Cryogenic Subsystem Requirements

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1 Introduction

1.1 Purpose

This document aims to present a set of technical specifications for the ngVLA cryogenic subsystem. Requirements defined in this document are drawn from the ngVLA preliminary system requirements document [AD01], the ngVLA environment specification document [AD02] and the ngVLA EMC/RFI specification document [AD03].

1.2 Scope

The scope of this document includes requirements for the cryogenic subsystem, as delivered for ngVLA integration. The following requirements will be discussed in this document:

- Operational performance requirements
    - Vacuum pump
    - Refrigerator
    - Compressor
- Mechanical interfaces
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- Environmental conditions
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    - Normal operating conditions
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- EMC/RFI requirements
- Maintenance requirements
- Transport requirements

1.3 Assumptions Made Regarding the ngVLA Cryogenics

The ngVLA cryogenics subsystem is directly related to the ngVLA Front End. The [AD05] document decribes the reference design for the ngVLA Front End; based on this document, the cryogenics subsystem assumes two Dewars, each equipped with a two-stage Gifford McMahon (GM) refrigerator and a single helium compressor per antenna.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD02	System Level Environmental Specifications	020.10.15.10.00-0001-SPE
AD03	EMC-RFI Specifications	020.10.15.10.00-0002-REQ
AD04	ngVLA Monitor and Control Interface Layer: Preliminary Requirements & Design Description	020.50.25.00.00.0002-DSN
AD05	ngVLA Front End Design Description	020.30.03.01.00-0003-DSN
AD06	ngVLA Cryogenic Subsystem Reference Design Description	020.30.10.00.00-0002-DSN
AD07	Rick Perley, "Notes on RFI Emissions Levels," 12/21/2006	VLA-VLBA Interference Memo #34

2.2 Reference Documents

The following documents are referenced within this text:

Reference No.	Document Title	Rev/Doc. No.
RD01	R. Rayet et. al., "ngVLA Front-End Receivers Thermal Study Initial Analysis Report," Callisto France S.A.S., 7/11/2018	020.30.10.00.00-0004-REP
RD02	Measured performance data memo, FA-40 helium compressor with VFD, Sumitomo SHI, July 2018	020.30.10.00.00-0005-REP

3 Overview of Subsystem Requirements

This document presents the ngVLA cryogenic subsystem technical specifications. The cryogenics performance requirements are driven by the Front End concept described in [AD05] and by maintenance and power requirements established for the project. It has been emphasized that for the ngVLA project to be successful, the annual operation cost shall not exceed the current VLA and VLBA budgets by more than a factor of three. This is quite challenging considering that ngVLA aims for about 10 times the number of antennas.

To meet the operations budget goal, the number of receivers per antenna has been reduced to two, compared to eight on the VLA, and the cryocoolers and the compressor have been equipped with variable frequency drives (VFDs) for adjustable cooling capacity. Having the capability to adjust the cooling power allows the supply of pressurized helium to be matched to the demand, while minimizing power consumption.

4 Functional Requirements

The purpose of the cryogenic subsystem is to cool the sensitive receiver electronics to reduce intrinsic thermal noise and maximize sensitivity. The key functions include

- Establish Dewar vacuum.
- Cooling of feeds and receiver gain stages.
- Maintain Dewar vacuum through cryo-pumping.
- Adjust cooling capacity to meet the temperature requirements while minimizing the power consumption.

5 Operational Performance Requirements

5.1 Vacuum Pump Requirement

The vacuum pump removes air trapped inside the closed volume of the Front End cryostat. When the atmosphere is evacuated, heat transfer by convection between the outside walls and the inside components of the Dewar becomes negligible. In practice, a minimum vacuum is required before starting the refrigerator. If this threshold is not reached, the thermal loading is high enough to overcome its cooling power, preventing the electronics from reaching the desired temperature. It has been established that a Dewar pressure of 10^{-2} mbar is needed at the start for a successful cool down. Therefore, the vacuum pump selected must have a base pressure lower than this 10^{-2} mbar threshold (Table 1).

