem feed positioning fluctuations (axial, lateral, tilt) shall not exceed the gain stability defined in WVR1175 over changes in main antenna elevation up to 3° under Precision Operation conditions.	WVR1175, WVR0903, WVR0907
Feed Position Accuracy: Normal Performance	WVR1304	Gain fluctuations resulting from WVR subsystem feed positioning fluctuations (axial, lateral, tilt) shall not exceed the gain stability defined in WVR1176 over changes in main antenna elevation up to 3° under Normal Operation conditions.	WVR1176, WVR0904, WVR0908
Ground Pickup: Precision Performance	WVR1305	The WVR subsystem shall minimize sensitivity to ground pickup to within 5 mK drift over timescales up to 5 min and changes in main antenna elevation up to 3° during Precision Operation conditions.	WVR0903, WVR0907, WVR0011
Ground Pickup: Normal Performance	WVR1306	The WVR subsystem shall minimize sensitivity to ground pickup to within 30 mK drift over timescales up to 20 min and changes in main antenna elevation up to 3° during Normal Operation conditions.	WVR0904, WVR0908, WVR1174

The Fraunhofer distance ($2D^2/\lambda$) for an 18 m antenna is 2.7 km at 1.2 GHz, 17 km at 8 GHz, and 250 km at 116 GHz. CAL0303 is driven by science at 8 GHz or higher. Therefore, the calculations below assume a cylindrical main beam with 18 m diameter at all atmospheric layers of interest (< 8 km AGL). The Fraunhofer distance for a 6 m antenna is 1.9 km at 8 GHz. While this implies a growing linear beam width at increasing distances from the aperture, this does not affect the calculations below due to available headroom. The Fraunhofer distance for a 2 m dish at 22 GHz is approximately 600 m. As a result, the calculations below assume an expanding WVR beam cross-section with distance from the aperture.

The WVR and main antenna geometry is illustrated in Figure 5 (next page).

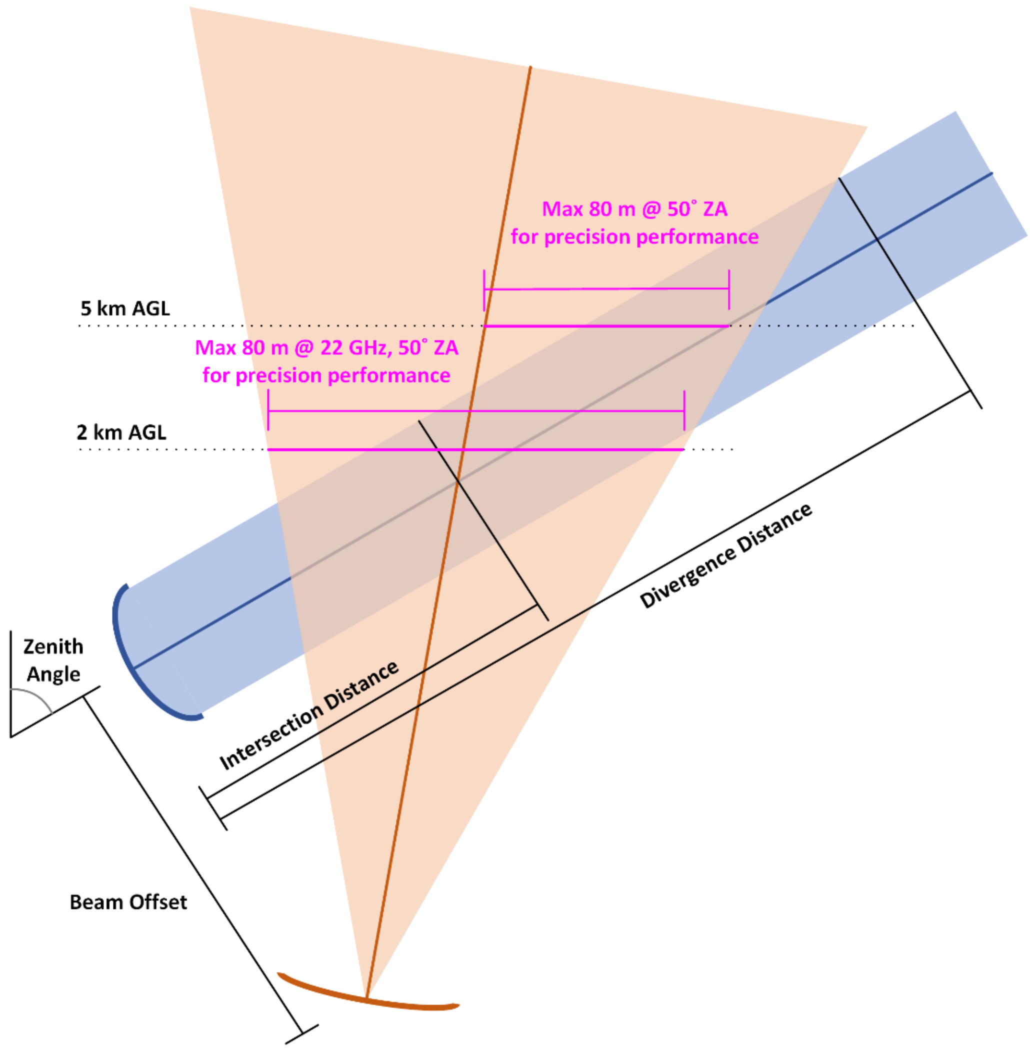

Figure 5: Simplified geometry of WVR antenna and main antenna. Not to scale.

The requirements are derived as follows:

- *Boresight Intersection Distance:* The WVR beam must sample the main beam of the hosting 6m or 18m antenna at all altitudes where water vapor contributes significantly to the PWV column. Atmospheric water vapor density is distributed following an approximately exponential decay with scale height of 2 km AGL [e.g. RD04 Sec. 13.1.1]. The boundary layer within this altitude constitutes the primary volume of interest to the WVR subsystem in which to sample PWV fluctuations on short timescales (WVR0002) dominated by thick-screen (3D) turbulence. The WVR beam must sample the vertical PWV column within a maximum allowable lag of 8 sec to avoid unacceptable decorrelation of water vapor across the beam [AD07]. For a typical tropospheric advection speed of 10 m/s, the maximum allowable lag across the main beam is therefore 8 sec, or 80 m parallel to the ground, at 2 km AGL during Precision Operation conditions. As explained below, this implies a maximum zenith angle for Precision Performance of 55˚; this angle is defined in WVR0907. The axis intersection distance is then set to 2.4 km, optimized for coincident beams at 2 km AGL with a 35˚ main beam zenith angle; the latter is the anticipated weighted mean zenith angle within a range extending to 55˚, based on VLA pointing statistics sampled over one year of observations. An additional constraint on the intersection distance is that it must ensure that the WVR half-power beam-width (HPBW) will envelop the main beam cylinder in a ground-parallel cross-section at 2 km AGL when the main beam is oriented at 55˚ zenith angle (see Figure 5). This particular constraint does not need to be enforced here because it is naturally accommodated by the sufficient HPBW derived below.

- *Offset from Main Beam:* Approximately 90% of the total atmospheric PWV column can be sampled within an altitude of 5 km AGL. Adopting a maximum 8 sec lag (80 m) between the optical axes at a maximum altitude of 5 km, and assuming an intersection distance of 2.4 km and a 55˚ main beam zenith angle (WVR0907), the design of the main antenna must support installation of the WVR antenna such that its optical axis is located within 18 m from the main optical axis (maximum 26 arcmin boresight tilt against the main optical axis). This is captured in an interface assumption listed in Section 7.2.1. The resulting boresight separation is 87 m at an altitude of 14 km for a zenith-pointing main beam, and 290 m at a distance of 24 km for a main beam intersecting 14 km AGL at 55˚ zenith angle. These separation distances are sufficient to capture the slowly-varying continuum contribution in the main beam from high altitude clouds (e.g. cirrus) that consist of ice crystals but no liquid water, even for a low elevation main beam.
- *Beam Diameter:* As above for the lag across the main beam, the maximum allowable linear cross-section parallel to the ground for the WVR beam is 80 m at an altitude of 2 km AGL during Precision Operation conditions. This cross-section is proportional to $HPBW/cos(ZA)^2$ with degeneracy between the WVR HPBW and the maximum zenith angle for Precision Operation condition. This function rises steeply for $ZA > 50°$. Therefore, to maximize HPBW (and minimize dish size) without significantly restricting the zenith angle range available for Precision Operation, and to avoid difficulties for achieving Precision Performance at large airmass, the maximum zenith angle is restricted to 55˚. The requirement for WVR HPBW is then 45 arcmin at 22 GHz. This is equivalent to illuminating 26 m at 2 km AGL for a zenith pointing beam. This in-turn will ensure headroom for tropospheric advection speeds >10 m/s and other non-idealized conditions at high elevation angles, and sufficient performance at lower elevation angles. This illumination size is also appropriate for the WVR beam sampled from (or near) a 6 m antenna without incurring unacceptable decorrelation of water vapor across the beam [AD07]. The implied WVR antenna diameter is approximately 1.4 m when accounting for losses and feed taper. The 22 GHz WVR half-power beam and 18 m cylinder will cease to overlap beyond a divergence distance of approximately 27 km from the aperture, assuming an 18 m offset as above. The WVR beam will completely envelop the main beam cylinder between 1.9 km and 9 km from the aperture, again assuming a maximum allowable 18 m offset. For a fixed dish size with equivalent 31 arcmin HPBW at 31.5 GHz, the divergence distance will be approximately 9 km from the aperture.
- *Pointing Accuracy:* The WVR beam must be pointed to within 10 m parallel to the ground at 2 km AGL (equivalent to 1 sec lag at 10 m/sec), when oriented toward 55˚ zenith angle. The pointing must therefore be accurate to within 6 arcmin rms, where this accuracy refers to the 2D radial error (or mean of a Rayleigh distribution) as discussed in [AD07]. This required accuracy encompasses deformation contributions from both the WVR antenna structure and the main antenna structure or dedicated tracking structure on which the WVR antenna will be mounted. This is applicable under both Precision and Normal Operation conditions. It is assumed in Section 7.2.1 that the angular stability of the 18m antenna structure onto which the WVR assembly will be mounted shall not exceed 2 arcmin rms during Precision and Normal Operating Environment conditions. Therefore, assuming that errors sum in quadrature, the requirement for WVR antenna pointing is 5 arcmin rms when mounted to a fixed surface (e.g. a rigid test rig on the ground).
- *Feed Position Accuracy:* Incorrect positioning of the feed (and subreflector if present) will result in gain errors. The feed setting must be sufficiently stable to satisfy the requirements for gain drift

