Cryogenic Subsystem Reference Design Description

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Change Record

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A	2019-07-24	A. Lear	All	Incorporate minor edits by M. McKinnon; prepare document for approvals and release

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1 Introduction

1.1 Purpose

This document provides a description for the cryogenic subsystem reference design. The purpose of the cryogenic subsystem is to cool the sensitive receiver electronics to reduce intrinsic thermal noise and maximize sensitivity. During the selection process emphasis was placed on power consumption and reliability as well as maintenance cost in order to meet the operating budget target.

1.2 Scope

The scope of this document is to present the complete cryogenic equipment selected for the ngVLA Reference Design. It starts with a hardware description of the pump, the refrigerator, and the compressor and it follows with the antenna interfaces requirements. The environmental conditons and the various mode of operation are also presented. The M&C interface with the rest of the control electronics is described in detail, but no budgetary information is listed.

1.3 Assumptions Made Regarding the ngVLA Cryogenics

The ngVLA cryogenics is directly related to the ngVLA Frontends. [AD05] describes the reference design for the ngVLA Front End. Based on this information, the cryogenics subsystem assumes two Dewars per antenna, each equipped with a two-stage Gifford McMahon (GM) refrigerator, with both connected to a single Helium compressor.

2 Related Documents and Drawings

2.1 Applicable Documents

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

Ref. No.	Document Title	Rev/Doc. No.
AD01	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	Monitor and Control Interface Layer: Preliminary Requirements & Design Description	020.30.45.00.00.0004-DSN
AD05	Front End Design Description	020.30.03.01.00-0003-DSN
AD06	Cryogenics Subsystem Requirements	020.30.10.00.00.0001-REQ
AD07	R. 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:

Ref. 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
RD03	Wootten, D. Urbain, W. Grammer and S. Durand, "The ngVLA Cryogenics," 231th AAS meeting, January 8–12 2018 National Harbor, MD	Poster session
RD04	D. Urbain, "ngVLA Cryogenics Subsystem Concept," URSI meeting, January 4–7, 2017, Boulder, CO	n/a
RD05	D. Urbain, W. Grammer, et al., "Improved Power Efficiency for Cryogenics at the VLA," ICC19 June 20–23 2016, San Diego CA	Cryocoolers 19, Edited by S.D. Miller and R.G. Ross Jr, pp. 505–511
RD06	D. Urbain, W. Grammer, S. Sturgis, "ngVLA Cryogenics Reference Design," ngVLA Reference Design Workshop, Socorro NM, July 2018; private communication	n/a
RD07	James Gregg, "MTBF Report on EVLA Cryogenics," NRAO, Socorro NM, 3/29/2016, Private Communication	n/a
RD08	Adixen_SD Pump Service Manual	Alcatel Vacuum Technology pp. 54-98, 2011

2.3 Vocabulary

In the following document, refrigerator, cold-head, and cryocooler represent the same piece of equipment. Dewar and cryostat are also interchangeable.

3 Overview of Subsystem Requirements

This document presents the design discription of the ngVLA cryogenic subsystem. The performance requirements for the cryogenics are driven by the Front End concept 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 budget by more than a factor of three. This is quite challenging considering that the project is aiming for about ten times the number of antennas.

In order 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 Key Experiments that Led to the Reference Design

4.1 The Green Antenna VFD Experiment

The Green Antenna initiative was initiated by the NRAO Socorro Electronics Division in 2015, with a goal of finding ways to reduce the power consumption and improve reliability of the VLA. The VFD experiment described in [RD05] demonstrated the speed of the refrigerators used to cool the Front Ends could be reduced, with limited impact on the temperature of the cooled electronics. Table 1 shows the temperature variations for six VLA Dewars as the refrigerator speed is reduced to 30 Hz in 5 Hz steps. This experiment was essential in showing that most of the VLA receivers do not require the full cooling capacity of their refrigerator after cooldown. In addition, a variable-speed refrigerator could reduce the total helium flow required from the associated compressor.

	C Band		X Band		Ku Band		K Band		Ka Band		Q Band	
Frequency	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K	D1st in K	D2nd in K
50 Hz	0.0	0.1	0.0	0.2	0.0	0.6	1.2	0.1	1.3	0.1	2.6	0.4
45 Hz	1.3	0.2	1.3	0.6	1.3	0.8	2.5	0.2	3.9	0.6	7.7	0.7
40 Hz	**2.6**	**0.3**	**2.6**	**0.8**	**1.3**	**1.2**	**3.8**	**0.4**	**5.2**	**1.2**	**12.8**	**1.8**
35 Hz	5.2	1.2	5.1	2.0	2.6	3.1	5.1	0.6	3.9	4.4	17.9	2.6
30 Hz	7.8	1.3	9.0	2.5	3.9	5.6	9.0	1.1	7.8	6.0	33.0	7.7

Table 1 - Results of the VFD experiment at the VLA.

4.2 The Variable-Speed Compressor Experiment

This experiment used a Quantum Design HAC4500 helium compressor equipped with a commercial inverter, to show how the speed of the compressor could be adjusted to meet the flow requirement as the number of refrigerators connected to it increases. Figure 1 [RD03] shows the results of the experiment. As the number of refrigerators drops, the demand for pressurized helium from the compressor is reduced and the speed of the motor can be lowered. When the motor slows down, its power consumption drops, and the operating cost is reduced proportionally.