The ngVLA Front End concept has two cryostats, each with an approximate volume of 60–70 liters. It is desired to pump down both receivers in less than 15 minutes. The actual pump down time is difficult to estimate because it depends on many factors (pumping orifice size, presence of multi-layer insulation (MLI), cleanliness of the surfaces, etc.). Nevertheless, a quick calculation shows that an empty volume of 130 liters will require a 2 l/s pumping speed to reach 10^{-2} mbar in approximately 14 minutes. The minimum pumping speed is therefore specified at 2 l/s, but a larger capacity is recommended.

Vacuum pump minimum base pressure	10^{-2} mbar
Minimum pumping speed	2 l/s

Table 1 - Minimum requirements for the vacuum pump.

5.2 Cryocooler Requirements

The Front End design description [AD05] presents the ngVLA receiver concept. A new type of feed-horn selected for Bands 3–6 has allowed all six frequency bands to be fitted in two cryostats. A thermal analysis done by Callisto [RD01] (Table 2) gives us preliminary numbers for heat loads on both cryostats.

Cold-Head	Dewar A (Band 1)	Dewar B (Bands 2–6)
1st stage	9.88 W at 50 K	18.4 W at 50 K
2nd stage	3.08 W at 15 K	4.3 W at 15 K

Table 2 - Calculated thermal loads for the ngVLA cryostats (ambient temperature 20°C and vacuum pressure 10^{-6} mbar).

These calculated values are preliminary and some load reductions are possible by receiver design optimization. The sensitive electronics need not be cooled down to 15 K to give the desired sensitivity; 20 K is the temperature limit that needs to be achieved by the second stage of the cryocooler.

Based on this information, the following cooling capacities for the refrigerator have been selected (Table 3):

- **1st stage:** The cold-head shall have enough cooling capacity on the first stage when running at maximum speed to absorb 20W of heat and maintain the stage temperature at 80 K or below.
- **2nd stage:** The cold-head shall have enough capacity on the second stage when running at maximum speed to absorb 5W of heat and maintain the stage temperature at 20 K or below.

Cold-head	Cooling capacity	Temperature	Speed
1st stage	20 W	80 K	60 Hz
2nd stage	5 W	20 K	60 Hz

Table 3 - Cold-head specifications.

5.3 Helium Compressor Requirements

The helium compressor shall have enough flow capacity to run two medium-size refrigerators at nominal speed, each with a flow requirement that does not exceed 20 scfm for a supply pressure of 300psi. Because the energy cost is a major concern for ngVLA, the power consumption of the helium compressor shall not exceed 5 kW when operating at 60 Hz.

Table 4 lists the compressor performance requirements.

Electrical supply	3 phase 200V 60 Hz
Power consumption	Max 5kW at 60 Hz
Ambient temperature	–30°C to 45°C
Flow at 60 Hz and 300 psi supply pressure	40 scfm min
Weight	< 150 kg
Maintenance	30,000 hours

Table 4 - Helium compressor specifications.

6 Mechanical Interfaces

The various mechanical interfaces described below will be documented in greater detail in future ICDs.

6.1 Receiver/Front End Mechanical Interface

Each Front End assembly is equipped with one cold-head that can be removed for service. However, the cylinder housing the cold-head displacer shall be permanently attached to the cryostat because it has many hardware connections to the rest of the Dewar assembly.

6.2 Antenna Mechanical Interface

6.2.1 Available Space on the Antenna Platform

The antenna platform shall provide a volume of L(1.8m) x W(1.75m) x H(1.2m) for the compressor.

6.2.2 Mechanical Interface with the Antenna Platform

The helium compressor will be installed on an antenna platform above the azimuth bearing but below the elevation axis. The platform shall support the weight of the compressor and service personnel with the required safety factor (TBD). The mounting brackets that attach the compressor to the platform shall support the mechanical stresses induced by antenna rotation at full speed, followed by maximum deceleration, and the force applied by high winds on the compressor outdoor unit. Table 5 lists the most important parameters.

Inclination	Within 5 degrees of horizontal
Slew	180 deg/min
Wind	Max 50 m/s
Magnetic field	≤ 150 Gauss
Weight (compressor plus 2 people)	350 kg

Table 5 - Mechanical limits for the compressor mount on the antenna platform.