described in Section 7.1.9 over timescales up to 20 minutes. These requirements must be satisfied while in the presence of structural deformations arising from changes in main antenna elevation (gravity) and environmental conditions (wind, temperature, solar loading). Changes in feed positioning will affect forward beam gain (as will elevation-dependent antenna deformations). However, the atmospheric brightness temperature contribution (and the cmb contribution) will be largely unaffected by changes in forward gain because this will be offset by broadening of the main beam and an increase in the gain of the near-in sidelobes (i.e. slight change in tropospheric illumination at the boresight intersection altitude). Thus, only weak coupling is anticipated between feed position fluctuations and changes in geometric gain. This relationship will be addressed [e.g. RD22] once an antenna optical design has been selected; the resulting requirement for feed position accuracy in units of length will be included in a future version of this document. Note that regardless of the resulting positional accuracy requirement, active compensation is strongly disfavored due to complexity and maintenance concerns, though this is not formally ruled out in a requirement.

- *Ground Pickup:* To satisfy the temperature drift requirements, the antenna and feed designs must minimize contamination from far-sidelobes. This demands low reflector edge illumination. The design process should consider algorithmic approaches for removing the temperature contribution from ground pickup [e.g. RD23] as they may argue for retaining a cleanly detectable signature from spillover in the measured data.

Specific requirements for antenna geometry are not included (e.g. offset Gregorian optics, reflector diameter, surface accuracy) because they are not directly constrained at the subsystem level. Lower-level design requirements will be developed by the design team, for example by considering trade-off analyses.

7.1.12 Computing Requirements

Parameter	Req. #	Value	Traceability
Quality Assurance for High-Level Data	WVR1406	The WVR subsystem shall automatically generate quality assurance indicators for WVR subsystem high-level data to be included in the data package delivered to consumers.	SYS0762, SYS2205, SYS2207

See Section 3.2 for the distinction between low-level and high-level data. The WVR delay calibration software (to be developed by the OFF subsystem) operates on the high-level data from all antennas.

7.1.13 Power Requirements

Parameter	Req. #	Value	Traceability
LRU DC Power	WVR1500	All WVR subsystem equipment powered from DC voltages shall utilize either the Main –48 VDC power system or voltages produced by the PSU modules, currently + 5.0 VDC, +/– 7.5 VDC +/– 17.5 VDC, and + 32.0 VDC.	ETR0821
LRU DC Power Regulation	WVR1501	WVR subsystem LRUs shall provide regulation and filtering of all input DC power.	ETR0803

Parameter	Req. #	Value	Traceability
–48 VDC Tolerance	WVR1502	WVR subsystem devices on the –48 VDC system shall tolerate voltages from –42.0 VDC to –60.0 VDC.	ETR0822
PSU Voltage Tolerance	WVR1503	WVR subsystem devices powered from the PSU modules shall tolerate +/– 10% of the rated voltages.	ETR0823
LRU AC Power	WVR1504	All WVR subsystem equipment powered from AC voltages shall utilize 480V/277V or 208V/120V 60 Hz AC Power.	ETR0819
AC Voltage Tolerance	WVR1505	All WVR subsystem equipment powered from the AC line shall tolerate variations of +/– 10%.	ETR0820
Low Power Design	WVR1506	The WVR subsystem shall be designed to minimize LRU power usage.	SYS2802

7.1.14 Assembly, Integration, and Verification Requirements

Parameter	Req. #	Value	Traceability
Subsystem Verification Tools	WVR1600	Test fixtures and procedures shall be provided for verification of the WVR subsystem.	SYS2811
System Verification Tools	WVR1601	The WVR subsystem shall provide tools to automate test execution and reporting as part of array element and system-level verification, including near real-time data display for interactive diagnosis by engineers.	SYS2813
Testing of Software and Firmware	WVR1602	WVR subsystem software and firmware shall be delivered with automated unit, integration, and regression testing suites.	SYS2814
AIV Software Tools	WVR1603	Development tools, compilers, source code, and the build system shall be delivered for all WVR subsystem software to enable maintenance over the life of the facility.	SYS2815
API ICDs and Software Definition	WVR1604	All APIs or other software interfaces with the WVR subsystem shall be defined in ICDs.	SYS2816
LRU ICDs	WVR1605	ICDs shall be delivered for all LRUs in the WVR subsystem.	SYS2818
ICD Automated Conformance Testing	WVR1606	Automated test results demonstrating conformance to WVR subsystem API ICDs shall be delivered with the product.	SYS2817

7.2 *Interface Requirements*

This section provides information about the interfaces of the WVR subsystem. These form a subset of the ngVLA N^2 Interface Control Diagram [RD24].

There are two classes of interfaces outlined below: Primary and Secondary. Primary Interfaces indicate a direct relationship between subsystems for which an Interface Control Document (ICD) is required. Secondary Interfaces indicate a relationship made possible by an intermediate direct interface. Secondary Interfaces do not require an ICD.

For each identified interface, where relevant, requirements are derived from the applicable ICD as listed in Section 2.2. All interface requirements that drive the design and verification of the WVR subsystem shall be listed in this section. Additionally, where relevant, assumptions regarding anticipated requirements for other subsystems are listed, to be incorporated into the ICD and requirements specification for the subsystem of interest.

The interfaces will be developed and documented to the extent possible as part of the WVR subsystem conceptual design effort, after which they will be governed by formal project change control processes. Approved ICDs shall be considered part of the requirements baseline.

The WVR subsystem interfaces are summarized in Figure 6. There are 15 interfaces in total: 8 primary interfaces and 7 secondary interfaces.

ANT					0011											ANT	Main Array Antenna
	INF				0021											INF	Array Infrastructure
		PSU			0022											PSU	DC Power Supply
			BMR		0023											BMR	Bins, Modules, and Racks
				EEC	0024											EEC	Antenna Electronics Environmental Control
					WVR	S	0025	0026	0027	S	S	S	S	S	0028	WVR	Water Vapor Radiometer
						MON										MON	Environmental Monitoring & Characterization
							HIL									HIL	Monitor and Control Hardware Interface Layer
								AFD								AFD	Antenna Fiber Distribution
									MCL							MCL	Monitor and Control
										ONL						ONL	Online Software
											OFF					OFF	Offline Software
												MSS				MSS	Maintenance & Support Software
													DST			DST	Datastores
														FIB		FIB	Central Fiber Infrastructure
															ATF	ATF	Antenna Time and Frequency

Figure 6: Subset of the ngVLA N² Interface Control Diagram focusing only on WVR subsystem interfaces. Primary interfaces are indicated by their document sequence IDs. Secondary interfaces are indicated by an S.

7.2.1 Primary Interface to ANT Subsystem

The ICD between the antenna electronics, including the WVR subsystem, and the Antenna (ANT) subsystem [AD12] details the mechanical interface between the WAM and the structure of the 18m antenna, and the AC power interface with the WUM (which controls supply to the WHM).

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Outfitted 18m Antennas	The WVR subsystem and ancillary interfaced elements shall be installed and operated on all 244 x 18m antennas (ANT subsystem).	CAL0304, SYS1061
WVR Beam Offset from Main 18m Beam	The WVR subsystem antenna optical axis shall be positioned within 18m from the main ANT subsystem antenna optical axis, defined at ground level for a zenith pointing main antenna beam.	CAL0303, WVR0907, WVR1300
Water Vapor Radiometer Mount: Angular Stability	The angular stability of the 18m antenna structure onto which the WVR assembly will be mounted shall not exceed 2 arcmin rms during Precision and Normal Operating Environment conditions.	Informed by ANT0621 in [RD27]

The assumption for WVR beam offset is motivated in Section 7.1.11. A stricter requirement is defined in [AD12] (ICD-ANT-WVR-0003: maximum 13 m separation).

The angular stability assumption informs WVR1302 in Section 7.1.11.