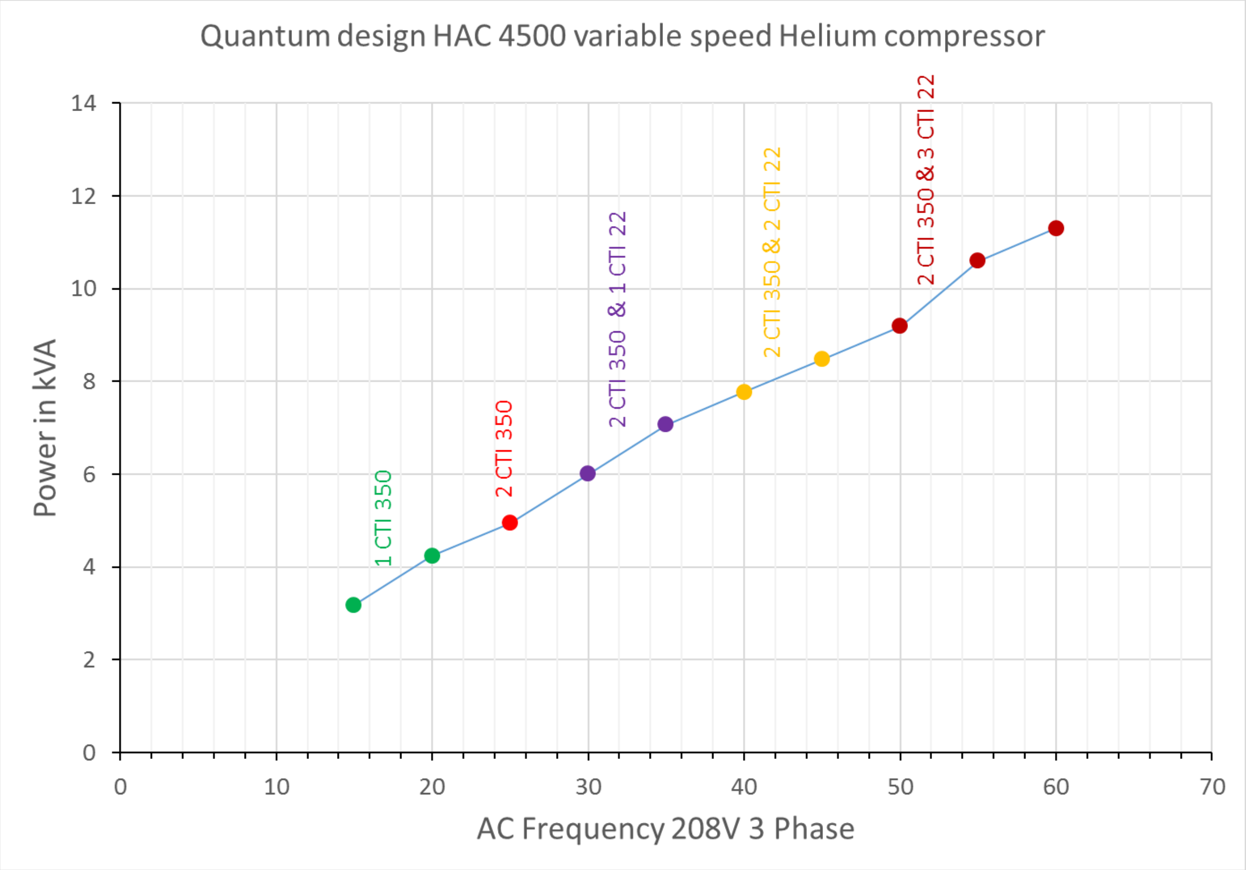


Figure 1 - Variable-speed compressor: capacity and power consumption vs. speed.

4.3 How Reliability is Linked to Operating Frequency

The two experiments described above were key to development of the ngVLA cryogenic reference design, and address how operations cost can be reduced by lowering power consumption. However, speed reduction has the added benefit of reducing mechical wear and improving associated reliability. This was clearly seen in the VLA maintenance data collected over several years [RD07]. The data did show a direct correlation between the refrigerator MTBF and their operating speed: a Model 22 refrigerator operates at 200 rpm, while a Model 350 runs at 72 rpm, and the maintenance interval for the Model 350 is on average three times longer than the Model 22.

4.4 Comparison of VLA and ngVLA Reference Design

Table 2 shows a direct comparision between the VLA and the ngVLA reference design. The data come from a VLA maintenance survey and from power measurements conducted on a prototype compressor and published in [RD02]. The maintenance index is a normalized reliability measure, based on VLA maintenance data, and scaling with total number of refrigerators. For instance, a single Model 350 refrigerator in the VLA run at full speed (60 Hz) has an index of 1, while a single Model 22 has an index of 3. The ngVLA reference design calls for running Model 350 refrigerators at 40 Hz, or 2/3 their nominal speed, so their associated index is 0.66. These indices are used to then estimate total maintenance effort based on number of refrigerators and their respective operating speeds, in both the VLA and ngVLA.

	VLA	ngVLA Reference Design	Ratio (ngVLA to VLA)
Number of Antennas	27 x 25m	214 x 18m + 19 x 6m + 30 18m	9.74
Helium Compressor	3 x 27 = 81	1 x 263 = 263	3.25
AC Power Consumption	81 x 6 = 486kW	263 x 3.75 = 986kW	2.03
Cryocoolers Per Antenna	1 x Model 22, 6 x Model 350, 1 x Model 1050	2 x Model 350	n/a
Total Number of Cryocoolers	27 x 8 = 216	263 x 2 = 526	2.43
Estimated Cryocooler Maintenance Index	27 x (1 x 3 +6 x 1+1 x 1) = 270	263 x (2 x 0.66) = 350	1.3

Table 2 - Comparison of VLA and ngVLA reference design.

The table shows that while the ngVLA has almost 10 times the number of antennas, the estimated energy cost from the cryogenic equipment should only double, and the maintenance required (and associated cost) is only 1.3 times that of the VLA. These numbers show that the reference design is well within the operating cost that was set initially for the ngVLA proposal.

5 Monitor and Control Interfaces

The cryogenic subsystem (Figure 2) is composed of the cryo M&C enclosure (compressor M&C [F525], compressor VFD, Dewar A VFD, Dewar B VFD and vacuum pump controller), the vacuum pump, the compressor outdoor unit, and the Dewar A and B cold-heads. The cryo M&C enclosure shall control the helium compressor and the vacuum pump, and drive both refrigerators. It will collect monitoring information from the weather station and the Front End M&C modules (F521 and F522), but will only accept commands from the antenna M&C module (M500).