6.3 Elevation Wrap and Helium Lines

The compressor is located on a platform behind the dish and above the azimuth bearing, and the Front End cryostats are located on a platform supported by the subreflector feedarm. The helium lines (two lines: one supply, one return) are run from the compressor to the receiver platform, through the elevation axis cable wrap. On the receiver platform, the supply line connects to a two-way manifold that splits the flow between the two refrigerators. A second two-way manifold recombines the refrigerator output flows into the return line. The helium lines shall be built with a combination of rigid seamless stainless steel tubing that is securely attached to the antenna structure and some flexible sections; see details below. The helium lines are part of the cryogenic subsystem, and their exact location and mounting points shall be described in a future antenna ICD.

6.3.1 Flexible Helium Lines

The various sections of flexible lines are described below:

- Between compressor and antenna platform, the flex-lines will allow easy connection to the compressor using Aeroquip 5400 series refrigerant couplings.
- Through the elevation wrap, a set of armored flex-lines will join the rigid sections of lines from the compressor platform and the sub-reflector feed harm. The armored flexible shell (Figure 1) will help maintain a uniform bending radius on the line through the elevation wrap, and will guarantee the

minimum bend radius is not exceeded. The life expectancy of the flex-lines shall exceed 20 years of antenna operation (number of flex cycles is TBD).

- Static bending radius 25 cm (10")
- Dynamic bending radius 70 cm (28")

- Between the antenna feedarm and receiver platform, the flex-lines will allow free translation of the receiver platform for band selection, and easy connection to the refrigerators mounted to the cryostats.

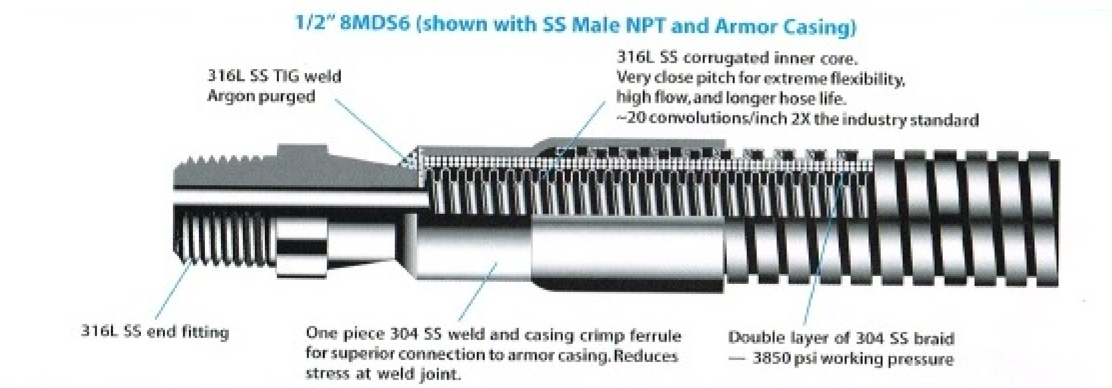


Figure 1 - Armored flex-line cross section view.

6.3.2 Rigid Helium Lines

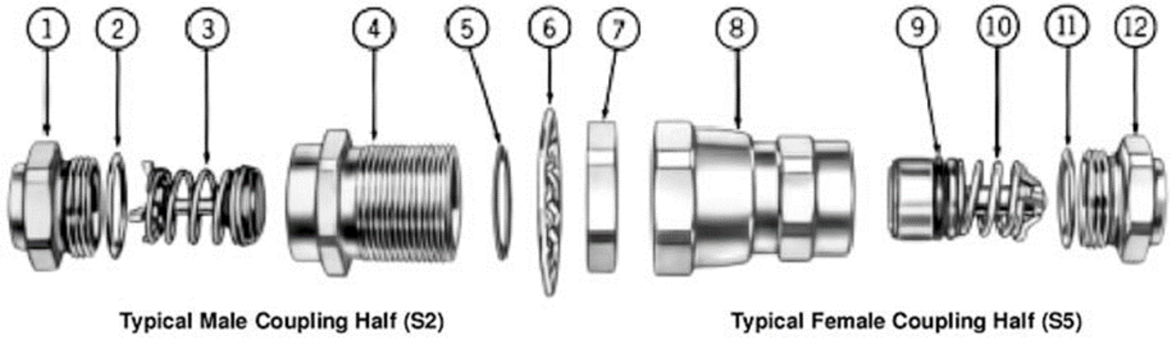
The rigid helium lines are made of seamless stainless steel ½" ID line, thoroughly cleaned inside to remove contaminants (oil and other chemical residues). The specified wall thickness is 0.065", with a working pressure of 4500 psig (e.g., Swagelok stainless steel seamless tubing).

