Cryogenic Subsystem Technical Requirements

020.30.10.00.00-0001-REQ

Status: **RELEASED**

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Change Record

Version	Date	Author	Affected Section(s)	Reason
A	2018-11-26	D. Urbain	All	Reference design document
A.1	2020-08-25	D. Urbain	All	New template initial draft
A.2	2020-09-04	D. Urbain	All	Made corrections following RIDs
A.3	2020-09-08	A. Lear	All	Minor copy edits and formatting; uploaded document into Adept EDMS
A.4	2020-09-09	D. Urbain	3.3 & 13.2 7.10.1	Corrected ref requirement numbers Change power consumption to 5.54kW
A.5	2021-04-07	D. Urbain	All	New flow-down diagram. Added system assumption and TASC description. Revised environmental requirement section, use updated Electronics Specification document to update this document.
A.6	2021-04-12	S. Burleigh	All	Minor copy editing
A.7	2021-04-12	A. Lenox	All	Minor formatting
A.8	2021-05-20	D. Urbain	All	Update of the document after review following RIDs
B	2021-06-11	D. Urbain	All	Prepared PDF for signatures & approvals
C	2023-09-14	D. Urbain	All	corrected spelling and grammar errors. Added RD16 and RD17. **Section 2.2** Removed CRY to MCL ICD in table. **Section 3.2** updated the text and figures to reflect the new location of the helium compressor, M&C electronics and pressure regulation module. **Section 4.2** updated the text to reflect the new location of the helium compressor **Section 6** updated the text to reflect the new location of the helium compressor **Section 6.5** Eliminated CRY0051 to comply with ECN 0005 **Section 7.1** updated the text to reflect the new location of the helium compressor **Section 7.2.1.1** Change or add requirements to reflect the changes in drawing 020.30.03.10.0001-DWG and 020.30.03.10.0002-DWG. **Section 7.2.5** Change text to comply with ECN 0005 and add requirements table for Glycol cooling. **Section 7.2.7** Update CRY1024 to comply with ETR0821 in ECN0001

				Section 7.2.8 Updated text to match HIL concept **Section 7.6.1** Added CRY0412 risk of implosion and CRY0413 risk of burn **Section 7.10.4** added CRY0996-CRY0999 and CRY1520 to comply with ECN0001 **Section 7.13** Revised CRY0989 and added CRY1530-CRY1535 to comply with ECN0001 **Section 7.14.5** Corrected duplication in requirement number CRY1043 **Section 12.1** Updated table

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1 Introduction

1.1 Purpose

This document presents the complete set of Level 2 subsystem requirements that should guide the design and development of the **cryogenic subsystem**. Requirements described in this document are derived from applicable ngVLA System Requirements and System-Level Specification documents as listed in the Applicable Documents table. The overall requirements hierarchy and management strategy are outlined in [AD01] and [AD02].

The content of these requirements is at the subsystem level, conforming to the system architecture [AD06], 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 Cryogenic Subsystem, as delivered for ngVLA integration. This includes the following:

- Hardware and software subsystem requirements that satisfy functional and nonfunctional System Requirements.
- 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 [AD02], and any other attributes needed for particular subsystems as determined by agreement between the Project Office Engineers and the Integrated Product Team (IPT) leads.
- Technical Performance Measures (TPMs) at the subsystem level, which support the Measures of Performance (MOPs) at the system level.
- 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	Rev. /Doc. No.
AD01	ngVLA Systems Engineering Management Plan	020.10.00.00.00-0001-PLA
AD02	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD03	ngVLA System Requirements	020.10.15.10.00-0003-REQ
AD04	L1 System Environmental Specifications	020.10.15.10.00-0001-SPE
AD05	L1 System EMI/RFI Requirements	020.10.15.10.00-0002-REQ
AD06	System-Level Architecture Model	020.10.20.00.00-0002-DWG
AD07	L1 Safety Requirements	020.80.00.00.00-0001-REQ

Ref. No.	Document Title	Rev. /Doc. No.
AD08	L1 Security Specifications	(In Prep.)
AD09	ngVLA Electronics Specifications	020.10.15.10.00-0008-REQ
AD10	System Technical Budgets	020.10.25.00.00-0002-DSN
AD11	EEC and CRY Equipment, Volume and Mass Requirements for 18m antenna	020.30.03.10.00-0001-DWG
AD12	EEC and CRY Equipment, Volume and Mass Requirements for 6m antenna	020.30.03.10.00-0002-DWG

2.2 Applicable ICDs

Ref. No.	Interface	Document No.
AD12	ICD: Cryogenics (CRY) to Antenna (ANT)	020.10.40.05.00-0131-ICD
AD13	ICD: Cryogenics (CRY) to Short Baseline Antenna (SBA)	020.10.40.05.00-0033-ICD
AD14	ICD: Cryogenics (CRY) to Bins Rack and Modules (BMR)	020.10.40.05.00-0044-ICD
AD15	ICD: Cryogenics (CRY) to Environmental and Control (EEC)	020.10.40.05.00-0045-ICD
AD16	ICD: Cryogenics (CRY) to Front End (FED)	020.10.40.05.00-0012-ICD
AD17	ICD: Cryogenics (CRY) to Antenna Fiber Optic (AFD)	020.10.40.05.00-0047-ICD
AD18	ICD: Cryogenics (CRY) to DC Power Supply (PSU)	020.10.40.05.00-0043-ICD
AD19	ICD: Cryogenics (CRY) to Monitor and Control HW IF Layer (HIL)	020.10.40.05.00-0046-ICD

2.3 Reference Documents

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

Ref. No.	Document Title	Rev./Doc. No.
RD01	ngVLA Cryogenic Subsystem Reference Design Description Document	020.30.10.00.00-0002-DSN
RD02	FA-70L Helium Compressor Operating Manual	Sumitomo (SHI) Cryogenics of America, Inc.
RD03	FA-40L Air-Cooled Helium Compressor Operation Manual	Sumitomo (SHI) Cryogenics of America, Inc.
RD04	Pascal Series Rotary Vane Pumps 5 to 21 m^3/h Operating Instructions	PFIEFFER Vacuum
RD05	ngVLA Front-End Receivers Thermal Study Analysis Report with 110K Intermediate Cooling Stage (05/12/2018)	Remi Rayet, Callisto, 12 Av. De Border Blanche, Villefranche de Lauragais F-31290, France
RD06	ngVLA Front-End Receivers Thermal Study Dewar-B Update (14/02/2020)	Remi Rayet, Antonella Simone, Callisto
RD07	Detail Specification: Plate, Tags and Bands for Identification of Equipment, General Specification for (28 Nov 1997)	MIL-DTL-15024

RD08	Detail Specification: Plate, Identification or Instruction, Metal Foil, Adhesive Backed General Specification for (06 Jul 2006)	MIL-P-19834
RD09	Department of Defense Standard Practice: Marking of Electronic Items (02 Nov 1999)	MIL-STD-13231
RD10	Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices) (25-Oct-1995)	MIL-STD-1686c
RD11	Electrostatic Discharge (ESD) Control Handbook for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices) (31 Jul 1994)	MIL-HDBK-263B
RD12	ANSI Standard Protection of Electrical and Electronic Parts, Assemblies and Equipment	ANSI/ESD S20.20-2014
RD13	US National Electrical Code (NEC)	NFPA 70
RD14	Cable Labeling Standard	ANSI / TIA 606-C
RD15	Front End Technical Requirements	020.30.05.00.00-0003-REQ
RD16	HITACHI for Ultra-low Temperature Applications Scroll compressor, Helium Refrigerant	S305DHV-40D2UC compressor model
RD17	Oxford Cryosystems ngVLA Design Description Document V3.3	James Parsons, Thomas Rich
RD18	Rotary Vane Pumps Operating Instructions Pascal Series	PFEIFFER Vacuum

3 Overview of Subsystem Requirements

3.1 Document Outline

This document presents the technical requirements for the cryogenic 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, along with 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.

In certain cases, parameters are simply noted with a TBD or TBC value. The goal in such cases is to identify parameters that will require definition in future releases of the cryogenic subsystem requirements as the associated technical issues are understood.

Section 11 identifies performance metrics to be monitored throughout the conceptual design phase. These metrics assist in trade-off analysis of various concepts, should tensions be identified between requirements.

3.2 Subsystem General Description

The purpose of the cryogenic subsystem is to cool sensitive Front End electronics to a very low temperature to minimize self-generated noise and optimize sensitivity. The subsystem is a closed-loop circuit (Figure 1) composed of a compressor that pressurizes helium gas before sending it to the cold heads (one per Front End Dewar), where it expands and cools. The lower-pressure helium is then returned to the compressor to complete the cycle. The helium flows through sections of flex-lines where there is motion and rigid stainless steel tubing everywhere else.

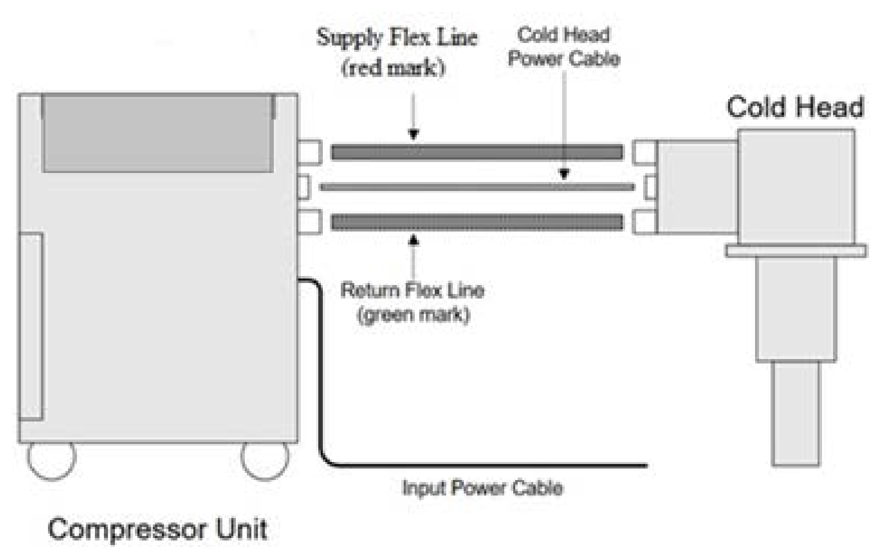

Figure 1 – Cryogenic subsystem closed loop.

Note: The cold head is also referenced as cryocooler in this document.

Figure 2 shows the location of the various cryogenic subsystem components on the antenna. The helium lines and the cold head power cables will go through the elevation wrap and be routed along the backup structure and the feed arm to the Front End (FE) junction box. Inside the FE junction box, the helium lines and vacuum hose from the Auxiliary enclosure will transition from rigid to flexible to run through the cable carrier. Monitor and Control (M&C) module communications will be done through fiber optic for reliability, noise immunity, and RFI protection.

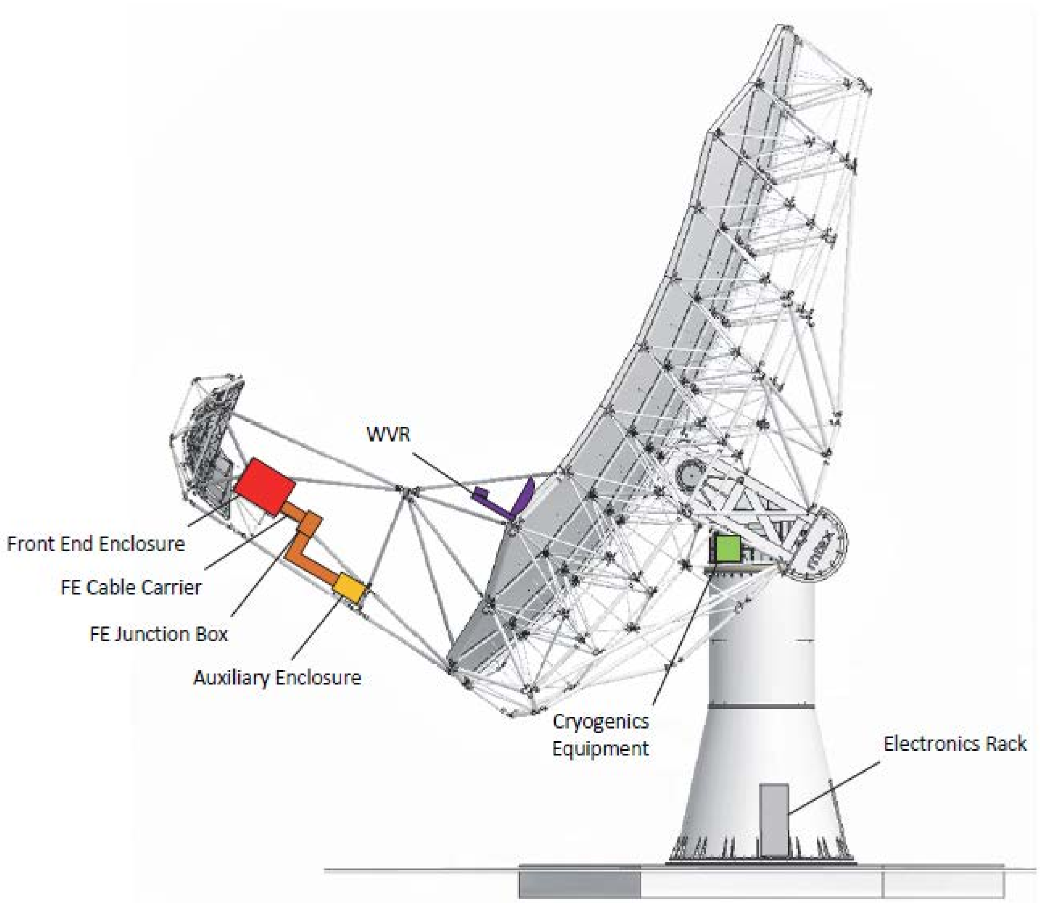

Figure 2 – 18m antenna view showing the location of the various components of the cryogenic subsystem.

The compressor is oil lubricated and cannot be tilted more than a few degrees during operation. Therefore, it must be installed below the elevation axis on the antenna. To avoid running Helium lines through the azimuth wrap, the compressor can be installed on a platform behind the primary reflector or inside the turn-head. The 18m antenna selected by the project has the compressor inside the turn-head, including the monitor and control electronics and the helium pressure regulation module. A representation of the cryogenic equipment in the turn-head is shown in Figure **3**.
The compressor control and power electronics are enclosed in an RFI enclosure to eliminate the risk of interference with the radio signal being detected. The helium pressure regulation assembly controls the closed loop circuit's supply pressure and compensates for pressure variations due to ambient temperature

changes or small leaks. The control electronics for the pressure regulation module are also located in the RFI enclosure that has to be located near the compressor to limit the power cable length and minimize the voltage drop.

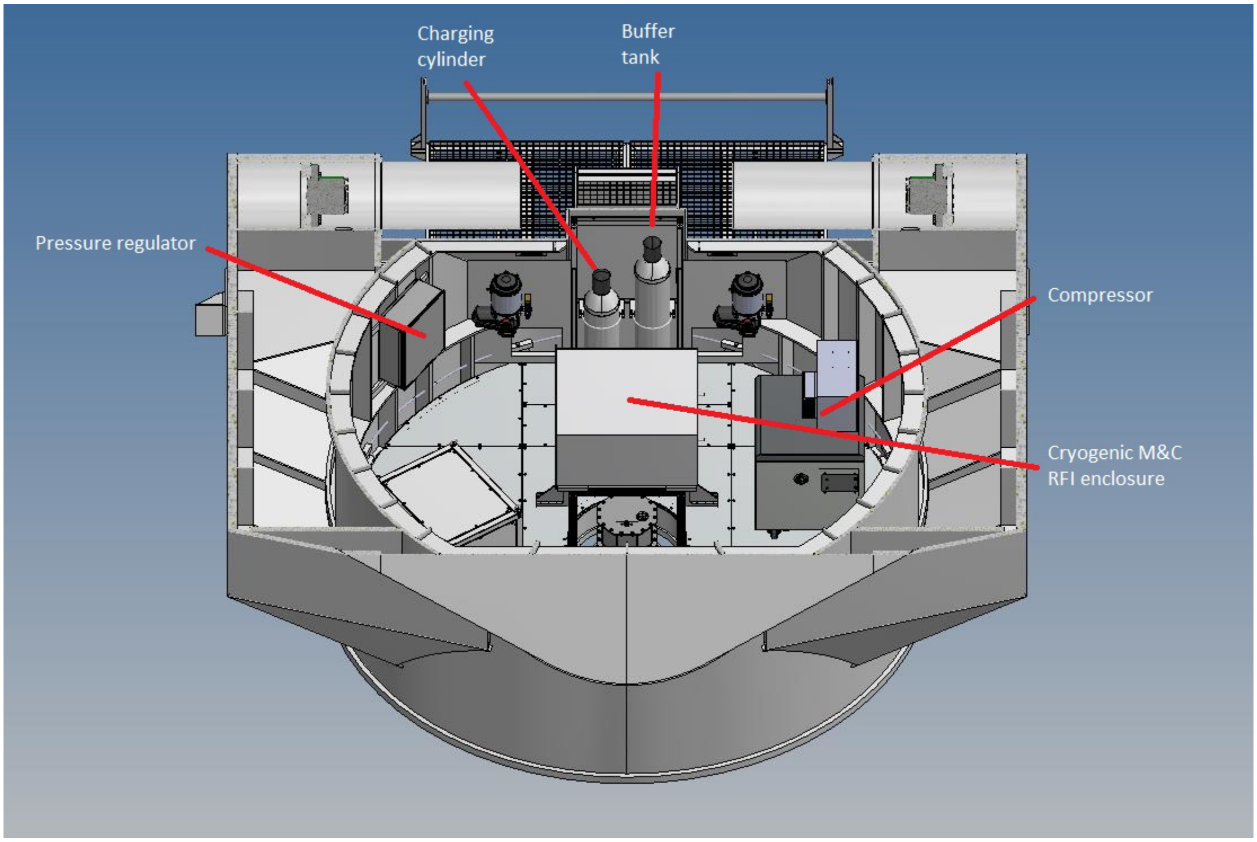

Figure 3 – cryogenic equipment located inside the antenna turn-head

The Front End receiver enclosure is located at the end of the antenna feed arm and provides weather protection for the two Front End receivers Cryostat–A & Cryostat–B; see Figure 4. Both Front Ends are cooled by separate cryocoolers independently controlled by a dual-channel M&C module. This cryocooler power and control electronics are placed with the vacuum pump M&C in an RFI-tight box inside the auxiliary enclosure, see Figure 2.

A vacuum manifold splits the vacuum line connected to the vacuum pump inside the auxiliary enclosure. It has two remotely controlled valves allowing the pump down of the selected Front End cryostat.

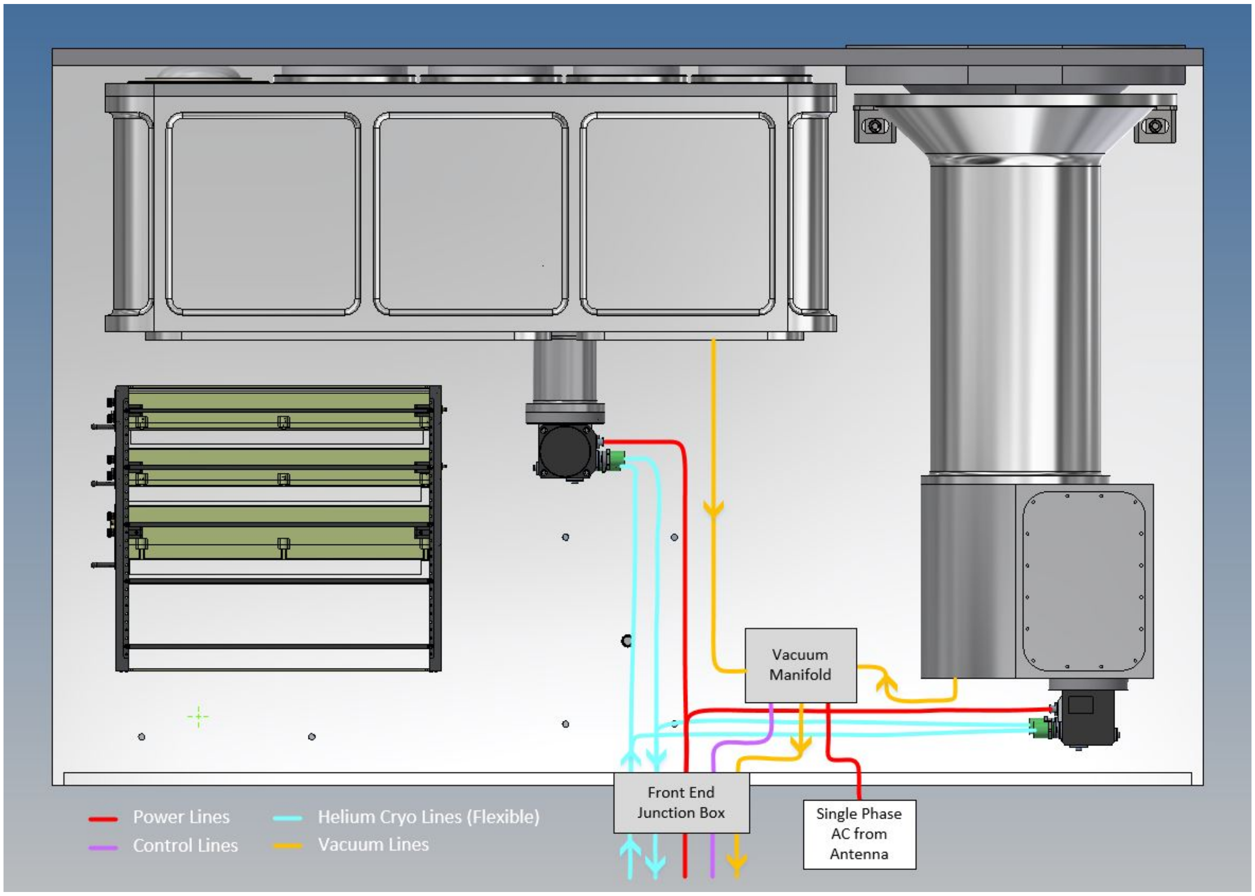

Figure 4 – Cryogenic equipment located in the Front End receiver enclosure.