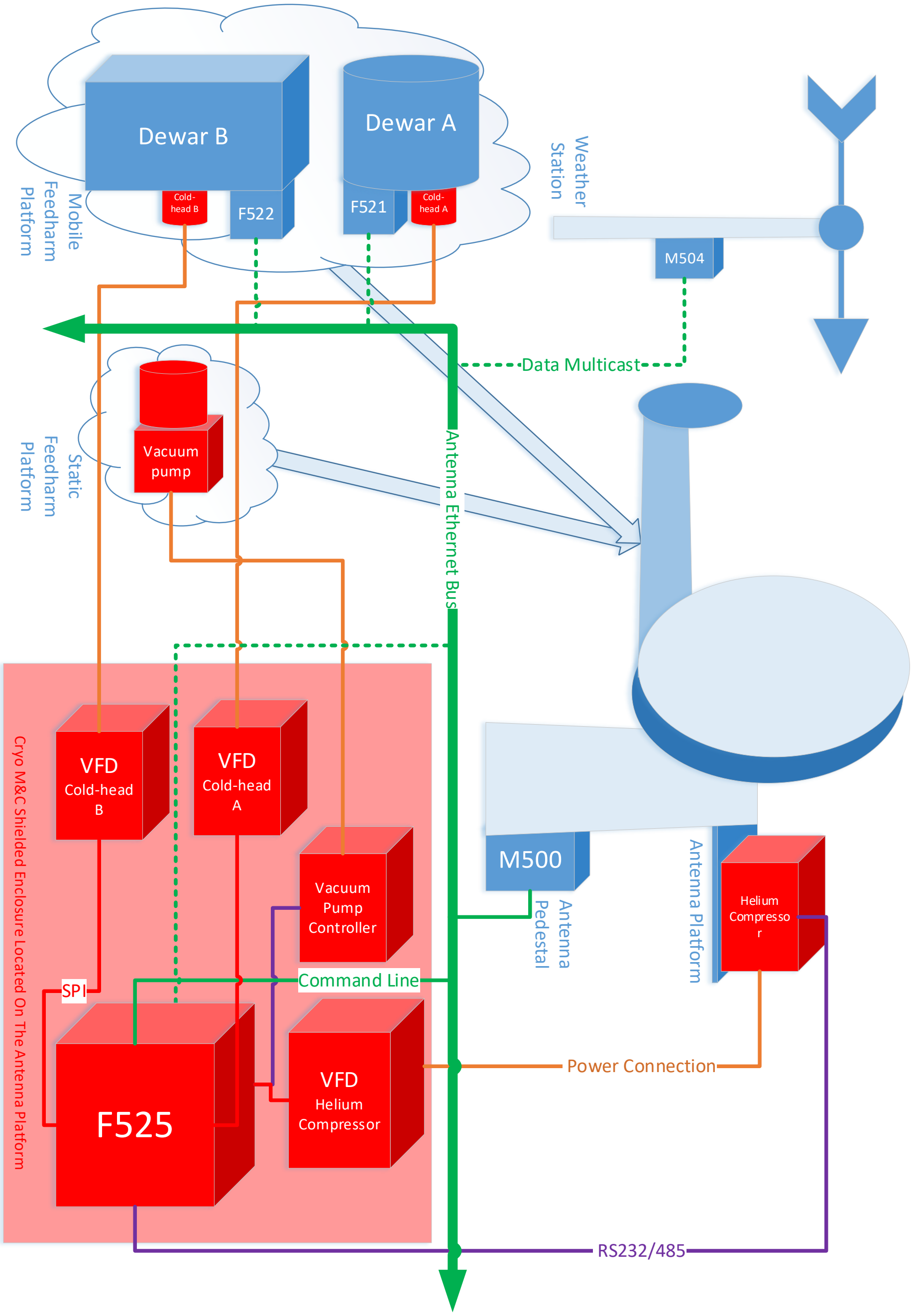


Figure 2 - Cryogenics Monitor and Control subsystem block diagram.

5.1 Monitoring Interfaces (Multicast on Ethernet bus)

5.1.1 Interface with Front End M&C

The compressor M&C (module F525) will use temperature and pressure information provided by individual cryostat M&C modules (F521, F522) to adjust independently the speed of each cold-head. Temperature and pressure data will be multicast by the F521 and F522 modules on the Ethernet bus and the F525 will collect the information stream directly.

5.1.1.1 F521 Dewar A Interface Module

The following values shall be monitored by the F521.

Dewar A	**Location**
Band 1	
$T_{b1\text{-}1}$ Temperature 1st stage	Feed
$T_{b1\text{-}2}$ Temperature 2nd stage	LNA
V_{d1} Vacuum pressure	Dewar A base plate
V_{p1} Vacuum pressure	Vaccuum manifold

Table 3 - F521 Dewar A monitor points.

5.1.1.2 F522 Dewar B Interface Module

The following values shall be monitored by the F522.

Dewar B	**Location**
Band 2	
$T_{b2\text{-}1}$ Temperature 1st stage	Radiation shield
$T_{b2\text{-}2}$ Temperature 2nd stage	LNA band 2
Band 3	
$T_{b3\text{-}2}$ Temperature 2nd stage	LNA band 3
Band 4	
$T_{b4\text{-}2}$ Temperature 2nd stage	LNA band 4
Band 5	
$T_{b5\text{-}2}$ Temperature 2nd stage	LNA band 5
Band 6	
$T_{b6\text{-}2}$ Temperature 2nd stage	LNA band 6
V_{d2} Vacuum Pressure	Dewar B base plate
V_{p2} Vacuum pressure	Vacuum manifold

Table 4 - F522 Dewar B monitor points.

5.1.2 Interface with the Nearest Weather Station

The compressor M&C 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 selected weather station M&C module (M504-xx, Table 5) will multicast the data on the Ethernet bus, and the F525 module will subscribe to the data stream and collect the information as needed.

5.1.3 M504 Weather Station Module

Environmental conditions	
T_{amb} Outside temperature	Weather station
W_{spd} Wind Speed	Weather station

Table 5 - M504 weather station monitor points.

5.2 Command Interface (Star Configuration Ethernet Bus)

5.2.1 Interface with Antenna Master M&C Module

The control messages to the compressor M&C will always come from the antenna master M&C module (M500). Any other module that needs to send a control message to the F525 will have to send it through the M500 and reciprocally. The flow of control messages (Table 6) will use the Ethernet bus in a star configuration with M500 as the central hub for the antenna.

Heat Dewar A	Turn on the heater inside Dewar A
Heat Dewar B	Turn on the heater inside Dewar B
Start Pump	Start the vacuum pump
Pump Dewar A	Open Dewar A solenoid vacuum valve
Pump Dewar B	Open Dewar B solenoid vacuum valve
Start Compressor	Start Helium compressor
Cool Dewar A	Start cold-head Dewar A
Cool Dewar B	Start cold-head Dewar B
Stop Pump	Stop vacuum pump
Stop Compressor	Stop Helium compressor
Standby Dewar A	Put the Dewar A in stanbby mode
Standby Dewar B	Put the Dewar B in standby mode
Close Solenoid Dewar A	Close Dewar A solenoid vacuum valve
Close Solenoid Dewar B	Close Dewar B solenoid vacuum valve

Table 6 - List of cryogenic commands from antenna master M&C module.

5.3 Serial RS232/485 Communications

5.3.1 Interface with the Vacuum Pump Controller

For the reference design, the vacuum pump controller (Table 7) 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 the oil temperature is not within the manufacturer's recommended range (Table 8).

T_{pump} Temperature of vacuum pump	Physical temperature of the pump. Must be within range to start the pump.
P_{vl} Pressure vacuum line	Pressure between the pump and the receiver vacuum manifolds.

Table 7 - Vacuum pump monitor points.

Heat vacuum pump	Turn on heater backing pump to bring its temperature within operating range
Start pump	Turn on the pumps
Stop pump	Turn off the pumps

Table 8 - Vacuum pump list of commands.

5.3.2 Interface with the Helium Compressor

The compressor M&C module (F525) 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 F525 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	
T_s	Scroll capsule
T_x	Oil heat exchanger input
T_r	Oil return line to Scroll capsule
T_g	Heat exchanger output gas
T_c	Coalescer input
Pressure	
P_s	Supply line
P_r	Return line
Frequency/speed	
F_c	Cooling fan speed
Current	
I_s	Scroll capsule current
I_f	Fan current

Table 9 - F525 compressor M&C module monitor points.