6.3.3 Helium Line Fittings

The interconnection between two rigid lines will use Swagelok compression fittings (Figure 2).

Figure 2 - Swagelok fittings for rigid helium line connections.

The other connections will use Aeroquip 5400 series (or similar) self-sealing gas fittings (Figure 3), which are standard couplings for cryogenic equipment. The O-ring and gasket material shall be made out of butyl rubber, to meet the environmental requirement and avoid leaks in extremely cold weather conditions.



Component Part Numbers

Item No.	Dash Size ▸ / O.D. Tube Size ▸	–4 / 1/4"–3/8"	–8 / 1/4"–5/8"	–12 / 5/8"–7/8"	–16 / 7/8"–1 3/8"	Line Ref.
	Typical Male Half					1
1	Tubing Adapter	202208–*–4	202208–*–8	202208–*–12	202208–*–16	2
2	O-Ring	22546–12	22546–17	22546–23	22546–28	3
3	Poppet Valve Assembly	5400–S20–4	5400–S20–8	5400–S20–12	5400–S20–16	4
4	Body	5400–17–4	5400–17–8	5400–17–12	5400–17–16	5
5	Gasket Seal	22008–4	22008–8	22008–12	22008–16	6
6	Lock Washer	5400–54–4S	5400–54–8S	5400–54–12S	5400–54–16S	7
7	Jam Nut	5400–53–4S	5400–53–8S	5400–53–12S	5400–53–16S	8
	Typical Female Half					9
8	Union Nut and Body Assembly	5400–S16–4	5400–S16–8	5400–S16–12	5400–S16–16	10
9	O-Ring	22546–10	22546–112	22546–116	22546–214	11
10	Valve and Sleeve Assembly	5400–S19–4	5400–S19–8	5400–S19–12	5400–S19–16	12
11	O-Ring	22546–12	22546–17	22546–23	22546–28	13
12	Tubing Adapter	202208–*–4	202208–*–8	202208–*–12	202208–*–16	14

*Specify O.D. Tubing size of adapter required in 16th of an inch. Example: –4 coupling with 3/8" O.D. tubing is 6/16 or –6. Part number is then 202208–6–4.

Figure 3 - Aeroquip 5400 series couplings.

7 Electrical Interface

Table 6 shows the cryogenics subsystem electrical power requirements from the antenna. These requirements will be described in more detail in a future antenna ICD.

Description	Voltage	Current max breaker protection	Frequency	Power consumption
Single phase	120 (±5%) VAC	35 A	60 Hz	1 kW max
3 Phase Delta configuration, 5 wires Ph1, Ph2, Ph3 and Neutral plus GND	200 (±10%) VAC	25 A	60 Hz	5 kW max

Table 6 - Antenna power requirements.

8 Environmental Conditions and Corresponding Operating Modes

8.1 Site Elevation

The ngVLA core array will be located at the Very Large Array site, on the plains of San Agustin (elevation 2100 m). The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. The cryogenic subsystem shall be designed to operate at altitudes ranging from sea level up to 2500 m.

8.2 Limits of Operating Conditions

The cryogenic subsystem shall operate normally within the environmental limits listed in Table 7.

Parameter	Req. #	Value
Solar Thermal Load	ENV0321	Exposed to full Sun
Wind	ENV0331	W ≤ 15 m/s average over 10 min.; W ≤ 20 m/s gust
Temperature	ENV0332	–20 °C ≤ T ≤ 45 °C
Precipitation	ENV0333	5 cm/hr over 10 min
Ice	ENV0334	No ice accumulation on outdoor compressor unit

Table 7 - Operating conditions.

8.3 Survival Conditions

Outside of the operating condition limits (Table 8) some degradation in performance is acceptable.

Parameter	Req. #	Value
Wind	ENV0341	0 m/s ≤ W ≤ 50 m/s average
Temperature	ENV0342	–30°C ≤ T ≤ 50°C
Radial Ice	ENV0343	2.5 cm
Rain Rate	ENV0344	16 cm/hr. over 10 min
Snow load	ENV0346	100 kg/m^2 on horizontal surfaces
Hail stones	ENV0347	2.0 cm diameter

Table 8 - Survival conditions.