3.3 Subsystem Boundary, Context, and External Interfaces

Figure 5 shows the cryogenic subsystem boundaries in the context of other systems on the antenna. External systems are shown in boxes with their Configuration Item (CI) number, in accordance with the Product Breakdown Structure (PBS) generated from the system architecture model. The ICD document number corresponding to each interface is displayed above the interconnect where it exists.

The lower-level products of the cryogenic subsystem are listed in order by their Configuration Item (CI) number, in accordance with the Product Breakdown Structure (PBS) generated from the system architecture model.

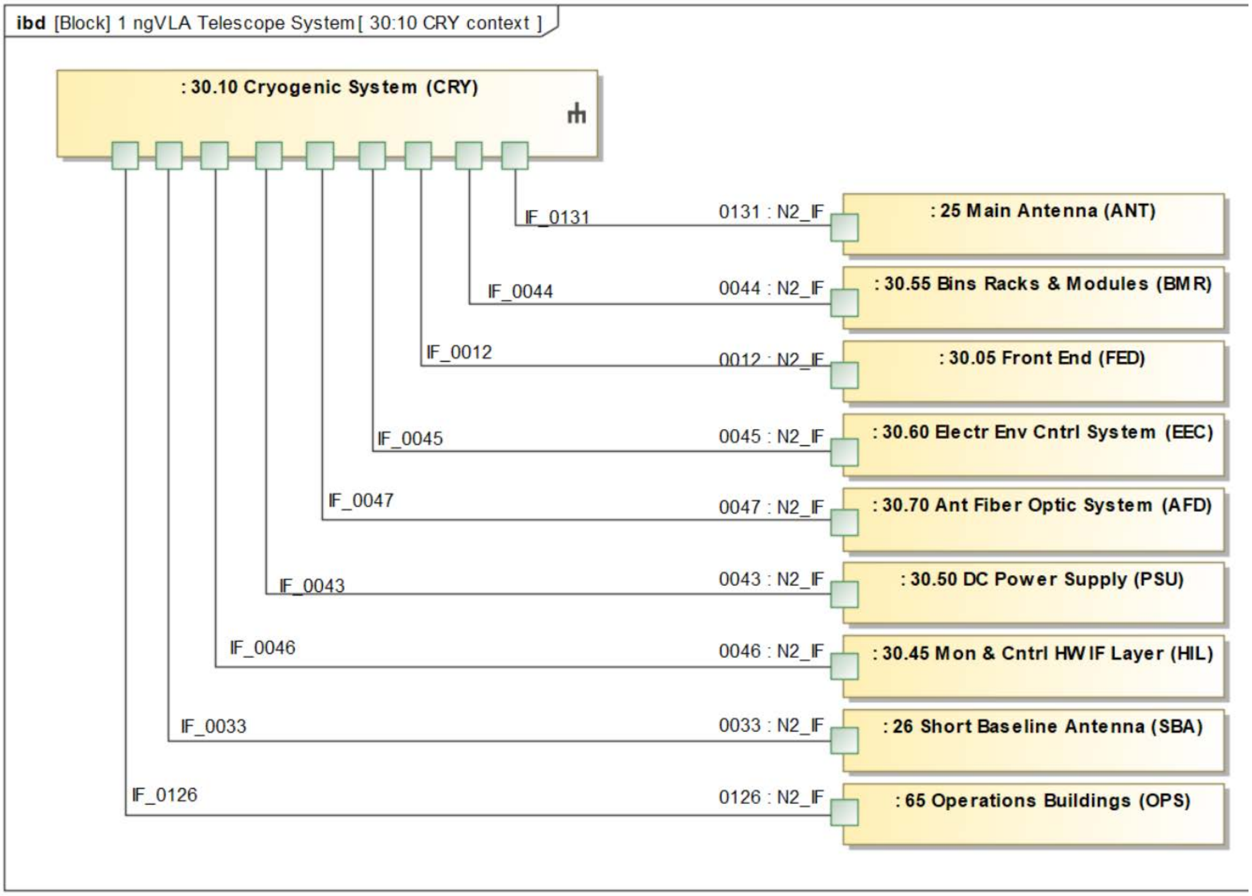

Figure 5- Context of Cryogenics Subsystems with other Antenna Subsystems

3.4 Key Requirements Summary

The following table summarizes the major subsystem requirements to provide the reader with a high-level view of the desired subsystem. Should there be a conflict between the requirements listed here and the descriptions in Sections 7 through 10, the latter shall take precedence.

Parameter	Summary of Requirement	Reference Requirements
Temperature Range for Normal Operation	The cryogenic subsystem shall perform normally in the temperature range of –25°C ≤ T ≤ 45°C.	CRY0002
Altitude Range	The cryogenic subsystem shall operate normally at altitudes ranging from sea level up to 2500 m.	CRY0020
MTBM	The cryogenic subsystem shall be designed with an expected MTBM for the entire subsystem of 8,333 hours.	CRY0100
Modularization	The cryogenic subsystem shall be modularized into Line Replaceable Units (LRU) whenever possible to facilitate site maintenance.	CRY0101
Preventive Maintenance	The cryogenic subsystem shall be designed with preventive maintenance (PM) interval no shorter than 1 year.	CRY0106

Parameter	Summary of Requirement	Reference Requirements
Serviceable Onsite	The cold head shall be serviceable/swappable onsite (antenna) by one technician within 2 hours.	CRY0109
Interchangeable LRU	Any LRU of the cryogenic subsystem shall be interchangeable with a spare LRU with no calibration, tuning or special alignment required.	CRY0110
LRU Physical Tracking Device	Each LRU shall be equipped with a standardized physical tracking label or device to facilitate status and location across the observatory. Whenever possible, these unique identification codes must be remotely accessible via an LRU physical tracking device.	CRY0200
LRU Monitoring	Each network connected LRU of the cryogenic subsystem shall provide on-board monitoring and diagnostics to determine the health and status of the unit.	CRY0220
Follow Safe Design Priorities	The cryogenic subsystem shall address safety of personal first followed by safety of equipment. The information needed to control the equipment must be unambiguous and easily understood.	CRY0400
Subsystem Self-Monitoring	The cryogenic subsystem shall monitor system health and prohibit actions likely to cause damage, or shut down system to prevent damage.	CRY0450
Design Life	The cryogenic subsystem shall be designed for an expected operational life of no less than 30 years.	CRY0600
Part Selection for Maintainability	The manufacturer of the compressor and cold head shall support their equipment and have sufficient spare parts inventory for the design life of the instrument (30 years).	CRY0601
Cooling Capacity	The cold head shall have enough cooling capacity to reach 80 K with a heat load of 20 W on the 1st stage and 20 K with heat load of 4 W on the 2nd stage.	CRY0800
Temperature Stability	The magnitude of temperature variations on the 2nd cryogenic stage shall not exceed 0.12 K over 200 seconds.	CRY0801
Compressor Flow Capacity	The compressor shall have enough flow capacity at 60 Hz to run two cold heads with the cooling capacity described in CRY0801.	CRY0803
Helium Pressure Regulation	The helium pressure regulation module shall maintain the required supply pressure ± 70 kPa (± 10 psi) over the temperature range listed in CRY0002.	CRY0809
Vacuum Pump Ultimate Pressure	The vacuum pump shall have a ultimate pressure ≤ 0.2 Pa.	CRY0812
Vacuum Pump Pumping Speed	The vacuum pump shall have a nominal pumping speed of 18 m^3/h.	CRY0813
Compressor Tilt Angle	The compressor shall operate normally with a tilt angle ≤ 5° from the horizontal.	CRY0900
Cryocooler Orientation	The cryocooler shall operate normally has the antenna move through its entire elevation range 12°–88°.	CRY0901

Parameter	Summary of Requirement	Reference Requirements
Vacuum Pump Allowed Tilt Angle During Operation	The vacuum pump shall be able to operate while the antenna moves in elevation 12° ≤ tilt angle ≤ 88°.	CRY0911
Metric Fasteners	The cryogenic subsystem shall use metric fasteners and request a non-compliance agreement where imperial hardware has to be used.	CRY0923
Compressor Power Consumption	The helium compressor shall not consume more than 5.54 kW.	CRY1001
Helium Quality	The cryogenic subsystem shall only use helium 99.999% pure or better.	CRY1200

4 Requirements Management

4.1 Requirements Definitions

Consistent with the Requirements Management Plan [AD02], 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 6 displays the relationships between the various requirements and concept documents that flow down to the **cryogenic subsystem**.

The cryogenic subsystem runs continuously, and its power consumption and reliability are critical to the operation cost. Some of the requirements flow down from the system requirements document.

The cryogenic equipment mounted on the antenna is distributed over three locations, the compressor and helium regulation circuit inside the turn-head, the cryocoolers inside the Front End enclosure, helium lines along the antenna feed arm, elevation wrap, and the cable carriers. While the turn-head and the Front End enclosure provide some environmental protection, the helium lines are exposed to the elements. Therefore, some of the requirements come from environmental specifications.
High-pressure helium is used in the cooling process, which imposes some safety requirements on the equipment and some protective measures for the service personnel.

The cryogenic subsystem is tightly connected to the Front End subsystem because it is designed to cool its sensitive electronics down to a very low and constant temperature to minimize self-generated thermal noise and improve gain stability. The cryogenic equipment's function and status need to be controlled and monitored remotely. Therefore, some of the key parameters for the cryogenic subsystem are directly related to the electronics specifications.

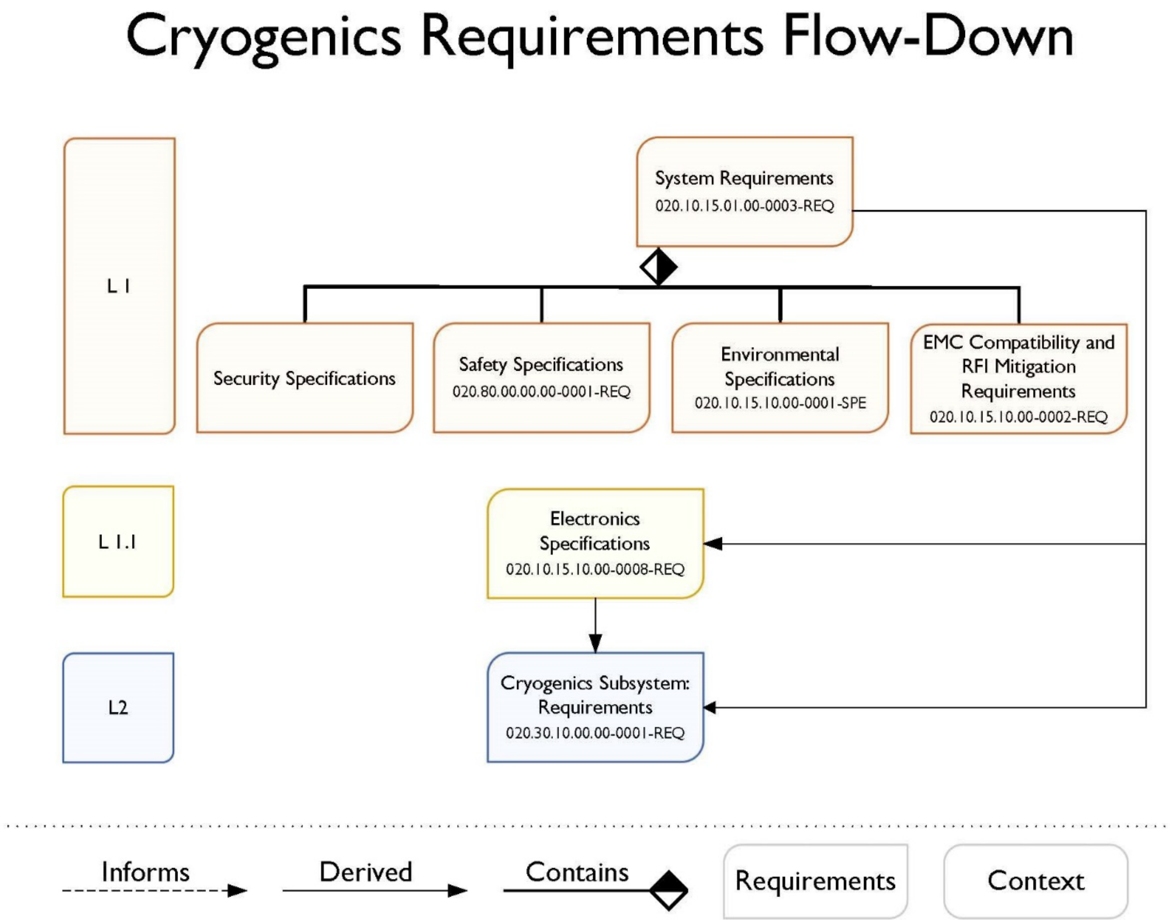

Figure 6 – Requirements flow-down to the Cryogenic Subsystem Requirements.

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 support 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 goal is to build the most generally capable system that will support the Key Science Goals within the programmatic cost and schedule constraints. Maintaining enumerated traceability between system requirements and subsystem requirements ensures that this trade-off process can be managed in a controlled way.

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."

5 Assumptions

5.1 General Assumption

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., HVAC, RTP system) unless explicitly stated otherwise.

5.2 System Assumption

The requirements listed in this document applied directly to the variable speed GM cryocooler concept selected for the reference design and represents the low-risk option for ngVLA. However, we are also investigating in parallel the ThermoAcoustic Stirling Cryocooler (TASC), which is a more uncertain option because the technology needs to be developed or adapted to meet the ngVLA key requirements but offers some real benefits in terms of power consumption and reliability for the project. A technical description of the TASC can be found in the Appendix with a list of the requirements that must be added, changed, or eliminated if the TASC is selected as a cryocooler for ngVLA.

6 Environmental Conditions

Figure 2 shows the distribution of the cryogenic equipment on the antenna; while the compressor, the helium regulation circuit, and the cryocooler are protected from the elements, the interconnecting helium lines are partially unprotected. The cryogenic equipment exposed to the weather must comply with the environmental specifications in [AD04].
Once the limits to operating conditions are exceeded, the antenna will be moved to its "stow-survival" position and the observation suspended. Some of the equipment will be place in stand-by mode but the cryogenic subsystem shall remain in operation due to the five minutes required to return to operation.

6.1 Operating Conditions

The cryogenic subsystem has to operate generally up to the limits of operating conditions and into the standby conditions, even if the performance requirements are relaxed for some other systems. As soon as the cryocooler stops, the Front Ends start to warm up, and contaminants that have been accumulating on the cold surfaces inside the cryostats from the cryo-pumping process begin to evaporate, progressively degrading the vacuum and increasing the thermal load by convection. When the vacuum pressure exceeds the value required to start the cryocooler, the Front End cannot be cooled back down without restoring a proper vacuum. The pump-down process requires bringing the temperature inside the Dewar above freezing (300–320 K recommended) to ensure all contamination can be pumped out. This process will take several hours and will leave the antenna with this Front End unusable for science.

Parameter	Req. #	Value	Traceability
Wind Speed Limits for Normal Operation	CRY0001	The cryogenic subsystem shall perform normally for wind speed 0m/s ≤ W ≤ 30m/s average.	ENV0361

Parameter	Req. #	Value	Traceability
Temperature Range for Normal Operation	CRY0002	The cryogenic subsystem shall perform normally in the temperature range –25°C ≤ T ≤ 45°C.	ENV0362
Precipitation for Normal Operation	CRY0003	The cryogenic subsystem shall perform normally for rainfall of 5 cm/hour over 10 minutes.	ENV0363
Ice Accumulation for Normal Operation	CRY0004	No ice accumulation shall be present on the moving parts of the cryogenic subsystem for normal operation, but equivalent to radial ice of 2.5 mm on static surfaces is acceptable.	ENV0364
Relative Humidity	CRY0006	The cryogenic subsystem shall operate normally for 0 ≤ RH ≤ 100%, condensation permitted.	ENV0365

Placing the helium compressor inside the turn-head alleviates the requirement for weather protection; ice accumulation and high wind are only a concern for the helium lines. The transition to liquid cooling for the compressor also eliminates the fan and ductwork required for the air-cooled configuration. During the testing phase, the cryogenic subsystem shall demonstrate that it can operate for any valid combination of the environmental parameters. High wind and very hot or cold temperatures, being the most demanding conditions, should be tested for during the system validation.

6.2 *Survival Conditions*

During the survival condition, the cryogenic subsystem is not required to run. However, as long as power is available on the antenna, it is recommended to maintain the compressor running at low speed and possibly in bypass through the IRV to keep the oil warm and avoid a time-consuming cold start procedure.

Parameter	Req. #	Value	Traceability
Wind Speed for Survival Condition	CRY0010	The cryogenic subsystem shall survive without damage wind speed of 0m/s ≤ W ≤ 50m/s average.	ENV0341
Temperature for Survival Condition	CRY0011	The cryogenic subsystem shall survive without damage at temperatures –30°C ≤ T ≤ 50°C.	ENV0342
Radial Ice for Survival Condition	CRY0013	The cryogenic subsystem shall survive without damage radial ice 2.5 cm thick.	ENV0343
Snow Load for Survival Condition	CRY0014	The cryogenic subsystem shall survive without damage snow load of 100 kg/m^2 on horizontal surfaces.	ENV0346
Hail Stone Size for Survival Condition	CRY0015	The cryogenic subsystem shall survive without residual loss of function or performance hail stones up to 2.0 cm in diameter.	ENV0347

Only the helium lines will be unprotected and exposed to the elements in the cryogenic equipment configuration proposed by the 18m antenna. The most fragile flexible sections will get some level of environmental protection from the elevation wrap and the cable carrier.

While in the operating conditions, any valid combination of environmental parameters shall be evaluated, in the survival conditions, each parameter shall be treated as stand-alone and be tested individually.

6.3 Transportation Conditions

During transportation, the cryogenic equipment is powered off and packaged for transport. The environmental transportation condition should be considered an extension of the survival conditions that the cryogenic equipment shall withstand without damage. The shock and vibration requirements for transporting the cryogenic equipment are defined in Section 7.10.3.

Parameter	Req. #	Value	Traceability
Transportation Solar Thermal Load	CRY0016	The packaged cryogenic equipment shall withstand without damage solar exposure (1200W/m^2) for the duration of the journey.	ENV0381
Transportation Temperature	CRY0017	The packaged cryogenic equipment shall survive without damage temperature in the –30°C ≤ T ≤ 50°C range for the duration of the journey.	ENV0382

6.4 Storage Conditions

During operation, the cryogenic subsystem spare parts and LRUs will be stored in a warehouse that will provide some regulation in temperature and humidity.

Parameter	Req. #	Value	Traceability
Storage Temperature	CRY0018	Component of the cryogenic subsystem shall be stored without damage at temperatures 0°C ≤ T ≤ 30°C.	ENV0372
Storage Relative Humidity	CRY0019	Component of the cryogenic subsystem shall be stored without damage at relative humidity 10 ≤ RH ≤ 90%.	ENV0373

6.5 Miscellaneous Environmental Requirements

The ngVLA will be centered in New Mexico (NM), but antennas will be scattered throughout the continental United States, Hawaii, and Puerto Rico. The altitude will impact the performance of the cryogenic subsystem, and the increased UV exposure will affect the life expectancy of some of the components. On the islands, the presence of a nearby ocean will increase corrosion problems due to the salty environment, and in the dry and windy NM plains, dust will intrude into every opening.

