ngVLA Electronics Memo No. 3

Advanced Stirling Pulse Tube Cryocooler and Variable Speed Gifford McMahon Cryocooler Trade Study

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28 August 2020

Abstract

The purpose of this memo is to evaluate two potential cryogenic systems for the ngVLA: the advanced cryocooler and the variable speed GM cryocooler. After a description of both technologies to highlight their key features, we explore the challenges presented by both systems, their technical readiness, and their impact on the rest of the telescope design. Finally, a table compares both systems and a recommendation is made for the ngVLA cryogenic system.

1 Introduction

The Next Generation Very Large Array (ngVLA) will have 263 antennas with baselines in excess of 1000 km and a broader frequency coverage than the current VLA telescope. Having operated the VLA for 40 years, NRAO knows that the running cost of the current cryogenic equipment used to cool the eight radio receivers per antenna would be prohibitively expensive on the scale of the ngVLA and that new techniques and technologies must be investigated.

The first step was to reduce the number of cryocoolers per antenna by broadening the frequency bandwidth of the radio receivers and integrating five of the six remaining frequency bands inside a single Dewar, thus reducing the number of cryocoolers per antenna to just two. The second step was to research new or upgraded technology that will improve the reliability of the cryogenic equipment and reduce the power consumption level such that the operation cost is kept within a factor of three times the current budget. The NRAO engineering team, with help from outside experts, has selected two types of cryocoolers that could meet the ngVLA requirements. The first comes from the space industry and is a flex bearing Stirling pulse tube cryocooler (called “advanced cryocooler” in the following text) [RD02]. The second one is a variable-speed Gifford McMahon (GM) cryocooler [RD03].

2 Advanced Cryocooler

This type of cryocooler was developed for the space industry where high reliability, light weight, and low power consumption are essential and cost is not the primary concern. These cryocoolers are very compact, and the compressor and cold head are tightly integrated, as seen in Figure 1.

Figure 1. Cryocooler with integrated compressor and cold head for space application (Northrop Grumman).

The reliability of the compressor stage comes from the flexure bearing technology that eliminates rubbing contact in linear motors. Figure 2 shows an example of flexure bearing design.

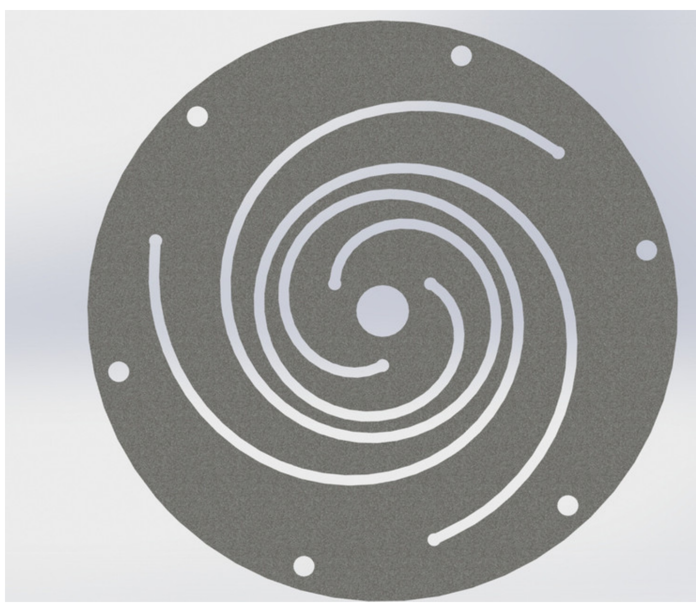


Figure 2. Example of flexure bearing design.

This type of bearing uses a thin metal sheet cut with a very specific spiral pattern that is flexible in the axial direction but radially stiff. Figure 3 shows a flexure bearing configuration for a linear motor application [RD04].

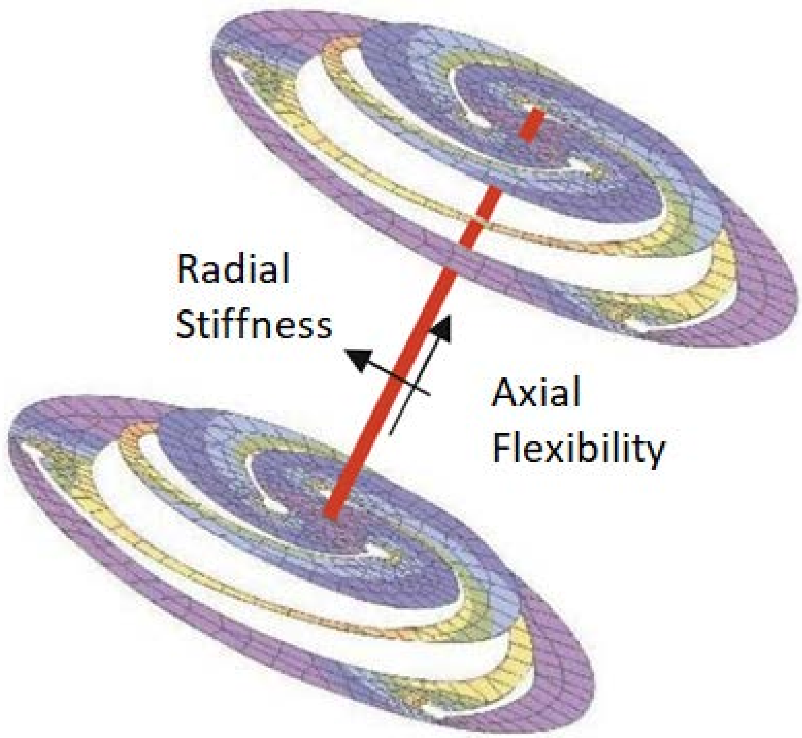


Figure 3. Flexure bearing arrangement for linear motors.

The original development was carried out by Oxford University and Rutherford Appleton Laboratory in the late 1980s. Because the movement of the spring is only in the axial direction, a shaft connected to a couple of these flexure bearing assemblies has perfect translation movement (see Figure 4).

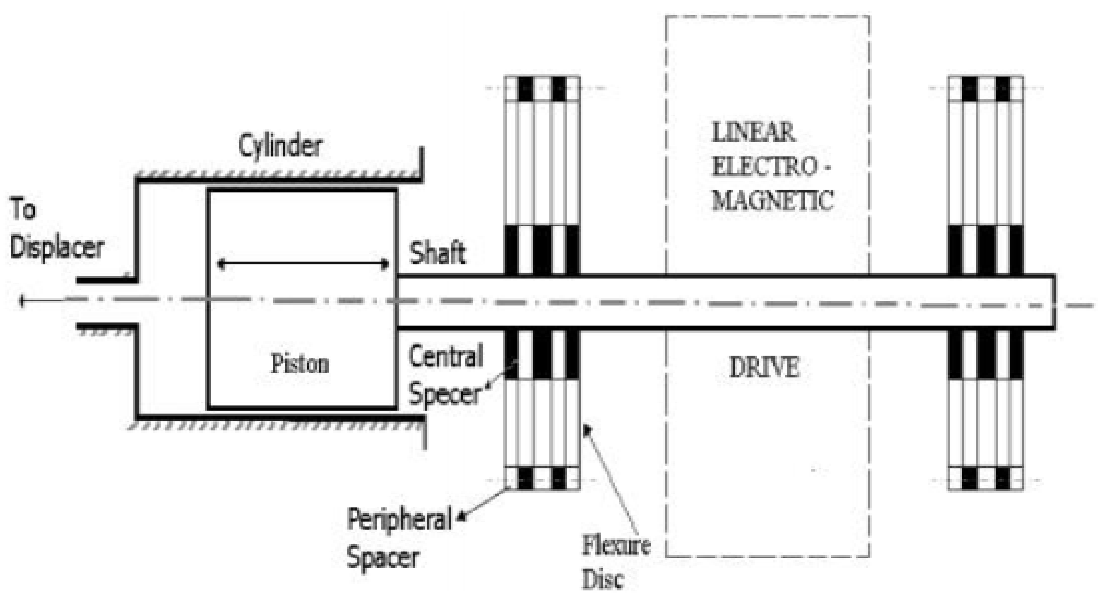


Figure 4. Cross section of a flexure bearing linear motor piston drive.