Interface requirements from [AD12] are listed as follows:

Parameter	Req. #	Value	Traceability
Water Vapor Radiometer Mount: Mass	WVR2001	Total combined mass of the WVR antenna and affixed equipment (cabling, liquid lines) shall not exceed the value defined in [AD21].	ICD-ANT-WVR-0001
Water Vapor Radiometer Mount: Mounting	WVR2002	The WVR antenna and affixed equipment shall mount to the 18m antenna as defined in [AD21].	ICD-ANT-WVR-0002
Water Vapor Radiometer Mount: Volume	WVR2003	Clear volume of the WVR assembly shall be as defined in [AD21].	ICD-ANT-WVR-0007
Water Vapor Radiometer Mount: Grounding Pathway	WVR2004	The WVR assembly shall interface with a grounding pathway provisioned on the 18m antenna structure.	[AD12]

7.2.2 Primary Interface to INF Subsystem

The ICD between the WVR subsystem and the Array Infrastructure (INF) subsystem [AD13] details the mechanical foundation and AC electrical distribution for stand-alone WVR units located within the footprint of the SBA.

Note that DC electrical distribution between a stand-alone WVR unit and the adjacent 6m antenna is to be covered separately by an interface between the PSU Subsystem and the INF Subsystem.

Similarly, fiber distribution between a stand-alone WVR unit and the adjacent 6m antenna is to be covered separately by an interface between the AFD Subsystem and the INF Subsystem.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Outfitted Elements within the SBA footprint	The WVR subsystem and ancillary interfaced elements shall be installed and operated using at least 3 dedicated stand-alone tracking mounts located within the footprint of the Short Baseline Array (SBA).	CAL0304, SYS1061

At least two tracking WVRs (one baseline) are needed for scientific operations. A third unit is required to ensure continuity of operations during maintenance on one unit.

7.2.3 Primary Interface to PSU Subsystem

The ICD between the WVR subsystem and the DC Power Supply (PSU) subsystem [AD14] details the DC power interfaces with the WUM and WDM modules, and the mechanical interface associated with wiring that traverses the WAM (and WTM/WPM for stand-alone WVR units situated within the SBA footprint).

See the note in Section 7.2.2 regarding the interface between the PSU and INF Subsystems for stand-alone SBA-based WVR units.

7.2.4 Primary Interface to BMR Subsystem

The ICD between the WVR subsystem and the Bins, Modules, and Racks (BMR) subsystem [AD15] details the mechanical interfaces between the WRM, WUM, and WDM and their RFI-shielded enclosures, and the secondary mechanical interface between the RFI-shielded WDM and the enclosing RFI-shielded electronics rack. The ICD also details the mechanical interfaces regarding environmental enclosures for the WRM and WDM.

7.2.5 Primary Interface to EEC Subsystem

The ICD between the WVR subsystem and the Antenna Electronics Environmental Control (EEC) subsystem [AD16] details the mechanical and thermal interfaces with the EEC-supplied glycol coldplate in each of the WRM, WUM, and WDM, and the mechanical interface associated with liquid glycol lines that traverse the WAM structure (and WTM/WPM for stand-alone WVR units situated within the SBA footprint).

Interface assumptions are listed as follows:

Assumption	Value	Traceability
WVR Receiver Liquid Heat Exchange Plate: Temperature	The EEC subsystem shall provide a liquid heat exchanger plate in the WVR Receiver Module maintained at a fixed year-round set point temperature of 8C during Precision and Normal Operation conditions.	WVR0006
WVR Receiver Liquid Heat Exchange Plate: Temperature Stability	The EEC subsystem shall maintain the temperature of the liquid heat exchanger plate in the WVR Receiver Module to within ±2C about the set point temperature during Precision and Normal Operation conditions.	WVR0006

- *Liquid Heat Exchanger Plate Temperature*: The option to adjust the liquid set point intermittently is excluded, to avoid calibration complications for WVR electronics. Set point considerations include the general trend for diminishing component reliability at increasing operating temperatures and the desire to avoid temperatures near the PTFE/Teflon Knee around 19C. The identified set point temperature of 8C is defined in the WVR Subsystem Design Description [RD08].
- *Liquid Heat Exchanger Plate Temperature Stability*: A commonly accepted stability requirement is needed so that the EEC subsystem can develop the design for the liquid thermal control network and the WVR subsystem can develop a compatible design for thermoelectric temperature control.

7.2.6 Primary Interface to HIL Subsystem

The ICD between the WVR subsystem and the Monitor and Control Hardware Interface Layer (HIL) subsystem [AD17] details the electronics and protocol interfaces with the WUM and effectively the WRM and WHM. While both monitor point data and WVR brightness temperature data will be transmitted over the M&C network, the latter is not anticipated to pass via the HIL subsystem and is addressed separately in Section 7.2.8. M&C for the WDM will pass directly to the M&C network, without requiring passage via the HIL subsystem.

7.2.7 Primary Interface to AFD Subsystem

The ICD between the WVR subsystem and the Antenna Fiber Distribution (AFD) subsystem [AD18] details the fiber optic cable interfaces with the WRM, WUM, and WDM, and the mechanical interface associated with cabling that traverses the WAM structure (and WTM/WPM for stand-alone WVR units situated within the SBA footprint).

See the note in Section 7.2.2 regarding the interface between the AFD and INF Subsystems for stand-alone SBA-based WVR units.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Data Transfer Rate	Data transfer rates up to 200 kB/sec shall be supported between the WUM and WDM per WVR unit.	WVR0002, WVR0005, WVR0008, WVR1071

An upper limit to the data transfer rate is estimated by assuming dual-polarization sampling at 10 Hz, with 2000 channels per polarization, and 16 bits per channel, yielding 80 kB/sec per antenna. With conservative overheads for metadata and M&C the limit is 200 kB/sec.

7.2.8 Primary Interface to MCL Subsystem

The ICD between the WVR subsystem and the CSW Monitor and Control (MCL) subsystem [AD19] details the interface with the WDM through which WVR brightness temperature data and associated metadata will be passed directly to the MCL subsystem, without passing via the HIL subsystem. The ICD also details 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 WUM, and the similar connection between the SBA-based WVR tracker pointing and the 6m array target pointing (this assumes that the SBA does not operate using subarrays).

Note that the primary interface between the WVR and HIL subsystems for monitor point data in Section 7.2.6 implies a secondary interface between the WVR subsystem and the MCL subsystem. These secondary interface aspects will not be addressed in the formal ICD between the WVR and MCL subsystems.

7.2.9 Primary Interface to ATF Subsystem

The ICD between the WVR subsystem and Antenna Time and Frequency (ATF) subsystem [AD20] details the timing interface with the WDM.

Timing and frequency reference for the WRM will be supplied independently from the ATF subsystem.

7.2.10 Secondary Interface to MON Subsystem

A secondary interface is present between the WVR subsystem and the Environmental Monitoring and Characterization (MON) subsystem. The requirements specification for the MON subsystem shall address this interface.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Weather Station Data	Surface weather stations provisioned by the MON subsystem shall sample ambient temperature, dew point temperature, ambient pressure, wind speed, wind direction, and relative humidity at least once per minute (goal: 10 sec)	CAL0303
Proximity of Weather Stations	MON subsystem weather stations shall be provisioned within a maximum distance of 3 km from each 6m and 18m antenna (goal: 1 km)	CAL0303
Access to Public Weather Data	The OFF subsystem shall be capable of accessing public data (e.g. satellite weather data, radiosonde derivatives) to be utilized for WVR delay calibration	CAL0303

WVR delay calibration will most likely required weather station data rather than antenna-based weather measurements which may be biased local effects. A maximum distance of 3 km between antennas and weather stations is motivated by the microscale/mesoscale boundary and the need for realistic flexibility when designing the station distribution.

7.2.11 Secondary Interface to ONL Subsystem

A secondary interface is present between the WVR subsystem and the CSW Online Software (ONL) subsystem. The requirements specification for the ONL subsystem shall address this interface.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Storage of High-Level Data	High-level data products from the WVR subsystem (brightness temperature spectra) shall be stored in the science data package for delivery to consumers via the Observatory Science Data Archive.	SYS0730

See Section 3.2 for the distinction between WVR subsystem low-level and high-level data.

7.2.12 Secondary Interface to OFF Subsystem

A secondary interface is present between the WVR subsystem and the CSW Offline Software (OFF) subsystem. The requirements specification for the OFF subsystem shall address this interface.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Storage of Calibration Solutions	Delay calibration solutions derived from the WVR subsystem high-level data and related weather monitor data (e.g. MON subsystem, public databases) shall be stored in the science data package for delivery to consumers via the Observatory Science Data Archive.	SYS0730
Delay Solution Uncertainty	The OFF subsystem WVR delay calibration inference software shall include estimated errors. This shall be verified as part of the test described in Section 9.2.15..	SYS0762
Data Flagging	The OFF subsystem WVR delay calibration inference software shall automatically identify and flag corrupted input data (e.g. RFI-affected data, faulty WVR subsystem data, and faulty MON subsystem weather data). This shall be verified as part of the test described in Section 9.2.15..	SYS2201, SYS4100
Automated Calibration for Standard Observing Modes	For Standard Observing Modes, the OFF subsystem shall generate delay calibration solutions from the WVR subsystem high-level data products via an automated pipeline. This shall be verified as part of the test described in Section 9.2.15.	SYS0750
Interactive Calibration	OFF subsystem software that is otherwise identical to that used for the automatic, non-interactive processing for Standard Observing Modes shall be provided to support manual generation and inspection of delay calibration solutions from WVR subsystem high-level data products. This shall be verified as part of the test described in Section 9.2.15.	SYS0760, SYS0761, SYS3506
Open Source Software	The OFF subsystem WVR delay calibration software shall be accessible to the community to foster algorithm development and non-standard applications (e.g. atmospheric research).	SYS4200
Quality Assurance for Calibration Data	The OFF subsystem shall automatically generate quality assurance indicators for WVR calibration solutions to be included in the data package delivered to consumers. This shall be verified as part of the test described in Section 9.2.15.	SYS0762, SYS2205, SYS2207

See Section 3.2 for the distinction between low-level and high-level data. The WVR delay calibration software (to be prototyped by the WVR subsystem and ultimately deployed and maintained by the OFF subsystem) operates on the high-level data from all antennas.