Thunderstorms also are common in the summer and could have catastrophic consequences if the system is not well protected. Lighting protection and proper grounding are essential for equipment safety. Because the antennas are remotely located and, for the most part, unattended, wildlife and rodents, in particular, are a concern and should be accounted for. All these parameters must all be addressed during the design phase.

Parameter	Req. #	Value	Traceability
Altitude Range	CRY0020	The cryogenic subsystem shall operate normally at altitudes ranging from sea level up to 2500 m.	ENV0351
Maximum Solar Flux	CRY0021	All equipment exposed to outside environment shall be designed for a maximum diurnal solar flux of 1200 W/m^2 from 0.3–60 µm.	ENV0360 ENV0561

Parameter	Req. #	Value	Traceability
UV Radiation	CRY0022	The cryogenic subsystem shall be designed for a maximum diurnal UV radiated flux of 100 W/m^2 from 280–400 nm.	ENV0562 ETR1125
Corrosion Resistance	CRY0030	The cryogenic subsystem shall use corrosion resistant materials and/or highly corrosion resistant coating and finish on surfaces to prevent corrosion that may impact the performance or structural integrity of the equipment over the system design life.	SYS2801 SAF0490 ENV0591
Lightning Protection	CRY0040	The cryogenic subsystem shall be protected against lightning electromagnetic impulse (LEMP) in accordance with IEC 62305-4.	ENV0512 ETR0825
Dust Protection	CRY0050	The cryogenic subsystem shall be protected against windblown dust, ashes, and grit.	ENV0541
Rodent Protection	CRY0060	The cryogenic subsystem shall be design to prevent rodent intrusion and possible damage to the wiring and electrical system.	ENV0551 ETR1127
Seismic Protection	CRY0070	The cryogenic subsystem shall be designed to withstand a low probability earthquake with up to 0.2 g peak acceleration in either the vertical or the horizontal axis.	ENV0521
Rain/Water Infiltration	CRY0080	Exposed cryogenic equipment shall be designed to withstand rainfall intensity up to 16 cm/hr., with droplets sized 0.5 to 4.5 mm, at a wind velocity of 15 m/s from the vertical to horizontal direction.	ENV0571

UV exposure will degrade certain materials over time, compromising mechanical properties and causing failures. Accelerated aging processes are available but are usually costly and should be reserved for very specific components. Components susceptible to UV damage shall be identified and protected from exposure wherever possible or scheduled to be replaced at the end of their expected life.

The seismic protection requirement could be addressed simultaneously with the vibration requirement because the same test equipment can simulate both.

7 Subsystem Requirements

- Parameter: Short (unique) name for the requirement.
- Req. #: Unique requirement number per [AD02]. The format is AAANNNN where AAA is the 3-digit identifier for the subsystem and NNNN is a four-digit number typically starting with 0001.
- Value: Textual description of the requirement. Minimize the use of special characters and formatting. Equations, analysis, and other substantiating information may be placed following a table.
- Traceability: Identify which higher-level requirement(s) this specific requirement is derived or copied from. In some cases, requirements can refine other requirements at the same level. Requirements need only be traced to one level higher; in most cases this will be a Level-1 System Requirement or Level-1 specification.

When complete, the full requirements set should answer the following questions:

1. Is the requirements set complete and does it conform to all higher-level documents?
2. Do individual requirements adhere to the following quality attributes?
   a. **Clear** – Unambiguous and not confusing to readers.
   b. **Complete** – Expresses a whole, single idea, and not portions of one or many.
   c. **Consistent** – Does not conflict with other requirements.
   d. **Correct** – Describes the user's intent without interpretation.
   e. **Design** – Does not impose a specific solution ("what," not "how").
   f. **Feasible** – Implementable with existing or projected technology and within cost and schedule.
   g. **Traceable** – Uniquely identifiable and able to be linked to higher-level or supporting requirement(s).
   h. **Verifiable** – Able to be confirmed either through test, inspection, analysis, or demonstration without unanticipated cost or schedule impacts.
3. Are non-functional requirements considered? (e.g. quality, reliability, maintainability, safety, security)
4. Does the requirements set leave open adequate trade space to consider varying designs? (i.e. the resulting design is not overly constrained)

7.1 Environmental Monitoring

The cryogenic subsystem is mounted on the antenna and, for the most part, protected from the elements, whether by the Front end enclosure or by the antenna turn-head. Only the lines transporting the helium gas between the compressor and the cryocoolers will be exposed. However, some other subsystems might be more vulnerable to the weather and could impact the cryogenic equipment like the Chiller. The cryogenic M&C needs to be aware of the ambient conditions to take necessary actions to protect the equipment. The cryogenic M&C will obtain the environmental information from the antenna M&C and will use that information to control the compressor. In case of loss of communication, the cryogenic subsystem will have to rely on internal sensors to protect itself. At that point, the hardware safeguards will prevent damage to the equipment.

Parameter	Req. #	Value	Traceability
Safety Weather Monitoring	CRY0300	The cryogenic subsystem shall be informed of the weather conditions by the antenna M&C to prohibit actions likely to cause damage or shut down systems to prevent damage.	SYS2502
Hardware Safeguards	CRY0301	In case of loss of environmental information, safeguards shall be implemented to protect the equipment and prevent damage.	SYS2402

7.2 Interface Requirements

In this section, requirements are derived from the applicable ICDs as listed in Section 2.2. The ICDs define the interfaces, but do not contain any requirements. All interface requirements that drive the design and verification of the subsystem shall be listed in this section.

7.2.1 Interface to Antenna (0131:N2_IF)

Figure 2 shows how the cryogenic subsystem equipment is distributed on the antenna. On the 18m antenna, the compressor has been moved inside the turn-head to be protected from the weather and to eliminate the service platform considered in the reference design. The cryocoolers attached to the Front End cryostats will be enclosed in the Front End enclosure, providing environmental protection. The helium lines will be secured to the antenna feed arm, and some sections will be exposed to the elements. The ICD will describe the mechanical and electrical interfaces between the cryogenic equipment and the antenna.

7.2.1.1 Mechanical Interface

The helium compressor needs to be mounted in the horizontal position for operation; the tilt angle shall not exceed 5°. The installation of the compressor on the antenna shall comply with this requirement. The antenna design shall reserve enough space for the cryogenic equipment; some volume and weight restrictions must be set to allow both subsystems to be developed independently.

The flexible helium lines have a recommended dynamic bending radius that must be respected to guarantee long-term reliability. Since the lines run through the antenna elevation wrap, the selected cable carrier shall comply with the bending radius requirement.

The vacuum pump will be located inside the auxiliary enclosure; how it will be mounted shall allow the pump to be operated even if the antenna is moving in elevation. Because both front ends have independent cryocoolers, one front end could be operational while the other is being serviced.

Parameter	Req. #	Value	Traceability
Compressor Tilt Angle	CRY0900	When mounted on the antenna, the compressor shall not be tilted by more than 5° from the horizontal for normal operation.	Compressor manufacturer operation manual
Compressor Volume	CRY0902	The compressor including the space around it required for service shall fit within the volume described in the latest revision of 020.30.03.10.0001-DWG for the 18m antenna and 020.20.03.10.0002-DWG for the 6m antenna.	AD11 AD12
Compressor Mass	CRY0903	The mass of the compressor shall not exceed 172 kg.	AD11 AD12
Helium Pressure Regulator Rack Volume	CRY0904	The helium pressure regulator rack including the clearance volume shall fit in the volume described in the latest revision of 020.30.03.10.0001-DWG for the 18m antenna and 020.20.03.10.0002-DWG for the 6m antenna.	AD11 AD12
Helium Pressure Regulator Rack Mass	CRY0905	The mass of the helium pressure regulator rack shall not exceed 59 kg.	AD11 AD12
Cryogenic M&C RFI Enclosure Volume	CRY0906	The cryogenic M&C RFI enclosure including the clearance volume shall fit in the volume described in the latest revision of 020.30.03.10.0001-DWG for the 18m antenna and 020.20.03.10.0002-DWG for the 6m antenna.	AD11 AD12
Cryogenic M&C RFI Enclosure Mass	CRY0907	The mass of the cryogenic M&C RFI enclosure shall not exceed 60 kg.	AD11 AD12
Flexible Helium Line Dynamic Bending Radius	CRY0908	The flexible helium line shall have a minimum dynamic bending radius of 250 mm.	Helium line manufacturer datasheet

Parameter	Req. #	Value	Traceability
Helium Pressure Regulator Controller Volume	CRY1560	The helium pressure regulator controller including the clearance volume shall fit in the volume described in the latest revision of 020.30.03.10.0001-DWG for the 18m antenna and 020.20.03.10.0002-DWG for the 6m antenna.	AD11 AD12
Helium Pressure Regulator Controller Mass	CRY1561	The mass of the helium pressure regulator controller shall not exceed 19 kg	AD11 AD12

7.2.1.2 *Electrical Interface*

The cryogenic subsystem uses AC power in 3-phase and single-phase configurations to run the compressor, the cryocoolers, the vacuum pump, and the vacuum manifold. When available, the high-voltage version of a compressor or a vacuum pump is preferred to reduce the current draw and allow a smaller wire gauge to be used for the antenna wiring.

Parameter	Req. #	Value	Traceability
Compressor Max Current Draw	CRY1010	The compressor current draw shall not exceed 10A at 480 VAC	RD3 RD16 RD17
Cryocooler Max Current Draw	CRY1011	The cryocooler current draw shall not exceed TBD.	
AC Voltages Available	CRY1012	All equipment in the ngVLA powered from AC voltages shall utilize 480 V/277 V or 208 V/120 V 60 Hz AC Power.	ETR0819
AC Voltage Tolerance	CRY1013	All equipment in the ngVLA powered from the AC line shall tolerate variations of +/– 10%.	ETR0820
Vacuum Pump Max Current Draw	CRY1014	The vacuum pump current draw shall not exceed 2A at 480VAC	RD18

Note: The maximum real power consumption for the compressor is set to 5.2 kW and the minimum power factor is 0.82. The apparent power is 5.2/0.82 = 6.34 kVA, current will then be equal to 6,340/(480*√3) = 7.6 A.

7.2.2 Interface to Short Baseline Array Antenna (6 m) (0033:N2_IF)

The installation of the cryogenic equipment on the 6m antenna could be different than the 18m, because of the reduced size of the dish; the turn-head might be too small to house the compressor and the rest of the cryogenics equipment. [AD12] defines the mechanical and electrical interfaces with the 6m antenna.

7.2.3 Interface to the Bins, Modules, and Racks Subsystem (0044:N2_IF)

Figure 4 shows the cryogenic equipment located inside the Front End enclosure. The Cryostat-A and Cryostat-B are both equipped with a single 2-stage cryocooler. A Tee junction divides the supply line to feed both cold heads while another Tee recombines the two return lines.
A vacuum manifold splits the vacuum pump line and connects each segment to one of the frontend cryostats through a solenoid valve to allow remote operation.

The control electronics for the vacuum manifold could be placed either in the front end or the auxiliary enclosure; this hasn't been decided yet.
The auxiliary enclosure will host the vacuum pump, some control electronics, and the VFDs for the two cold heads. The vacuum pump oil temperature must be kept above 12°C for operation; a sump heating element will be installed to warm the oil when necessary.

7.2.4 Interface to Front End (0012:N2_IF)

The cryogenic subsystem is used to cool the Front End sensitive electronics to cryogenic temperature to minimize thermal noise and improve sensitivity. The various frequency bands [RD15] will be located in two separate cryostats, as shown in Figure 4. The ICD will describe the mechanical interfaces between the cryocoolers and the cryostats and the required cooling capacities to achieve the 20 K temperature of the low noise amplifiers. The vacuum pump interface will also be described in the document.

Parameter	Req. #	Value	Traceability
Cooling Capacity	CRY0800	The cold head shall have enough cooling capacity to reach 80 K with a heat load of 20 W on the first stage and 20 K with heat load of 4 W on the second stage.	SYS1001 SYS1011 SYS1012 SYS1013
Temperature Stability	CRY0801	The magnitude of temperature variations on the 2nd cryogenic stage shall not exceed 0.12 K over 200 seconds (± 0.06K). This requirement applies when the antenna is tracking a source or moving to a source.	SYS4903 FE0530
Pump Down Time	CRY0815	The vacuum pump and manifold shall be able to evacuate the Front End Cryostat–A or Cryostat–B down to 1 Pascal in a time ≤ 2 hours if the cryostat has not been open to atmosphere.	SYS2601
Cool-down time	CRY0816	The cryogenic subsystem shall be able to cool the Front End Cryostat–A or Cryostat–B second stage down to 20 K in less than 12 hours once the vacuum pressure has reached 1 Pascal.	SYS2601
Warm-up time	CRY0817	The cryogenic subsystem shall be able to bring the Front End Cryostat–A or Cryostat–B internal temperatures above 293 K in less than 6 hours.	SYS2601

7.2.5 Interface to Antenna Electronics Environmental and Control Subsystem (0045:N2_IF)

The Glycol circuit will cool the compressor located inside the antenna turn-head. Liquid cooling is preferred because the heat dissipated by the compressor is not released inside the confined space of the turn-head.
If the TASC is selected, it will also be cooled by the Glycol circuit; but the difference will be in the location of the connection, Front End enclosure instead of the turn-head.

Parameter	Req. #	Value	Traceability
Compressor Glycol Cooling Flow	CRY1501	The flow rate of Glycol required at the Helium compressor shall be less or equal to 10 l/min	EEC0056
Compressor Glycol Cooling Temperature	CRY1502	The temperature of the Glycol delivered to the compressor shall be between 5°C and 10°C.	EEC0003

Parameter	Req. #	Value	Traceability
Compressor Glycol Cooling Temperature Stability	CRY1503	The Glycol delivered to the compressor will have a temperature stability of ±1°C/hour	EEC0002
Compressor Glycol Cooling Maximum Supply Pressure	CRY1504	The maximum Glycol supply pressure to the compressor shall be less than 903 kPa	EEC0059
Compressor Heat Dissipation	CRY1505	The heat dissipated by the compressor shall no exceed 6.4 kW	EEC0055
Cryogenic RFI Enclosure Glycol Cooling Flow	CRY1506	The flow rate of Glycol required at the cryogenic RFI enclosure shall be less or equal to 4.0 l/min	EEC0051
Cryogenic RFI Enclosure Glycol Cooling Temperature	CRY1507	The temperature of the Glycol delivered to the cryogenic RFI enclosure shall be between 5°C and 10°C.	EEC0003
Cryogenic RFI Enclosure Glycol Temperature Stability	CRY1508	The Glycol delivered to the cryogenic RFI enclosure will have a temperature stability of ±1°C/hour	EEC0002
Cryogenic RFI Enclosure Heat Dissipation	CRY1509	The heat dissipated by the cryogenic RFI enclosure shall not exceed 800 W	EEC0050
Helium Pressure Regulation Module Heat Dissipation	CRY1510	The maximum heat dissipated by the pressure regulation circuit in the turn-head ambient air shall be less or equal to 44 W	EEC0060
Vacuum Pump Heat Dissipation	CRY1511	The heat dissipated by the Vacuum pump inside the auxiliary enclosure shall not exceed 600 W	RD18

7.2.6 Interface to Antenna Fiber Distribution (0047:N2_IF)

The communication between a cryogenic M&C electronic module and the corresponding utility modules will follow the RS-232 protocol and use optical fiber. The utility modules will communicate via Ethernet protocol over optical fiber.

7.2.7 Interface to the Power Supply Subsystem (0043:N2_IF)

The power supply subsystem provides DC voltages for the various cryogenic subsystem electronics modules listed below:

- Auxiliary enclosure
  - Cryostat-A and Cryostat-B cold head drive Electronics
  - Temperature control electronics
  - Vacuum pump and feed heater M&C electronics
- Front end enclosure
  - Cryostat-A and Cryostat-B M&C electronics
- Antenna turn-head
  - Compressor VFD and M&C electronics

Parameter	Req. #	Value	Traceability
DC Voltages Available	CRY1024	All equipment in the ngVLA 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 and +/-17.5 VDC.	ETR0821
-48VDC Tolerance	CRY1025	Devices on the –48 VDC system shall tolerate voltages from –42.0 VDC to –60.0 VDC.	ETR0822
PSU Voltage Tolerance	CRY1026	Devices powered from the PSU modules shall tolerate +/- 10% of the rated voltages.	ETR0823

7.2.8 Interface to Monitor and Control Hardware Interface Layer (0046:N2_IF)

The cryogenic subsystem has M&C electronics in the Auxiliary enclosure and the turn-head; information like helium pressure, vacuum pressure, and temperature are collected and sent to the utility module at each location for monitoring and archiving.

The Cryostat-A and B temperatures will be collected by the enclosed electronics and transmitted to the Front End enclosure utility module for monitoring and archiving.

The cryogenic subsystem has its own M&C electronics to monitor temperatures, pressures and other status parameters, and control the speed of the compressor and the two cold heads to keep the Front End electronics cold while minimizing the power consumption. The operating parameters and status information collected have to be sent to the antenna M&C to be relayed to the central control building.

Commands sent from the central control building will go to the antenna supervisor module and be relayed to the utility module to be sent to the cryogenic M&C targeted. This ICD describes the communication protocol between the cryogenic M&C and the antenna M&C.

7.2.9 Interface to Operations Buildings (0126:N2_IF)

The service center will require some specific infrastructure to support the maintenance of the cryogenics equipment. A clean room class 10,000 or ISO 4 to repair the cryocoolers. A test chamber with cooling stations to measure the cooling power and do a 24-48 burn-in (early failure detection) of the cryocoolers after repair. Each station inside the test chamber will be equipped with a set of helium connections and a driver cable. The Helium connections will come from a compressor room and will use, for the most part, seamless stainless steel tubing. Each drive power will come from an FVD electronic module inside the test chamber. The test chamber will be soundproofed to reduce the noise level in the building. Flushing of the cryocooler after installation in the test cryostat will occur in the test chamber or within a specific area. A helium recovery system will be installed there to capture and recycle the helium used during the maintenance. The compressor room will have a set of Glycol connections and a 3-phase outlet for each compressor. The compressor maintenance will be done inside the cryo-machine shop, with an overhead crane and a fume hood to allow welding or brazing. For personnel safety, tall ceilings, and good ventilation are recommended for the cryogenic laboratory.

7.3 Maintenance and Operation Requirements

The cryogenic subsystem is a high-maintenance system because of its complexity, physical distribution, and continuous operation, with some sections exposed to an outdoor environment and antenna motion. One key design goal for ngVLA is to keep the operation cost within a factor of three of the current VLA budget. This is very challenging. High reliability, ease of maintenance, fault prediction, and remote diagnostics are critical for achieving that goal.

The cryogenic subsystem shall comprise LRUs that will be pre-assembled and stored, ready for maintenance. Some LRUs will have a remotely accessible tracking number, while others will have a digital ID or barcode for identification. The identification information shall be kept up to date and easily accessible by the service crew and the operation team to schedule maintenance and repair. This tracking information shall also be used to maintain a reliability log to identify possible defective components or inappropriate maintenance procedures.

System status information will be collected and archived continuously to be analyzed and correlated with the maintenance reports to develop failure prediction tools. A monitoring speed of 0.1 seconds is sufficient for the GM cryocoolers because of the 0.8–1.5 Hz operating frequency. However, if the TASC is selected, the operating frequency is much higher (approximately 30 Hz), and therefore, the archiving speed should be higher to monitor temperature variations related to the cryocoolers. The recommended minimum archiving rate is 0.01 second to satisfy the Nyquist sampling theorem (0.0167 second).

The antenna Mean Time Between Maintenance (MTBM) has been set to 1,500 hours [AD10], and the cryogenics subsystem has been allocated 18% of the budget. The entire cryogenics subsystem MTBM is (1500/ 0.18 = 8333) 8.333 hours.

The antenna has a Mean Time to Repair of less than 3 hours. Any service on the cryogenic subsystem shall meet this requirement. For example: swapping a cold head, replacing the compressor's adsorber, or a leaky helium line shall be possible in less than 3 hours.