If the shaft is connected to a piston and driven by a linear motor, the piston can move inside a cylinder without touching the walls. The lack of contact between surfaces eliminates the mechanical wear and the need for lubrication. Very tight mechanical tolerances between the piston and the cylinder wall limit blow by and allow gas compression (clearance seal). Because no lubrication is required, no oil/gas separation circuitry is needed. When designed correctly, the flexure of the bearing does not introduce metal fatigue and the bearing operates in the infinite life regime. Figure 5 shows the cross-section of a dual piston compressor configuration used in the advanced cryocoolers. Having the movement of two pistons synchronized and in opposite directions allows the system to be well balanced, limiting the vibrations [RD08]. An active counterweight system could be implemented to further suppress the vibrations for sensitive applications.

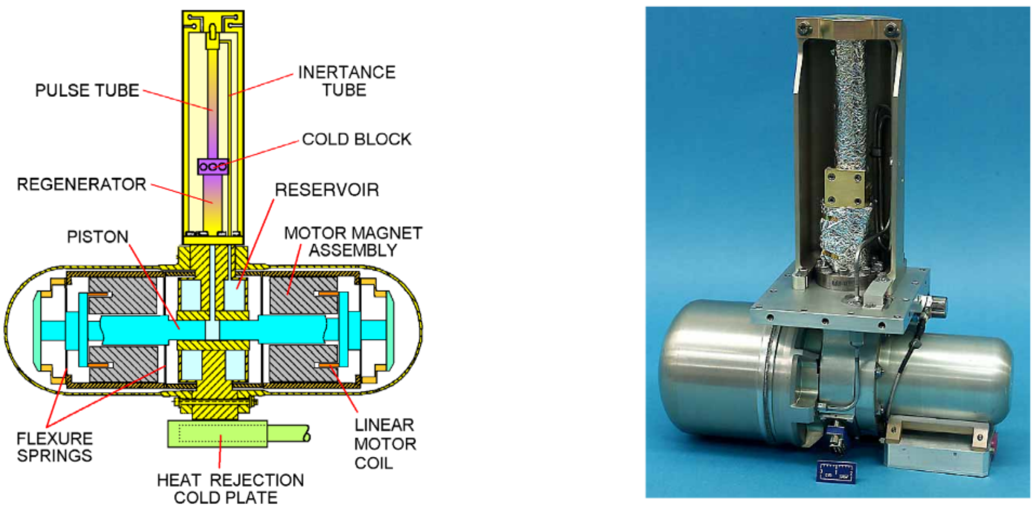


Figure 5. Flexure bearing dual piston compressor setup.

In the advanced cryocoolers, the pistons opposing each other move at approximately 70 Hz. By comparison, a GM cryocooler runs at approximately 1.2 Hz and requires valves to separate the compression and expansion phases of the thermal cycle.

The refrigerator portion of the cryocooler is a multistage pulse tube that, by design, has no moving parts and relies on a pressure oscillation generated by compression of Helium gas that goes through a regenerator to cool. For simplicity, Figure 6 compares the single-stage Stirling pulse tube cryocooler with the GM cryocooler. Unlike the latter, the Stirling-based cryocooler does not need valves to separate the compression and expansion phase of the thermal cycle.

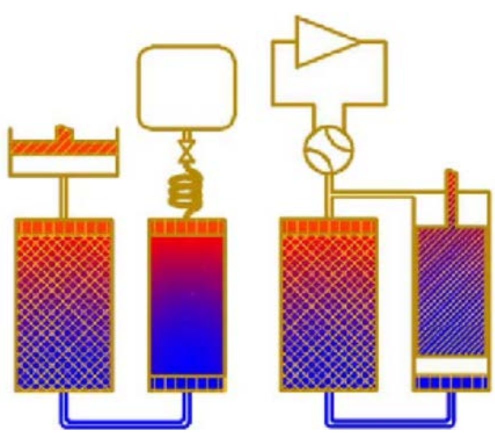


Figure 6. Single-stage Stirling pulse tube cryocooler (left) and GM cryocooler (right).

Figure 7 shows that the pressure waves generated by the piston displacement create inside the pulse tube some hot and cold spots. Figure 8 details the Stirling cycle, showing how heat is removed from the "cold block" and rejected to "room temperature" in the warm part of the tube. The cold part is used to cool the sensitive electronics and the warm part(s) require external cooling to dissipate the generated heat. In the case of ngVLA, a Glycol cooling circuit will remove the dissipated heat from the warm section(s) and cool the compressor. The portion of the electrical power required by the Glycol cooler to cool the cryocoolers needs to be added to the overall power consumption of the cryogenics subsystem for a fair comparison with the GM cryocoolers option.

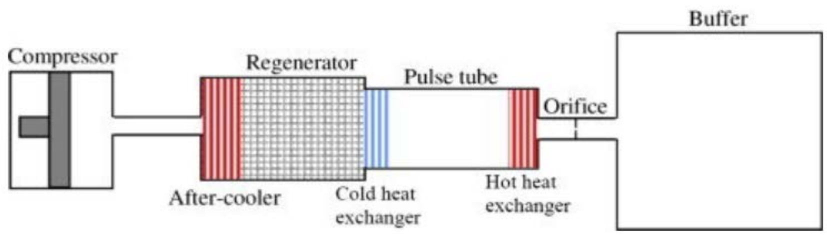


Figure 7. Single-stage Stirling pulse tube schematic.

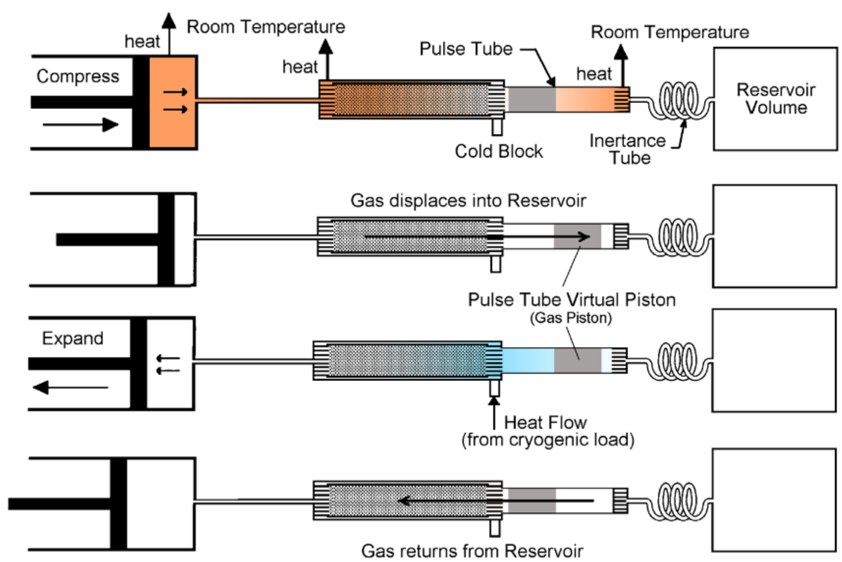


Figure 8. Pulse tube Stirling cooler refrigeration cycle.

Summary

The advanced cryocooler technology features high reliability and no maintenance. The flexure bearings control the movement of the pistons with precision mechanical tolerance seals that eliminate mechanical wear due to friction. The absence of oil lubrication greatly simplifies the compressor design and prevents any risk of contamination of the cold stages. The cryocooler has no moving parts that can fail, and the mode of operation that follows the Stirling thermal cycle is efficient and does not require a valve to isolate the compression phase from the expansion phase. The overall design is very compact, is lightweight, and has low power consumption, though it also presents a limited cooling capacity.

In our application, the thermal loads are higher than encountered in space missions and could exceed the cooling capacity of a single cryocooler. Having to use a second cryocooler would double the cost and make the mechanical design more complex and expensive. On the other hand, developing a new higher-capacity advanced cryocooler would compromise the technical readiness of this technology, and would require an important financial commitment for the project early on, to pay for NRE.