5.4 *SPI Communication with the Power Electronics*

The cryo M&C enclosure will house the compressor M&C module (Table 10) and power electronics VFDs (Table 11, Table 12), and will shelter them from the environment while providing RFI shielding. The compressor M&C module will communicate with the power electronics that drive the compressor capsule and the two cold-heads via SPI Bus (Table 13, Table 14, Table 15).

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.

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 voltage phase 1
V_{DWA-2}	Dewar A cold-head voltage phase 2

Table 11 - Dewar A VFD monitor points.

Frequency/speed	
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 voltage phase 1
V_{DWB-2}	Dewar B cold-head voltage phase 2

Table 12 - Dewar B VFD monitor points.

Start Scroll	Start Scroll capsule
Scroll Speed	Set speed of the Scroll capsule
Stop Scroll	Stop Scroll capsule

Table 13 - List of SPI commands with compressor VFD.

Start DWA	Start Dewar A cold-head
DWA speed	Set speed of Dewar A cold-head
Stop DWA	Stop Dewar A cold-head

Table 14 - List of SPI commands with Dewar A VFD.

Start DWB	Start Dewar B cold-head
DWB speed	Set speed of Dewar B cold-head
Stop DWB	Stop Dewar B cold-head

Table 15 - List of SPI commands with Dewar B VFD.

6 Operational Performance Requirements

6.1 *Vacuum Pump Requirement*

The purpose of the vacuum pump is to remove the 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, there is a minimum vacuum required before the refrigerator can be started. If this threshold is not reached, the thermal loading is high enough to overcome its cooling power, preventing the electronics from reaching the desired temperatures. 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.

The Front End concept for ngVLA 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 (Table 16). 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 16 - Minimum requirements for the vacuum pump.

6.2 *Onboard Vacuum Pump*

The antenna will be equipped with a vacuum pump powerful enough to evacuate the Front End cryostats below the 10^{-2} mbar pressure limit required to start the cryocoolers. A combination of a roughing pump and turbo pump was initially considered, but the overall cost was too high and not justified on the antenna. A simpler dual-stage rotary vane pump will provide the vacuum required to start the refrigerator, and will cost less than half as much.

It is important to note that an oil pump will introduce some restriction on the antenna movement while in operation, because oil could spill out of the vent port if tilted to certain orientations. A solenoid valve that can be remotely operated will provide the vacuum seal between the pump and the cryostat. The valve will be computer controlled to open during cool down but to close as soon as the Dewar pressure goes below 2.0 x 10^{-3} mbar, at which point the cryo pumping by the refrigerator becomes more efficient than a mechanical pump. This is very important to avoid back streaming and contamination of the vacuum space with oil. A second solenoid valve is placed at the exhaust port to backfill the pump and vacuum line when the pump is turned off, to prevent the vacuum from sucking oil through the inlet port and into the line.

The vacuum pumps commercially available are designed to operate in a controlled environment and have a limited temperature range for operation. For example, the viscosity of the oil will change with the ambient temperature, affecting the performance of the pump or possibly causing premature failure if the pump is run outside its recommended operating range. The pump and control electronics should also be protected from rain or any excess moisture, and if the temperature of the enclosure is not controlled, a heating blanket should be used to warm up the oil in the pump before a cold start-up.

For the reference design, the Alcatel rotary vane vacuum pump model Adixen 2015SD was selected. The basic specifications are listed in the Table 17. The pump will be equipped with the oil level switch (OLS36) and the oil mist eliminator (OME 25HP) combined with the oil drain kit (ODK 2). The first option will monitor the oil level, while the second kit will help with the recovery of the oil that accumulates in the mist eliminator when the pump operates at high pressure [RD08].

Voltage	120 VAC @ 60 Hz
Startup current at 12°C	35A (recommended fuse protection 20A)
Current at maximum flow	5.7A
Power	3/4 HP, 0.55 kW
Rotation speed	1800 rpm @ 60Hz
Pumping speed	10.6 cmf / 5 l/s
Base pressure closed gas ballast	2.0 x 10^{-3} mbar
Environment storage	–5°C to +40°C
Operating (mineral oil)	+12°C to +40°C
Maximum relative humidity	80% up to 30°C decrease linearly to 50% at 40°C

Table 17 - Alcatel Adixen 2015SD vacuum pump specifications.

6.3 *Vacuum Pump Equipment for the Integration Center and Service Vehicle*

When a Front End cryostat is assembled for the first time or after being opened for repair, it is recommended to run the pump for an extended period to remove as many contaminants as possible and allow some of the internal components to outgas. It is therefore recommended to use a turbo pump with a scroll backing pump at the Front End integration center, to achieve a much lower cryostat pressure before cool down. In addition to a powerful vacuum pump, a heating blanket might be used to accelerate the outgassing of the Dewar walls, and obtain a better vacuum in a reduced amount of time.

For the integration center, we have selected the Agilent Varian vacuum system with TwistTorr 304FS turbo and TS 300 dry scroll pump. Table 18 lists the key specifications.

Voltage	120 VAC @ 60Hz
Power	450 VA max
Scroll pumping speed	8.8 cfm / 4.15 l/s
Scroll TS 300 Base pressure	1.3 x 10^{-2} mbar
TwisTorr 304FS max frequency	1350 Hz
TwisTorr 304Fs pumping speed	180 l/s
TwisTorr 304FS Base pressure	1.0 x 10^{-10} mbar
Environment storage	–20°C to +70°C / 0–95% humidity
Operating	+5°C to +4 °C / 0–90% humidity

Table 18 - Agilent TwisTorr 304FS turbo pump system.

6.4 *Cryocooler Requirements*

The Front End Design Description [AD05] presents the ngVLA receiver concept. A new type of feed-horn selected for Bands 3–6 allows all six frequency bands to fit in two cryostats. A thermal analysis done by Callisto [RD01] (Table 19) gives us preliminary numbers for the 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 19 - Calculated thermal loads for the ngVLA cryostats (ambient temperature 20°C and vacuum pressure 10^{-6} mbar).

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

- **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 20 - Cold-head specifications.

6.5 Cold-Head Selection

Several GM refrigerators on the market have the required cooling capacities, but fewer are designed to operate at variable speed. For the ngVLA reference design, we selected the Trillium 350CS (Figure 3; Table 21) because it has the right cooling capacities and can run at variable speed. This model has been used at the VLA for many years and has demonstrated good reliability. It is easy to maintain and could be repaired in-house at very reasonable cost in parts and labor: estimated at ~$250 and six hours, respectively [RD07].

Figure 3 - Trillium 350CS refrigerator.