Parameter	Req. #	Value	Traceability
MTBM	CRY0100	The cryogenic subsystem shall be designed with an expected MTBM for the entire subsystem of 8,333 hours.	SYS2610 SAF0500
Modularization	CRY0101	The cryogenic subsystem shall be modularized into LRUs whenever possible to facilitate site maintenance.	SYS2403
Self-Diagnostic Function	CRY0102	The cryogenic subsystem shall incorporate self-diagnosis functions to identify faults based on previously identified failures and their recorded data.	SYS2405
Configuration Monitoring	CRY0103	The cryogenic subsystem shall include monitoring and tracking of the system configuration to the LRU level, including LRUs that are not network-connected for operation.	SYS2406
Local Engineering Console	CRY0104	The cryogenic subsystem shall include an engineering console for each LRU to communicate system status and assist in real-time diagnosis.	SYS2407 ETR0910
Monitor Data Stream and Archiving	CRY0105	The cryogenic subsystem shall stream and archive monitor data at variable rates (0.01 second to 10 minutes) for automated use by predictive maintenance programs and for direct inspection by engineers and technicians.	SYS2408
Preventive Maintenance	CRY0106	The cryogenic subsystem shall be designed with preventive maintenance (PM) intervals no shorter than 1 year.	SYS3200

Parameter	Req. #	Value	Traceability
Failure Prediction Tools	CRY0108	The cryogenic subsystem shall include automated fault prediction tool to identify a problem in the system before failure in order to avoid unscheduled down time. This tool will use trends in monitored data to help schedule maintenance before a failure occurs.	SYS3221 ETR0911
Serviceable Onsite	CRY0109	The cold head shall be serviceable/swappable onsite (at antenna) by one technician in less than 3 hours.	SYS2611 SAF0890
Interchangeable LRU	CRY0110	Any LRU of the cryogenic subsystem shall be interchangeable with a spare LRU with no calibration, tuning, or special alignment required. It will be decided during the development phase if the cryocooler will need a guiding tool to be replaced on the antenna.	SYS2611 ETR1170
Preclusion of Assembly Error	CRY0111	The cryogenic subsystem shall be designed to prevent any possible assembly error (unique connector type and keyed backplane with specific alignment pins).	SYS2611 SAF0160 SAF0170 SAF0730 ETR1141 ETR1158 ETR1183
LRU Easy Removal and Replacement	CRY0112	The cryogenic subsystem shall provide guides and location pins to facilitate LRU mounting.	SYS2611 SAF0730 SAF0740 ETR1183
LRU Damage Prevention	CRY0113	The cryogenic subsystem LRU shall make use of stand-offs, brackets and handles to protect system components from damage during shop and onsite maintenance.	SAF0630 ETR1177
Direct Access	CRY0114	The cryogenic LRU(s) shall be mounted such that removal of any LRU will not require the removal of any other LRU.	SYS2611 SAF0190 ETR1178 ETR1180
MTTR	CRY0115	The Mean Time to Repair or Replace any LRU on the cryogenic subsystem shall be less than 3 hours.	SYS2611

7.4 Electronics Reliability and Maintainability

7.4.1 Electronic Component Selection

The cryogenic subsystem is a complex electromechanical system, and the reliability of the M&C electronics is crucial to meet the MTBF requirements. The components used in the fabrication of the M&C electronics must be sourced from reputable suppliers and whenever possible from a preferred ngVLA parts list. Having a common component library across the ngVLA project will reduce the spare parts inventory, lower the procurement cost and simplify the reliability analysis.

Depending on their location on the antenna, some electronic modules will see harsher environmental conditions than others. Components shall be selected based on these conditions.

Parameter	Req. #	Value	Traceability
Component Sources	CRY0150	Components shall be sourced from reputable, proven manufacturers, vendors, and/or distributors as determined in the purchase requisition process.	ETR0901
Standard Component Libraries	CRY0151	Managed libraries shall be kept of commonly used electronic components and hardware.	ETR0902
Component Environmental Specifications	CRY0152	Electronic and mechanical components used in the ngVLA system shall always be used in accordance with their specified environmental specifications (storage/operation temperature, humidity, altitude derating, corrosion resistance, etc.).	ETR0903

7.4.2 Reliability Analysis and Robustness Analysis

All electronic modules from the cryogenic subsystem shall be subjected to a reliability analysis utilizing approved reliability analysis software. This analysis will help determine the MTBF of the assembly and identify weaknesses in the design. The reliability analysis results are a required part of the design review process.

A robustness analysis shall also be performed on the LRUs to ensure that the hardware will behave consistently and reliably under any operating conditions.

Parameter	Req. #	Value	Traceability
Reliability Analysis	CRY0160	A Reliability, Availability, Maintainability (RAM) analysis shall be performed by each designer at the LRU level to locate weak design points and determine whether the design meets the Maintenance and Reliability requirements.	ETR0904
Robustness Analysis	CRY0170	All ngVLA electronics designs shall be subject to a robustness analysis. Results of this analysis are a required part of the design review process.	ETR0905

7.4.3 Programmable Devices

7.4.3.1 Firmware Field Upgradability and Storage Location

Firmware for all LRUs shall be stored locally at the antenna. No hardware shall be dependent on a connection to the central M&C system to boot up and become operational in a basic configuration.

Parameter	Req. #	Value	Traceability
Local Firmware	CRY0180	All programmable devices shall have a local copy of the firmware at the antenna site. Firmware for basic functional and diagnostic purposes satisfies this requirement, but that may be configured remotely for normal operation.	ETR0906
Firmware Updates	CRY0181	All devices containing firmware shall be upgradeable remotely, i.e. without visiting the antenna.	ETR0907

7.4.3.2 Watchdog Timers and Recovery

All complex programmable devices shall utilize watchdog timers and power supervisors to detect lockups and attempt self-recovery. Additionally, reset connections shall be provided via a local M&C device to allow remote commanded resets to be sent to these devices.

Parameter	Req. #	Value	Traceability
Watchdog Timers	CRY0190	All complex programmable devices shall utilize watchdog timers and power supervisors to detect lockups and attempt self-recovery.	ETR0908
M&C Commanded Reset for DC Powered Devices	CRY0191	All DC powered 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.	ETR0909
M&C Commanded Reset for AC Powered Devices	CRY0192	All AC powered LRUs shall be connected to a remotely controllable Power Distribution Unit (PDU) or similar device which can be remotely commanded via the M&C system to power cycle each individual device.	ETR0912

7.5 System Monitoring Requirements

7.5.1 LRU Marking

LRU designation references any item replaceable at the operational location: antenna or equipment room, for example. All LRUs must be marked with a physical label containing a predefined set of information (see [AD09]) that will be placed on an easily accessible outside surface of the unit.

Parameter	Req. #	Value	Traceability
LRU Physical Marking Label Contents	CRY0201	Each LRU shall be marked with model number/name, serial number, and hardware revision level as defined in MIL-STD-13231 [RD09] and the unique part number (defined in Section 3, ngVLA Documentation Management Plan (020.10.10.10.00-0001-PLA).	SAF0060 SAF1020 ETR0401
LRU Physical Marking Label Ruggedness	CRY0205	The LRU physical marking label shall conform to the specifications outlined in US DOD standards MIL-DTL-15024 [RD07] to ensure durability.	ETR0409

7.5.2 LRU Identification

It is essential for the project to uniquely identify LRUs (any component that can be replaced on the antenna, compressor, cold head, adsorber, helium lines, etc.) to be able to track and locate them. The identification can be a digital ID number or a simple bar code, but this information will allow the project to manage inventory, schedule and organize maintenance, and keep service logs. Having maintenance records will help identify design mistakes, defective components, improper maintenance procedures, lack of personnel training, or simple negligence.

For example, the cold head, will have digital ID number that will be readable by the closest M&C module while the charcoal adsorber will only have a label for identification, both are LRUs. The cold head will have to be serviced periodically, while the adsorber could be disposable or rebuildable TBD.

Parameter	Req. #	Value	Traceability
LRU Physical Tracking Device	CRY0200	Each LRU shall be equipped with a standardized physical tracking label or device (e.g. bar code or RFID tags) to facilitate status and location across the observatory. Whenever possible these unique identification codes must be remotely accessible and visible.	SYS3600 SYS3900 SYS3902 SYS2406 SYS3700 ETR0402
LRU Tracking Label and Tag Specifications	CRY0202	The physical tracking label and/or device attached to each LRU shall conform to the specifications outlined in US DOD standards MIL-DTL-15024 [RD07] and MIL-P-19834 [RD08].	ETR0405 SYS2801 SYS3900 SYS3910 SYS3600

7.5.2.1 Remote M&C Identification

All LRUs with connectivity to the M&C system shall identify itself when polled by the network supervisor. Outside of the required data, useful information could be added. For example, the compressor M&C could have the in-service date of the adsorber to help schedule maintenance.

Parameter	Req. #	Value	Traceability
Remote Identification	CRY0203	Any device with any connectivity to the Monitor & Control System shall identify itself when polled via the Monitor and Control Network. Minimum information to be reported is: 1. Module/Model Number 2. Serial Number 3. CID Number which leads to all documentation 4. Hardware Revision Level 5. Software Revision Levels (if applicable) 6. Firmware Revision Levels (if applicable) 7. UID and IUID from physical tracking tag or device	ETR0403 SYS2406 SYS3600 SYS3602 SYS3603

7.5.2.2 Non M&C Connected LRU Identification

Devices declared as LRUs that would not ordinarily be connected to the M&C system shall provide a mechanism of identification readable by the nearby M&C connected device. For example, the cold head could have a readable ID implemented as a serial non-volatile memory.

Parameter	Req. #	Value	Traceability
LRU Remote ID for Devices With No Direct M&C Connection	CRY0204	LRUs that would not ordinarily be connected to the M&C system shall provide unique identification via a non-volatile memory readable by a nearby M&C connected device. Information to be provided includes (but is not limited to): 1. Module / Model Number 2. Serial Number 3. CID Number which leads to all documentation 4. Hardware Revision Level 5. Software Revision Levels (if applicable) 6. Firmware Revision Levels (if applicable) 7. UID and IUID from the physical tracking device	ETR0404 SYS2406

7.5.3 Remote Monitoring

Remote monitoring is critical to the success of the ngVLA project. The cryogenic subsystem status must be available from the Control Building or anywhere a network connection is available. A Graphical User Interface (GUI) will provide easy access to the data (temperature sensor, pressure sensors, vacuum sensors, flow sensors, etc.) for a quick health check or troubleshooting. The collected data will be archived for error diagnostic, fault prediction, and reliability analysis. A fast archiving rate shall be available for remote diagnostic and troubleshooting purposes. 0.1 second is sufficient for the GM system, but for the TASC, the rate shall be increased to 0.01 second.

Parameter	Req. #	Value	Traceability
LRU Periodic Self-tests and Alerts	CRY0221	Any LRU with internal M&C capability or connected to an external M&C module shall perform self-tests at power on and on a periodic basis. When the device is out of specification, it shall generate a prioritized alert for processing by the operator and maintenance scheduler.	SYS3102 ETR0910
Monitor Archive	CRY0222	Monitor data and alerts shall be archived at their generated rate for the full life of the equipment.	SYS3103 SYS2408 SYS2801
Fast Read-Out Mode	CRY0223	The cryogenic subsystem shall make fast read-out available for remote engineering diagnostics of all LRUs.	SYS3105
Intelligent LRU with Advanced Diagnostics	CRY0224	When possible, the cryogenic subsystem LRUs shall be smart devices with on-board diagnosis that can be accessed remotely for troubleshooting.	SYS3101 ETR0911
Thermal Protection Monitoring	CRY0225	The LRU shall be able to monitor the state of thermal protection features. An exception is if the activated thermal protection disables the LRU's M&C interface.	ETR0808

7.6 Safety and Security

Personnel and equipment safety are the primary concerns for ngVLA, and every measure that will reduce the risk of injury or damage must be implemented. This can be as simple as warning labels or installation of protections on exposed sharp edges or corners.

7.6.1 Personnel Safety

The safety of the personnel is the priority for the project. The cryogenic equipment must be designed to be safe and easy to handle. Nevertheless, high voltages, hot surfaces during operation, and high pressures present risks. The staff working on the cryogenic equipment must be well-trained and aware of the potential dangers, and work procedures must be developed and approved by the safety committee to prevent accidents.

Parameter	Req. #	Value	Traceability
Follow Safe Design Priorities	CRY0400	The cryogenic subsystem shall address safety of personnel first followed by safety of equipment. The information needed to control the equipment must be unambiguous and easily understood.	SAF0031, SAF0190 SAF0200, SAF0750 SAF0970, SAF1060 SAF1130
Warning Labels	CRY0401	Warning labels shall be applied on the cryogenic subsystem modules to inform the personnel of possible hazard or special handling information (electrical shock hazard, high temperature hazard, etc.).	SYS2700, SYS2704 SAF0100, SAF0050 SAF0170, SAF0750 SAF1010, ETR1008 ETR1010, ETR1011 ETR1012, ETR1015
Labeling Quality	CRY0402	Labels shall withstand environmental conditions, be waterproof, and not detach or become unreadable with repeated handling or UV exposure.	ETR0409
Mass and Center of Gravity Marking	CRY0403	All LRUs shall include at least one clearly visible label indicating the weight of the LRU in pounds (lbs.) and kilograms (kg). Location of the center of mass shall be clearly indicated on equipment that will need to be handled with a lifting device. The label shall be compliant with the standards at the time of installation.	SAF1050, ETR0406 SYS2700
Lifting Handles	CRY0404	Any cryogenic subsystem LRU with a mass of 5 kg ≤ W ≤ 40 kg shall be equipped with handles for handling. The number of persons required for handling shall be indicated. The label shall be compliant with applicable standards at the time of installation.	SAF0160, SAF0210 SAF0240, SAF0260 ETR0406, ETR0407 ETR0408, ETR1178
LRU Multiple Person Lift Label	CRY0411	If the LRU weighs in excess of 50 lbs. (22.68 kg), a clearly visible label indicating "Multiple Persons Lift Required" along with the number of persons required shall be included. The label shall be compliant with applicable standards at the time of installation.	SYS2700 SAF1050, ETR0407

Parameter	Req. #	Value	Traceability
Lifting Points	CRY0405	Any cryogenic subsystem LRU with a mass > 40 kg shall have lifting point(s) (eye bolts or slots) allowing handling with an overhead crane or a forklift. The lifting point location shall be clearly identified and the label shall be compliant with applicable standard at the time of installation.	SAF0160, SAF0210 SAF0240, SAF0250 ETR0406, ETR0407 ETR0408, ETR1178
Sharp Edges Protection	CRY0406	The cryogenic subsystem shall protect sharp edges that cannot be eliminated from the design with covers or coatings	SAF0540, ETR1172
Pressurized Vessel Testing	CRY0407	Any pressurized vessel shall be pressure tested to one and a half time (x 1.5) the maximum operating pressure.	SAF0034, SAF0036
Protection from Risk of Overpressure	CRY0408	The cryogenic subsystem shall comply with the pressurized equipment safety requirements. The cryogenic subsystem shall be equipped with overpressure relief valves to eliminate the risk of explosion or a large pressure burst that could harm personnel or damage equipment.	SAF0720, SAF0780 SAF0850
Flexible Helium Line Working Pressure	CRY0409	The flexible helium line shall have a working pressure >5.8 e^{+6} Pascal (850 psi).	SAF0520
Rigid and Flexible Lines Mechanical Attachment	CRY0410	Both rigid and flexible lines shall be firmly attached and/or protected against all external stresses and strains to ensure that no risk to personnel or equipment is posed by a rupture.	SAF0520
Risk of implosion	CRY0412	A cryostat under a vacuum presents a risk of implosion in case of sudden rupture of a vacuum window for example. Personnel should know the danger and window materials selected to avoid catastrophic failure.	
Risk of burn	CRY0413	Some surfaces inside a compressor can be hot enough to burn the skin. The service personnel shall wait 30 minutes after powering off a compressor before opening it. A cryostat shall not be open when the inside temperature is below ambient because a cold surface can burn the skin.	
High Voltage Safety Protection	CRY0420	The cryogenic subsystem shall comply with the electrical safety protection requirements. All circuitry, connectors, terminals and wiring carrying high voltages (i.e. at or above 50 Volts DC or 50 Volts RMS AC) shall be insulated or protected to prevent accidental contact during operation, inspection, or routine maintenance.	SAF0050, SAF0070 SAF0080, SAF0090 SAF0120, SAF0690 ETR1001, ETR1002 ETR1003, ETR1004 ETR1005

Parameter	Req. #	Value	Traceability
Contact with High Voltage during Diagnosis & Repair	CRY0421	In situations where exposure to high voltages (i.e. at or above 50 Volts DC or 50 Volts RMS AC) may be possible during in-depth diagnosis and repair, procedures for minimizing risk of contact shall be provided in a maintenance manual for the subsystem or equipment under repair.	ETR1004 SYS2700 SAF0070 SAF0090
Safety Interlocks	CRY0422	Safety interlocks shall be used in situations where high voltages (i.e. >= 50 Volts) could be exposed.	ETR1017 SAF0690,SAF0070 SAF0090,SAF0930
Equipment Stability	CRY0430	Any cryogenic subsystem equipment or assembly shall be stable under foreseen operating conditions or shall be anchored to the antenna structure to provide the required stability.	SAF0470
Protection from Moving Parts	CRY0431	Any moving part that presents a risk for personnel shall be equipped with a grid, a screen, or a mesh to avoid any possible contact and prevent any risk of personnel injury.	SAF0640

7.6.2 Equipment Safety

Most of the time the cryogenic equipment will operate remotely and without personnel supervision. It is essential for the system to be smart enough to protect itself in case of malfunction of one of its components. In the eventuality of M&C module failure, some hardware protection shall be integrated in the design to guarantee that the system keeps running safely or is shut down properly.

Parameter	Req. #	Value	Traceability
Subsystem Self-Monitoring	CRY0450	The cryogenic subsystem shall monitor its system health and prohibit actions likely to cause damage. The monitor may also shut down the system to prevent damage.	SYS2701 SAF0037 ETR0807
Hardware Failsafe Implementation	CRY0451	The cryogenic subsystem shall be designed with hardware fail-safe in specific LRUs, where an M&C failure or malfunction could potentially damage that system.	SAF0042
Initial Safe State Power-Up	CRY0452	When powered up, the cryogenic subsystem shall initialize safely for personnel and equipment without human intervention.	SAF0041
Vacuum pump safety interlock	CRY0453	A safety interlock shall close the Front End cryostat inlet valves in the vacuum manifold and stop the vacuum pump if the antenna passes the zenith point to prevent oil spill.	CRY0401
Thermal Protection	CRY0454	LRUs shall be thermally protected.	ETR0807

7.6.3 Electrostatic Discharge Protection and Testing

The dry New Mexico environment makes Electrostatic Discharge (ESD) a problem that must be addressed during the design of the LRUs. This concern is even more relevant when, for example, an enclosure is open, exposing the internal hardware during service on the antenna. Proper ESD protections must be implemented, and safe handling procedures established to minimize the risk of ESD damage during operation, handling, and storage.

Parameter	Req. #	Value	Traceability
ESD Susceptibility Testing	CRY0480	Qualification units of all enclosed ngVLA LRUs shall be tested for susceptibility to ESD damage and an ESD class determined. See [AD09] for more details on testing requirements.	ETR0501 ETR0505 ETR0506 EMC0471 EMC0472 EMC0473
ESD Protection	CRY0481	ESD protection of equipment and workspaces shall be based on USDOD MIL-STD-1686C [RD10] and MIL-HDBK-263B [RD11] or ANSI/ESD S20.20-2014 [RD12].	SAF0710 ETR0502
ESD Packaging and Storage	CRY0482	Equipment and components sensitive to damage from ESD shall be packaged, shipped, and stored in ESD protective packaging. This packaging shall only be sealed and opened at ESD-safe workstations.	ETR0503 SYS3904
Prevention & Discharge of Electrostatic Charge Build-Up	CRY0483	Equipment and assemblies made using dielectric materials or coated with nonconductive coatings shall be designed to prevent build up or to dissipate excessive electrostatic charge.	ETR0504 SYS2801 SYS2700 SAF0710

7.7 Configuration Management

The cryogenic subsystem will have custom firmware in the M&C and VFDs and software to interface with the other M&Cs. A GUI will provide easy access to the system status to the user.

Parameter	Req. #	Value	Traceability
Version Control for Software and Firmware	CRY0500	All custom software and firmware specific to the cryogenic subsystem shall be version controlled via a configuration management process.	SYS3602

7.8 System Lifecycle Requirements

The cryogenic subsystem shall be designed to last the expected 20 years of ngVLA operational life (the operational life is defined to start at the full operations milestone and close-out of the construction project) plus the ten years of construction. The spare parts required for the service and repair of the equipment must be available for the whole period. LRUs shall be stored in temperature-controlled warehouses to ensure they are safe and ready to use.