The cooling capacity variations with cryocooler orientation impose additional restrictions on mechanical design that could increase the overall cost. The external cooler required to dissipate generated heat degrades the power budget and compromises the overall reliability. Finally, the mechanical design and materials must be revised to lower the construction cost and simplify the manufacturability.

3 GM Cryocoolers

Standard GM Cryocooler

The standard GM cryocooler is currently in operation at the VLA and has been a part of radio astronomy history since the late 1970s. Unlike the advanced cryocoolers, this type of cryocooler requires maintenance because the compressor is lubricated and has mechanical wear from contact and friction. The cold head has a displacer that moves inside a cylinder with surface contact and no lubrication because of the very low temperature during operation. The displacer seals, bearings, and O-rings present in the cold head need to be replaced periodically.

The Helium gas is mixed with oil for lubrication and cooling of the compressor, but both must be separated before the compressed gas reaches the supply line and cold head. The separation is done in three steps (see Figure 9): the bulk oil separator, the final/mist separator, and the charcoal trap adsorber. The oil captured by the first two stages is recycled back to the compressor capsule; the oil trapped by the adsorber is not. The adsorber is a disposable part of the compressor that must be exchanged every 30,000 hours to avoid saturation and possible contamination of Helium lines and cold heads.

The compressors are heavy pieces of equipment that consume several kW and dissipate most of this power as heat that needs to be removed. For ngVLA, the plan is to have the compressor outside on a platform above the azimuth bearing and cable wrap of the antenna. The heat generated by the compressor is transferred to the ambient air via a heat exchanger and a cooling fan.

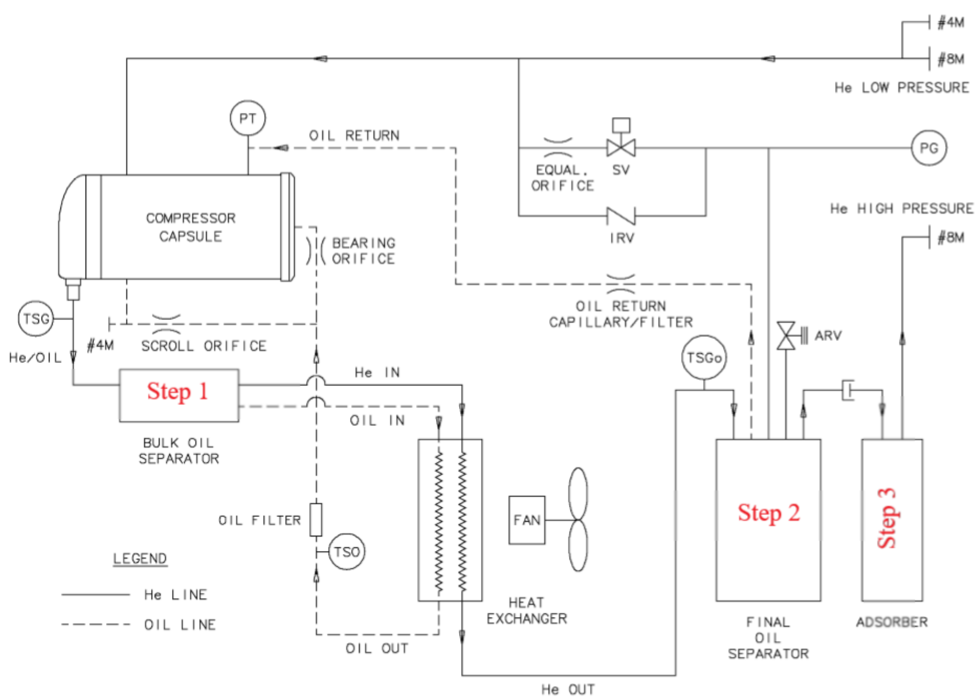


Figure 9. Compressor Helium and oil separation circuit; image taken from [RD09].

In a GM system, the cold head has between one and three displacer stages and could reach 4 K for the superconducting market (MRI). The cold head has contact seals on the displacer assembly (to avoid Helium blow-by) that wear out and need to be replaced to maintain the cooling capacity. Figure 10 shows the cross-section of a two-stage GM cold head with the displacer seals circled in red [RD10].

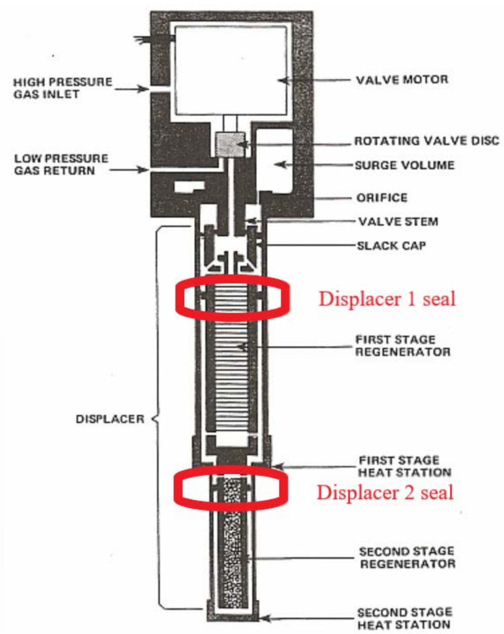


Figure 10. Cross section of two-stage GM cryocooler.

A cold head valve actuated by the motor synchronizes movement of the displacer with the connection to the compressor's high and low pressure sides. Figure 11 shows the GM thermal cycle and synchronization of the displacer movement with the valve, and the connection to the high and low pressure areas.

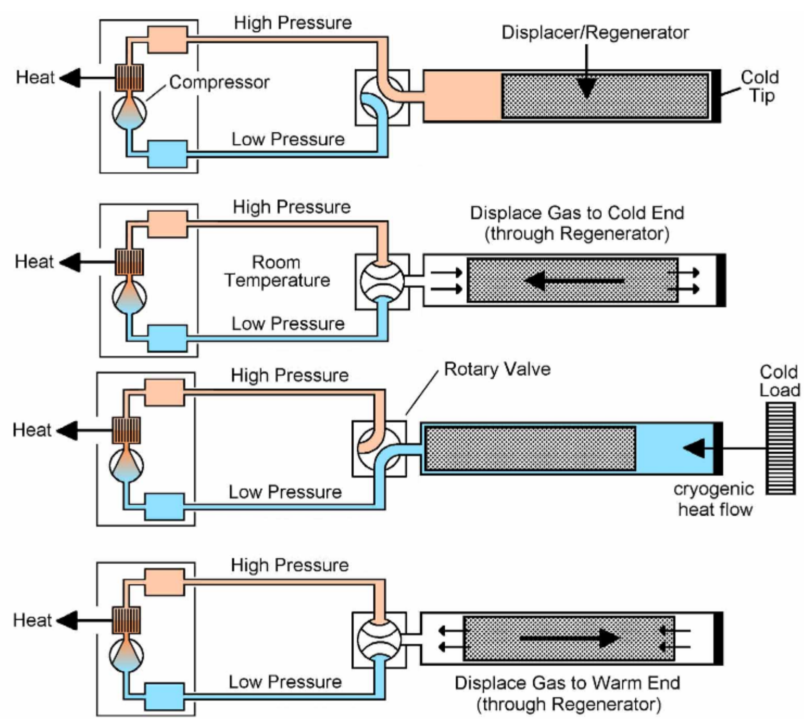


Figure 11. GM cycle.

The GM cryocoolers have many moving parts and need to be refurbished regularly to restore their cooling capacity. The maintenance periodicity directly relates to the displacer speed. At the VLA, for example, the smaller cold heads that run at 200 rpm will need service three times more often than the larger model, which runs at 72 rpm [RD11].

Summary

The GM cryocoolers have demonstrated a long service life, and they can be serviced and rebuilt almost infinitely. They are commercially available from several manufacturers at a reasonable cost and with a wide range of temperature and cooling capacity. In general, the GM cryocoolers are power hungry because their thermal cycle is less efficient than the Sterling cycle, and the compressor and the cold head are not always well matched in size. The compressor is very often oversized, and a portion of the high-pressure Helium generated is bypassed internally and does not contribute to the cooling process. The required lubrication makes them susceptible to oil contamination and imposes a regular maintenance schedule.