Cold-head	Trillium 350CS
1st stage cooling capacity	20 W
2nd stage cooling capacity	5 W
Flow	12.5 scfm
Weight	22lbs

Table 21 - Trillium 350CS specifications at 60 Hz.

6.6 *Helium Compressor Requirements*

The helium compressor shall have enough flow capacity to run two Trillium 350CS refrigerators at nominal speed. Because energy cost is a major concern for ngVLA, the power consumption of the helium compressor shall not exceed 5kW when operating at 60 Hz. The Trillium 350CS has an estimated flow of 12.5 scfm when operating at 60 Hz [RD07]. Table 22 lists the performance requirements.

Compressor Speed	Supply pressure	Return pressure	Flow	Power
60 Hz	300 psi	<100 psi	>30 scfm	<5kW

Table 22 - Helium compressor specifications at 60Hz.

6.7 *Helium Compressor Selection*

The Scroll capsules that are used in modern helium compressors are manufactured mostly by two companies, Hitachi and Copeland, and are only available in a limited range of sizes. Numerous companies on the market use their Scroll capsules to build helium compressors for the cryogenic market. However, only a very limited number of these are designed for outdoor application. Because the radio astronomy market is small in comparison with the medical field (MRI) and the semiconductor industry (sputter deposition), the development of a custom model designed from the ground up for outdoor use would be cost prohibitive, especially given the limited applications for such an item.

For the reference design, the solution was to enter into a collaborative effort with Sumitomo SHI in Allentown, PA, to suitably modify one of their existing products. Basically, they took their mid-size compressor model, the FA-40, and added a commercial VFD for variable-speed operation. The flow and power measurements done at the factory on this hybrid unit have shown it has the right capacity for our application (Figure 4).

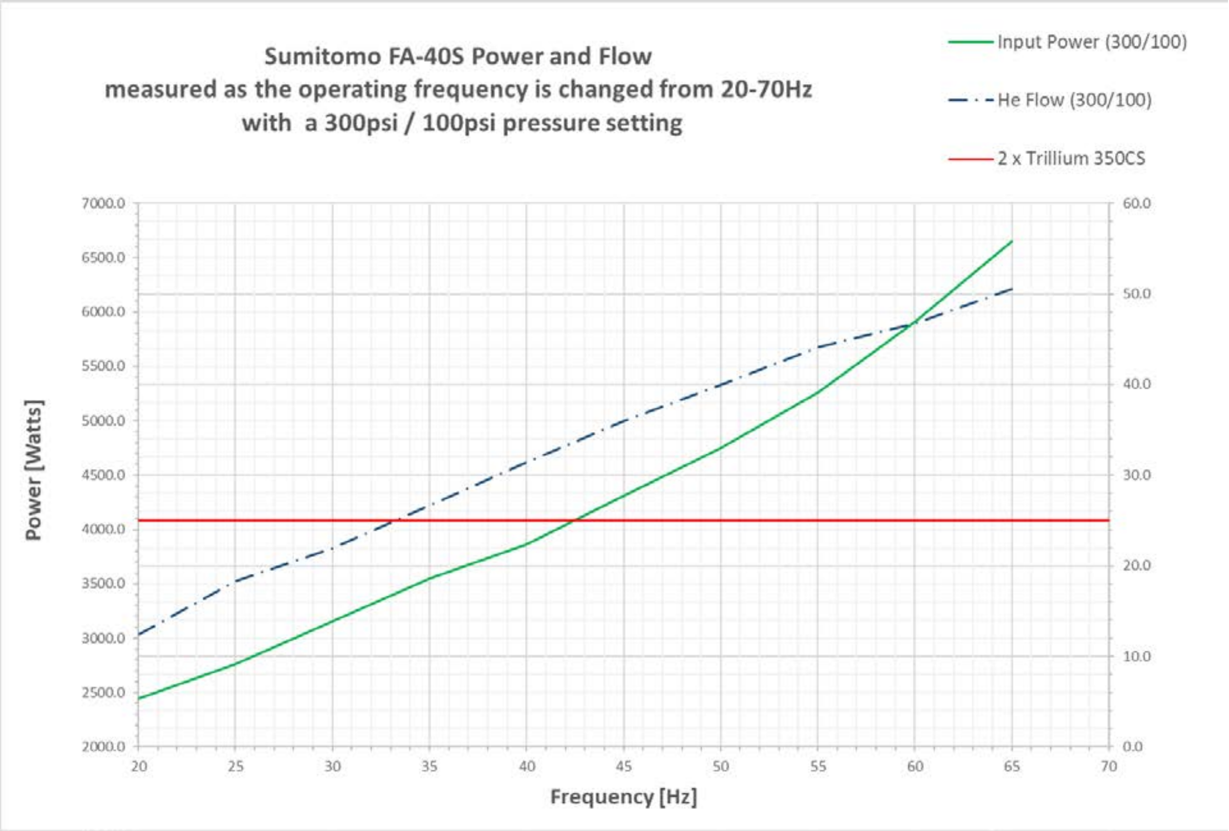


Figure 4 - Sumitomo FA-40 helium compressor flow and power measurement versus VFD operating frequency, 20-70 Hz.

The second phase of the collaboration will integrate the FA-40 compressor capsule within the outdoor enclosure developed for the FA-70 model (Figure 5), to create the first ngVLA helium compressor prototype (model “FA-40S”).

Figure 5 - Sumitomo FA-70 outdoor enclosure.

Table 23 lists the preliminary specifications for the modified FA-40 compressor.

Model	FA-40S
Electrical supply	3-phase 200V at 60 Hz
Power consumption	4.8 kW at 60 Hz
Flow capacity	49.2 scfm at 60 Hz *
Cooling Air	22 m^3/min at 60 Hz **
Maintenance Interval	35,000 hours
Ambient temperature	-30°C to 45°C **

Table 23 - Sumitomo FA-40S specifications. Notes: * data from Copeland catalog, ** data from Sumitomo FA-70 compressor specifications.

7 Mechanical Interfaces

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

7.1 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. The mechanical interface for the Trillium 350Cs is described below and shown in Figure 6.