There are several algorithmic approaches for inferring delay calibration solutions from WVR data [e.g. RD05, RD12, RD20, RD21]. The optimal approach for ngVLA is not yet clear, nor is it clear that this can be answered definitively prior to testing with the production equipment. For example, it may be optimal to solve for delays using multiple antennas within a maximum radius (e.g. use group data to solve for low-accuracy delays, then per antenna to fine-tune the solutions per antenna).

7.2.13 Secondary Interface to MSS Subsystem

A secondary interface is present between the WVR subsystem and the CSW Maintenance & Support Software (MSS) subsystem. The requirements specification for the MSS subsystem shall address this interface.

7.2.14 Secondary Interface to DST Subsystem

A secondary interface is present between the WVR subsystem and the CSW Datastores (DST) subsystem. The requirements specification for the DST subsystem shall address this interface.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Archive Period	All data products from the WVR subsystem shall be archived for the life of the facility (as defined in WVR0301).	SYS0731, SYS0732, SYS0739
Storage of Low-Level Data	Low-level data products from the WVR subsystem (monitor data and diagnostic subset of high-level data) shall be archived at their generated rate in the Observatory Monitor Database.	SYS3402, SYS3103
Storage of Quality Control Data	Repairs, test data, and associated information on each LRU in the WVR subsystem shall be recorded in the Observatory Quality Control Database.	SYS3404
Configuration Monitoring	Tracking and status data for every WVR subsystem LRU shall be recorded in the Quality Control Database, including LRUs out of service (e.g. in transit, in storage, under repair).	WVR0705

Storage of WVR calibration solutions (derived from the WVR subsystem high-level data; see also Section 7.2.12) and related weather monitoring data (i.e. data from the MON subsystem and public databases) is assumed to be within the science data packet after OFF subsystem processing, i.e. in the Observatory Science Data Archive provisioned by the DST subsystem.

7.2.15 Secondary Interface to FIB Subsystem

A secondary interface is present between the WVR subsystem and Central Fiber Infrastructure (FIB) subsystem. The requirements specification for the FIB subsystem shall address this interface.

Interface assumptions are listed as follows:

Assumption	Value	Traceability
Data Transfer Rate	Data transfer rates up to 200 kB/sec shall be supported from the WDM per WVR unit to the centralized processing facility.	WVR0002, WVR0005, WVR0008, WVR1071

An upper limit to the data transfer rate is estimated by assuming dual-polarization sampling at 10 Hz, with 2000 channels per polarization, and 16 bits per channel, yielding 80 kB/sec per antenna. With conservative overheads for metadata and M&C the limit is 200 kB/sec.

7.3 Safety Requirements

The requirements presented in this section focus on protecting personnel. Requirements for the protection of equipment are incorporated throughout Section 7.1.

Parameter	Req. #	Value	Traceability
Safety of Personnel	WVR9000	The WVR subsystem design shall comply with all relevant federal, state, and NRAO (e.g. [AD10]) occupational health and safety regulations.	SAF1150, SAF1160
Workspace ESD Protection	WVR9001	ESD protection of equipment and workspaces and operational environments shall comply with ETR0502.	ETR0502
Ergonomic Principles	WVR9002	WVR subsystem LRUs shall be designed to reduce discomfort, fatigue, and psychological stress faced by personnel under intended conditions of interaction by taking ergonomic principles into account.	SAF0190
Use of PPE	WVR9003	WVR subsystem LRUs shall be designed with adequate clearances and access to be compatible with the use of necessary or foreseeable personal protective equipment (e.g. footwear, gloves).	SAF0200
LRU Safe Packaging	WVR9004	Packaging for WVR subsystem LRUs shall ensure safety for personnel during transport and storage.	SAF0240
LRU Lifting Handles	WVR9005	WVR subsystem LRUs with weight less than 50 lbs shall be equipped with clearly labeled handles for lifting by an individual person.	SAF0260, ETR0408, [AD10]
LRU Hoist Points	WVR9006	WVR subsystem LRUs with weight greater than 50 lbs, or shape of any weight that precludes single-person lift, shall be equipped with clearly labeled hoist points to enable compatibility with lifting gear.	SAF0250, ETR0408
LRU Two-Person Lifting Handles	WVR9007	WVR subsystem LRUs with weight between 50 to 70 lbs shall be equipped with clearly labeled handles for lifting by two people	ETR0407
LRU Weight and Center of Gravity Marking	WVR9008	Each WVR subsystem LRU shall include at least one clearly visible label indicating the weight in pounds and center of gravity to assure safe lift. The label shall be compliant with applicable standards at the time of installation.	SAF1050, ETR0406
Power Switch Labels	WVR9009	WVR subsystem LRUs that contain power switches shall contain at least one clearly visible label indicating the existence and location of the switches. The label shall be compliant with applicable standards at the time of installation.	ETR1010
LRU Removal and Installation Instructions	WVR9010	WVR subsystem LRUs shall have instructions for safe removal and installation.	SAF1080

Parameter	Req. #	Value	Traceability
Connections in Hot Swap Configuration	WVR9011	In hardware designed to be hot swapped (i.e. installed or removed with power applied), WVR subsystem interconnect shall be designed such that safety grounds, structural grounds, and power returns are connected first on installation and disconnected last on removal.	ETR0815
Protections Against Direct and Indirect Contact	WVR9012	WVR subsystem LRUs shall be designed to protect personnel against danger of physical injury or other harm caused by direct or indirect contact.	SAF0090
Hot Connect & Disconnect Warning Labels	WVR9013	In situations where disconnecting cables or pulling of equipment with power on can cause damage, WVR subsystem LRUs shall exhibit clearly visible labels to warn on this condition.	ETR0410
Safe Dissipation of Energy Stored in Circuits	WVR9014	The WVR subsystem design shall ensure safe dissipation of energy stored in circuits without risk to exposed personnel, e.g. during LRU hot-swaps.	SAF0940
Emergency Cutoff Switch Labels	WVR9015	Any WVR subsystem equipment containing an Emergency Cutoff Switch shall contain at least one clearly visible label indicating the existence and location of that switch.	ETR1011
Safety Ground Labels	WVR9016	Any WVR subsystem equipment containing a critical safety ground connection shall contain at least one clearly visible label indicating the existence and location of that connection.	ETR1012
Hazardous Condition or Operation Labels	WVR9017	Any WVR subsystem equipment that produces hazardous or startling conditions at startup, at shutdown, or in normal operation shall contain a least one clearly visible label identifying the condition. This could include any motion, startling sounds, or bright light.	ETR1013
Safety Instruction Labels	WVR9018	Critical instructions to safely remove, install, or interact with any WVR subsystem equipment shall be affixed to the device with at least one clearly visible label.	ETR1014
Arc Flash Hazard Warning Labels	WVR9019	In any situation where there exists the possibility of the WVR subsystem generating an arc-flash, clearly visible label(s) shall be affixed stating this hazard. This can include, but is not limited to: connection or disconnection of cables & connectors, installing or removing hot pluggable equipment, or actuating switches & circuit breakers.	ETR1015
Electrical and Optical Label Safety Standards	WVR9020	All WVR subsystem electrical and optical safety labels shall be compliant with applicable standards at the time of installation.	ETR1016

Parameter	Req. #	Value	Traceability
Personnel Safety Inspection Documentation	WVR9021	The WVR subsystem shall provide documentation that indicates in the instructions the type and frequency of inspection and maintenance required for personnel safety reasons.	SAF0500
Falling or Ejected Parts	WVR9022	The WVR subsystem design shall prevent risks from falling or ejected objects, including during LRU hot-swaps (e.g. accidental release of fluid).	SAF0530
LRU Sharp Edges	WVR9023	WVR subsystem LRUs shall avoid features likely to cause injury, e.g. sharp edges, rough surfaces.	SAF0540, ETR1172
Inspection Manual	WVR9024	An inspection manual shall be provided for the WVR subsystem in which demanding and/or risky procedures to be performed in the repair center shall be documented, for example procedures to minimize risk in situations where exposure to terminals of storage devices is required during detailed diagnosis & repair.	ETR1007

7.4 Requirements for Design

7.4.1 Printed Circuit Boards

Parameter	Req. #	Value	Traceability
PCB Compliance	WVR7100 –7101	WVR subsystem PCBs shall comply with ETR0701 and ETR0712 regarding PCB standards.	ETR0701, ETR0712
PCB Materials	WVR7102 –7106	WVR subsystem PCBs shall comply with ETR0702–0705, and ETR0707 regarding PCB substrates, plating, and solder masks.	ETR0702, ETR0703, ETR0704, ETR0705, ETR0707
PCB Edge Connector Finger Plating	WVR7118	WVR subsystem PCBs shall comply with ETR0718 regarding PCB edge connector finger plating.	ETR0718
PCB Markings	WVR7107 –7111	WVR subsystem PCBs shall comply with ETR0706–0708, ETR0713, and ETR0716 regarding solder mask color, overlay legend, and identification information.	ETR0706, ETR0707, ETR0708, ETR0713, ETR0716
PCB Test Points	WVR7112 –7114	WVR subsystem PCBs shall comply with ETR0709–0711 regarding test points for power supplies, FPGAs, and critical signals.	ETR0709, ETR0710, ETR0711
PCB Design for Automated Assembly & Test	WVR7115	If more than 50 of a specific WVR subsystem PCB type will be produced or if it is known automated assembly and/or test capability is required, then the PCB shall be designed with the features needed to support these processes.	ETR0717