Limitations of the Standard GM Cryocooler

The graph in Figure 12 shows the Helium circuit supply and return pressures versus the flow, for a Sumitomo FA-40 compressor that runs at 40 Hz. To create this graph, the cold head has been replaced by an adjustable needle valve. When the valve is closed, there is no Helium flowing through the circuit; all the pressurized Helium generated by the compressor capsule is going through the Internal Relief Valve (IRV); see Figure 9 for location of the valve. The IRV allows passage of Helium from the high pressure side to the low pressure side, preventing compressor over-pressure. As the needle valve opens slowly, Helium starts flowing through the circuit and the differential pressure begins to drop.

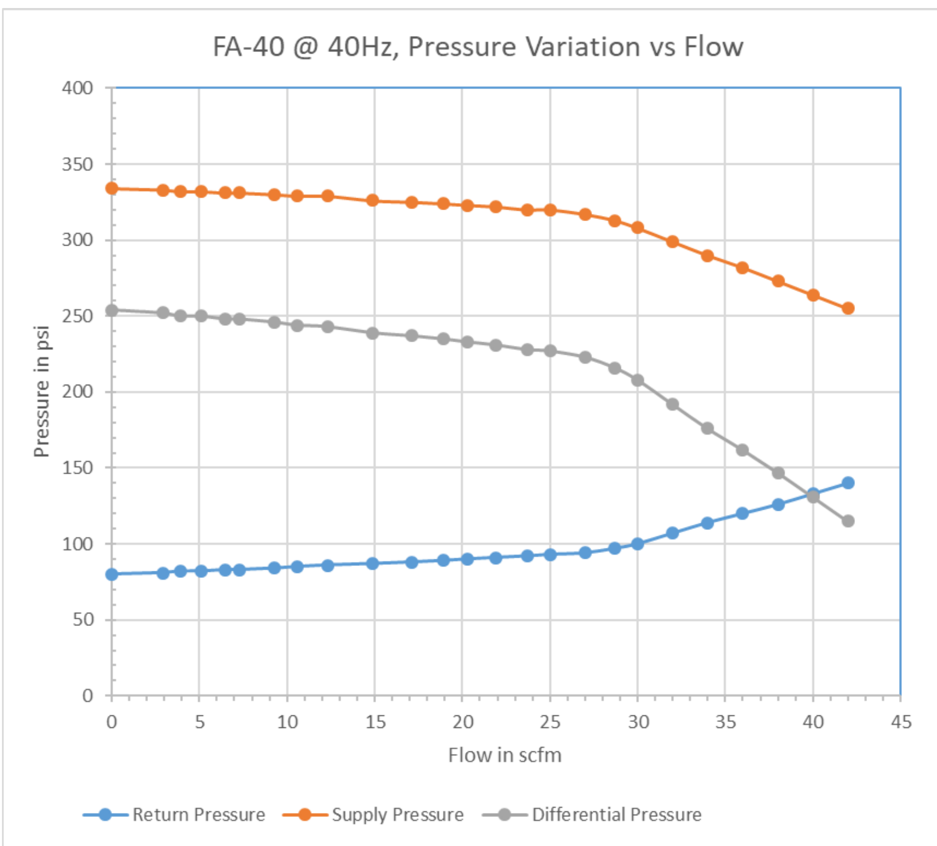


Figure 12. Flow and pressures for a Sumitomo FA-40 compressor at 40 Hz.

The flow of pressurized Helium produced by the compressor is divided between the needle valve and the IRV. When the flow reaches 28–29 scfm, there is an inflection in the pressure curves and the pressures start to change more rapidly with the flow. This knee in the curve occurs when the IRV closes completely and all flow produced by the compressor is going entirely through the needle valve. To be in that regime at 40 Hz, the differential pressure (supply pressure minus return pressure) has to be below 210 psi.

For example, using a FA-40 Sumitomo compressor that runs at 40 Hz connected to one Trillium CS350 cold head that runs at nominal power frequency 60 Hz, the supply pressure is 313.4 psi and the return pressure is 92.1 psi, giving a differential pressure of 221.3 psi (Table 1).

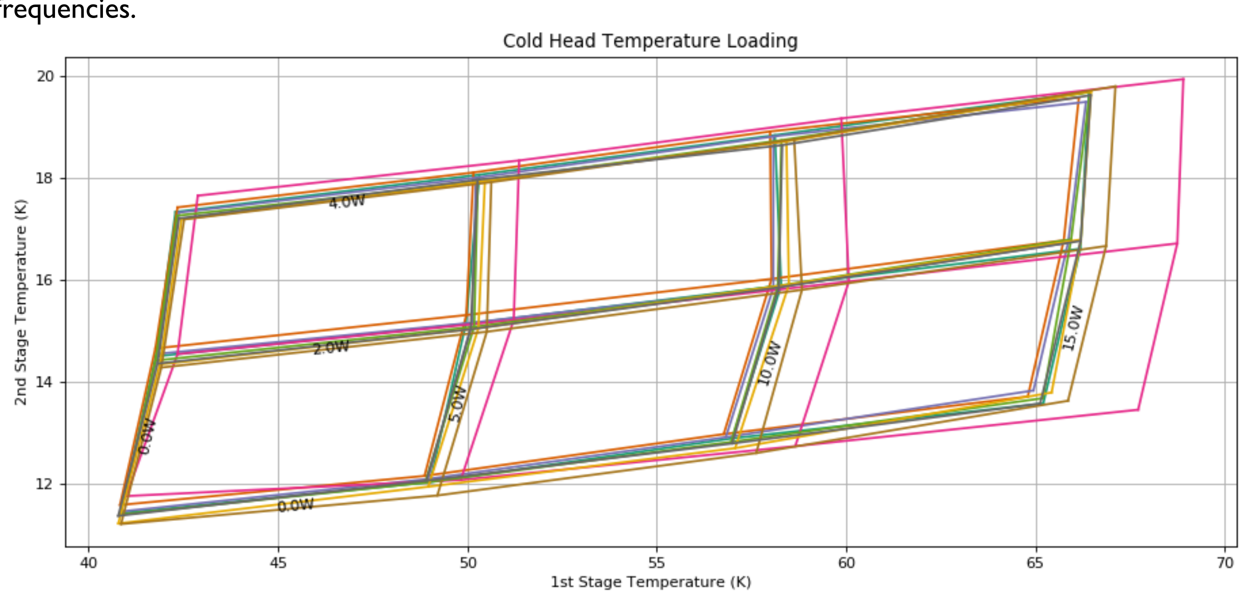
Compressor Frequency (Hz)	Supply Pressure (psi)	Return Pressure (psi)	Differential Pressure (psi)	Helium Flow Cold head (scfm)	Power consumption (kW)	Power Factor
35	309.5	99.1	210.4	25.6	3.395	0.854
40	313.4	92.1	221.3	27.1	3.951	0.861
45	318.1	90.9	227.2	28.2	4.354	0.878
50	324.8	88.5	236.3	28.7	4.782	0.891
55	324.05	84.88	239.17	28.7	5.278	0.908
60	327.33	86.04	241.29	28.9	5.886	0.915

Table 1. Cold head flow and power consumption for various compressor operating frequencies.

Table 1 lists the supply and return pressure and the flow for a single Trillium 350 cold head that runs at 60 Hz and a compressor that operates at frequencies between 35 Hz and 60 Hz. The power consumed by the compressor and the power factor are recorded at the same time.

When the operating frequency increases, the operating point moves to the left away from the knee in the curve and more flow is diverted through the IRV, and at the same time, the power consumption goes up. In our example, the Trillium 350 cold head has very similar flow for 35Hz and 60Hz compressor operating frequency; the cooling capacities are very similar but the power consumption almost doubles.

Figure 13 shows the load maps for the Trillium 350 cold head at eight different compressor running frequencies.



60Hz , 55Hz , 50Hz , 48Hz , 45Hz , 42Hz , 40Hz , 35Hz

Figure 13. Trillium 350 cold head load maps for compressor frequency 35–55 Hz.