Parameter	Req. #	Value	Traceability
Design Life	CRY0600	The cryogenic subsystem shall be designed for an expected operational life of no less than 30 years.	SYS2801 SAF0490

Parameter	Req. #	Value	Traceability
Part Selection for Maintainability	CRY0601	The manufacturer of the compressor and cold head shall support their equipment and have sufficient spare parts inventory for the 30 years design life of the instrument.	SYS2805
Critical Spares	CRY0602	Critical spare parts for the cryogenic subsystem shall be identified and provided with sufficient inventory to support the equipment for the 30 years design life of the instrument,	SYS2812
Storage	CRY0603	Any LRU from the cryogenic subsystem shall be packaged for storage conditions without incurring any damage for a period of at least 2 years.	ETR0503

7.9 Performance Requirements

To guarantee optimum LNA performance, the cryogenics subsystem must have enough cooling capacity to cool both Front End cryostats down to 20 K on their second stage. Once cold, the temperatures must be stable to meet the system gain stability requirement even when the antenna is in motion. The system requires the temperature stability on the second stage to be 0.12 K over 200 seconds [SYS4902]. The temperature stability requirement refers to the peak-to-peak value, and the temperature should be sampled fast enough to account for the natural variation produced by the thermal cycle of the cryocooler (minimum of 2.4 Hz for the GM system and 30 Hz for the TASC).

This very challenging requirement will impose some restrictions on the cooling capacity variation with orientation for the cryocoolers. If the cryocooler cannot meet the requirement, an active temperature control will be added to help maintain the temperature stability as the antenna moves in elevation. This requirement applies when the antenna is tracking a source or when the antenna is moving to a source (maximum speed 45° per minute).

The diameter of flexible and rigid lines that compose the closed-loop circuit and carry the pressurized helium from the compressor to the cryocoolers and back shall be selected to provide the required flow while minimizing the pressure drops. By analogy with an electrical circuit, the pressure drop would correspond to a voltage drop, and the Helium line's conductance would be the wire's resistance. The voltage drop reduces the power available at the load, while the pressure drop reduces the differential pressure and the corresponding cooling power, resulting in lower efficiency of the cryocooler.

The purpose of the helium pressure regulation circuit is to reduce the diurnal pressure oscillations observed at the VLA and compensate for the small helium leaks. The system should be able to keep the supply pressure within a window of 10 psi to help maintain the cryocooler efficiency and extend the time interval between required maintenance.

When the compressor starts, a small delay (15 seconds) should be introduced before the cold head can be started for the supply and return pressures to stabilize. In cold weather conditions, when the ambient air temperature is between –30°C and 0°C, the compressor has to go through a cold start procedure to warm up the oil and get the system ready. The cryocoolers should remain turned off until the compressor is warm and fully operational.

The vacuum pump must be able to evacuate both Front End cryostats down to 1 Pascal (7.5 millitorrs), which is the pressure required to start the cryocoolers. The pump-down time will be longer if the Front End cryostat is recently built or if it has been opened to air, and it will be shorter if it is a simple thermal cycle.

Parameter	Req. #	Value	Traceability
Compressor Flow Capacity	CRY0803	The compressor shall have enough flow capacity at 60 Hz to run two cold heads at nominal speed with the cooling capacity described in CR0801.	SYS1001 SYS1011 SYS1012 SYS1013 FE0446
Time to Establish Supply Pressure	CRY0804	The compressor shall provide full supply pressure within 15 seconds after being switched on. This requirement does not apply in cold start condition when the ambient air temperature range from –35°C to 0°C and the oil needs to be heated.	Design Decision
Supply Line	CRY0805	The helium circuit shall provide high-pressure helium connection points to two cold heads inside the Front End enclosure.	FE0446
Return Line	CRY0806	The helium circuit shall provide low-pressure helium connection points to two cold heads inside the Front End enclosure.	FE0446
Pressure Drop Supply Line	CRY0807	The helium circuit shall supply high-pressure helium to the connection points inside the Front End enclosure with pressure drop ≤ 70 kPa (10 psi).	Design Decision
Pressure Drop Return Line	CRY0808	The helium circuit shall return low-pressure helium from the connection points inside the Front End enclosure with pressure drop ≤ 70 kPa (10 psi).	Design Decision
Helium Pressure Regulation	CRY0809	The helium pressure regulation module shall maintain the required supply pressure within a 70 kPa window (10 psi) over the temperature range listed in CRY0002.	Design Decision
Helium Leakage Compensation	CRY0810	The helium pressure regulation module shall have enough helium volume to compensate for normal leaks in the circuit for a period of one year.	SYS2610
Helium Pressure Regulation Buffer Tank Volume	CRY0811	The helium pressure regulation module buffer tank shall have enough volume to maintain the supply pressure at the required value over –25°C to 45°C temperature variation.	Design Decision
Vacuum Pump Ultimate Pressure	CRY0812	The vacuum pump shall have an ultimate pressure ≤ 0.2 Pascal (1.5 millitorr).	Design Decision
Vacuum Pump Pumping Speed	CRY0813	The vacuum pump shall have a nominal pumping speed ≥ 18 m^3/h.	Design Decision
Vacuum Line Conductance	CRY0814	The vacuum line between the vacuum pump and the vacuum manifold inside the Front End enclosure shall have a minimum conductance of 7.2 m^3/h.	Design Decision
Pump Down Time	CRY0815	The vacuum pump and manifold shall be able to evacuate the Front End cryostat–A or Cryostat–B down to 1 Pascal in a time less than 2 hours if the cryostat has not been open to atmosphere.	SYS2601

Parameter	Req. #	Value	Traceability
Cool-down time	CRY0816	The cryogenic subsystem shall be able to cool the Front End Cryostat–A or Cryostat–B second stage down to 20 K in less than 12 hours once the vacuum pressure has reached 1 Pascal.	SYS2601
Warm-up time	CRY0817	The cryogenic subsystem shall be able to bring the Front End Cryostat–A or Cryostat–B internal temperatures above 293 K in less than 6 hours.	SYS2601

7.10 Mechanical Requirements

7.10.1 Mechanical Requirements Driven by the Antenna

Figure 2 shows the distribution of the cryogenic subsystem on the antenna. The compressor and helium pressure regulation module are inside the turn-head, while the cryocoolers are integrated with the Front End cryostats and placed inside an enclosure on the antenna feed arm. The orientation of the cryocoolers will change as the antenna moves in elevation but they must maintain their cooling power over the full range of motion. Because limited space is reserved on the antenna for the cryogenic subsystem, some volume and weight restrictions apply.

Parameter	Req. #	Value	Traceability
Cryocooler Orientation	CRY0901	The cryocooler shall operate normally as the antenna moves through its entire elevation range from 12°–88°.	
Vacuum Pump Volume	CRY0909	The vacuum pump shall fit a volume of L 600 mm x H 400 mm x W 400 mm.	
Vacuum Pump Mass	CRY0910	The vacuum pump shall not weigh more than 35 kg.	
Vacuum Pump Allowed Tilt Angle During Operation	CRY0911	The vacuum pump shall be able to operate while the antenna moves in elevation 12° ≤ tilt angle ≤ 88°.	

7.10.2 Couplings and Hardware Requirements

The standard coupling type for cryogenic equipment using pressurized helium is the Aeroquip 5400 series. It is commonly used in the air conditioning and refrigeration industry, provides low air inclusion and helium loss during coupling, and allows connection under pressure. The fasteners used in the assembly of the cryogenic subsystem shall be metric whenever possible and made of stainless steel for corrosion resistance. TORX and hexagonal heads are preferred for reliability, and captive screws shall be used for panel assembly to avoid dropping screws during service on the antenna.

Parameter	Req. #	Value	Traceability
Flexible Helium Line End Couplings	CRY0920	The flexible helium line shall have Aeroquip 5400-S5-8 female fittings.	Coupling used as industry standard
Couplings	CRY0921	The cryogenic subsystem shall use Aeroquip 5400 series couplings for helium interfaces between LRUs.	Coupling used as industry standard

Parameter	Req. #	Value	Traceability
Coupling Marking	CRY0922	The cryogenic subsystem couplings shall be clearly marked in green to identify return connections and red to identify supply connections.	SAF0740 Color code adopted by the industry
Metric Fasteners	CRY0923	The cryogenic subsystem shall use metric fasteners and request a non-compliance agreement where imperial hardware must be used.	ETR1161
Stainless Steel Hardware	CRY0924	The hardware used on the cryogenic subsystem shall be stainless steel for long lasting life.	SYS2801 SAF0490 ETR1163
Type of Fasteners	CRY0925	Pan head or flat-head screws shall use Textron TORX type 6-point star shaped screw heads driven by TORX type drivers. All cap head screws shall utilize hexagonal Allen type screw heads driven by hex type driver.	ETR1166 ETR1167 ETR1168
Hardware Retention	CRY0926	All nut and bolt type hardware interfaces shall use retention techniques to prevent loosening.	SYS2700 SYS2801 ETR1169
Captive Fasteners	CRY0927	All panels that need to be removed on the antenna for service shall use captive fasteners to prevent loss of hardware during maintenance.	SAF0530

7.10.3 Shock and Vibration Requirements

The cryogenic equipment will be exposed to shocks and vibrations during shipping and handling, transport on the service vehicle, and operation on the antenna. The LRUs must be designed to resist these, and/or protective enclosures, shipping crates, and vibration isolators must be used to ensure they have the required protection. On the antenna, vibration mitigation is most important for connectors and fittings. Cables and helium lines shall be mechanically supported to prevent interconnecting loosening.

Parameter	Req. #	Value	Traceability
General vibration	CRY0930	The cryogenic subsystem LRUs packaged for transportation and any equipment installed on the antenna shall be designed to withstand persistent vibration. The origin of the vibration could be transportation, mechanical movement, or even wind. See 9.1.6 for more details on the vibration specification and testing.	ENV0531 ENV0532 ENV0581 SAF0810 ETR1179
Mechanical Shocks	CRY0940	The cryogenic subsystem LRUs shall be designed to survive mechanical shock levels from handling as defined in Table 1 when packaged for transportation.	ENV0582 ETR1179
Generated Vibration	CRY0950	The cryogenic subsystem when in operation shall not induce vibration or shock that exceeds the levels safe for the other systems.	SAF0810

The table below list the height and the number of drop that an LRU packaged for transportation shall survive with no damage based on the total mass of the assembly.

Mass of Package	Height of Drop	Type of Handling
0 kg to 25 kg	75 cm	Drop on each face and corner. Total of 26 drops.
25 kg to 50 kg	75 cm	Drop on each corner. Total of 8 drops.
50 kg to 100 kg	35 cm	Drop on each bottom edge and bottom face. Total of 5 drops.
> 100 kg	25 cm	Drop on each bottom edge and bottom face. Total of 5 drops.

Table 1 – Modified drop heights for logistic transit drop test

7.10.4 Surface Finish requirements

The various component of the cryogenic subsystem could be made of steel, aluminum, stainless steel, plastic, or composite materials. The surface finish shall provide adequate protection based on environmental and electrical conduction requirements.

Anodization shall not be used on structural components made of Aluminum because this type of finish could hide cracks; a chromate finish is recommended.

Parameter	Req. #	Value	Traceability
Chromate Converted Surfaces	CRY0990	Aluminum surfaces where electrical conduction is required (RFI/EMI or safety grounding) shall be treated using a Chromate Conversion process as outlined in MIL-DTL-5541E. Either Class 1A or Class 3 can be used based on requirements determined by the designer.	ETR1143
Stainless Steel Surfaces	CRY0991	Stainless steel can be used for RFI/EMC housing where deemed feasible by the designer. Surfaces can be painted but shall be left bare where electrical conduction is necessary.	ETR1144
Anodized Surfaces	CRY0992	Aluminum surfaces where no electrical conductivity is required can be anodized. Anodizing shall be of a color not mistakable for chromate (i.e. clear, yellow, brown, or gold). Anodizing shall not be used on surfaces requiring electrical conductivity for RFI/EMI shielding or good safety ground conduction and shall never be scraped or sanded off to achieve this. Anodizing shall not be used on structural components	ETR1145
Painted Surfaces	CRY0993	Surfaces requiring paint shall be painted with white or light color paint suitable for the surface material and environmental conditions the surface will experience.	ETR1146

Parameter	Req. #	Value	Traceability
Colored Paint Marking	CRY0994	Surfaces which need to be painted specific colors for safety and/or maintenance marking shall be painted with the appropriate color paint suitable for the surface material, environmental conditions, and wear and tear the surface will experience.	ETR1147
Surface Preparation for Painting	CRY0995	Before painting, all surfaces shall undergo proper surface preparation suitable for the material and paint shall be used.	ETR1188
Materials for Surface Exposed to a Vacuum Environment	CRY0996	Surfaces exposed to a vacuum environment shall be made from non-porous to avoid outgassing and contamination and deterioration of the vacuum environment.	ETR1192, SYS2610, SYS2700, SAF0140, SAF0490,
Cleanliness of Surfaces Exposed to a Vacuum Environment	CRY0997	Surfaces exposed to a vacuum environment shall be designed to be easily cleaned by wiping them with a lint-free cloth and 99% purity Isopropyl Alcohol	ETR1213, SYS2610, SYS2700, SAF0140, SAF0490
Powder Coating	CRY0998	Surfaces requiring powder coating shall be properly prepared for the surface material and environmental conditions the surface will experience.	ETR1194, SYS2106, SYS2700, ENV0591, SAF0140, SAF0490, SAF0880
Painted Surface Lifetime	CRY0999	Painted surfaces shall be painted with a paint rated to last at least 10 years in the environmental conditions it will be exposed to.	ETR1195, SYS2106, SYS2700, ENV0591, SAF0140, SAF0490, SAF0880
Powder Coated Surface Lifetime	CRY1520	Powder coated surfaces shall be coated with a material rated to last at least 20 years in the environmental conditions it will be exposed to.	ETR1196, SYS2106, SYS2700, ENV0591, SAF0140, SAF0490, SAF0880

7.11 Wiring and Cables

The cryogenic subsystem is composed of several modules that are installed in various locations on the antenna. Interconnecting cables are required to provide power, send commands, and collect information for monitor points between modules. Robust military-type connectors shall be used to avoid failure, and each cable shall be well-documented to guarantee proper assembly.

Inside modules, specific wire color codes shall be respected to simplify maintenance and provide consistency across antenna electronics.

Different connectors and colored labels shall be used on the cables connected to a specific module to prevent mistakes during assembly and maintenance.

7.11.1 Documentation

Parameter	Req. #	Value	Traceability
Cable Documentation	CRY0960	All wiring, cables, and harnesses installed in the ngVLA system shall be documented in accordance to ngVLA Drafting and Documentation Standards.	ETR1101 SYS2700

7.11.2 Labeling of Wiring and Cables

Parameter	Req. #	Value	Traceability
Cables and Harnesses Labeling	CRY1008	The cryogenic subsystem shall use labels on all cables, harnesses, and connectors to allow identification while cables and harnesses are installed. The labels shall comply with the ANSI standard TIA-606-C [RD14].	ETR1102 SYS2700
Switches and Controls Labeling	CRY1009	The cryogenic subsystem shall have labels on switches and controls used by technical personnel marking their function clearly.	ETR1010 ETR1011

7.11.3 Wiring Color Standard

Noncommercial equipment designed specifically for ngVLA shall comply with the approved wire color standard.

Parameter	Req. #	Value	Traceability
DC Wire Color Standard	CRY0962	The wiring of custom cryogenic equipment for ngVLA shall comply with the approved color standard. +3.3 VDC Pink +5.0 VDC Orange +7.5 VDC White with Orange stripe –5.0 VDC Brown -7.5 VDC White with Brown stripe +12 VDC Blue +13.5 VDC White with Blue stripe –12 VDC Tan –13.5 VDC White with Tan stripe +15 VDC Red +17.5 VDC White with Red stripe –15 VDC Yellow –17.5 VDC White with Yellow stripe +20 to <+30 VDC Grey or Slate >+30 VDC White with Grey or Slate stripe –48 to –54 VDC Purple or Violet All return for DC voltages and LVS Black All Earth, chassis and safety grounds Green or Green with Yellow stripe Standard TTL White with Black and Orange stripes Standard LVTTL White with Black and Violet Standard LVDS Yellow with Blue stripe (+signal) Blue with Yellow stripe (–signal) Standard RS422/485 Orange with Blue stripe (+signal) Blue with Orange stripe (–signal) LVAS White	ETR1105, ETR1106 ETR1107, ETR1108 ETR1154, ETR1109 ETR1155, ETR1110 ETR1111, ETR1112 ETR1113, ETR1114 ETR1115, ETR1116 ETR1117, ETR1118 ETR1119, ETR1120 ETR1121, ETR1122 ETR1123, SYS2700 SAF0070
AC Wiring Color	CRY0963	All AC wiring colors shall conform to US NEC requirements.	ETR1124, SYS2700 SAF1000, SAF1170

7.12 Wire Insulation Type

Low Voltage DC and signal wiring shall utilize Irradiated PVC-type insulation certified to meet the UL 1430 specification. This shall be rated at 300 VDC minimum over a temperature range of -55°C to +105°C.

Wiring inside a vacuum space shall present low outgassing properties and resist thermal cycles down to cryogenic temperature without damaging or changing mechanical properties. Wire gauge and material shall be selected carefully to minimize voltage drop and heat transfer to the cold stages.

Parameter	Req. #	Value	Traceability
Wiring Insulation Type	CRY0970	Low-voltage DC and signal wiring shall utilize Irradiated PVC type insulation certified to meet the UL 1430 specification. This shall be rated at 300 VDC minimum over a temperature range of –55°C to +105°C.	ETR1157 SYS2700 SAF0120
Wiring Insulation Type inside Vacuum Space and Exposed to Cryogenic Temperature	CRY0971	Wiring inside the vacuum space shall have very low outgassing properties and resist temperature cycling down to cryogenic temperature without damage or change in mechanical properties. Wire rated for this specific environment shall be used.	ETR1157

7.13 Connectors

It is a well-established fact that connectors represent a prevalent source of failure, and minimizing the number of interconnects must be one of the parameters considered during the design phase of the cryogenic subsystem. Connectors shall be selected for their reliability and ease of use. Keyed and tool-free with a locking mechanism type are preferred to simplify interconnection on the antenna and reduce maintenance time.

Parameter	Req. #	Value	Traceability
Connector Documentation	CRY0980	All connectors installed in the ngVLA system shall be documented in accordance to ngVLA Drafting and Documentation Standards.	ETR1133
Connector labeling	CRY0981	All connectors shall be labeled in accordance with ANSI Standard TIA-606-C [RD14].	ETR1134
Connector Current rating	CRY0982	All connector pin current limits shall be followed. Use of multiple pins to gain an increased current rating shall not be permitted. Where the use of multiple pins is required for signal performance, each pin shall be rated to handle the total current load.	ETR1135
Connector Environmental Rating	CRY0983	All connectors shall be utilized in accordance with their designed environment.	ETR1136
Cable Mating Cycles	CRY0984	The specified data sheet rating for mating cycles allowed for a connector type shall be followed.	ETR1137
No Exposed Live Terminals	CRY0985	Live signal or power pins in connectors shall not be exposed while connectors are unmated.	ETR1140
Connector Uniqueness & Keying	CRY0986	Connectors that are similar or closely located shall be sufficiently unique or keyed to prevent incorrect connectors from being mated.	ETR1141
Common Connectors	CRY0987	Connectors used repeatedly across multiple devices shall have critical signal pinouts standardized.	ETR1142

Parameter	Req. #	Value	Traceability
Connector Alignment Guides	CRY0988	Connectors used in blind mate or back plane applications shall utilize some mechanism to ensure alignment of the connector during installation to avoid damage to the connector.	ETR1158
LRU Multi-pin Connector Retention	CRY0989	Between LRUs and other major assemblies, the designer shall use multipin electrical connectors and retention features compliant with US DoD standard MIL-DTL-38999M (RD46). Series I, II, & IV are preferred however, series III can be used with the proper retention features.	ETR1197, SYS2601, SYS2610
Internal Cable – Connector Retention	CRY1530	Connectors internal to LRUs and major subassemblies are left to the discretion of the designer. Positive retention techniques shall be utilized on these connectors to assure that they do not loosen or become disconnected over time.	ETR1198, SYS2601, SYS2610
Single Fiber Optic Cable – Connector Retention	CRY1531	Single fiber optic cables shall utilize connectors with positive retention features. This could be latching type connectors, bayonet connectors or, in the case of FC type connectors commonly used in shielded RF applications, safety wire or some form of retention clamp.	ETR1206, SYS2601, SYS2610
PCB – Board to Cable Retention	CRY1532	Wire/cable connections to printed circuit boards shall utilize connectors with positive retention features such as latches or screws. Flex print connectors with latched clamps are also acceptable. Connectors which clamp the conductor with screws are not permitted.	ETR1208, SYS2601, SYS2610,
PCB – Board to Board Connector retention	CRY1533	Printed circuit boards interconnected by board to board connectors shall be designed to ensure positive retention of the connection between the two boards. This can be accomplished using features of the connectors and/or through the mounting design of the board.	ETR1209, SYS2601, SYS2610,
Blind Mate Connector Retention	CRY1534	Equipment housings utilizing blind mate connectors shall be designed to ensure positive retention of the connectors. This can be accomplished using screws, latches or other similar means.	ETR1211, SYS2601, SYS2610

Parameter	Req. #	Value	Traceability
Connector Retention Analysis	CRY1535	The designer shall analyze their designs and take steps to ensure that all connectors are securely retained and will not work loose with time. For this analysis, both performance over time in the antenna and survivability during transport and storage shall be considered. The designer shall publish these results in a memo and be prepared to discuss their analysis, and the techniques used to address the results, in the design reviews for their equipment and subsystems.	ETR1212, SYS2601, SYS2610

7.14 Power Requirements

7.14.1 AC Power

The power to the compressor is frequency controlled by a VFD to minimize power consumption. The power to drive each cold head is also frequency controlled by a separate VFD located in the auxiliary enclosure. The compressor power consumption shall be kept under 5.54 kW to stay within the operating cost budget limit set by the project (VLA x 3). The power factor shall also be kept above 0.82 at all operating frequencies to limit the wasted power and control the power factor for the core array. When available, the high voltage compressor version is preferred to lower the current load and reduce the power cable wire gauge size, saving weight and money. The compressor startup power is also essential because it will set the size of the circuit breaker. In the core array, the helium compressor must be started following a predetermined sequence to limit the in-rush load on the electrical infrastructure.