Parameter	Req. #	Value	Traceability
PCB solder profiles	WVR7116	For WVR subsystem PCBs containing large complex components (e.g. BGAs), spare PCBs and components shall be procured to be used for building soldering profiles for both assembly and long-term maintenance use.	ETR0715
PCB Optimum HF Performance and Low Emission	WVR7117	WVR subsystem PCBs shall be designed to optimize HF performance and minimize RF emission.	ETR0714

7.4.2 Soldering and Electrical Connections

Parameter	Req. #	Value	Traceability
Soldering and Electrical Connections	WVR7200	The WVR subsystem shall comply with ETR1301 regarding electrical connections.	ETR1301

7.4.3 Power

Parameter	Req. #	Value	Traceability
Power and Grounding	WVR7300 –7305	The WVR subsystem shall comply with ETR0801–0804 and ETR0813–0814 regarding power and grounding.	ETR0801, ETR0802, ETR0803, ETR0804, ETR0813, ETR0814
Current and Thermal Protection	WVR7306 –7310	The WVR subsystem shall comply with ETR0805–0808 and ETR0816 regarding over current and thermal protections.	ETR0805, ETR0806, ETR0807, ETR0808, ETR0816
Power Operations Sequences	WVR7311 –7316	The WVR subsystem shall comply with ETR0809–0812 regarding sequences for power operations and power-on indicators.	ETR0809, ETR0810, ETR0811, ETR0812
Transient Protection of LRU I/O & Power Connections	WVR7317	The WVR subsystem shall utilize Transient Voltage Suppression devices on sensitive analog and digital I/O signals and power supplies entering or exiting a LRU. RF and other signals that will be adversely affected by the inclusion of these devices are exempt from this requirement.	ETR0818

7.4.4 Component Sourcing

Parameter	Req. #	Value	Traceability
Component Sources	WVR7400	WVR subsystem components shall be sourced from reputable, proven manufacturers, vendors and/or distributors.	ETR0901
Standard Component Libraries	WVR7401	The WVR subsystem shall utilize, and where necessary contribute to, managed libraries of electronic components and hardware.	ETR0902

7.4.5 Mechanical

Parameter	Req. #	Value	Traceability
Wiring & Cables	WVR7500–7536	The WVR subsystem shall comply with ETR1101–1132, ETR1154–1157, and ETR1189 regarding mechanical properties of wiring & cables.	ETR1101–1132, ETR1154–1157, ETR1189
Connectors	WVR7537–7552	The WVR subsystem shall comply with ETR1133–1142, ETR1158–1160, and ETR1185–ETR1187 regarding mechanical properties of connectors.	ETR1133–1142, ETR1158–1160, ETR1185–1187
Connector Retention	WVR7593–7602	The WVR subsystem shall comply with ETR1197–1199 and ETR1206–1212 regarding connector types and retention.	ETR1197–1199, ETR1206–1212
Lighting	WVR7559–7564	The WVR subsystem shall comply with ETR1148–1153 regarding light sources	ETR1148–1153
Mechanical Assemblies	WVR7565–7590	The WVR subsystem shall comply with ETR1161–1184 and ETR1190–ETR1191 regarding mechanical properties of assemblies	ETR1161–1184, ETR1190–1191
Stress Safety Factor for Failure	WVR7591	A minimum stress safety factor of 1.5 with respect to the yield point, or equivalent (e.g. CFRP), shall be used in the design of all WVR subsystem mechanical components which in case of a failure lead to an Unacceptable or Undesirable hazard risk.	SYS2801
Stress Safety Factor for Survival	WVR7592	A minimum stress safety factor of 1.1 with respect to the yield point, or equivalent (e.g. CFRP), shall be used in the design of all WVR subsystem mechanical components for survival conditions.	SYS2801

7.4.6 Documentation

Parameter	Req. #	Value	Traceability
As-Built Drawings	WVR8000	As-built drawings shall be provided for all custom hardware and facilities delivered as part of the WVR subsystem.	SYS6001
Operations and Maintenance Manuals	WVR8001	Operations and Maintenance Manuals shall be provided for each LRU in the WVR subsystem, including all software and installation/upgrades.	SYS6002
Units	WVR8002	Design materials and documentation for the WVR subsystem shall use SI (metric) units. Imperial units may also be shown for clarity.	SYS6003
Language	WVR8003	The language used for written documentation shall be English.	SYS6004

Parameter	Req. #	Value	Traceability
Electronic Document Format	WVR8004	Documents and drawings of record shall be delivered in PDF. Native, editable file formats shall also be delivered.	SYS6005
Component Testing and Subsystem Verification Documentation	WVR8005	All test and acceptance procedures for the WVR subsystem shall be documented.	SYS2811

8 Key Performance Parameters

Key Performance Parameters (KPPs) identify critical subsystem capabilities or characteristics that may either have a detrimental impact on the effectiveness of efficiency of the system if not met, or could have a very large positive impact if the specification is exceeded. The following KPPs are identified for optimization and monitoring throughout the design phase.

Key Performance Parameter	Req. #
Receiver physical temperature stability	WVR0006
WVR antenna pointing accuracy	WVR1302
Delay measurement noise	WVR0001
Delay measurement drift	WVR0901
Reliability	WVR1003

Table 1: WVR Subsystem KPPs.

9 Verification

The design will be verified to meet the requirements by analysis (A), inspection (I), demonstration (D), or test (T), each defined below.

Verification by Analysis: The of the subsystem to the requirement is demonstrated by appropriate analysis (hand calculations, finite element analysis, modeling and simulation, etc.).

Verification by Inspection: The compliance of the subsystem to the requirement is determined by a simple inspection of the subsystem or of its design documentation.

Verification by Demonstration: The compliance of the subsystem to the requirement is determined by a demonstration.

Verification by Test: The compliance of the subsystem to the requirement is determined by means of a test with and associated analysis of test data.

Multiple verification methods are allowed over the course of the design phase. The primary (final) verification method to be used for the product during the qualification phase prior to its Critical Design Review is identified below.

Requirements to be verified by Analysis, Demonstration, or Test are assigned an identifier given by the last two digits of the corresponding requirement from Section 9.2, which are all prefixed by WVR79. For example, identifier 03 refers to WVR7903.

9.1 Verification Methods

9.1.1 Functional and Performance Requirements

Req. #	Parameter/Requirement	A	I	D	T
WVR1005	Altitude Range		*		
WVR1019	Solar Thermal Load: Precision Operation				**05**
WVR1020	Solar Thermal Load: Normal Operation				**05**
WVR1014	Temperature: Precision Operation				**05**
WVR1021	Temperature: Normal Operation				**05**
WVR1016	Temperature: Limited Operation				**05**
WVR1015	Temperature Rate of Change: Precision Operation				**05**
WVR1022	Temperature Rate of Change: Normal Operation				**05**
WVR1023	Precipitation: Precision Operation				**08**
WVR1024	Precipitation: Normal Operation				**08**
WVR1025	Precipitation: Limited Operation				**08**
WVR1026	Ice Accumulation		*		
WVR1027	Precipitable Water Vapor: Precision Operation		*		
WVR1028	Precipitable Water Vapor: Normal Operation		*		
WVR1029	Wind: Precision Operation	**03**			
WVR1030	Wind: Normal Operation	**03**			
WVR1031	Wind: Limited Operation	**03**			
WVR1047	Relative Humidity: Limited Operation		*		
WVR1032	Survival: Wind	**03**			
WVR1017	Survival: Temperature				**05**
WVR1033	Survival: Radial Ice		*		
WVR1034	Survival: Water Infiltration				**08**
WVR1035	Survival: Snow Load Depth		*		
WVR1036	Survival: Snow Load Pressure		*		
WVR1037	Survival: Hail Stones				**07**
WVR1050	Lightning Protection of Structures and Housings		*		
WVR1006	Lightning Protection of Electronics		*		
WVR1038	Seismic Protection				**06**
WVR1039	General Vibration Protection				**06**
WVR1010	Mechanical Shock Protection				**06**
WVR1007	Dust Protection				**08**
WVR1008	Rodent Protection		*		
WVR1040	Solar Radiation Protection: UV		*		
WVR1041	Corrosion Protection		*		
WVR1042–1046	ESD Protection				**09**
WVR1018	Storage: Temperature				**05**
WVR1048	Storage: Relative Humidity		*		
WVR1049	Transportation: Temperature				**05**
WVR0350	Spurious Signal Level				**14**
WVR1012	Emission Verification Frequencies				**14**
WVR0351	Low Frequency Emission				**14**
WVR0352	Relay Contact Arcing		*		
WVR0353	Amplifiers & Oscillators		*		