8.4 M&C Interfaces

The compressor M&C Module will be delivered with the Cryo M&C Enclosure. It shall control the helium compressor and both refrigerators as well as the vacuum pump. It will collect monitoring information from various sub assemblies but will only receive commands from the antenna M&C.

8.5 Monitoring Interfaces (Multicast on Ethernet Bus)

8.5.1 Interface with Front End M&C

The compressor M&C Module will use temperature and pressure information provided by the individual cryostat M&C Modules to adjust independently the speed of each cold-head. The temperature and pressure data will be multicast by the Cryostat M&C modules on the Ethernet bus.

8.5.2 Interface with Nearest Weather Station

The compressor M&C Module will use monitored information from the nearest ngVLA weather station to select or modify certain modes of operation. For example, the starting speed during the start-up procedure will be adjusted based on the ambient temperature. The weather station M&C module will multicast the data on the Ethernet bus, and the compressor M&C Module will subscribe to the data stream and collecting the information as needed.

8.6 Command Interface (Star Configuration Ethernet Bus)

8.6.1 Interface with Antenna Master M&C Module

The control messages to the compressor M&C Module will always come from the antenna master M&C module. Any other module that needs to send a control message to the compressor M&C Module will do so through the antenna master M&C module and reciprocally. The flow of control messages will use the Ethernet bus in star configuration with the antenna master M&C module as the central hub for the antenna.

8.7 Serial RS232/485 Communications

8.7.1 Interface with the Vacuum Pump Controller

For the reference design, the vacuum pump controller is located inside the cryo M&C enclosure. The compressor M&C module will communicate with the vacuum pump controller through a serial RS232/485 connection. A hardware interlock will prevent the pump from running if oil temperature is not within the manufacturer's recommended range.

8.7.2 Interface with the Helium Compressor

The compressor M&C module is located with the compressor power electronics (VFD) inside a shielded weather proof enclosure. The temperature and pressure sensors listed in Table 9 are placed in various locations inside the compressor outdoor unit. The compressor M&C module will communicate with the compressor outdoor unit and retrieve the information through a serial interface. The compressor information will be multicast by the compressor M&C module on the Ethernet bus to make it available to other modules.

Sensor type	Location
Temperature	
Ts	Scroll capsule
Tx	Oil heat exchanger input
Tr	Oil return line to Scroll capsule
Tg	Heat exchanger output gas
Tc	Coalescer input
Pressure	
Ps	Supply line
Pr	Return line
Frequency/speed	
Fc	Cooling fan speed
Current	
Is	Scroll capsule current
If	Fan current

Table 9 - Outdoor compressor monitor points.

8.8 SPI Communication with the Power Electronics

The cryo M&C enclosure will house the compressor M&C module and the power electronics (VFDs) and shelter them from the environment while also providing RFI shielding. The compressor M&C module will communicate with the power electronics that drives the compressor capsule and cold-heads via SPI Bus. Table 10, Table 11, and Table 12 show monitor points for compressor VFD and Dewars A and B.

Sensor type	Location
Frequency/speed	
F_{comp}	Speed scroll capsule
Current	
I_{comp1}	Compressor Scroll capsule current phase 1
I_{comp2}	Compressor Scroll capsule current phase 2
I_{comp3}	Compressor Scroll capsule current phase 3
Voltage	
V_{comp1}	Compressor Scroll capsule voltage phase 1
V_{comp2}	Compressor Scroll capsule voltage phase 2
V_{comp3}	Compressor Scroll capsule voltage phase 3

Table 10 - Compressor VFD monitor points.

Sensor type	Location
Frequency/speed	
F_{DWA}	Speed cold-head receiver Dewar A
Current	
I_{DWA-1}	Dewar A cold-head current phase 1
I_{DWA-2}	Dewar A cold-head current phase 2
Voltage	
V_{DWA-1}	Dewar A cold-head current voltage phase 1
V_{DWA-2}	Dewar A cold-head current voltage phase 2

Table 11 - Dewar A VFD monitor points.