To generate the maps, thermal loads are applied to the first and second stages using heat resistors and a dual-channel programmable power supply. The load on the first stage varies from 0 to 15 Watts in 5-Watt steps while the load on the second stage varies from 0 to 4 Watts in 2-Watt steps. These load maps are a common 2D representation of a refrigerator cooling capacity.

This measurement shows a small variation in cooling capacity of the cold head with the compressor operation frequency (pink is 35 Hz and orange is 60 Hz), and confirms that as the frequency goes up, most of the added flow is bypassed by the IRV and does not contribute to the cooling.

To run a single Trillium 350 cold head, the Sumitomo FA-40 is oversized, but having the ability to run the compressor at lower speed allows the flow to be adjusted to maintain cooling capacity while reducing power consumption significantly.

Variable-Speed GM Cryocooler

Variable-speed operation of the GM cryocooler addresses some of the limitations of the standard system. In a standard GM cryocooler, the compressor is always oversized to ensure the required Helium supply. The excess flow is bypassed internally by the IRV and not used for cooling. The cold head is also selected with excess cooling capacity to meet the desired cooling time rather than the steady state thermal load [RD03]. If a precise temperature is necessary, additional heat is applied and adjusted through a control loop. Having the ability to change the speed of the compressor and cold head allows users to adjust the cooling capacity to meet their needs, limiting the bypassed Helium flow and cryocooler cooling power.

When the cryocooler runs slower, the wear and tear is reduced and the interval between maintenance is extended, improving reliability. This was demonstrated using maintenance data from the VLA and is documented in [RD11].

Adjusting the speed of the compressor changes the amount of high-pressure Helium produced and limits the amount of Helium bypassed internally that doesn't contribute to the cooling. The compressor runs cooler and the heat rejection is lowered, so the oil separation is more efficient, reducing the amount of oil that could reach the adsorber. The variable speed of the GM cryocooler does not change the efficiency of the thermal cycle but optimizes the cold head's cooling capacity to meet the thermal load and adjusts the production of pressurized Helium to eliminate the bypassed flow through the IRV. The reliability is improved and the interval between maintenance extended.

4 Advanced Cryocooler Impact on Dewar Design

The advanced cryocooler uses a pulse tube type cryocooler with the advantage of having no moving parts but also the inconvenience of a cooling capacity that varies with orientation. Pulse tube cryocoolers have their optimum cooling performance in the vertical direction and see a degradation in performance when tilted to the side. When the telescope moves in elevation, the cryocooler orientation changes and its cooling capacity varies. To limit this effect, the cryocooler would be placed at a 45° angle from the vertical position. In this orientation, as the antenna moves through the full range of elevation, the cryocooler angle would remain within $\pm 45°$, limiting the cooling capacity variation within a reasonable range.

The initial thermal analysis of the ngVLA Dewar-A and Dewar-B [RD12] has shown that the thermal load exceeded the capacity of the two-stage advanced cryocooler currently available. Developing a new cryocooler with larger cooling capacity would require NRAO to invest a large amount of money up front for NRE, and Northrop Grumman to commit an engineering team to the project. This effort would be expensive and time consuming, and would present a risk for the project. In addition, the long-term reliability of the new cooler would not be demonstrated by many years of continuous operation.

One solution proposed by NG was to add an intermediate stage at 110 K that would be cooled by a separate single-stage advanced cryocooler. Having this intermediate stage drastically reduces the radiative load on the 50 K stage but has only a marginal effect on the 15 K stage. This solution has a strong impact on the design of Dewar A and Dewar B, with a second radiation shield at 110 K required and additional space required for the second cryocooler.

Summary of Impact

- 45° orientation recommended for both pulse tube cryocoolers:
  - More complex design because of the 45° orientation.
- Additional intermediate stage at 110 K:
  - Possible larger Dewar volume required to fit the additional radiation shield.
- Second advanced cryocooler:
  - Two mechanical interfaces with the Dewar.
  - Possible larger volume required to accommodate two advanced cryocoolers.
  - Larger Dewars might impact the design of the protective enclosure and could be a problem for the smaller 6m antenna.
  - Might restrict access to other components and make maintenance more difficult.
- Tight mechanical integration of advanced cryocoolers and Dewar:
  - Unlike the GM system, where the cryocooler and Dewar interface is simple and allows the cold head to be replaced on the antenna, the advanced cryocooler is tightly integrated with the Dewar and does not allow any antenna maintenance.
- Integration of compressor and cryocooler:
  - Power dissipation at the cryocooler Dewar interface increases the amount of heat generated inside the protective enclosure.
  - Connection to the chiller is required to remove dissipated heat from the Front End enclosure.

5 Dewar-A and Dewar-B Thermal Study Results

At this stage of the project, only paper designs are required. The Front End group decided on two Dewar concepts. Dewar-A has the lower 1.2–3.5 GHz frequency band, while the five higher bands covering 3.5–116 GHz with a gap for the oxygen line are integrated in Dewar-B. A thermal analysis was conducted by an external expert (Callisto, France) on both Dewars to estimate the thermal loads and help with the selection of the cryocoolers [RD13, RD14]. These studies compared a two-stage GM cryocooler against a dual advanced cryocooler with the additional 110 K radiation shield. The results of the thermal studies are summarized in the tables below. The 50K temperature was arbitrary chosen for the thermal study but in practice a temperature around 80K is acceptable.

Dewar-A @ +20°C Ambient Temperature	GM Cryocooler Heat Lift in Watts	Advanced Cryocooler Heat Lift in Watts
110 K stage	n/a	10.01
50 K stage	9.88	0.43
20 K stage	3.08	2.37

Dewar-B @ +40°C Ambient Temperature	GM Cryocooler Heat Lift in Watts	Advanced Cryocooler Heat Lift in Watts
110 K stage	n/a	19.3
50 K stage	11.8	4.1
20 K stage	3.5	3.5

The Table below lists the cooling capacities of the GM cryocooler and advanced cryocoolers considered for this trade study. The information for NGAS coolers comes from [RD02] and [RD16], while the information for the Trillium comes from a load map done at NRAO at 40Hz compressor frequency.

	Trillium 350 Cooling Capacity in Watts	NGAS HEC Single Stage Cooling Capacity in Watts	NGAS LT-RSP2 Cooling Capacity in Watts
110K stage	n/a	20	n/a
60K stage	10	n/a	5
20K stage	5	n/a	2.6

Notes

The load on the 110 K stage for the Dewar-B could be reduced by adding more layers of MLI, but is still within the capability of the single-stage advanced cryocooler.

The addition of the 110 K radiation shield reduces the load on the 50 K stage significantly because most of the thermal load comes from radiative loading of the Dewar walls. However, the impact on the 15 K stage loading is negligible because most of the heat load comes from radiation through the vacuum windows that are not impacted by the additional radiation shield.

Some multilayer Infrared (IR) filters cooled by the 50 K stage load are placed between each window and feed horn to intercept some of the load, but their impact on the incoming radio signal has to be as low as possible to maintain good receiver sensitivity. This requires a delicate balance between IR attenuation, RF transmission, and the physical temperature of the vacuum window. If the vacuum window gets too cold, condensation could form on the outside surface under certain environmental conditions and the signal would be attenuated, having a strong impact on the receiver sensitivity. This problem is well described in Callisto's report [RD14].

6 Comparison Tables

Option	**Power Consumption**
Variable-Speed GM Cryocooler	Both Dewar-A and Dewar-B use trillium 350 cold heads that draw about 200 W of electrical power. The compressor uses about 4 kW for a total of 4.4 kW at 40 Hz.
Advanced Cryocooler	Both Dewar-A and Dewar-B need two advanced cryocoolers to get cold: a single stage to cool the 110 K radiation shield and a dual stage to cool the 50 K and 15 K stages. The estimated power consumption is 160 W for the single stage and 700 W for the dual stage. In addition to the cryocoolers, some power must be added for the portion of the chiller used to remove the dissipated heat from the cryocoolers. An estimated 220 W per advanced cryocooler combination/Dewar is necessary. So the total power consumption comes to 2.16 kW, approximately half the power consumed by GM system.
Preferred Option	The advanced cryocooler will require half the power of the GM system or less depending on the compressor operating frequency.