Req. #	Parameter/Requirement	A	I	D	T
WVR0354	Silicon Controlled Rectifiers		*		
WVR0355	Gaseous Discharge Devices		*		
WVR0356	Static Discharge Mitigation		*		
WVR0357	Display Shielding		*		
WVR1011	Digital Equipment Shielding		*		
WVR0358–0359	COTS Immunity Standards		*		
WVR0360–0361	Step Voltage Fluctuations				**11**
WVR0362–0365	Voltage Dips				**11**
WVR0366–0367	Voltage Interruptions				**12**
WVR0368–0369	Voltage Surges and Bursts				**11**
WVR0370–0371	Conducted Noise				**11**
WVR0372–0374	ESD Thresholds				**09**
WVR0375	Input Dynamic Range				**10**
WVR0376	Input Protection				**10**
WVR0377	Instantaneous Dynamic Range				**10**
WVR0301	Design Life		*		
WVR0302	Lifecycle Cost Optimization		*		
WVR0303	Part Selection for Maintainability		*		
WVR0304	Critical Spares		*		
WVR1004	Modularization		*		
WVR0500	Interchangeable LRU		*		
WVR0501	LRU easy removal and replacement		*		
WVR1003	LRU MTBM	**02**			
WVR0502	Automated Re-Configuration				**13**
WVR1002	Preventive Maintenance Interval	**02**			
WVR0503	Provision of Predictive Tools		*		
WVR0504	Provision of Diagnostic Tools				**13**
WVR0505	Engineering Console				**13**
WVR0506	Criteria for Scheduling Maintenance		*		
WVR0507	Use of Failure Analysis in Spares Planning		*		
WVR0508	LRU Storage		*		
WVR0510	Maintenance Tiers		*		
WVR0511	Optimization for Maintenance		*		
WVR1009	Transportation Protection		*		
WVR0517	Battery Use		*		
WVR0518	Memory		*		
WVR0519	Local Firmware		*		
WVR0520	Firmware Updates				**13**
WVR0521	Electronic Test and Measurement Equipment – Maintenance & Calibration		*		
WVR0201	LRU Monitoring				**13**
WVR0600	LRU Alerts				**13**
WVR0601	Fast Read-Out Modes				**13**
WVR0602	Intelligent LRUs				**13**
WVR0603	Watchdogs				**12**
WVR0604	M&C Commanded Reset for DC Powered Devices				**13**

Req. #	Parameter/Requirement	A	I	D	T
WVR0605	M&C Commanded Reset for AC Powered Devices				**13**
WVR0606	Periodic Self-Tests				**13**
WVR0607	Self-Monitoring				**12**
WVR0700–0704	LRU Physical and Online Identification				**13**
WVR0705	Configuration Monitoring		*		
WVR0706	Version Control		*		
WVR0001	Delay Measurement Noise: Precision Performance				**05**
WVR0900	Delay Measurement Noise: Normal Performance				**05**
WVR0901	Delay Measurement Drift: Precision Performance				**05**
WVR0902	Delay Measurement Drift: Normal Performance				**05**
WVR0903	Slew Drift: Precision Performance		*		
WVR0904	Slew Drift: Normal Performance		*		
WVR0905	Limited Performance				**05**
WVR0002	Tropospheric Sampling Rate		*		
WVR0907	Accessible Field of View: Precision Performance	**04**			
WVR0908	Accessible Field of View: Normal Performance	**04**			
WVR0909	Solar Observing Performance				
WVR0005	Processed Frequency Range		*		
WVR1070	Gaps in Frequency Coverage		*		
WVR0008	Spectral Resolution		*		
WVR1071	Sampled Polarizations		*		
WVR1072	Bandpass Stability: Precision Performance				**05**
WVR1073	Bandpass Stability: Normal Performance				**05**
WVR1074	Local Oscillator Stability				**05**
WVR0009	System Noise Temperature: Precision Performance		*		
WVR1170	System Noise Temperature: Normal Performance		*		
WVR1171	Antenna and Receiver Noise Temperature ($T_{ant}+T_{rx}$)				**15**
WVR0010	Atmospheric Temperature Measurement Error: Precision Performance				**15**
WVR1173	Atmospheric Temperature Measurement Error: Normal Performance				**15**
WVR0011	Atmospheric Temperature Measurement Drift: Precision Performance				**15**
WVR1174	Atmospheric Temperature Measurement Drift: Normal Performance				**15**
WVR1175	Gain stability: Precision Performance				**05**
WVR1176	Gain stability: Normal Performance				**05**
WVR1177	Gain Drift: Precision Performance				**05**
WVR1178	Gain Drift: Normal Performance				**05**
WVR0006	Receiver Physical Temperature Stability: Precision Performance				**05**
WVR1200	Receiver Physical Temperature Stability: Normal Performance				**05**
WVR1300	Boresight Intersection Distance				**15**
WVR0003	Antenna HPBW		*		
WVR0004	Total Pointing Accuracy	**04**			
WVR1302	WVR Antenna Pointing Accuracy	**04**			

Req. #	Parameter/Requirement	A	I	D	T
WVR1303	Feed Position Accuracy: Precision Performance	04			
WVR1304	Feed Position Accuracy: Normal Performance	04			
WVR1305	Ground Pickup: Precision Performance	04			
WVR1306	Ground Pickup: Normal Performance	04			
WVR1406	Quality Assurance for High-Level Data				15
WVR1500	LRU DC Power		*		
WVR1501	LRU DC Power Regulation				11
WVR1502	–48 VDC Tolerance				11
WVR1503	PSU Voltage Tolerance				11
WVR1504	LRU AC Power		*		
WVR1505	AC Voltage Tolerance				11
WVR1506	Low Power Design		*		
WVR1600	Subsystem Verification Tools		*		
WVR1601	System Verification Tools				13
WVR1602	Testing of Software and Firmware				13
WVR1603	AIV Software Tools				13
WVR1604	API ICDs and Software Definition		*		
WVR1605	LRU ICDs		*		
WVR1606	ICD Automated Conformance Testing				13

9.1.2 Interface Requirements

Req. #	Parameter/Requirement	A	I	D	T
WVR2001	Water Vapor Radiometer Mount: Mass		*		
WVR2002	Water Vapor Radiometer Mount: Mounting		*		
WVR2003	Water Vapor Radiometer Mount: Volume		*		
WVR2004	Water Vapor Radiometer Mount: Grounding Pathway		*		

9.1.3 Safety Requirements

Req. #	Parameter/Requirement	A	I	D	T
WVR9000	Safety of Personnel	01			
WVR9001	Workspace ESD Protection	01			
WVR9002	Ergonomic Principles	01			
WVR9003	Use of PPE	01			
WVR9004	LRU Safe Packaging	01			
WVR9005	LRU Lifting Handles	01			
WVR9006	LRU Hoist Points	01			
WVR9007	LRU Two-Person Lifting Handles	01			
WVR9008	LRU Weight and Center of Gravity Marking	01			
WVR9009	Power Switch Labels	01			
WVR9010	LRU Removal and Installation Instructions	01			
WVR9011	Connections in Hot Swap Configuration	01			
WVR9012	Protections Against Direct and Indirect Contact	01			
WVR9013	Hot Connect & Disconnect Warning Labels	01			
WVR9014	Safe Dissipation of Energy Stored in Circuits	01			
WVR9015	Emergency Cutoff Switch Labels	01			

Req. #	Parameter/Requirement	A	I	D	T
WVR9016	Safety Ground Labels	01			
WVR9017	Hazardous Condition or Operation Labels	01			
WVR9018	Safety Instruction Labels	01			
WVR9019	Arc Flash Hazard Warning Labels	01			
WVR9020	Electrical and Optical Label Safety Standards	01			
WVR9021	Personnel Safety Inspection Documentation	01			
WVR9022	Falling or Ejected Parts	01			
WVR9023	LRU Sharp Edges	01			
WVR9024	Inspection Manual	01			

9.1.4 Requirements for Design

Req. #	Parameter/Requirement	A	I	D	T
WVR7100–7101	PCB Compliance		*		
WVR7102–7106	PCB Materials		*		
WVR7118	PCB Edge Connector Finger Plating		*		
WVR7107–7111	PCB Markings		*		
WVR7112–7114	PCB Test Points				11
WVR7115	PCB Design for Automated Assembly & Test		*		
WVR7116	PCB Solder Profiles		*		
WVR7117	PCB Optimum HF Performance and Low Emission		*		
WVR7200	Soldering and Electrical Connections		*		
WVR7300–7305	Power and Grounding				11
WVR7306–7310	Current and Thermal Protection				11
WVR7311–7316	Power Operations Sequences				11
WVR7317	Transient Protection of LRU I/O & Power Connections				11
WVR7400	Component Sources		*		
WVR7401	Standard Component Libraries		*		
WVR7500–7536	Wiring & Cables		*		
WVR7537–7552	Connectors		*		
WVR7593–7602	Connector Retention		*		
WVR7559–7564	Lighting		*		
WVR7565–7590	Mechanical Assemblies		*		
WVR7591	Stress Safety Factor for Failure		*		
WVR7592	Stress Safety Factor for Survival		*		
WVR8000	As-Built Drawings		*		
WVR8001	Operations and Maintenance Manuals		*		
WVR8002	Units		*		
WVR8003	Language		*		
WVR8004	Electronic Document Format		*		
WVR8005	Component Testing and Subsystem Verification Documentation		*		

9.2 *Verification Requirements*

Analysis, Demonstration, and Test verification requirements are presented in the table below and explained in the subsequent text. Note that the analyses, demonstrations, and tests listed below comprise a minimal set necessary to ensure final verification of all requirements presented in this document. As noted in Section 9.1, multiple verification methods are allowed over the course of the design phase. As a result, not all analyses, demonstrations, or tests are listed below for the WVR subsystem over its design life.