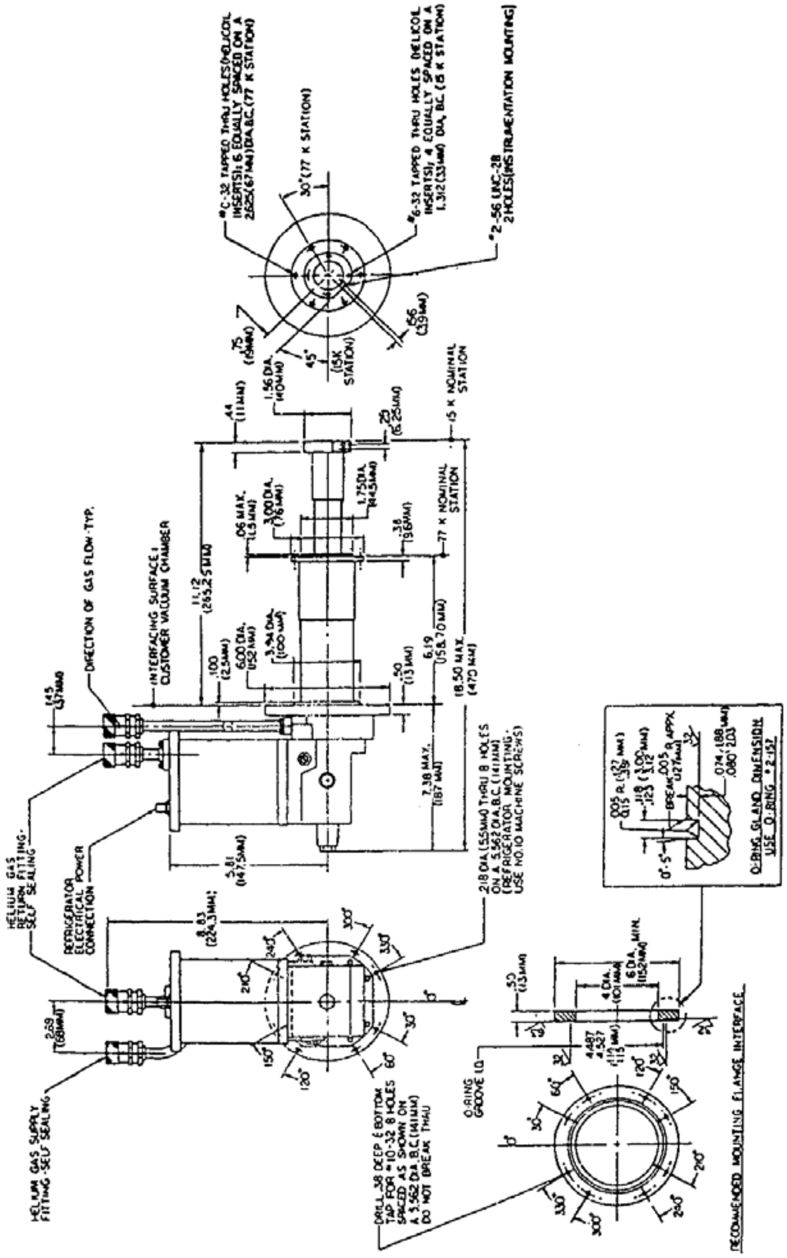


Figure 6 - Cold-head mechanical interface with cryostat.

7.2 Antenna Mechanical Interface

7.2.1 Required Space on the Antenna Platform

The antenna platform shall allow a 30 cm space behind the compressor outdoor unit for air suction, and a 100 cm space in front of the heat exchange for air discharge. An additional 15 cm space on the left side and 50 cm space on the right side shall be available; see Figure 7.

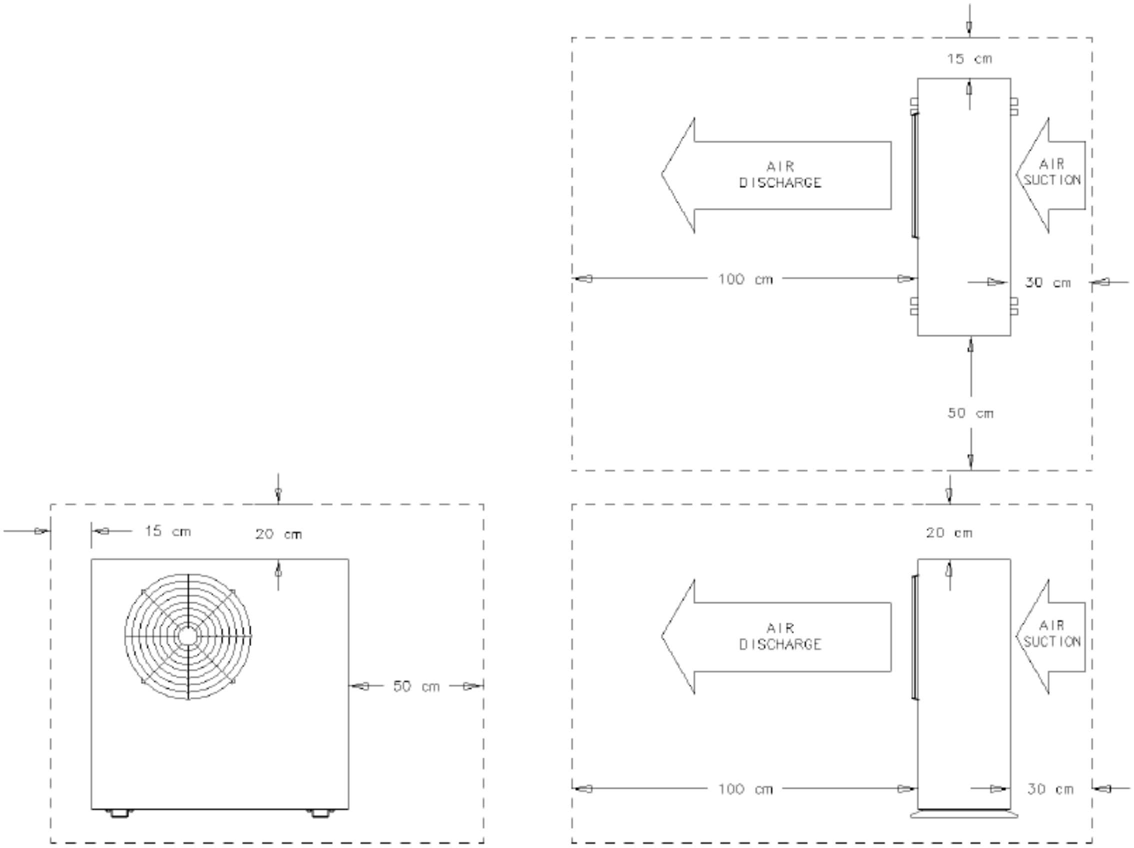


Figure 7 - Compressor space requirements on the antenna platform.

7.2.2 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 rotation of the antenna at full speed, followed by maximum deceleration, and the force applied by high winds on the compressor outdoor unit. Table 24 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	≤ 150 kg

Table 24 - Mechanical limits for the compressor mount on the antenna platform.

7.2.3 Compressor M&C Enclosure Interface

The compressor M&C enclosure contains the Control and Power electronics for the cryogenics subsystem. It will be located on the antenna platform and have a cold plate where glycol is circulating for cooling.

7.3 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.

7.3.1 Flexible Helium Lines

The various sections of flexible line are specified as follows:

- 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 8) 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.