Option	**Maintenance**
Variable-Speed GM Cryocooler	The GM cryocooler requires regular maintenance to prevent drop in efficiency and catastrophic failure. Every 30,000 hours the compressor adsorber needs to be replaced, and the cryocooler usually needs a rebuild every 20,000 hours on average.
Advanced Cryocooler	This type of cryocooler was designed for space and military applications, so no maintenance is required. It is a completely sealed system with no lubrication, therefore no oil management is necessary and there is no risk of contamination. The only drawback is the system cannot be repaired; it must be replaced in the event of a failure.
Preferred Option	The advanced cryocooler does not require any maintenance, whereas the GM system requires regular service.

Option	**Reliability**
Variable-Speed GM Cryocooler	If the maintenance is done properly and in a timely manner, the GM cryocooler is reliable. Even if the system breaks, it could be completely rebuilt.
Advanced Cryocooler	The advanced cryocooler is extremely reliable, but the chiller required to remove the dissipated heat is much less reliable.
Favorable to	The advanced cryocooler is extremely reliable, but it requires an external chiller to remove the dissipated heat at the Dewar interface. The glycol chiller we are contemplating using for ngVLA has a reliability comparable to the Scroll compressor used by the GM system.

Option	Cooling Capacity
Variable-Speed GM Cryocooler	The selected GM cryocooler has plenty of capacity to cover the estimated thermal heat loads of Dewar-A and Dewar-B. The variable-speed operation allows the cooling capacity to be adjusted to match the loads while minimizing power consumption and maintenance.
Advanced Cryocooler	The advanced cryocoolers are very compact and lightweight because they were designed for space application where volume and mass cost a premium. They have a limited cooling capacity which explains why two cryocoolers need to be used in parallel to cool Dewar-A or Dewar-B. At this time, it is still uncertain that even a dual system will have enough capacity to cool the Dewar-B.
Preferred Option	Larger cooling capacity for GM cryocooler could be adjusted with the variable speed option. With the Dewar-B it seems that we are exceeding the cooling capacity of the available advanced cryocoolers.

Option	Volume and Mass
Variable-Speed GM Cryocooler	The mass and volume of the GM system is significantly higher mainly due to the compressor weighing over 140 kg and measuring 948 x 1016 x 391 mm. The cold heads are about 15 kg each. When you add the Helium lines that run from the compressor all the way to the Front End enclosure, the total mass of the GM system exceeds 250 kg.
Advanced Cryocooler	Each advanced cryocooler has a mass of 10 kg or less, so the overall mass of the cryogenic equipment is reduced by approximately 80%. However, the mass located inside the Front End enclosure on the antenna feed arm is comparable for both systems. Being located on the separate platform behind the main dish, the GM compressor has very limited impact on the design of the antenna feed arm.
Preferred Option	The advanced cryocooler has a smaller overall mass, but the mass located on the antenna feed arm is comparable. Because the compressor and cryocoolers are integrated, the volume required by the advanced cryocoolers inside the Front End enclosure might be larger.

Option	Mechanical Interface
Variable-Speed GM Cryocooler	The mechanical interface of the GM system is very simple with a sleeve insert that is permanently attached to the Dewar and allows the cold head to be replaced on the antenna.
Advanced Cryocooler	The advanced cryocooler interface is more complex because of the 45° angle mount and the fact that two cryocoolers are needed per Dewar. The geometry of the advanced cryocooler is also more complex and we have to avoid mechanical interference between the two cryocoolers.
Preferred Option	Simpler mechanical interface for the GM cryocooler.

Option	Sensitivity to Motion or Orientation
Variable-Speed GM Cryocooler	The GM system can be operated in any orientation and the cooling capacity variation is not significant. For example, ALMA placed the cryocooler parallel to the antenna elevation axis to minimize the temperature variation with elevation.
Advanced Cryocooler	The pulse tube cooling capacity is sensitive to orientation with the vertical position being optimum. The Stirling pulse tube is less sensitive because of the higher frequency of operation and the absence of valves but it is recommended not to exceed ±45° from the vertical position. To meet this requirement, both advanced cryocoolers need to be mounted with a 45° offset position.
Preferred Option	The GM cryocooler has the advantage because it is less sensitive to motion and orientation. The temperature stability of the cryocooler translates directly into the gain stability of the low noise amplifiers it cools and the ngVLA requirement might be too tight to be met with the advanced cryocooler.

Option	Heat Rejection and Management
Variable-Speed GM Cryocooler	The heat removed by the cold head is transported away from the Dewar by the Helium gas. The compressor is air cooled and the heat produced by the compression of the Helium is transferred to the oil that is cooled by the heat exchanger and the fan.
Advanced Cryocooler	In the advanced cryocooler, the compressor and cold head are tightly integrated and the heat generated needs to be moved away from the Dewar interface by an external Glycol circuit.
Preferred Option	The GM system is simpler and does not rely on an external chiller.

Option	Cost Estimate
Variable-Speed GM Cryocooler	The GM system has other commercial applications, for example, in the medical field to cool MRI scanners and in the semiconductor industry to evacuate sputter machines. Therefore, the GM system benefits from the economy of scale. The cost is approximately $60,000 per antenna.
Advanced Cryocooler	The advanced cryocoolers have only been manufactured in very small quantities for space missions. The fabrication process will have to be adapted for a larger production run. Because of the limited cooling capacity, each Dewar requires two coolers, which almost doubles the cost. The current cost estimate is approximately $400,000 per antenna.
Preferred Option	The initial cost of the advanced cryocooler is so much higher than the GM system that it would take longer than the expected lifetime of the telescope to recover the construction cost difference [RD15].

7 Summary Table

	Variable-Speed GM Cryocooler	Advanced Cryocooler
Power Consumption	0	1
Maintenance	0	1
Reliability	1	1
Cooling Capacity	1	0
Volume and Mass	1	1
Mechanical Interface	1	0
Sensitivity to Motion and Orientation	1	0
Heat Rejection and Management	1	0
Cost	1	0
Total	**7**	**4**

8 Conclusion

The low power consumption and absence of required maintenance make the advanced cryocooler very attractive for ngVLA. However, its limited cooling capacity requires the combination of two cryocoolers to cool the Dewar-A, and is not sufficient to cool the Dewar-B in the current configuration. More work needs to be done on the IR filtering for the Dewar-B to reduce the thermal load on the 15 K stage to a level compatible with the advance cryocooler cooling capacity.

The impact on the design of the Dewar may be significant and will add to the fabrication cost of the Front End. If we add the fact that an external chiller is required to remove the heat generated by the cooler, the reliability of the complete system becomes more or less equivalent to that of the GM system.

Given that the advance cryocoolers are designed for space missions, the unit construction cost is very high and is not optimized for large production. Northrop Grumman attempted to cut costs by using lower-cost materials and reducing the required testing, but the initial cost is still too high to be competitive with the GM system. This is even when the cost savings due to lower power consumption and maintenance over a 30-year life cycle are taken into account.

At this stage of development in the ngVLA project, the potential benefits offered by the advanced cryocooler are outweighed by the very high initial cost, the limited cooling capacity, and the added complexity to the Dewar design.

A cryogenic system based around variable-speed compressors and VFD GM cryocoolers is therefore the preferred option for the ngVLA project.