Parameter	Req. #	Value	Traceability
AC Power and Grounding Design	CRY1000	Design and installation of all AC power and grounding wiring shall conform to US National Electrical Code NFPA 70 [RD13].	ETR0801
Compressor Power Consumption	CRY1001	The helium compressor shall not consume more than 5.54 kW.	CON002
Compressor Power Factor	CRY1002	The helium compressor shall have a power factor larger than 0.82 at any operating frequency.	CRY1005
Start-Up Power Consumption	CRY1003	The helium compressor start-up power consumption shall not exceed 23.5 kVA.	ETR0805
Harmonic Distortion	CRY1004	The helium compressor shall not induce total harmonic distortion (current) onto the electrical supply that exceeds TBD level.	SYS2802
Phase Imbalance	CRY1005	The helium compressor shall not induce phase imbalance (current) onto the electrical supply that exceeds TBD level.	SYS2802
Compressor Operating Frequency	CRY1006	The compressor shall be able to operate at variable speed to reduce power consumption. The range of operating frequency is 35 Hz ≤ F ≤ 60 Hz.	SYS2802
Cold Head Operating speed	CRY1007	The cold head shall be able to operate at variable speed to reduce helium flow consumption. The range of operating speed is 35 rpm ≤ F ≤ 70 rpm.	SYS2802

Parameter	Req. #	Value	Traceability
Switches and Controls Labeling	CRY1009	The cryogenic subsystem shall have labels on switches and controls used by technical personnel marking their function clearly.	ETR1010 ETR1011

7.14.2 DC Power

Most LRUs will be provided DC power supply voltages from a separate isolated DC–DC converter-based power supply running from the AC line or a battery-backed –48 VDC power supply system. These external DC voltages are poorly regulated and should be considered raw power. Each LRU will need to provide final internal regulation for all required voltages.

Parameter	Req. #	Value	Traceability
DC Power & Grounding Design	CRY1020	Design and installation of all DC power distribution and grounding wiring shall conform to ngVLA system and RFI/EMC requirements.	ETR0802
DC LRU Power Input	CRY1021	Input power to all LRUs shall be considered raw power. Internal regulation and filtering are required.	ETR0803
Power Supply Dedicated Returns	CRY1022	All power supplies shall have dedicated current return paths.	ETR0813
Power Supply Returns Separate from Ground	CRY1023	Structural/chassis components and signal grounds shall never be used as a power supply return path.	ETR0815

7.14.3 Grounding and Over-Current Protection

The LRU chassis or housing shall be electrically connected to the antenna structure using a dedicated grounding strap or wire. The cryogenic subsystem M&C modules shall be able to sense, and report activated over-current protection devices wherever possible.

Parameter	Req. #	Value	Traceability
LRU Grounding	CRY1030	The cryogenic subsystem LRUs, with the exception of the cold heads (which will be grounded through the Front Ends) shall have a grounding point easily identifiable and each connection path to the antenna ground shall have a resistance of less than 10 mΩ. This low resistance connection shall help with lightning protection and static electricity build-up.	SAF0710 ETR0804
Overcurrent Protection	CRY1031	All electronics LRUs shall have an overcurrent protection.	ETR0805
Overcurrent Protection Device Monitoring	CRY1032	The cryogenic M&C system shall be able to monitor the state of over-current protection devices in an LRU. An exception is if the circuit protection device activated disables the LRU's M&C interface.	ETR0806

7.14.4 Thermal Protection

All cryogenic subsystem LRUs shall have a protection circuit able to detect over-temperature conditions and power down modules or send them into low-power mode.

A two-level approach is recommended: when the temperature reaches the first level, an alarm is sent to the array operation to evaluate the situation and make possible corrections. When the temperature reaches the second level, the LRU goes into over-temperature protection mode with no external intervention required.

During the design phase, designers shall consider the ambient temperature range and the maximum elevation to optimize the thermal performance of the LRU, perform a thermal analysis and/or a test.

Parameter	Req. #	Value	Traceability
Thermal Protection	CRY1050	Cryogenic subsystem LRUs shall be thermally protected.	ETR0807
Thermal Protection Monitoring	CRY1051	The LRU shall be able to monitor the state of thermal protection features. An exception is if the thermal protection activated disables the LRUs M&C interface. In this situation the LRU ceases to communicate and should be presumed as bad by the responding technician (i.e. they take a spare with them and swap the LRU after evaluating M&C connections).	ETR0808
Thermal Analysis	CRY1052	The designer shall analyze their designs and take steps to optimize thermal performance with a focus on proper cooling, thermal stability, and the elimination of hot spots. They shall publish these results in a memo and be prepared to discuss their analysis and the techniques used to address the results in the design reviews for their equipment and subsystems.	ETR0816

7.14.5 Powered System Operational Design

Because of the large number of antennas and the remote location of some of them, the ability of the cryogenic subsystem to survive and recover after a power outage is essential. When the power returns, the cryogenic subsystem shall recover autonomously to a state suitable for normal operation. If full recovery is not possible, the system shall remain in a state safe for the equipment and generate an alarm to alert the service center.

The cryogenic subsystem in each antenna shall be able to be fully operated by service personnel at the local site without interaction with operations or the central M&C system.

For custom LRUs, the power indicator shall comply with the requirement CRY1043. For commercial units, the standard power indication should be sufficient.

Parameter	Req. #	Value	Traceability
On-Site Reset/Start-Up Sequence	CRY1040	All ngVLA antenna electronics shall be able to start up and shut down locally at the antenna site with no intervention from operations, even in the event of no M&C and/or audio communications between the antenna and array operations.	ETR0809

Parameter	Req. #	Value	Traceability
Power Outage Behavior	CRY1041	All system electronics shall enact a sequential managed shutdown procedure in response to power outages, placing the system in a safe standby state in order to avoid damage to hardware and minimize recovery time. This low power safe mode may be commanded via the local M&C system or, in the event of lost communications, enacted automatically within the LRU based on the combination of no commands received and monitored local conditions such as temperature or supply voltage.	ETR0810
Automated Recovery Sequence	CRY1042	All ngVLA antenna electronics shall enact procedures to autonomously recover from a power outage in a state suitable for normal operations, or at least to a safe state.	ETR0811
DC Powered LRU Power "ON" Indicator	CRY1043	LRUs and power supplies shall contain externally visible LED power indicators with "steady blue" indicating "nominal operation" and "blinking blue" indicating "power is on but not meeting nominal conditions." In RFI shielded enclosures, these may be implemented with small LEDs or light pipes.	ETR0812

7.15 Helium Quality and Recovery

The cryogenic subsystem uses helium gas as a refrigerant; the purity of the gas has to be extreme because any contaminant will condense and freeze at 20 K, possibly degrading performance or damaging the equipment. Helium is a gas in limited supply on Earth and is expensive, even more so in the ultra-high purity form required for this application. It is essential to design the cryogenic maintenance building with a recovery process that will allow helium gas used during the maintenance to be recycled.

Parameter	Req. #	Value	Traceability
Helium Quality	CRY1200	The cryogenic subsystem shall only use helium 99.999% pure or better. Lesser grade will compromise the operation of the cryogenic subsystem and could cause premature failure.	SYS2801
Flexible Helium Line Cleanliness	CRY1201	The flexible helium line shall be clean, free of any oil or contamination, and be pressurized with Grade-5 helium gas at 1.38e^{+6} Pascal.	ETR1181
Helium Recovery	CRY1202	The cryogenic subsystem shall be designed to allow helium recovery during maintenance operation and to minimize waste.	SAF0850 SAF0860

7.16 Radio Frequency Interference/Electro-Magnetic Compatibility (RFI/EMC)

All running equipment is inclined to generate RFI/EMC, which could significantly impact the performance of the telescope. The cryogenic subsystem M&C electronics and power circuitry must be tested, and proper protection implemented to reduce the emission level below the required threshold.

The M&C electronics and VFDs will be placed in a shielded enclosure, and copper lines will be filtered. Fiber is preferred for communication between modules.

7.16.1 Spurious Signals/Radio Frequency Interference Generation

Parameter	Req. #	Value	Traceability
EMC/RFI Mitigation in Designs	CRY1300	RFI/EMC requirements shall be in compliance with and tested per the ngVLA System EMC/RFI Mitigation Requirements.	ETR0601
Spurious Signal Level	CRY1301	The spurious signal generated by the cryogenic electronics shall not exceed the equivalent isotropic radiated power limits in Table 2.	EMC0310

The Table 2 list the allowable radiation level by frequency band, is based on unity gain and assumes the RFI enters through a sidelobe of the antenna, for more details please look at [RD05].

Freq. (GHz)	1	2	4	6	8	10	20	30
F_h (w/m²)	1.5E-19	1.1E-18	8.9E-18	2.9E-17	6.3E-17	1.2E-16	1.2E-15	4.3E-15
$EIRP_h$ (W)	1.9E-16	1.4E-15	1.1E-14	3.7E-14	7.9E-14	1.5E-13	1.6E-12	5.4E-12
$EIRP_h$ (dBm)	**–127**	**–119**	**–110**	**–104**	**–101**	**–98**	**–88**	**–83**

Table 2 – Allowable radiation from electronics components

7.16.2 Electromagnetic Compatibility Requirements

Any component of the cryogenic subsystem shall demonstrate complete electromagnetic compatibility (EMC) with other equipment mounted on the antenna. Electromagnetic interference (EMI) with the antenna or other subsystems shall be avoided. The following requirements shall be fulfilled to achieve EMC/RFI recommended levels. Other methods could be used as long as they are at least as efficient as the proposed solutions. The equipment designer should exercise due diligence in limiting the harmful emissions generated by their design.

Parameter	Req. #	Value	Traceability
Drive System Shielding	CRY1302	All motor leads, both power and control, shall be filtered.	EMC0320
Relay Contact Arcing	CRY1303	All relay contacts and actuators shall be properly bypassed with snubber circuits, shielded, and/or filtered.	EMC0321
Amplifiers & Oscillators	CRY1304	All amplifiers and oscillators shall be mounted in shielded enclosures that will provide effective shielding of radio frequency energy.	EMC0322
Silicone Controlled Rectifiers	CRY1305	Silicon-controlled rectifier switching devices shall not be used unless phase controlled and zero current crossing switching techniques are used.	EMC0323
Static Discharge Mitigation	CRY1306	Means shall be employed to reduce static electricity and the consequent radio frequency noise generated in any rotating machinery.	EMC0325

Parameter	Req. #	Value	Traceability
Display Shielding	CRY1307	All displays (LCD, plasma, LED, CRT) shall have an RFI shield in front of the display to avoid radiated RFI. 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 M&C System).	EMC0326
Digital Equipment Shielding	CRY1308	All digital equipment, whether a simple logic circuit, embedded CPU, or rack mounted PC shall be shielded and have its AC power line and communication line(s) filtered at the chassis.	EMC0327
EMC Test Frequencies	CRY1309	The frequency range to be covered by these design measures for radiated radio-frequency interference (RFI) suppression shall extend from 50 MHz up to 12 GHz. Demonstration of EMC above 12 GHz is not required because mitigation at 12 GHz and below is expected to be adequate at higher frequencies. An exception is made for the fundamental and harmonic frequencies of LO signals, which shall be tested up to 40 GHz.	EMC0328

7.17 Miscellaneous Requirements

While an air-cooled compressor was considered in the reference design, moving the compressor inside the antenna turn-head triggered a change to liquid-cooled to benefit from the reduced size and the dissipation of the heat outside of the antenna structure.

Oil pumps have proven their reliability on the VLA; the only problem is that the oil limits the operating range such that when the temperature is below 12°C, the oil's viscosity impairs the operation of the pump. Since the pump is not located in a controlled environment like the vertex room on the VLA antenna, a heater must be mounted on the pump to preheat the oil before usage. In one direction, the oil pump can be tilted 0°–90°, but oil will spill if the antenna passes the zenith and the pump runs. A safety interlock should prevent this, but an oil recovery circuit could be implemented for safety and reliability.

Parameter	Req. #	Value	Traceability
Compressor Liquid-cooled	CRY1400	The compressor shall be liquid-cooled	ECN0001
Vacuum Pump Heater	CRY1410	The vacuum pump shall have a heater that controls the temperature of the pump and keeps it within the 12°C to 45°C operating range over the ambient temperature in CRY0002.	Vacuum pump user manual
Vacuum Pump Oil Recovery	CRY1420	The vacuum pump shall have an oil recovery feature that prevents oil spill if the antenna elevation move exceeds 90°.	VLA Experience

8 Safety

8.1 Safety Requirements

The table below presents all parameters with traceability to the safety specifications document [AD08].

Parameter	Req. #	Value	Traceability
Corrosion Resistance	CRY0030	The cryogenic subsystem shall use corrosion-resistant materials and/or use highly corrosion-resistant coating and finish on surfaces.	SAF0490
MTBM	CRY0100	The cryogenic subsystem shall be designed with an expected MTBM for the entire subsystem of 8,333 hours.	SAF0500
Serviceable Onsite	CRY0109	The cold head shall be serviceable/swappable onsite (on the antenna) by one technician in 2 hours.	SAF0890
Preclusion of Assembly Error	CRY0111	The cryogenic subsystem shall be designed to prevent any possible assembly error (unique connector type and keyed backplane with specific alignment pins).	SAF0160 SAF0170 SAF0730
LRU Easy Removal and Replacement	CRY0112	The cryogenic subsystem shall provide guides and location pins to facilitate LRU mounting.	SAF0730 SAF0740
LRU Damage Prevention	CRY0113	The cryogenic subsystem LRU shall make use of stand-offs, brackets and handles to protect system components from damage during shop and onsite maintenance.	SAF0630
Direct Access	CRY0114	The cryogenic LRU(s) shall be mounted such that removal of any LRU will not require the removal of any other LRU.	SAF0190
LRU Physical Marking Label Contents	CRY0201	Each LRU shall be marked with the model number/name, serial number and hardware revision level as defined in MIL-STD-13231 [RD09] and the fully qualified CID number (as defined in section 3 of the ngVLA Documentation Management Plan (020.10.10.10.00-0001-PLA).	SAF0060 SAF1020
Follow Safe Design Priorities	CRY0400	The cryogenic subsystem shall address safety of personal first followed by safety of equipment. The information needed to control the equipment must be unambiguous and easily understood.	SAF0031 SAF0190 SAF0200 SAF0750 SAF0970 SAF1060 SAF1130
Warning Labels	CRY0401	Warning labels shall be applied on the cryogenic subsystem modules to inform personnel of possible hazard or special handling information (electrical shock hazard, high temperature hazard, etc.).	SAF0100 SAF0050 SAF0170 SAF0750 SAF1010
Mass and Center of Gravity Marking	CRY0403	Mass and location of the center of mass shall be clearly indicated on equipment that will need to be handled with a lifting device.	SAF1050
Lifting Handles	CRY0404	Any cryogenic subsystem LRU with a mass 5 kg ≤ W ≤ 40 kg shall be equipped with handles for handling. The number of person required for handling shall be clearly indicated.	SAF0160 SAF 0210 SAF0240 SAF0260

Parameter	Req. #	Value	Traceability
Lifting Points	CRY0405	Any cryogenic subsystem LRU with a mass < 40 kg shall have lifting point(s) (eye bolts or slots) allowing handling with an overhead crane or a fork-lift. The lifting point location shall be clearly identified.	SAF0160 SAF0210 SAF0240 SAF0250
Sharp Edges Protection	CRY0406	The cryogenic subsystem shall protect sharp edges that cannot be eliminated from the design with covers or coatings.	SAF0540
Pressurized Vessel Testing	CRY0407	Any pressurized vessel shall be pressure tested to x1.5 times the maximum operating pressure.	SAF0034 SAF0036
Protection from Risk of Overpressure	CRY0408	The cryogenic subsystem shall comply with the pressurized equipment safety requirements. The cryogenic subsystem shall be equipped with overpressure relief valves to eliminate the risk of explosion or large burst of pressure that could harm personnel or damage equipment.	SAF0720 SAF0780 SAF0850
Flexible Helium Line Working Pressure	CRY0409	The flexible helium line shall have a working pressure > 5.8 e^{+6} Pascal (850 psi).	SAF0520
Rigid and Flexible Lines Mechanical Attachment	CRY0410	Both rigid and flexible lines shall be firmly attached and/or protected against all external stresses and strains to ensure that no risk to personnel or equipment is posed by a rupture.	SAF0520
High Voltage Safety Protection	CRY0420	The cryogenic subsystem shall comply with the electrical safety protection requirements.	SAF0050 SAF0070 SAF0080 SAF0090 SAF0120 SAF0690
Equipment Stability	CRY0430	Any equipment or assembly of the cryogenic subsystem shall be stable under foreseen operating conditions or shall be anchored to the antenna structure to provide the required stability.	SAF0470
Protection from Moving Parts	CRY0431	The cooling fan on the compressor shall be covered with a grid that shall prevent any risk of personnel injury.	SAF0640
Subsystem Self-Monitoring	CRY0450	The cryogenic subsystem shall monitor system health and prohibit actions likely to cause damage or shut down to prevent damage.	SAF0037
Hardware Failsafe Redundancy	CRY0451	The cryogenic subsystem shall be designed with hardware failsafe redundancy in case of M&C failure or malfunction.	SAF0042
Initial Safe State Power Up	CRY0452	The cryogenic subsystem shall initialized in a safe state for personnel and equipment without human intervention when powered up.	SAF0041

Parameter	Req. #	Value	Traceability
ESD Protection	CRY0481	ESD protection of equipment and workspaces shall be based on USDOD MIL-STD-1686C (RD10) and MIL-HDBK-263B (RD11) or ANSI/ESD S20.20-2014 (RD12).	SAF0710
Design Life	CRY0600	The cryogenic subsystem shall be designed for an expected operational life of no less than 30 years.	SAF0490
Coupling Marking	CRY0922	The cryogenic subsystem couplings shall be clearly marked in green to identify return connections and red to identify supply connections.	SAF0740
Stainless Steel Hardware	CRY0924	The hardware used on the cryogenic subsystem shall be stainless steel for long lasting life.	SAF0490
Captive Fasteners	CRY0927	All panels that need to be removed on the antenna for service shall use captive fasteners to prevent loss of hardware during maintenance.	SAF0530
Transport Vibration	CRY0930	The cryogenic subsystem shall be designed to withstand transportation vibration.	SAF0810
Generated Vibration	CRY0950	When in operation, the cryogenic subsystem shall not induce vibration and shock that exceed the safe levels for the other nearby systems	SAF0810
LRU Grounding	CRY1030	The cryogenic LRUs, with the exception of the cold heads (which will be grounded through the Front Ends), shall have an easily identifiable grounding point, and each connection path to the antenna ground shall have a resistance <10 mΩ. This low-resistance connection shall help with lightning protection and static electricity build-up.	SAF0710
Helium Recovery	CRY1202	The cryogenic subsystem shall be designed to allow helium recovery during maintenance operation and minimize waste.	SAF0850 SAF0860

8.2 *Safety Hazard Analysis*

8.2.1 Hazard Severity

Hazard severity categories are defined (Table 3) 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 3 – Hazard severity categories.