Parameter	Req. #	Value	Traceability
Safety Hazard Analysis	WVR7901	The WVR subsystem shall be subject to a personnel safety hazard analysis and review.	SYS2700
Reliability Analysis	WVR7902	The WVR subsystem shall be subject to a reliability analysis and review.	ETR0904, SYS3204
Stress Analysis	WVR7903	The WVR subsystem shall be subject to a stress analysis and review.	SYS2801
Optics Analysis	WVR7904	The WVR subsystem shall be subject to an optics analysis and review.	ETR0905
Thermal Test	WVR7905	The WVR subsystem shall be subject to a thermal test and review.	ETR0905
Vibration Test	WVR7906	The WVR subsystem shall be subject to a vibration test and review.	ETR0905
Impact Test	WVR7907	The WVR subsystem shall be subject to an impact test and review.	SYS2801
Infiltration Test	WVR7908	The WVR subsystem shall be subject to an infiltration test and review.	SYS2801
ESD Test	WVR7909	The WVR subsystem shall be subject to an ESD test and review.	ETR0501, ETR0505, ETR0506
Headroom Test	WVR7910	The WVR subsystem shall be subject to a headroom test and review.	ETR0601
Power Test	WVR7911	The WVR subsystem shall be subject to a power test and review.	ETR0905
Control Test	WVR7912	The WVR subsystem shall be subject to a control test and review.	ETR0905
Engineering Software Test	WVR7913	The WVR subsystem shall be subject to an engineering software test and review.	ETR0905
Calibration Software Test	WVR7914	The WVR subsystem shall be subject to a calibration software test and review.	SYS2831
RFI/EMC Test	WVR7915	The WVR subsystem shall be subject to RFI/EMC tests and review.	ETR0601
End-To-End Performance Test	WVR7916	The WVR subsystem shall be subject to an end-to-end performance test and review.	SYS2811

9.2.1 Safety Hazard Analysis

A Safety Hazard Analysis shall be performed for the WVR subsystem to identify safety critical areas and hazards for personnel, and to identify the safety measurement to be used. A Hazard Analysis shall list all possible hazards, including an assessment of their severity and probability, and shall show that safety considerations are included in all stages of the project including assembly, training, maintenance, etc.

Safety provisions and alternatives needed to eliminate hazards or reduce their associated risk to a level acceptable to ngVLA shall be described. As the design of the system progresses, the Hazard Analysis shall be kept up to date reflecting new considerations, data, and/or information. The following issues shall be considered:

1. Safety-related interface considerations among various system elements, e.g., material compatibility, electromagnetic interference, inadvertent activation, fire initiation and propagation, hardware and software controls, etc.
2. Environmental hazards including handling and operating environments.
3. All hazards related to operating, testing, maintenance and emergency procedures.
4. Any other identified hazards.
5. A description of any risk reduction methods employed for each hazard like safety-related equipment, safeguards, interlocks, system redundancy, hardware or software fail-safe design considerations, etc.

As examples, none of the items in the following list (not meant to be exhaustive) shall lead to an unacceptable or undesirable hazard risk for the equipment or human beings:

- One or two independent operator errors
- One operator error plus one hardware failure
- One or two hardware failures
- One or two software failures
- Partial or complete loss of energy, reference signals, or control communications
- Emergency braking of the antenna
- Earthquakes happening for whatever position of the antenna
- Wind loads
- Direct or nearby lightning strikes

9.2.1.1 Hazard Severity

Hazard severity categories are defined (Table 2) to provide a qualitative measure of the mishap.

Category	Description	Definition
I	Catastrophic	Death, severe injury, or system loss
II	Critical	Major injury, major occupational illness, major system damage
III	Marginal	Minor injury, minor occupational illness, minor system damage
IV	Negligible	Less than minor injury/occupational illness and minor system damage

Table 2: Hazard severity categories.

- System loss: the system cannot be recovered at reasonable cost (less than 1% of total construction budget).
- Major system damage: the system can be recovered but extensive industrial support is necessary and/or the system is out of operation for more than three weeks.
- Minor system damage: the system can be repaired by ngVLA without any support from industry and/or the system is less than three weeks out of operation.

9.2.1.2 *Hazard Probability*

Table 3 shows the probability classification of hazards occurring during the 20 years of expected full operations.

Level	Definition	Description
A	Frequent	Likely to occur frequently (typically once a year)
B	Probable	Will occur several times (6 to 10 times in 20 years)
C	Occasional	Likely to occur (2 to 5 times in 20 years)
D	Remote	Unlikely but possible to occur (typically once in 20 years)
E	Improbable	So unlikely that occurrence can be assumed not to be experienced (>20 years)

Table 3: Probability levels.

9.2.1.3 *Hazard Risk Acceptability Matrix*

The following two matrices (Table 4 and Table 5) define the degree of acceptability of the various hazard categories:

Frequency of Occurrence	I Catastrophic	II Critical	III Marginal	IV Negligible
Frequent	I A	II A	III A	IV A
Probable	I B	II B	III B	IV B
Occasional	I C	II C	III C	IV C
Remote	I D	II D	III D	IV D
Improbable	I E	II E	III E	IV E

Table 4: Hazard classification matrix.

Hazard risk index	Assessment criteria
I A to I D, II A, B; III A	Unacceptable
II C, D; III B; IV A	Undesirable (ngVLA decision required)
I E; II E; III C; IV B	Acceptable with review by ngVLA PE
III D, E; IV C, IV D, IV E	Acceptable without review by ngVLA PE

Table 5: Hazard acceptability matrix.

9.2.2 Reliability Analysis

A reliability, availability, and maintainability analysis shall be performed to determine if the WVR subsystem design meets the MTBM requirements, to identify weaknesses in the design that could ultimately lead to increased maintenance costs (including projected availability of spares and viability of critical vendors), and to estimate MTTR for equipment.

The Parts Count Method or the more accurate (but more time consuming) Parts Stress Analysis Prediction approach, both described in [RD09], or other equivalents, shall be used for predicting the reliability of WVR subsystem electronics. The Parts Stress Analysis Prediction approach may be used if results from the former do not comply with the Maintenance and Reliability requirements. For non-electronic parts the values from [RD10] or data from manufacturers or other databases may be used.

Some ngVLA antennas will be operated at an elevation up to 2500m above sea level, where temperature and pressure might decrease the MTBF relative to that at low elevations. These conditions shall be taken into specific account in the reliability prediction by using the environmental factor given in [RD09]. The analysis shall result in estimates of MTBF and MTTR, assuming that any required preventive maintenance is performed.

9.2.3 Stress Analysis

A computational analysis shall be performed to estimate stresses arising in the WVR subsystem WAM (dish, mount, feed arms), both with and without mounting of the fully-loaded WRM and WUM enclosures (which will include glycol thermal control cold plates provisioned by the EEC subsystem). Analysis for the stand-alone WVR units provisioned within the footprint of the SBA shall also include the WTM and WPM. The analysis shall assess the following load combinations:

1. Gravity + Limiting Operation Wind + Emergency Braking Shock
2. Gravity + Survival Limit Wind

The analysis shall utilize CFD or extrapolated wind tunnel pressure distributions, and FEA, or equivalents.

9.2.4 Optics Analysis

An analysis shall be performed to ensure that the WVR subsystem satisfies antenna requirements for pointing and optical gain stability under Precision, Normal, and Limited Operation conditions. This shall include deformation under gravity over the range of main antenna elevations, feed positioning errors, temperature, solar loading, wind over a range of impact vectors, and ground pickup.

The analysis shall utilize FEA, CFD, and physical optics analysis software (e.g. GRASP), or equivalents.

It may be necessary to incorporate local effects from the main antenna (e.g. wind redirection), in which case it may be necessary to incorporate WVR subsystem elements into the computational analyses performed by the 18m antenna vendor.

9.2.5 Thermal Test

A thermal performance test shall be performed for the WRM, WUM, and WDM, each as an integrated unit (i.e. LRU). The tests shall utilize an environmental chamber to test functionality working together with EEC subsystem glycol thermal control over the full range of Precision, Normal, and Limited operating temperatures. Survival, storage, and transportation temperature limits shall also be verified.

(The EEC subsystem shall independently perform computational and thermal analyses and associated tests to ensure compliance with the WVR subsystem requirements, prior to combined testing with WVR subsystem LRUs.)

A thermal performance test shall also be performed for the WAM structural elements (and computational analysis if necessary, e.g. if non-COTS components are used). This shall verify that the dish and mount (including WTM and WPM for SBA-based units) satisfy the pointing requirements under the full range of operating temperatures, and that no permanent deformation is induced by temperatures ranging to the Survival limits.

9.2.6 Vibration Test

A test shall be performed to ensure that all WVR subsystem equipment meets vibration and shock requirements, including seismic requirements. Testing shall utilize a 3-axis table and a drop-test rig, or equivalents.

9.2.7 Impact Test

A test shall be performed to ensure that the WVR subsystem WAM structural elements (dish, trusses) satisfy the Survival requirement for hail impact.