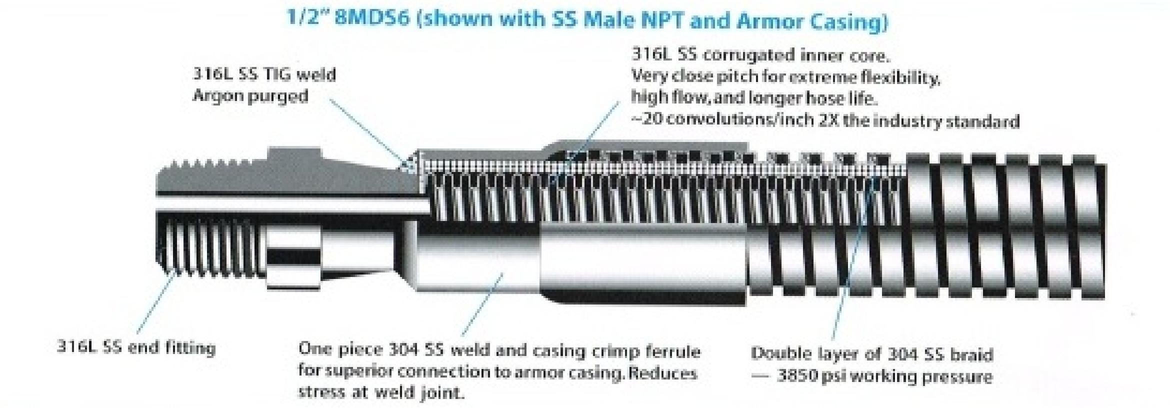


Figure 8 - Armored flex-line cross-section view.

7.3.2 Rigid Helium Lines

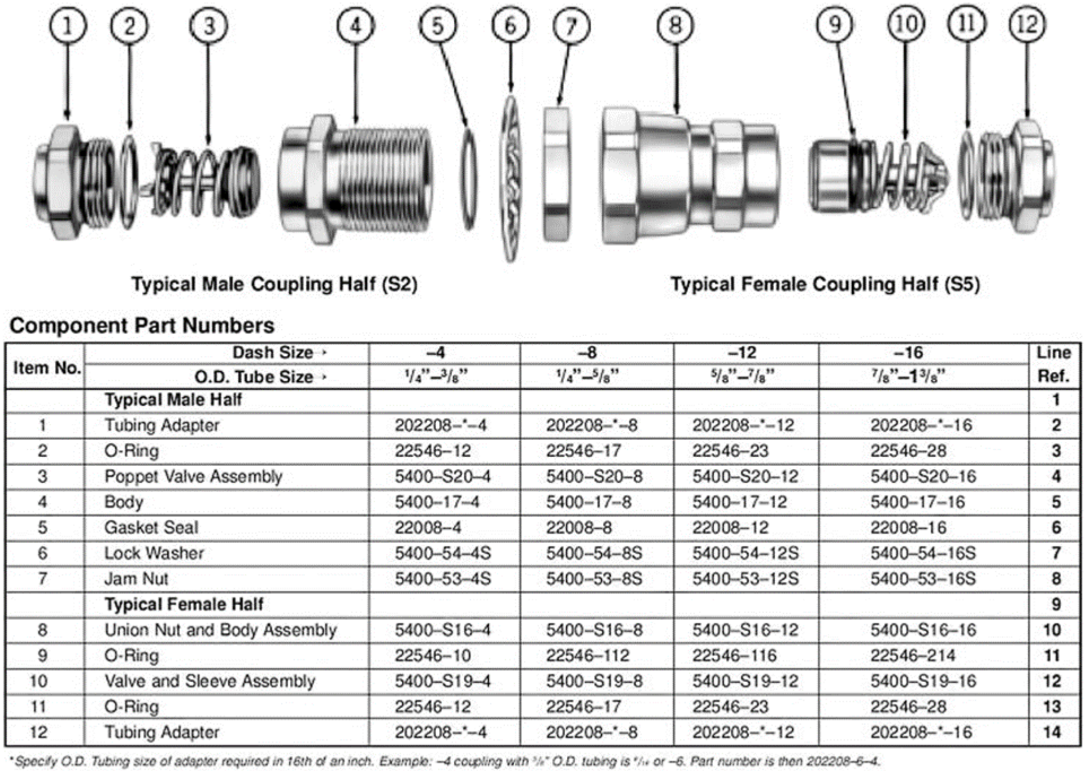
The rigid helium lines are made of seamless stainless steel 0.5” ID line that have been thoroughly cleaned inside to remove contaminants (oil and other chemical residues). The specified wall thickness is 0.065” with a working pressure of 4500 psig (Swagelok stainless steel seamless tubing).

7.3.3 Helium Line Fittings

The interconnection between two rigid lines will use Swagelok type compression gas fittings (Figure 9).

Figure 9 - Swagelok fittings for rigid helium lines.

The other connection will use Aeroquip 5400 series self-sealing gas fittings (Figure 10), standard for cryogenic equipment. The O-ring and gasket material shall be made out of butyl rubber to meet environmental requirements and avoid leaks in extremely cold weather conditions.



Component Part Numbers

Item No.	Dash Size ›	–4	–8	–12	–16	Line
	O.D. Tube Size ›	1/4"–3/8"	1/4"–5/8"	5/8"–7/8"	7/8"–1 3/8"	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 10 - Aeroquip 5400 series couplings.

8 Electrical Interface

The cryogenics subsystem electrical power requirements from the antenna are shown in Table 25. The electrical power requirements will be described in more detail in a future antenna ICD.

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

Table 25 - Cryogenic subsystem power requirements.

9 Environmental Conditions and Corresponding Operating Modes

9.1 Site Elevation

The ngVLA will have a core array 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.

9.2 Limits of Operating Conditions

The cryogenic subsystem shall operate normally within the environmental limits listed in Table 26.

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

Table 26 - Normal operating conditions.

9.3 Survival Conditions

Subsystem survival conditions are detailed in Table 27. Outside of the limits of the operating conditions, some degradation in performance is acceptable. It is difficult to address every possible weather condition, but we can review a few scenarios and describe how the cryogenic subsystem is expected to respond.

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 27 - Survival conditions.

9.3.1 Extreme Heat

When the ambient temperature rises above 45°C the compressor might have difficulties maintaining the temperature of the Scroll capsule within the operating range. The cooling fan in front of the compressor's heat exchanger operates at variable speed: as the oil temperature increases with outside temperature, the compressor control electronics ramps the fan speed up to maximum. If the cooling fan is not capable of maintaining the system temperature below the upper limit, the speed of the Scroll capsule shall be decreased slowly to reduce the heat dissipation. The compressor M&C module will adjust the speed of the two cold-heads accordingly to maintain the delta pressure (Supply pressure minus Return pressure) and keep both receivers as cold as possible.