System loss: The system cannot be recovered at reasonable cost (<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.

8.2.2 Hazard Probability

Table 4 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 4 – Probability levels.

8.2.3 Hazard Risk Acceptability Matrix

The following two matrices (Table 5 and Table 6) 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 5 – 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

Hazard risk index	Assessment criteria
III D, E; IV C, IV D, IV E	Acceptable without review by ngVLA PE

Table 6 – Hazard acceptability matrix.

8.2.4 Requirements on Operational Hazards

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; or
- wind loads.

The last three are only relevant to subsystems housed in/on the antenna.

8.2.5 Hazard Analysis

The purpose of a Hazard Analysis is to identify safety critical areas, evaluate hazards, and 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.

8.3 Hazard List

Hazard description	Hazard risk index
Helium leak, from bad seal, cracked weld joint or metal fatigue hairline crack	IV A
Vacuum leak	IV A
Burst of Helium line	IV D
Burst of buffer tank	III D
Burst of supply tank	II D
Drop of compressor during lift	I D
Drop of Helium pressure regulation assembly during lift	I D

Hazard description	Hazard risk index
Breakage of vacuum hose	III B
Breakage of Helium line	III B
Over pressure relieve valve failure	III B
Helium circuit contamination	IV A
Scroll capsule seizure	IV B
Fan motor failure	III C
Electrical short circuit	III B
Oil spill	IV C
Cryostat implosion	I E
Skin burn from hot or cold surface	II D

9 Requirements for Design

9.1 Analysis and testing Requirements

9.1.1 Thermal Analysis

The Front End thermal loads will be calculated using the ThermXL thermal analysis package from ESATAN-TMS.

9.1.2 Electromagnetic Compatibility Requirements

All digital equipment shall be shielded and have its AC power line filtered at the chassis. Optical fiber is preferred for communication between M&Cs and control lines, but if copper is used, it has to be filtered at the chassis. All switching devices, the motor amplifier, and the control circuit shall be mounted in a shielded enclosure that will effectively shield radio frequency energy. The frequency range to be covered by these design measures for Radio-Frequency Interference (RFI) shall extend from 50 MHz up to 12 GHz.

9.1.3 Reliability, Availability, Maintainability Analysis

A Reliability, Availability, and Maintainability analysis shall be performed to locate weak design points and determine whether the design meets the maintenance and reliability requirements. ngVLA suggests applying the Parts Count Method for predicting the system's reliability as described in the MIL-HDBK-217F, but the designer may propose to use other methods. For non-electronic parts, the values of NPRD-95 may be used, or data from manufacturers or other databases may be used.

9.1.4 Wind Analysis

The system's behavior under high wind conditions shall be tested in a wind tunnel or similar facility where high wind can be generated and applied to the equipment in a specific direction and angle.

9.1.5 Environmental Chamber

The operating temperature range shall be demonstrated by running the equipment in an environmental chamber that covers the full temperature range (–25°C to 45°C).

9.1.6 Vibration Analysis

All equipment shall be designed to withstand persistent vibration with a power spectral density defined in Figure 7. LRUs shall be tested to this vibration specification along all three axes as described in the MIL-STD-810H Method 514.8 Procedure I for General Vibration, for a period of 60 minutes. LRUs shall be tested to this vibration specification along all three axes as described in the MIL-STD-810H Method 514.8 Procedure I for General Vibration, for a period of 60 minutes.

The vibration mitigation requirement is especially applicable to all mechanical connectors. All cables shall be mechanically supported to mitigate vibration loosening of connectors [AD04–ENV0531].AD04–ENV0531].

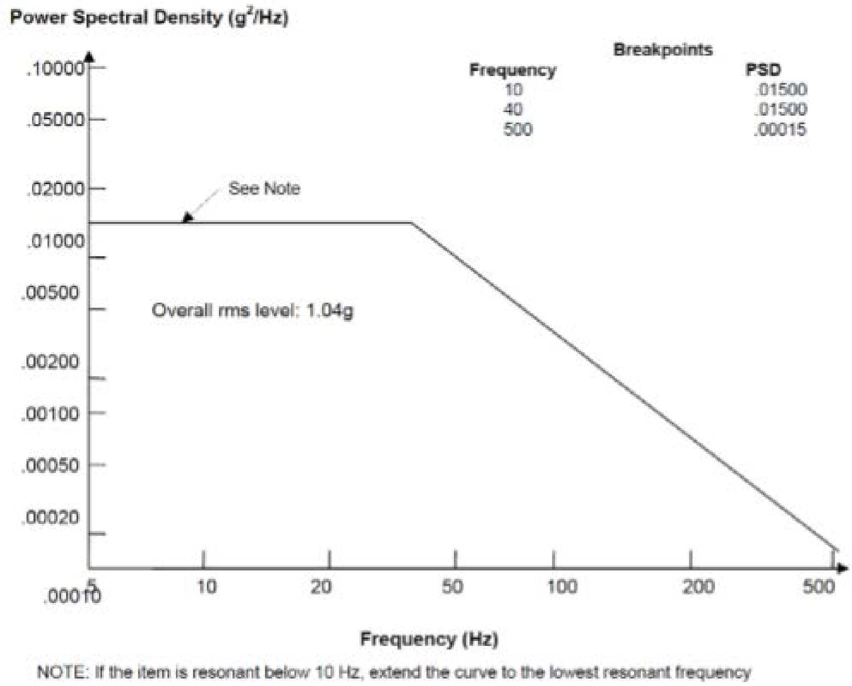

Figure 7 – Power spectral density of design spectra for vibration mitigation.

9.2 Materials, Parts, and Processes

9.2.1 Fasteners

All fasteners shall be metric except those that are on off-the-shelf units. Stainless steel shall be used for long term corrosion resistance [AD09–ETR1161].

9.2.2 Paints

To limit the effect of solar heating and protect against corrosion, outside panels, and enclosures shall be painted of white color suitable for the surface material and environmental conditions the surface will experience. A surface preparation suitable for the material and paint shall be used [AD09– ETR1146].

9.2.3 Surface Treatment

Aluminum surfaces requiring electrical conduction (RFI/EMI or safety grounding) shall be treated using a Chromate Conversion process as outlined in MIL-DTL-5541E. Either Class 1A or Class 3 can be used based on requirements determined by the designer [AD09–ETR1143].AD09–ETR1143].

Stainless steel can be used for RFI/EMC housing where deemed feasible by the designer. Surfaces can be painted but shall be left bare where electrical conduction is necessary [AD09–ETR1144].AD09–ETR1144].

Aluminum surfaces where no electrical conductivity is required can be anodized. Anodizing shall be of a color not mistakable for Chromate (i.e., clear, yellow, brown, or gold). Anodizing shall not be used on surfaces requiring electrical conductivity for RFI/EMI shielding or good safety ground conduction and shall never be scraped or sanded off to achieve this [AD09–ETR1145].AD09–ETR1145].

9.2.4 Rodent Protection

All equipment shall be designed to prevent rodent damage. At a minimum, this may involve protecting all cables with flexible or rigid conduit or equivalent. Any penetrations within enclosures shall mitigate the risk of rodent damage [AD09–ETR1127].AD09–ETR1127].

9.2.5 Labels

All cables, and switches, junction boxes, sensors, and similar equipment shall be labeled in English and Spanish.

9.2.6 Name Plates and Product Marking

As a general rule, all LRUs shall be equipped with nameplates which are visible after installation (see AD09 section 4.1 for more information).

10 Documentation Requirements

A complete and up to date documentation is essential for a project like ngVLA that has an expected operation life of more than 20 years.

Parameter	Req. #	Value	Traceability
As-built drawings	CRY0700	As-built drawings shall be provided for all custom hardware and facilities delivered as part of the system.	SYS6001
Operations and Maintenance Manuals	CRY0701	Operations and Maintenance Manuals shall be provided for each LRU in the system.	SYS6002
Units	CRY0702	Design materials and documentation shall use ISO standards and SI (metric) units. Imperial units may also be shown for clarity.	SYS6003
Language	CRY0703	The language used for written documentation shall be English.	SYS6004
Electronic document format	CRY0704	Documents and drawings of record shall be delivered in PDF. Native, editable file formats shall also be delivered.	SYS6005

11 Technical Metrics

Technical Metrics are used throughout the project and should be monitored throughout project design and development. These parameters strongly influence the eventual effectiveness of the facility and are useful high-level metrics for trade-off decisions. Technical Performance Measures are a category of technical metrics defined at the subsystem level.

11.1 Definitions

The technical metrics below are further described in the Systems Engineering Management Plan [AD01]:

Key Performance Parameters (KPPs): The essential parameters to achieving the key science goals. These are capabilities or characteristics so significant that failure to reach the threshold value of performance can cause the system concept to be reevaluated, or even the program to be reassessed or terminated. Must have a threshold and an objective value. In a trade-off study, everything can be traded off except a KPP. The ngVLA KPPs are tied to a subset of the ngVLA Level-0 Science Requirements. An example of a KPP may be continuum sensitivity.

Measures of Effectiveness (MoEs): These are measures closely related to operational achievement and overall success criteria for the project. MoEs reflect overall Observatory and user satisfaction (e.g., performance, safety, reliability, availability, affordability, operability, and maintainability). These metrics can be expressed on a scale with no fixed threshold. The ngVLA MoEs are tied to a subset of the Level-0 Stakeholder Requirements. An example of a MoE might be calibration efficiency.

Measures of Performance (MoPs): Measures that are components of, or contribute to, MoEs or KPPs. That characterize physical or functional attributes relating to system operation. MoPs measure attributes considered essential to system capability and capacity to perform its operational objectives. The ngVLA MoPs are tied to a subset of the Level-1 System Requirements [AD04]. An example of a MoP might be the A/T ratio of the system, supporting the continuum sensitivity KPP.

Technical Performance Measures (TPMs): These are lower level measures, typically aligned with Level-2 subsystem requirements that support the MoPs. An example might be receiver noise temperature, contributing to the system-level A/T MoP.

Figure 8 summarizes the relationships between these technical metrics and their associated source requirements.

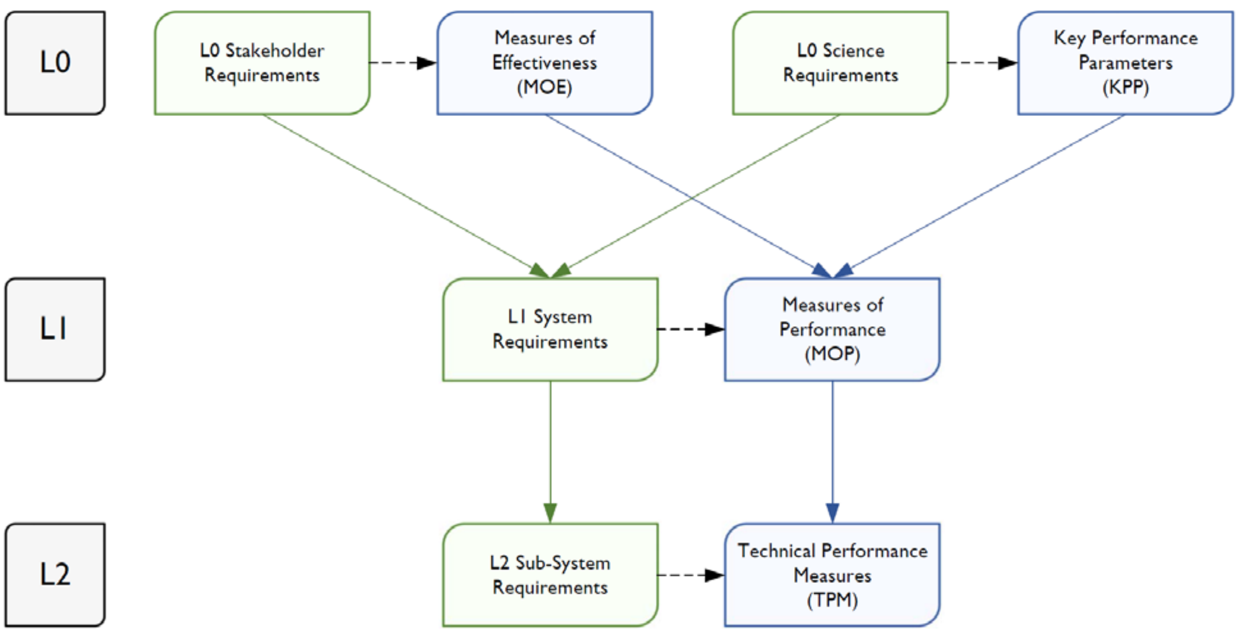

Figure 8 – Relationship of the various technical metrics to the L0 through L2 requirements. The relationships between the various technical metrics is also shown.

11.2 Technical Performance Measures

The Technical Performance Measures are requirements that closely impact the overall performance of the ngVLA system and are therefore considered of higher importance. The following Technical Performance Measures are identified for optimization and monitoring throughout the design phase.

Technical Performance Measures	Req. #
Cooling capacity	CRY0800
Temperature stability	CRY0801

Technical Performance Measures	Req. #
Compressor flow capacity	CRY0803
Compressor power consumption	CRY1001

Table 7 – ngVLA Key Performance Parameters.

11.2.1 Cooling Capacity

The cryogenic subsystem's sole purpose is to cool the sensitive Front End electronics down to 20 K to minimize self-generated thermal noise, boost amplification, and improve stability. The amount of heat the cryocooler must remove depends on the Front End cryostat design, the internal cabling, and the number of active components.

Thermal analysis conducted by an expert (Callisto, France [RD05 & RD06]) calculated the thermal loads for the Front End Cryostat–A and Cryostat–B and recommended cooling capacities to match the loads. The highest capacity is required because the same cryocooler will be used on both cryostats. A test cryostat will be built to measure the cooling capacity of the cryocooler. It will serve as a thermal model for a new thermal analysis to verify with actual measurements the computer model's accuracy.

11.2.2 Temperature Stability

The temperature stability requirement flows down from the gain stability requirement. Any temperature variation in the second stage will translate into a gain variation on the LNA (dG/G estimated at 0.12/K). The temperature stability will be measured on the thermal model first; if it is not achievable by the cryocooler alone, an active temperature control will have to be implemented.

11.2.3 Compressor Flow Capacity

A single compressor will connect two cryocoolers, each requiring a certain amount of pressurized helium based on operating speed and temperature. The compressor must have enough capacity to meet the highest demand on both cryocoolers. The flow will be measured in the laboratory with two cryocoolers mounted to two identical test cryostats with adjustable heat loads.

11.2.4 Compressor Power Consumption

The cryogenic subsystem runs continuously and represents a significant portion of the power consumed by the VLA. It was established early on that for the ngVLA project to be successful, the operating cost would have to be capped at three times that of the VLA. The VLA with 27 antennas and three compressors per antenna, each using 6 kW, has a power budget of (27 x 3 x 6 = 486 kW). The ngVLA project will have 263 antennas with a single compressor per antenna; the maximum allowed power per compressor is 5.54 kW ((486 x 3) / 263 = 5.54 kW). The compressor power consumption will be measured in the lab with two cryocoolers.

Note: the power might be allowed to exceed 5.54 kW for short periods, but the steady state consumption shall not.

12 Verification

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

Verification by Analysis: The fulfillment of the specified performance shall be demonstrated by appropriate analysis (hand calculations, finite element analysis, thermal modeling, etc.), which will be checked by the ngVLA project office during the design phase.

Verification by Inspection: The compliance of the developed system is determined by a simple inspection (of the design documentation or deliverables) or measurement.

Verification by Demonstration: The compliance of the developed feature is determined by a demonstration.

Verification by Test: The compliance of the developed subsystem with the specified performance shall be demonstrated by an acceptance test.

Multiple verification methods are allowed over the course of the design phase, although the primary (final) verification method is identified below.

12.1 Subsystem Requirements

Req. #	Parameter/Requirement	A	I	D	T
CRY0001	Wind speed limits for normal operation				*
CRY0002	Temperature range for normal operation				*
CRY0003	Precipitation for normal operation				*
CRY0004	Ice accumulation for normal operation				*
CRY0006	Relative Humidity				*
CRY0010	Wind speed for survival condition				*
CRY0011	Temperature for survival condition				*
CRY0013	Radial ice for survival condition				*
CRY0014	Snow load for survival condition				*
CRY0015	Hail stones size for survival condition				*
CRY0016	Transportation solar radiation	*			
CRY0017	Transportation Temperature	*			
CRY0018	Storage temperature	*			
CRY0019	Storage relative humidity		*		
CRY0020	Altitude range				*
CRY0021	Maximum solar flux		*		
CRY0022	UV radiation		*		
CRY0030	Corrosion resistance	*			
CRY0040	Lightning protection	*			
CRY0050	Dust protection			*	
CRY0060	Rodent protection		*		
CRY0070	Seismic protection	*			
CRY0080	Rain/Water Infiltration				*
CRY0100	MTBF	*			
CRY0101	Modularization		*		
CRY0102	Self-diagnostic function			*	
CRY0103	Configuration monitoring			*	
CRY0104	Engineering console			*	
CRY0105	Monitor data stream and archiving			*	
CRY0106	Preventive maintenance	*			
CRY0108	Failure prediction tools	*			
CRY0109	Serviceable onsite			*	
CRY0110	Interchangeable LRU			*	
CRY0111	Preclusion of assembly error		*		
CRY0112	LRU easy removal and replacement		*		

Req. #	Parameter/Requirement	A	I	D	T
CRY0113	LRU damage prevention		*		
CRY0114	Direct access		*		
CRY0115	MTTR	*			
CRY0150	Component Sources	*			
CRY0151	Standard Component Libraries	*			
CRY0152	Component Environmental Specifications	*			
CRY0160	Reliability Analysis	*			
CRY0170	Robustness Analysis	*			
CRY0180	Local Firmware			*	
CRY0181	Firmware Updates			*	
CRY0190	Watchdog Timers				*
CRY0191	M&C Commanded Reset for DC Powered Devices			*	
CRY0192	M&C Commanded Reset for AC Powered Devices			*	
CRY0200	LRU physical tracking device		*		
CRY0201	LRU physical marking label contents		*		
CRY0202	LRU tracking label & tag specifications				*
CRY0203	Remote identification			*	
CRY0204	LRU remote ID for devices with no direct M&C connection			*	
CRY0205	LRU Physical Marking Label Ruggedness				*
CRY0221	LRU Periodic Self-tests and Alerts			*	
CRY0222	Monitor Archive			*	
CRY0223	Fast Read-Out Mode			*	
CRY0224	Intelligent LRU with Advanced Diagnostics			*	
CRY0225	Thermal protection monitoring			*	
CRY0300	Weather monitoring			*	
CRY0301	Hardware safeguards				*
CRY0400	Follow safe design priorities		*		
CRY0401	Warning labels		*		
CRY0402	Labeling quality				*
CRY0403	Mass and center of gravity marking		*		
CRY0404	Lifting handles		*		
CRY0405	Lifting points		*		
CRY0406	Sharp edges protection		*		
CRY0407	Pressurized vessel testing				*
CRY0408	Protection from risk of overpressure				*
CRY0409	Flexible Helium line working pressure				*
CRY0410	Rigid and flexible lines mechanical attachment		*		
CRY0411	LRU Multiple person lift label		*		
CRY0412	Risk of implosion	*			
CRY0413	Risk of burn	*			
CRY0420	High voltage safety protection	*			
CRY0421	Contact with High Voltage during Diagnosis & Repair	*			
CRY0422	Safety Interlocks				*
CRY0430	Equipment stability		*		
CRY0431	Protection from moving parts		*		

Req. #	Parameter/Requirement	A	I	D	T
CRY0450	Subsystem self-monitoring				*
CRY0451	Hardware failsafe implementation				*
CRY0452	Initial safe state power up				*
CRY0453	Vacuum pump safety interlock				*
CRY0454	Thermal protection				*
CRY0480	ESD susceptibility testing				*
CRY0481	ESD protection	*			
CRY0482	ESD packaging and storage				*
CRY0483	Prevention & discharge of electrostatic charge build-up				*
CRY0500	Version control for software and firmware		*		
CRY0600	Design life	*			
CRY0601	Part selection for maintainability	*			
CRY0602	Critical spares	*			
CRY0603	Storage				*
CRY0700	As-built drawings		*		
CRY0701	Operations and maintenance manuals		*		
CRY0702	Units		*		
CRY0703	Language		*		
CRY0704	Electronic document format		*		
CRY0800	Cooling capacity				*
CRY0801	Temperature stability				*
CRY0803	Compressor flow capacity				*
CRY0804	Time to establish supply pressure				*
CRY0805	Supply line		*		
CRY0806	Return line		*		
CRY0807	Pressure drop supply line			*	
CRY0808	Pressure drop return line			*	
CRY0809	Helium pressure regulation			*	
CRY0810	Helium leakage compensation	*			
CRY0811	Helium pressure regulation buffer tank volume				*
CRY0812	Vacuum pump ultimate pressure		*		
CRY0813	Vacuum pump pumping speed		*		
CRY0814	Vacuum line conductance	*			
CRY0815	Pump down time				*
CRY0816	Cool down time				*
CRY0817	Warm-up time				*
CRY0900	Compressor tilt angle		*		
CRY0901	Cryocooler orientation				*
CRY0902	Compressor volume		*		
CRY0903	Compressor mass		*		
CRY0904	Helium pressure regulator rack volume		*		
CRY0905	Helium pressure regulator rack mass		*		
CRY0906	Cryogenic M&C RFI enclosure volume		*		
CRY0907	Cryogenic M&C RFI enclosure mass		*		
CRY0908	Flexible Helium line dynamic bending radius		*		
CRY0909	Vacuum pump volume		*		