9.2.8 Infiltration Test

A test shall be performed to ensure the WVR subsystem WRM satisfies requirements for infiltration by dust and water, and performance requirements under barometric pressure and relative humidity changes.

9.2.9 Electrostatic Discharge Test

A test shall be performed to ensure that the WVR subsystem satisfies requirements for electrostatic discharge protection. See [AD06].

9.2.10 Headroom Test

A test shall be performed to ensure that the WVR subsystem satisfies requirements for dynamic range and headroom. See [AD01].

9.2.11 Power Test

A test shall be performed to assess impacts to the WVR subsystem from instabilities and noise introduced to the input voltages, and to ensure compliance with grounding and current protections. The test shall also verify predicted heat loads from the WRM, WUM, and WDM to be managed by the EEC subsystem. Conducted immunity is discussed in [AD03 Sec. 4.3].

9.2.12 Control Test

Computational and empirical testing shall be performed to ensure that the WVR subsystem satisfies requirements to self-monitor and manage malfunctions or failures in internal components or connected subsystems. Examples include

- Failure of a critical component (e.g. FPGA)
- Failure of a non-critical component (e.g. redundant monitor point)
- Malfunction of a critical component where a correction procedure is available
- Malfunction of a non-critical component where a correction procedure is available
- Detection of a temperature rise due to EEC subsystem liquid circulation failure
- Loss of M&C connection
- Loss of ATF subsystem timing solutions

Empirical tests shall utilize standard bench equipment with electronic triggers and noise injection.

9.2.13 Engineering Software Test

A test shall be performed to ensure that engineering software in the WVR subsystem satisfies, for example, commanded reset requirements, connection to the M&C network, and the full suite of diagnostic and regression testing requirements.

The test shall utilize real-time empirical data with a functional prototype of the WVR subsystem including thermal control.

9.2.14 RFI/EMC Test

Tests shall be performed to ensure that the WVR subsystem satisfies RFI requirements.

These shall be performed using production equipment placed in a reverberation chamber or equivalent, and possibly supplemented with directional testing in an anechoic chamber or equivalent, the latter if necessary to identify the source of a leak or emission. See [AD03].

9.2.15 End-To-End Performance Test

Tests shall be performed to ensure that the full suite of WVR subsystem hardware, software, and electronics meet precision performance requirements including noise temperature, gain stability, thermal stability, antenna alignment accuracy, and all necessary functionality attained through interfaces with other subsystems.

The performance tests shall be conducted in an operationally representative setting using advanced prototypes connected to test fixtures that simulate system integration under appropriate environmental conditions. Test rigs shall be installed at different ngVLA sites so as to sample representative environmental conditions, for example on the Plains of San Agustin and at VLBI stations with significantly different conditions such as St. Croix and Mauna Kea.

10 Appendix

10.1 Abbreviations and Acronyms

Acronym	Description
AC	Alternating Current
AD	Applicable Document
ADC	Analog-to-Digital Converter
AFD	Antenna Fiber Distribution (ngVLA Subsystem)
AGL	Above Ground Level
AIV	Assembly, Integration, and Verification
ALMA	Atacama Large Millimeter/Sub-Millimeter Array
ANT	Antenna (ngVLA Subsystem)
API	Application Programming Interface
ATF	Antenna Time and Frequency (ngVLA Subsystem)
BMR	Bins, Modules, and Racks (ngVLA Subsystem)
CAL	Prefix from ngVLA Calibration Requirements [AD07]
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Plastic
CoDR	Conceptual Design Review
COTS	Commercial Off-The-Shelf
CSW	Computing and Software (ngVLA Subsystem)
CWVR	Compact Water Vapor Radiometer (JVLA Subsystem)
DBE	Digital Back End
DC	Direct Current
DST	Datastores (ngVLA Subsystem)
ECN	Engineering Change Notice
EEC	Antenna Electronics Environmental Control (ngVLA Subsystem)
EM	Electro-Magnetic
EMC	Electro-Magnetic Compatibility; also prefix from ngVLA System EM Compatibility and RFI Mitigation Requirements [AD03]
ENV	Prefix from ngVLA System Environmental Specifications [AD02]
ESD	Electrostatic Discharge
ETR	Prefix from ngVLA Electronics Specifications [AD06]
FAT	Factory Acceptance Test
FDR	Final Design Review
FEA	Finite Element Analysis
FIB	Central Fiber Infrastructure (ngVLA Subsystem)
FPGA	Field-Programmable Gate Array
HIL	Hardware Interface Layer (ngVLA Subsystem)
HPBW	Half-Power Beam-Width
ICD	Interface Control Document
I/F	Interface
INF	Array Infrastructure (ngVLA Subsystem)
IPT	Integrated Product Team
ISO	International Organization for Standardization
JVLA	Jansky Very Large Array

KPP	Key Performance Parameter
LEMP	Lightning Electromagnetic Impulse
LNA	Low Noise Amplifier
LO	Local Oscillator
LRU	Line Replaceable Unit
M&C	Monitor and Control
MCL	Monitor and Control (ngVLA Subsystem)
MON	Environmental Monitoring & Characterization (ngVLA Subsystem)
MSS	Maintenance & Support Software (ngVLA Subsystem)
MTBF	Mean Time Between Failure
MTBM	Mean Time Between Maintenance
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
ngVLA	Next Generation Very Large Array
NRAO	National Radio Astronomy Observatory
OFF	Offline Software (ngVLA Subsystem)
ONL	Online Software (ngVLA Subsystem)
OPS	Operations Buildings (ngVLA Subsystem)
PDR	Preliminary Design Review
PDF	Portable Document Format
PDU	Power Distribution Unit
PE	Project Engineer
PSU	DC Power Supply (ngVLA Subsystem)
PWV	Precipitable Water Vapor (with column/path length w)
RD	Reference Document
RFI	Radio Frequency Interference
SAF	Prefix from ngVLA L1 Safety Requirements [AD04]
SAT	Site Acceptance Test
SBA	Short Baseline Array
SEC	Prefix from ngVLA L1 Security Requirements [AD05]
SI	International System of Units
SNR	Signal to Noise Ratio
SRDP	Science Ready Data Products
SRR	Subsystem Requirements Review
SYS	Prefix from ngVLA System Requirements [AD01]
VAC	Volts AC
VDC	Volts DC
VLA	Jansky Very Large Array
WAM	WVR Antenna Module (WVR LRU)
WDM	WVR Digital Processing Module (WVR LRU)
WHM	WVR Feed Heater Module (WVR LRU)
WPM	WVR Pier Module (WVR LRU)
WRM	WVR Receiver Module (WVR LRU)
WTM	WVR Tracker Module (WVR LRU)
WUM	WVR Utility Module (WVR LRU)
WVR	Water Vapor Radiometer (ngVLA Subsystem)

020.45.00.00.00-0001-REQ-C-WATER_VAPOR_RADIOMETER_SUBSYS_TECH_REQS

Final Audit Report 2022-01-24

Created:	2022-01-19
By:	Anne Lear (alear@nrao.edu)
Status:	Signed
Transaction ID:	CBJCHBCAABAAcHwUI3-n0D8o-3SCWiuvw-ZncPgZtQBE

"020.45.00.00.00-0001-REQ-C-WATER_VAPOR_RADIOMETER_SUBSYS_TECH_REQS" History

Document created by Anne Lear (alear@nrao.edu)
2022-01-19 - 6:27:10 PM GMT- IP address: 67.0.231.129

Document emailed to Steven Durand (sdurand@nrao.edu) for signature
2022-01-19 - 6:28:20 PM GMT

Email viewed by Steven Durand (sdurand@nrao.edu)
2022-01-19 - 9:36:11 PM GMT- IP address: 65.154.176.62

Document e-signed by Steven Durand (sdurand@nrao.edu)
Signature Date: 2022-01-19 - 9:42:19 PM GMT - Time Source: server- IP address: 65.154.176.62

Document emailed to R. Selina (rselina@nrao.edu) for signature
2022-01-19 - 9:42:22 PM GMT

Email viewed by R. Selina (rselina@nrao.edu)
2022-01-19 - 9:56:33 PM GMT- IP address: 67.0.232.130

Email viewed by R. Selina (rselina@nrao.edu)
2022-01-23 - 5:11:04 PM GMT- IP address: 75.161.212.50

Document e-signed by R. Selina (rselina@nrao.edu)
Signature Date: 2022-01-23 - 10:45:08 PM GMT - Time Source: server- IP address: 75.161.212.50

Document emailed to Thomas Kusel (tkusel@nrao.edu) for signature
2022-01-23 - 10:45:13 PM GMT

Email viewed by Thomas Kusel (tkusel@nrao.edu)
2022-01-24 - 1:51:31 PM GMT- IP address: 192.131.232.128

Document e-signed by Thomas Kusel (tkusel@nrao.edu)
Signature Date: 2022-01-24 - 1:53:08 PM GMT - Time Source: server- IP address: 192.131.232.128

Document emailed to Willem Esterhuyse (westerhu@nrao.edu) for signature
2022-01-24 - 1:53:11 PM GMT

Email viewed by Willem Esterhuyse (westerhu@nrao.edu)
2022-01-24 - 2:05:35 PM GMT- IP address: 105.224.252.103

Document e-signed by Willem Esterhuyse (westerhu@nrao.edu)
Signature Date: 2022-01-24 - 2:15:04 PM GMT - Time Source: server- IP address: 105.224.252.103

Agreement completed.
2022-01-24 - 2:15:04 PM GMT