In an extreme case, the internal thermal protection will shut down the compressor to protect the Scroll capsule from overheating. The compressor will re-start automatically when the temperature drops below a manufacturer preset value. However, the compressor M&C will disable the compressor auto-restart if the ambient temperature is too high, in order to avoid repetitive ON/OFF cycles.

9.3.2 Extreme Cold

When the ambient temperature drops below –20°C, keeping the Scroll capsule properly lubricated might be problematic. The compressor M&C shall use information from internal temperature sensors and the nearest weather station to control the cooling fan. The fan cools the Helium and the oil that runs through the heat exchanger: when the fan slows down the cooling efficiency of the system drops and the temperature of the oil and helium gas should rise.

If stopping the fan is not enough to keep the oil temperature within range, the compressor M&C will need to start reducing the speed of the refrigerators. This is because when the cold-heads run slower, less helium gas flows through the lines that are exposed to the cold weather and more gas is recirculated internally, which should raise the internal system temperature. In very extreme conditions, both refrigerators may need to be turned off completely, to allow the compressor to run in bypass mode.

As a last resort, the compressor M&C might have to lower the speed of the Scroll capsule and bypass the heat exchanger to keep the Scroll capsule running. As long as the capsule is running and some oil is circulating, the time to get the system operational again when the weather improves is minimized.

9.3.3 Extreme Wind

In extreme wind conditions, the antenna will be parked and observing suspended. It is unlikely that high winds could damage the cooling fan, but the compressor M&C monitors the fan current and will power it off if needed. If the fan is turned off, the compressor will rely on the wind to cool the heat exchanger. The compressor M&C will then use the wind speed information provided by the weather station and the internal monitor points to adjust the speed of the capsule and the cold-heads.

Note: It is recommended an outdoor enclosure be placed over the helium compressor for protection against heavy rain, hail storms and high winds, and to avoid snow and ice accumulation directly on the structure.

10 Modes of Operation

10.1 Start-Up Mode

The start-up procedure will depend on the ambient temperature. The compressor M&C will use environmental data provided by the nearest weather station and internal monitor points to set the Scroll capsule start-up speed, and will determine if the heat exchanger should be bypassed or not. As the oil temperature increases, the scroll capsule speeds up and the oil starts flowing through the heat exchanger. The compressor M&C starts the cooling fan and adjusts its speed as needed. When the compressor is fully operational and ready, the cold-heads can be started.

10.2 Cool-Down Mode

The cool-down mode is also the high power mode. The Cool command is sent by the antenna M&C and the compressor M&C to start the cold-heads: they are initially run at maximum speed to minimize the cool down time. The compressor capsule speed and fan speed are adjusted to provide the right amount of flow at the right pressure in order to maintain optimum cooling efficiency. This is the phase when the power consumption is the highest.

10.3 Observing Mode

Observing mode starts when the cryostats are cold and ready for science. The individual Front End M&C modules relay temperature information to the compressor M&C that controls the speed of the cold-heads and the Scroll capsule. The system will constantly adjust the speed of the compressor and the refrigerators to maintain the sensitive electronics at the required temperature, and at the same time minimize the power consumption.

10.4 Warm-Up Mode

To warm up a cryostat to service its cold-head, or to replace it with a spare unit, it is sufficient to stop the cold-head drive. If both systems are turned off simultaneously, the compressor can be switched off. In cold weather, if the system will be down for a limited time, the compressor could be left running in bypass mode at low speed to keep the oil warm and minimize start-up time.

10.5 Recovery Mode

We consider recovery mode any start-up procedure after the cryogenics subsystem suffers an unscheduled shutdown. This situation is usually due to loss of power to the compressor. The compressor M&C will analyze its monitor points and collect information about environmental conditions to determine if it is safe to proceed with the start-up procedure.

10.6 Stand-By Mode

A cryostat may be placed in stand-by mode when it is not scheduled for observations for a period of time (length TBD). The antenna M&C directs the compressor M&C to run the cryostat warmer by slowing down the refrigerator(s). The second-stage temperature is nevertheless kept below 30 K to maintain active cryo pumping and prevent vacuum run-away. Stand-by is the lowest power mode, and is not considered an observing mode. The cryogenic subsystem shall be able to transition to observing mode in less than 30 minutes (TBC). The stand-by mode could be total, when both cryostats are not used or partial if only one of the cryostats is not needed.

10.7 Bypass Mode

Bypass mode is active in extremely cold weather conditions, when the Front End and other antenna subsystems are non-operational. In this mode, both cold-heads are turned off to keep the compressor oil warm and minimize start-up time when weather conditions improve. Bypass mode could also be used for troubleshooting and monitoring the compressor performance. In this mode, the helium is recirculating inside the compressor through an internal bypass valve.

11 EMC/RFI Requirements

The digital electronics in the M&C modules and high-power switching electronics in the VFD drives create RFI emissions and are a concern and RFI shielding is necessary. The following measures will be taken in this regard.

11.1 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 3-phase power between them will have to be shielded and have a ground connection at both ends.

11.2 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.

11.3 Cooling of Cryo M&C Enclosure

The active electronics inside the M&C enclosure will generate heat. Because it is a shielded enclosure, it is recommended to use a cold plate cooled by Glycol, instead of forced-air cooling. It will be easier to keep the box RFI tight and weatherproof if air vents are not used.

12 Maintenance

12.1 Scheduled Maintenance

Scheduled cryogenics maintenance (Table 28) will be performed when the antenna is serviced. Because of the large number of antennas, one antenna will have a major overhaul every 35,000 hrs (four years).

Compressor charcoal trap adsorber replacement	≥ 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 28 - Scheduled maintenance.

12.2 Onsite Maintenance

All scheduled maintenance shall be performed at the site when the antenna is serviced. Unscheduled repairs shall also be done at the site. When a compressor fails the unit will be replaced. This requires depressurization of the helium circuit.

12.3 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).

13 Shipping/Transport and Acceptance Test

13.1 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.

13.2 Transport between Integration Center and Antenna

The compressor will 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.

13.3 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.

14 Appendix

14.1 Compressor 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 of the parameters to consider for the enclosure include the following:

- 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)

14.2 Abbrevations and Acronyms

Acronym	Description
AD	Applicable Document
LNA	Low Noise Amplifier
LRU	Line-Replaceable Unit
M&C	Monitor and Control
MLI	Multi Layer Insulation
MRI	Magnetic Resonance Imaging
MTBF	Mean Time Between Failure
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
RD	Reference Document
rpm	Revolution per minute
SPI	Serial Peripheral Interface
UV	UltraViolet
VFD	Variable Frequency Drive
VLA	Jansky Very Large Array