Req. #	Parameter/Requirement	A	I	D	T
CRY0910	Vacuum pump mass		*		
CRY0911	Vacuum pump allowed tilt angle during operation			*	
CRY0920	Flexible Helium line end couplings		*		
CRY0921	Couplings		*		
CRY0922	Coupling marking		*		
CRY0923	Metric fasteners		*		
CRY0924	Stainless steel hardware		*		
CRY0925	Type of fasteners		*		
CRY0926	Hardware retention		*		
CRY0927	Captive fasteners		*		
CRY0930	General vibration				*
CRY0940	Mechanical shocks				*
CRY0950	Generated vibration				*
CRY0960	Cable documentation		*		
CRY0962	DC wire color standard		*		
CRY0963	AC wiring color		*		
CRY0970	Wiring insulation type	*			
CRY0971	Wiring Insulation Type inside Vacuum Space and Exposed to Cryogenic Temperature	*			
CRY0980	Connector documentation		*		
CRY0981	Connector labeling		*		
CRY0982	Connector current rating	*			
CRY0983	Connector environmental rating	*			
CRY0984	Connector mating cycles	*			
CRY0985	No exposed live terminals	*			
CRY0986	Connector uniqueness & keying		*		
CRY0987	Common connectors	*			
CRY0988	Connector alignment guides	*			
CRY0989	LRU multi-pin connector retention		*		
CRY0990	Chromate converted surfaces		*		
CRY0991	Stainless steel surfaces		*		
CRY0992	Anodized surfaces		*		
CRY0993	Painted surfaces		*		
CRY0994	Colored paint marking		*		
CRY0995	Surface preparation for painting		*		
CRY0996	Materials for surface exposed to a vacuum environment			*	
CRY0997	Cleanliness of surfaces exposed to a vacuum environment		*		
CRY0998	Powder coating		*		
CRY0999	Painted surface lifetime			*	
CRY1000	AC power and grounding design		*		
CRY1001	Compressor power consumption				*
CRY1002	Compressor power factor				*
CRY1003	Start-up power consumption				*
CRY1003	Start-up power consumption				*
CRY1004	Harmonic distortion				*

Req. #	Parameter/Requirement	A	I	D	T
CRY1005	Phase imbalance				*
CRY1006	Compressor operating frequency				*
CRY1007	Cold head operating frequency			*	
CRY1008	Cables and harnesses labeling		*		
CRY1009	Switches and controls labeling		*		
CRY1010	Compressor max current draw				*
CRY1011	Cryocooler max current draw				*
CRY1012	AC voltages available	*			
CRY1013	AV voltages tolerance	*			
CRY1020	DC power & grounding design	*			
CRY1021	DC LRU power input	*			
CRY1022	Power supply dedicated returns	*			
CRY1023	Power supply returns separate from ground	*			
CRY1024	DC voltages available	*			
CRY1025	-48VDC tolerance	*			
CRY1026	PSU voltage tolerance	*			
CRY1030	LRU grounding		*		
CRY1031	Overcurrent protection				*
CRY1032	Overcurrent protection device monitoring				*
CRY1040	On-Site Reset/Start-Up Sequence				*
CRY1041	Power outage behavior			*	
CRY1042	Automated recovery sequence			*	
CRY1043	DC powered LRU power “ON” indicator	*			
CRY1050	Thermal protection				*
CRY1051	Thermal protection monitoring			*	
CRY1052	Thermal analysis	*			
CRY1200	Helium quality		*		
CRY1201	Flexible Helium line cleanliness		*		
CRY1202	Helium recovery		*		
CRY1300	EMC/RFI mitigation in designs				*
CRY1301	Spurious Signal Level				*
CRY1302	Drive System Shielding		*		
CRY1303	Relay Contact Arcing		*		
CRY1304	Amplifiers & Oscillators		*		
CRY1305	Silicone Controlled Rectifiers		*		
CRY1306	Static Discharge Mitigation		*		
CRY1307	Display Shielding		*		
CRY1308	Digital Equipment Shielding				*
CRY1309	EMC Test Frequencies				*
CRY1400	Compressor liquid cooled		*		
CRY1410	Vacuum pump heater				*
CRY1420	Vacuum pump oil recovery				*
CRY1501	Compressor Glycol cooling flow	*			
CRY1502	Compressor Glycol cooling temperature	*			
CRY1503	Compressor Glycol cooling temperature stability	*			
CRY1504	Compressor Glycol maximum supply pressure	*			

Req. #	Parameter/Requirement	A	I	D	T
CRY1505	Compressor heat dissipation	*			
CRY1506	Cryogenic RFI enclosure Glycol cooling flow	*			
CRY1507	Cryogenic RFI enclosure Glycol cooling temperature	*			
CRY1508	Cryogenic RFI enclosure Glycol cooling temperature stability	*			
CRY1509	Cryogenic RFI enclosure heat dissipation	*			
CRY1510	Helium pressure regulation module heat dissipation	*			
CRY1511	Vacuum pump heat dissipation	*			
CRY1520	Powder-coated surface lifetime	*			
CRY1530	Internal cable connector retention	*			
CRY1531	Single fiber optic cable connector retention	*			
CRY1532	PCB board to cable retention	*			
CRY1533	PCB board-to-board connector retention	*			
CRY1534	Blind mate connector retention	*			
CRY1535	Connector retention analysis	*			
CRY1560	Helium pressure regulator controller volume	*			
CRY1561	Helium pressure regulator controller mass	*			

13 Appendix

13.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter Array
AIV	Acceptance, Integration, and Verification
CDR	Critical Design Review
CoDR	Conceptual Design Review
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
FDR	Final Design Review
GUI	Graphical User Interface
IPT	Integrated Product Team
I/F	Interface
ICD	Interface Control Document
IPT	Integrated Product Team
IRV	Internal Relieve Valve
IUID	Item Unique Identification
KPP	Key Performance Parameter
LRU	Line Replaceable Unit
LVAS	Low Voltage Analog Signal
LVS	Low Voltage Signal
LVDS	Low Voltage Differential Signal
M&C	Monitor and Control
MOE	Measure of Effectiveness
MOP	Measure of Performance
ngVLA	Next Generation Very Large Array
NRAO	National Radio Astronomy Observatory
PE	Project Engineer
RD	Reference Document
RFI	Radio Frequency Interference
RPM	Revolution Per Minute
TASC	ThermoAcoustic Stirling Cryocooler
TBC	To Be Confirmed
TBD	To Be Determined
TPM	Technical Performance Measure
UID	Unique Identification
VFD	Variable Frequency Drive
VLA	Very Large Array

13.2 Thermoacoustic Stirling Cryocooler

13.2.1 Technical Description

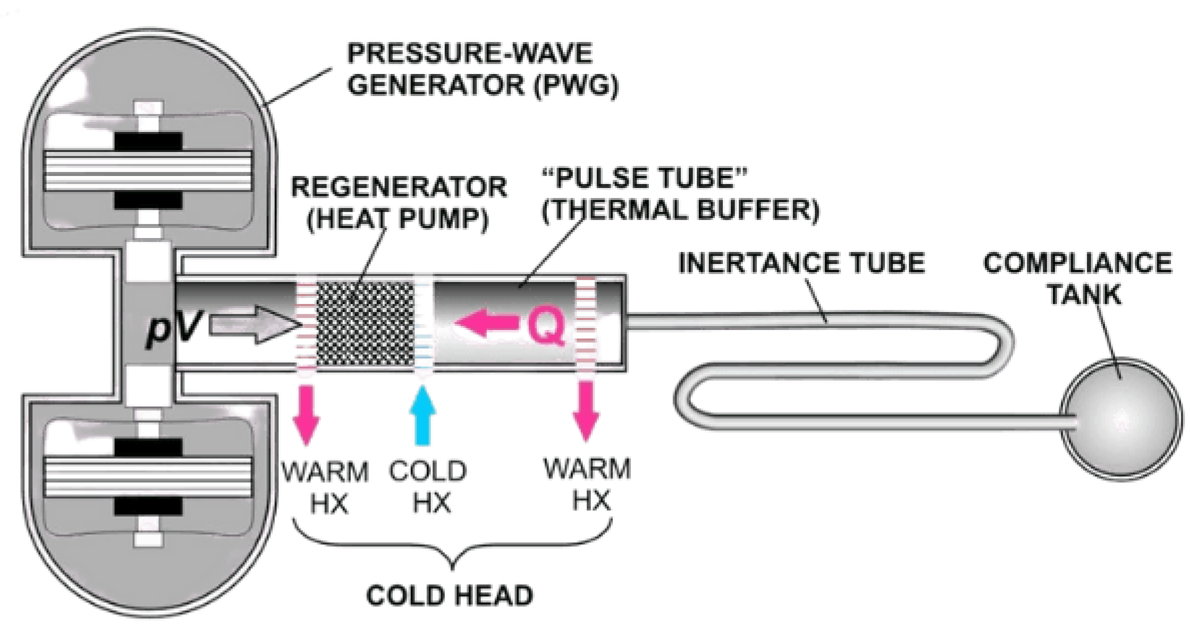

Figure 9 – Basic components of a TASC copied from RIX industries Web page

The TASC is composed of a compressor or pressure wave generator that has two linear reciprocating motors that use flex bearing technology to drive pistons; there is no contact with the cylinder walls but very small annular gaps that create non-contacting seals (clearance gap) that drastically limit the gas flow passing the pistons. The synchronized movement of the pistons in opposite directions generates the pressure wave (pV) that travels through the pulse tube. The regenerator cools the incoming high-pressure wave and transfers the accumulated heat to the gas when it returns to the PWG after the expansion phase. A proper cryocooler design synchronizes the cycle's expansion phase with the presence of a high-pressure wave at the bottom of the pulse tube. Cycling between compression and expansion generates two warm and one cold sections for a single-stage pulse tube. The heat of the warm section needs to be dissipated by an external cooling system (glycol loop or cooling fans), while the cold section is used to cool the Front End electronics. For simplicity, a single-stage pulse tube is represented in Figure 9, but a dual-stage pulse tube is necessary to reach the 20 K temperature required.

The dual-stage TASC concept being developed by RIX Industries is shown in Figure 10 and Figure 11. The pressure wave from the generator enters the first pulse tube with a coaxial arrangement with the regenerator in the center. The hot side of Pulse Tube 1 is connected to the upper compliance volume by an inertance tube. To make the assembly more compact, the inertance tube is coiled around the two compliance volumes (both volumes are external to the vacuum space). The cold side of the Pulse Tube 1 connects to the second regenerator that is in series with the second pulse tube. The inertance tube of the second pulse tube wraps around the 80 K stage to keep the gas cold and then connects to the lower compliance volume. With this configuration, the second cold stage can reach 20K, the required temperature for optimum performance of the LNAs.Figure 10 and . The pressure wave from the generator enters the first pulse tube with a coaxial arrangement with the regenerator in the center. The hot side of Pulse Tube 1 is connected to the upper compliance volume by an inertance tube. To make the assembly more compact, the inertance tube is coiled around the two compliance volumes (both volumes are external to the vacuum space). The cold side of the Pulse Tube 1 connects to the second regenerator that is in series with the second pulse tube. The inertance tube of the second pulse tube wraps around the 80 K stage to keep the gas cold and then connects to the lower compliance volume. With this configuration, the second cold stage can reach 20K, the required temperature for optimum performance of the LNAs.

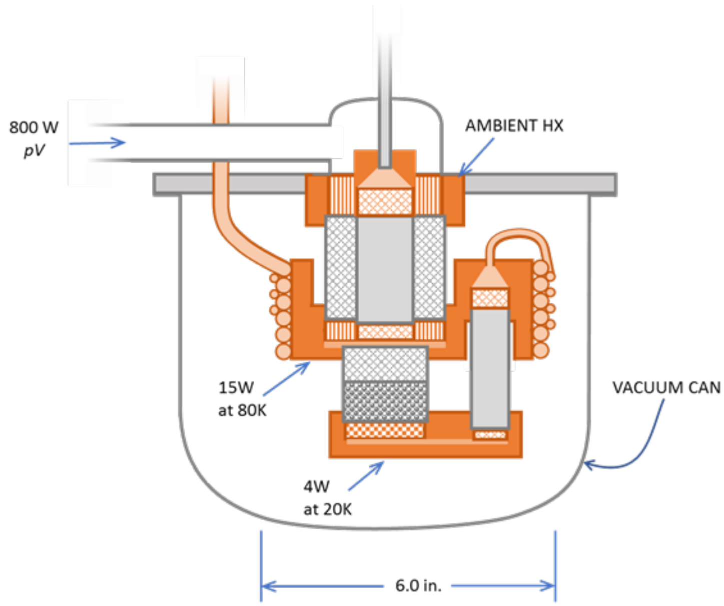

Figure 10 – Dual stage "pulse tube" concept from RIX Industries

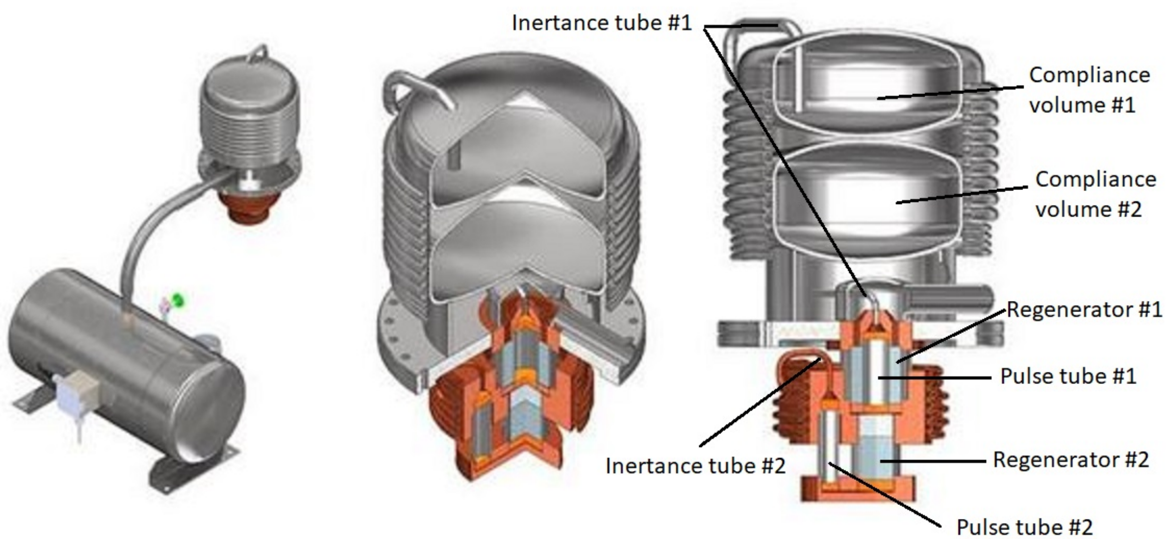

Figure 11 – 3D drawing of the dual stage TASC concept from RIX Industries.

13.2.2 Revised List of the Requirements

The absence of lubrication and mechanical wear makes this type of compressor extremely reliable and virtually maintenance-free. The pulse tube type cold head has no moving parts or valves that wear out and require periodic service; it is a purely passive assembly with infinite operating life expectancy. This type of technology has been used for various space missions with no reported failure. Because the TASC uses a pressure wave, the compressor and the cryocooler must be in close proximity; their separation usually is at most one meter. This mechanical arrangement of the compressor and the cryocooler introduces new requirements but eliminates others. The table below lists the requirements that must change if the TASC option is selected for ngVLA.

The feasibility study report by RIX Industries states that a TASC with the appropriate cooling capacities could be done. It was decided that a single larger PWG driving two dual-stage pulse tubes was a better solution for ngVLA due to the limited space inside the Front End enclosure and the mass restriction imposed by the feed indexer. The list of requirements that follows reflects this configuration.

Parameter	Req. #	Value	Traceability
Serviceable Onsite	CRY0109	n/a Service onsite is not required for the TASC with the exception of charging the circuit with helium in case of pressure drop.	SAF0890
Interchangeable LRU	CRY0110	Each Front End Dewar has a separate cold head but they are connected to a common PWG. The TASC is an integrated system that is not designed to be serviced on the antenna. Any work done on the TASC will required depressurization of the system and the helium should be recover to save cost. The complete Front End enclosure will be considered the LRU.	ETR1170
Compressor Flow Capacity	CRY0803	n/a The TASC uses an oscillating pressure or pressure wave to cool, there is no continuous flow of helium that could be measured.	SYS1011 SYS1012 SYS1013 FE0446
Time to Establish Supply Pressure	CRY0804	n/a The TASC does not have a supply and return side. The compressor generates a pressure oscillation that travels inside the pulse tube and creates hot and cold spots in the circuit.	
Supply Line	CRY0805	n/a see CRY0804	FE0446
Return Line	CRY0806	n/a See CRY0804	FE0446
Pressure Drop Supply Line	CRY0807	n/a See CRY0804	
Pressure Drop Return Line	CRY0808	n/a See CRY0804	

Parameter	Req. #	Value	Traceability
Helium Pressure Regulation	CRY0809	n/a See CRY0804	
Helium Leakage Compensation	CRY0810	n/a The TASC is a very compact and completely sealed system with a small volume of helium in comparison with the GM option. Because of the reduced volume of helium gas and the physical location inside the Front End enclosure, the pressure change due to ambient temperature variation should be negligible. The TASC expected leak rate shall be very small and shall not require a pressure regulation circuit. The helium pressure shall be monitor during scheduled antenna maintenance visits, and the system recharged as needed.	
Helium Pressure Regulation Buffer Tank Volume	CRY0811	n/a See CRY0810	
Compressor Tilt Angle	CRY0900	n/a Because the TASC compressor does not use oil, it does not have the same tilt angle restriction. The compressor can run in any orientation, but as a pulse tube the cryocoolers are restricted in tilt angle to avoid gravity induced instabilities that could affect its cooling efficiency.	
Cryocooler Orientation	CRY0901	Pulse tube cryocoolers could suffer from gravity induced instability. In order for the cryocooler to operate normally as the antenna moves through its entire elevation range from 12°–88°, its orientation will be offset from the vertical position to limit its tilt angle to ± 38°.	
Compressor Volume	CRY0902	The TASC PWG has to be located inside the Front End enclosure, it shall fit within a volume of L 660 mm x W 455 mm x H 365 mm.	
Compressor Mass	CRY0903	The mass of the PWG shall not exceed 90 kg.	
Helium Pressure Regulation Module Volume	CRY0904	n/a See CRY0810	
Helium Pressure Regulation Module Mass	CRY0905	n/a See CRY0810	
Cryogenic M&C Enclosure Volume	CRY0906	For the TASC, the cryogenic M&C electronics will be relocated to the Auxiliary enclosure. The volume required is TBD.	
Cryogenic M&C Enclosure Mass	CRY0907	The mass of the cryogenic M&C electronics shall not exceed TBD.	

Parameter	Req. #	Value	Traceability
Flexible Helium Line Dynamic Bending Radius	CRY0908	n/a. See CRY0804	
Flexible Helium Line End Couplings	CRY0920	n/a See CRY0804	
Couplings	CRY0921	n/a The TASC is an integrated system with no coupling required.	
Coupling Marking	CRY0922	n/a See CRY0921	SAF0740
Phase Imbalance	CRY1005	The TASC compressor runs on single phase power 208 VAC, the load on each phase will have to be balanced at the antenna level.	
Compressor Operating Frequency	CRY1006	n/a TASC input power can be amplitude modulated on-the-fly to match the cooling demand but the frequency shall remain constant at 30Hz.	
Cold Head Operating Frequency	CRY1007	n/a The pulse tube part of the TASC has no moving part and therefore nothing that could be adjusted on-the-fly. Modulation is done on the compressor amplitude only.	
Flexible Helium Line Cleanliness	CRY1201	n/a See CRY0804	ETR1181

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