Sensor type	Location
F_{DWB}	Speed cold-head receiver Dewar B
Current	
I_{DWB-1}	Dewar B cold-head current phase 1
I_{DWB-2}	Dewar B cold-head current phase 2
Voltage	
V_{DWB-1}	Dewar B cold-head current voltage phase 1
V_{DWB-2}	Dewar B cold-head current voltage phase 2

Table 12 - Dewar B VFD monitor points.

9 EMC/RFI Requirements

The digital electronics in the M&C modules and the high power switching electronics in the VFD drives require shielding from RFI emissions. The following sections describe the measures taken in this regard.

9.1 *Shielding of Compressor Outdoor Unit*

The compressor outdoor unit has a Scroll capsule that runs at variable speed due to a VFD located in the Cryo M&C Enclosure. The cable that carries the three-phase power between them will have to be shielded and have a ground connection at both ends.

9.2 *Shielding of Cryo M&C Enclosure*

The Cryo M&C Enclosure contains the compressor M&C interface LRU, the VFD LRUSs for the Scroll capsule, and the two cold-heads, as well as controllers for the cooling fan and vacuum pump. All the electronics listed above can generate RFI and must be contained within an RFI-tight enclosure(s). The connections to the M&C enclosure shall be done through special filtered connectors. The whole assembly must meet the VLA RFI requirements [AD07]. The validation of the shielded enclosure will be done in the VLA reverberation chamber with a specially designed test set.

10 Maintenance

10.1 Scheduled Maintenance

Scheduled maintenance will be performed on the cryogenics system when the antenna is being serviced (Table 13). Because of the large number of antennas, it is anticipated that one antenna will have a major overhaul every 35,000 hours.

Compressor Charcoal trap adsorber	≥ 35,000 hrs of operation
Compressor heat exchanger cleaning	≥ 35,000 hrs of operation
Compressor fan motor bearing replacement	≥ 35,000 hrs of operation
Cold-head replacement	≥ 35,000 hrs of operation
System static pressure recharge (He)	≥ 10,000 hrs (TBC)
Compressor oil refill	≥ 35,000 hrs of operation

Table 13 - Scheduled maintenance.

10.2 Onsite Maintenance

All scheduled maintenance (see Table 13) shall be performed at the site when the antenna is being serviced. Unscheduled repairs shall also be done at the site, unless it is a compressor failure that requires depressurization of the helium circuit to be fixed.

10.3 Maintenance at the Service Center(s)

All compressor repairs that require depressurization of the helium circuit shall be done at the service center(s). Cold-head overhaul shall also be done at the service center(s).

11 Shipping/Transport and Acceptance Test

11.1 Shipping from Manufacturer to Integration Center

The compressor shall be mounted on a wood pallet with tilt sensors and shock sensors to ensure safe delivery by truck and early detection of possible abuse.

11.2 Transport between Integration Center and Antenna

The compressor shall be transported from the integration center to the antenna in a truck equipped with a crane that will allow the compressor to be lifted up to the antenna platform.

11.3 Acceptance Test

The compressor shall be tested at the factory and delivered with a complete set of test data and a compliance report. The cold-heads shall also be tested at the factory and delivered with the load maps and the compliance reports.

The M&C enclosure will be tested in the reverberation chamber to ensure compliance with the VLA requirements. A recently-serviced compressor or cold-head will be tested at the integration center and will have to pass a series of acceptance tests prior to being released as a spare unit.

12 Appendix

12.1 Enclosure

For the reference design we are not considering an outside enclosure for the outdoor compressor unit; however, the possibility to add such an enclosure to the antenna platform will be evaluated during the design phase. Some parameters to consider for the enclosure include:

- Weather protection
    - Avoid snow/ice accumulation on compressor
    - Minimize exposure to rain water (corrosion)
    - Shield the cooling fan from high winds
    - Prevent damage from hailstorms
    - Reduce sun damage (UV)
- Impact on antenna design
    - Extra weight on platform
    - Extra volume on platform
    - Extra cost
    - Reduced accessibility
    - Increased maintenance time (enclosure must be removed to access compressor outdoor unit)

12.2 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ICD	Interface Control Document
LNA	Low Noise Amplifier
LRU	Line-Replaceable Unit
M&C	Monitor and Control
MLI	Multi Layer Insulation
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
RD	Reference Document
SPI	Serial Peripheral Interface
VFD	Variable Frequency Drive
VLA	Jansky Very Large Array