9 Reference Documents

Ref. No.	Title	Authors, Publication
RD01	Flexure bearing support, with particular application to Stirling machines	United States patent 5,522,214 June 4, 1996
RD02	Advanced Cryocoolers for ngVLA	Larry D'Addario, Caltech: ngVLA Optics Workshop, Pasadena, CA, June 20, 2018
RD03	Improved Power Efficiency for Cryogenics at the Very Large Array	D. Urbain, W. Grammer, G. Peck, J. Jackson, S. Durand, International Cryocooler Conference, San Diego, CA

RD04	Development of the LSF 95XX 2nd generation flexure bearing coolers	J.C. Mullie, P.C. Bruins, T. Benschop, M. Meijers THALES Cryogenics B.V. SPIE Conference 2005
RD05	Development Progress of Long Life Twin Piston Pressure Oscillator	L. Duband, A, Ravex and P. Rolland *Advances in Cryogenic Engineering*, Vol. 39
RD06	Modeling an Analysis of Deformation on a Flexure Bearing in Linear Compressor	Vennapusa V. Sivareddy *IJMERR*, Vol. 3, No.1, January 2014
RD07	AIM-Space Cryocooler Program	M. Mai, I. Ruhlich, A. Schreiter, S. Zehner AIM Infrarot-Module Gmbh Heilbronn, Germany
RD08	Refrigeration Systems for Achieving Cryogenics Temperatures	Ronald G. Ross, Jr., Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
RD09	FA-40H and FA-40L Air-Cooled Helium Compressor Operating Manual	Sumitomo (SHI) Cryogenics of America, Inc. 1833 Vultee Street, Allentown, PA 18103
RD10	https://www.arscryo.com/cryocooler-principles-of-operation	Advanced Research Systems, 7476 industrial Park Way, Macungie, PA 18062
RD11	MTBF Report on EVLA Cryogenics	James Gregg, Socorro NM, March 29, 2016 NRAO Private Communication
RD12	ngVLA Front-End Thermal Study Initial Analysis Report (11/07/2018)	Remi Rayet, Callisto, 12 Av. De Border Blanche, Villefranche de Lauragais F-31290, France
RD13	ngVLA Front-End Receivers Thermal Study Analysis Report with 110K Intermediate Cooling Stage (05/12/2018)	Remi Rayet, Callisto
RD14	ngVLA Front-end Receivers Thermal Study Dewar-B Update (14/02/2020)	Remi Rayet, Antonella Simone, Callisto
RD15	Cost Comparison between the Stirling Pulse Tube Advance Cryocoolers Concept and the Reference Design Gifford McMahon Cryogenic System	NRAO Internal Document # 020.30.10.00.00-0005-REP
RD16	High Efficiency Cryocooler Performance	D. Durand, T. Nguyen. E. Tward Northrop Grumman Aeronautics Systems

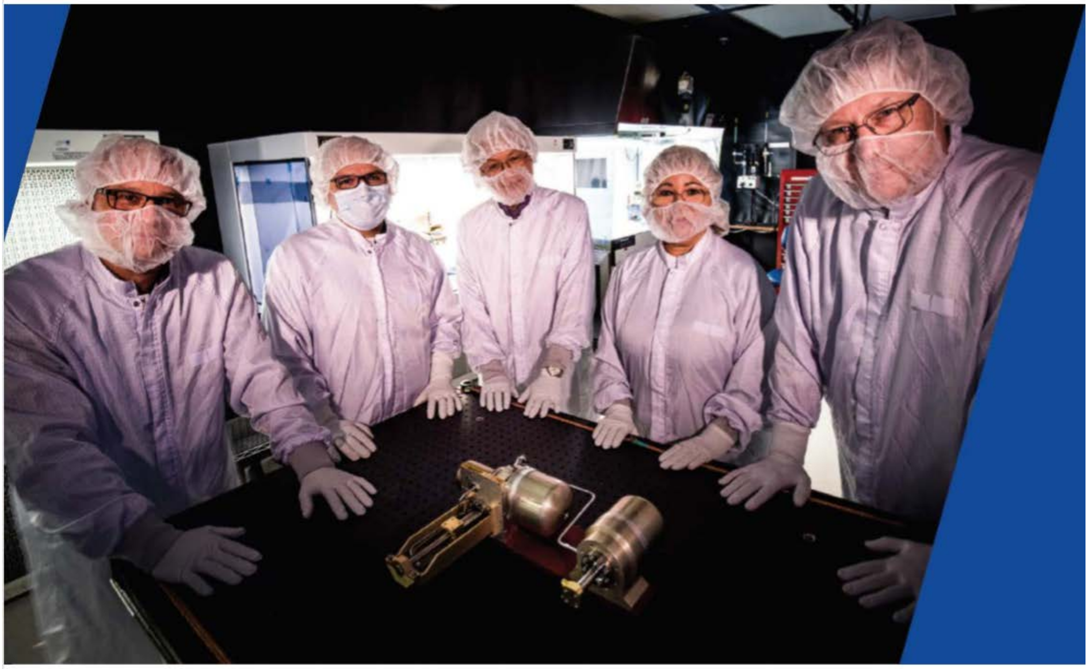
10 Acronyms

EVLA	Extended VLA
GM	Gifford McMahon
ngVLA	Next generation VLA
MLI	Multi-Layer Insulation
MRI	Magnetic Resonance Imaging
NRAO	National Radio Astronomy Observatory
NGAS	Northrop Grumman Aeronautics Systems
NRE	Non-Recurring Engineering
VFD	Variable Frequency Drive
VLA	Very Large Array

11 Appendix

Northrop Grumman Cryocoolers

NORTHROP GRUMMAN



Web: http://www.northropgrumman.com/Capabilities/HighEfficiencyCryocoolers cryocoolers@ngc.com

NGAS is the Preeminent Supplier of Efficient, Highly Reliable Space Pulse Tube Cryocoolers

NORTHROP GRUMMAN

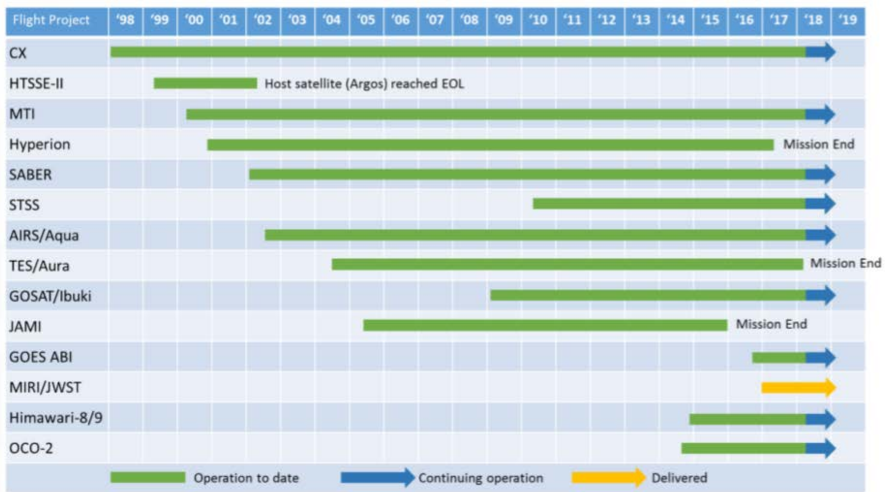
- Since 1990, NGAS has developed the pulse tube cryocooler into a space qualified product that has supplanted the Stirling cryocooler technology as the U.S.' premier long life cooler of space payloads.
- The reliable refrigeration device, the completely passive pulse tube cryocooler cold head with no moving parts, enables the wide operating temperature ranges on both the heat rejection and cooling temperatures.
- NGAS has produced more long-life, flexure-bearing, non-wearing, flight coolers than the rest of U.S. industry combined.
- There are a number of NGAS units of four different designs in orbit and all are performing nominally. Two have been in operation for 18 years with no change in performance.

Approved for public release: 16-2339

NGAS Cryocooler Flight Heritage – *Over 230 Years of On-Orbit Performance*

NORTHROP GRUMMAN

NGAS has produced more space flight coolers than the rest of US industry combined



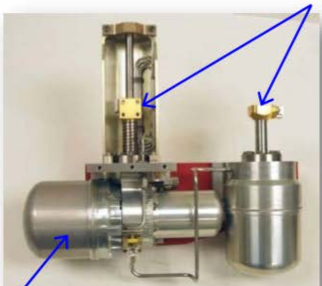
100% Successful On-Orbit Performance

Approved for public release: 16-2339

Northrop Grumman is the Leader in Space Cryocoolers With TRL 9 Flight Heritage

NORTHROP GRUMMAN

Cold Heads



Compressor

- Thermal-Mechanical Unit (TMU)
  - Highly mass efficient cooler (HEC)
  - One or two-stages (photo shows 2-stage)
  - Cools cryogenic load(s)
  - Intrinsically low output vibration
- Cryocooler Control Electronics (CCE) and Software
  - Drives TMU
  - Provides temperature control
  - Active vibration control
  - Provides user interface and telemetry
  - Radiation-hardened

Discriminators for NGAS Pulse Tube Cryocoolers

Reliability: Non-wearing compressor and no moving parts in cold head
SWAP: Enabled by compressor and CCE design. High Efficiency.
Maturity: TRL 9. Over 230 years combined on-orbit operation without a failure

Approved for public release: NG16-1903

HEC Cryocoolers for Space Applications

NORTHROP GRUMMAN

- Northrop Grumman's **TRL 9** HEC cooler—**unmatched legacy of success in space cryocoolers**
- Space cryocooler system includes flight electronics and pulse tube cryocooler - all TRL 9
- Available in **one and two stage** cooling configurations, enabling thermal control of multiple sites
- Pulse Tube design provides very **low output vibration**
- Electronics provides **active vibration dampening**, as well as temperature control
- High Efficiency over a **wide range of operating temperature**
- **Low mass** reduces system level cost
- Cold head optimized for different operating temperatures

High Efficiency Cooler	
Refrigeration Capacity (in 25°C ambient)	2W @45 K 10W@77 K 23W@150 K
Compressor Input Power	Up to 180W
Reliability	> 98 % at 10 years (88,000 hours)
Environment	-40°C to +70°C
Exported Vibration	< 50 mN drive axis
Exported Vibration	<200 mN pulse tube axis
Mass (Single Stage Cooler)	< 4.5 kg
Mass (Electronics)	3.8 kg

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Approved for public release: NG16-1903

HEC Cooler Family

NORTHROP GRUMMAN

Linear Cold Head

Coaxial Cold Head

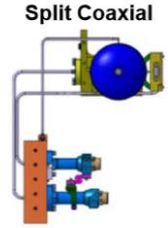
Linear with Remote Coaxial

Design Has Been Adapted to Variety of Applications

- Same Compressor
- Same Electronics
- Same Software
- Built to Print & Customized Cold Heads

Integral Coaxial

Split Coaxial



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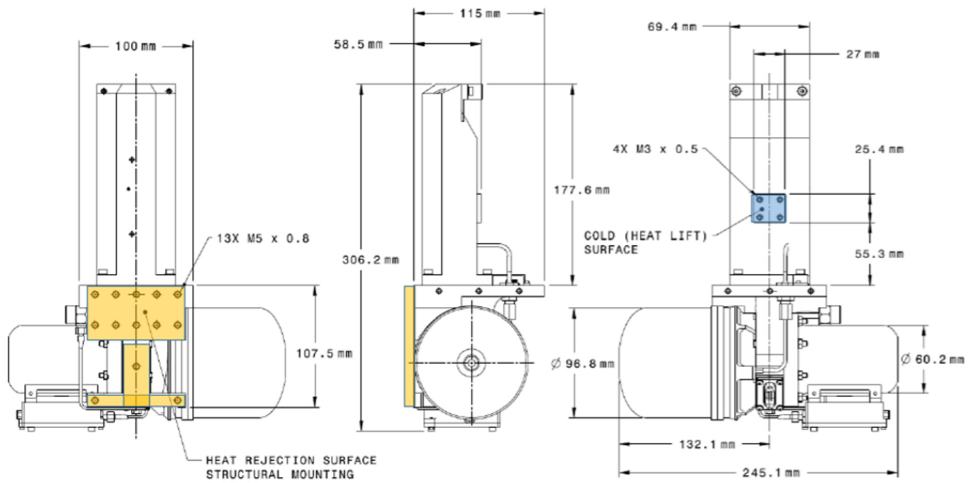
Approved for public release; NG 18-1368 dated 6/14/18.

Cooler Envelope and Interfaces (1 of 2)

NORTHROP GRUMMAN

Linear Cold Head Configuration



Orange area indicate heat rejection and structural mounting surface

462928-2 TMU

Blue is cold interface

7

Cooler Envelope and Interfaces

NORTHROP GRUMMAN

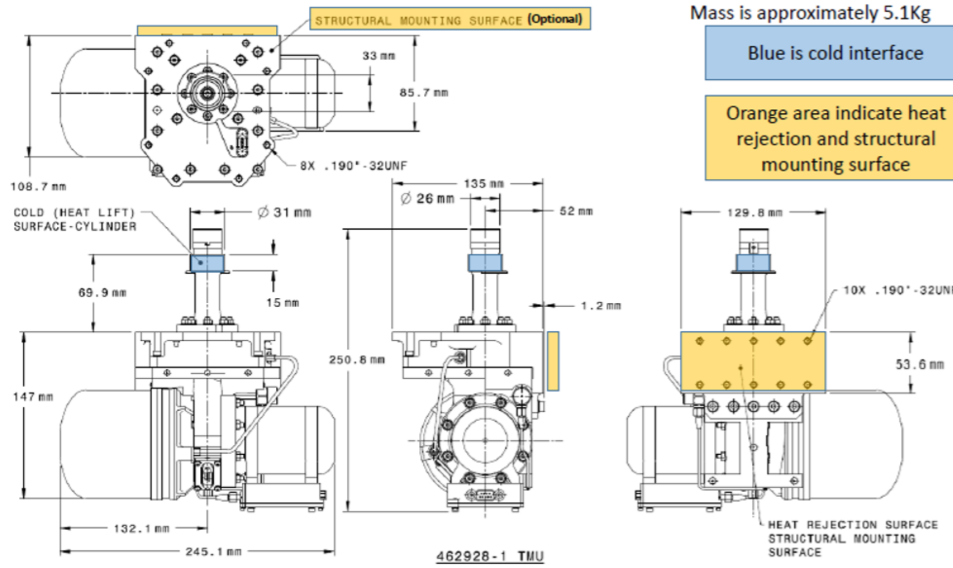
26 AUGUST 2015

Coaxial Cold Head Configuration

Mass is approximately 5.1Kg

Blue is cold interface

Orange area indicate heat rejection and structural mounting surface



462928-1 TMU

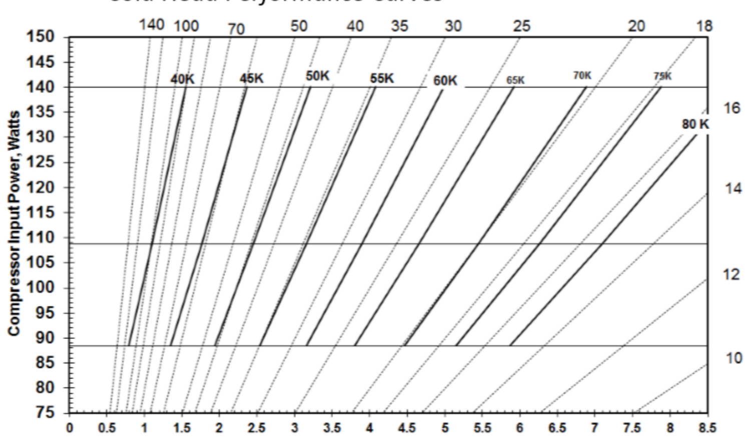
8

Pulse Tube Coolers Provide Range of Operating Temperatures

NORTHROP GRUMMAN

HEC flight coolers have been delivered in single stage versions for cooling at 41K, 60K, 65K, 67K, 95K & in 2-stage versions for 95K/180K & 53K/160K

Cold Head Performance Curves



Custom performance tuning for other temperatures and higher performance is available

9

Northrop Grumman Cryocoolers Provide Superior Performance and Reliability

NORTHROP GRUMMAN

- Four Product Lines address specific markets needs
  - Micro, Mini, HEC, HCC
- Product Line scaled from Proven TRL 9 HEC class coolers – design lowers risk and leverages performance
- High reliability from non-mechanical pulse tube, non-wearing flexure bearings compressor reduces cost of ownership
- High thermal efficiency from superior design
- Low vibration, low mass provides system advantages
- Coolers operate over wide range of temperatures
- Multiple coldhead configurations available
  - Linear, coaxial pulse tubes
  - Joule Thomson
  - Single or multi-temperature
- Flexible cooler integration options

Microcooler

Minicooler

High Efficiency Cooler

High Capacity Cooler

Web: http://www.northropgrumman.com/Capabilities/HighEfficiencyCryocoolers
Email: cryocoolers@ngc.com

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