The Next-Generation Very Large Array Cryogenics

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Reference Design

The ngVLA cryogenic system reference design assumes the use of modern but reasonably mature technology, with predictable system performance based on manufacturer specifications and measurements, in house testing, and historical data. This permits accurate estimation of construction and operation costs, and a well-defined low risk path for development. Nevertheless, the reference design is not yet fully optimized and it might not represent the final selection for the ngVLA project.

A two-stage Gifford-McMahon (GM) type refrigerator is retained, as it can readily cool to temperatures below 20°K, as required for optimum receiver noise performance. Other advantages are its relative insensitivity to physical orientation (**Fig.1**), proven reliability and low maintenance cost. Use of a Variable Frequency Drive (VFD) on the displacer drive motor effectively allows cooling capacity to be adjusted dynamically: at a lower speed for steady-state operation, or at a higher speed during cool-down. Running a refrigerator at lower speed also reduces the wear on the moving parts, and consequently extends the service life.

In a cryogenics system, the refrigerator is the element that requires the most maintenance, but the helium compressor is by far the most power-hungry component. It ends up consuming a significant fraction of the electrical power supplied to the antenna, so minimizing its power draw is essential to keeping the operations budget within acceptable limits. The solution for the reference design is an efficient scroll-type compressor capsule driven at variable speed, to provide just the needed amount of helium flow to the cryocoolers. As the speed of a cryocooler is lowered, its helium flow drops proportionally, reducing the demand on the compressor. Having a variable-speed compressor allows the output flow to be optimally adjusted to match the varying load on the refrigerator. Since power consumption of the compressor decreases linearly with the speed, the average energy cost will be lower than with a fixed-speed compressor.

Compressors of this type are in production and readily available, though in higher capacities than may be required for ngVLA. An example in **Fig.2** below shows the power consumption vs speed (helium flow) for a Quantum Design HAC4500 compressor.

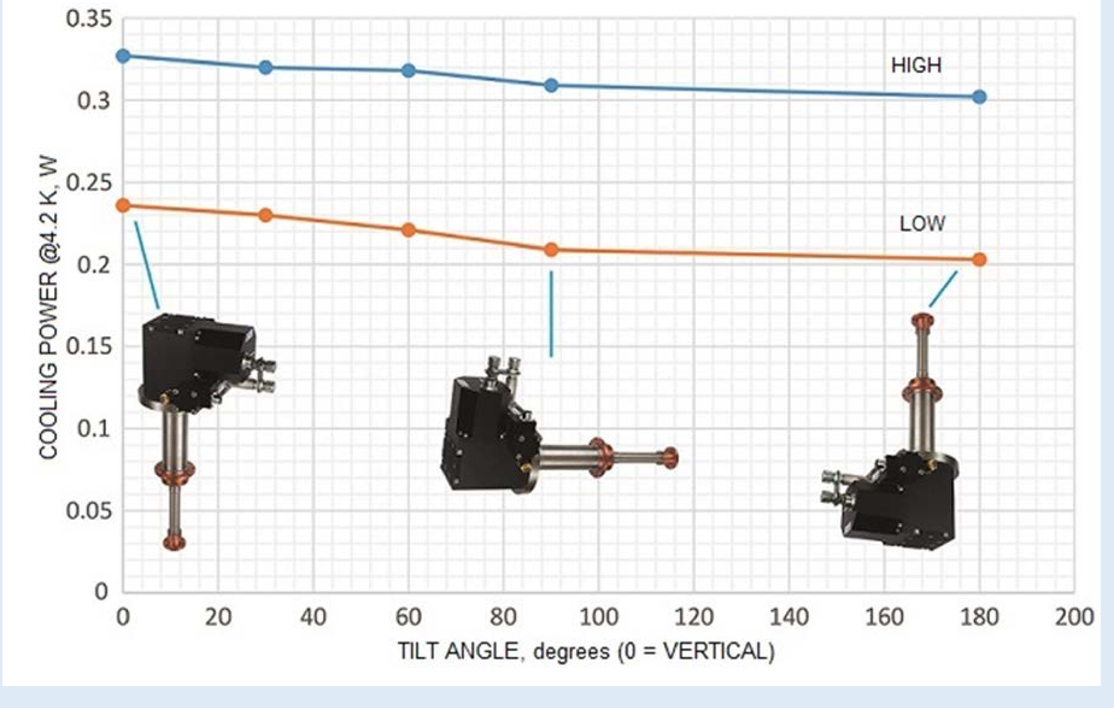


Figure 1: Relationship between 2nd stage cooling capacity and GA-1 cryocooler orientation at high and low power settings.

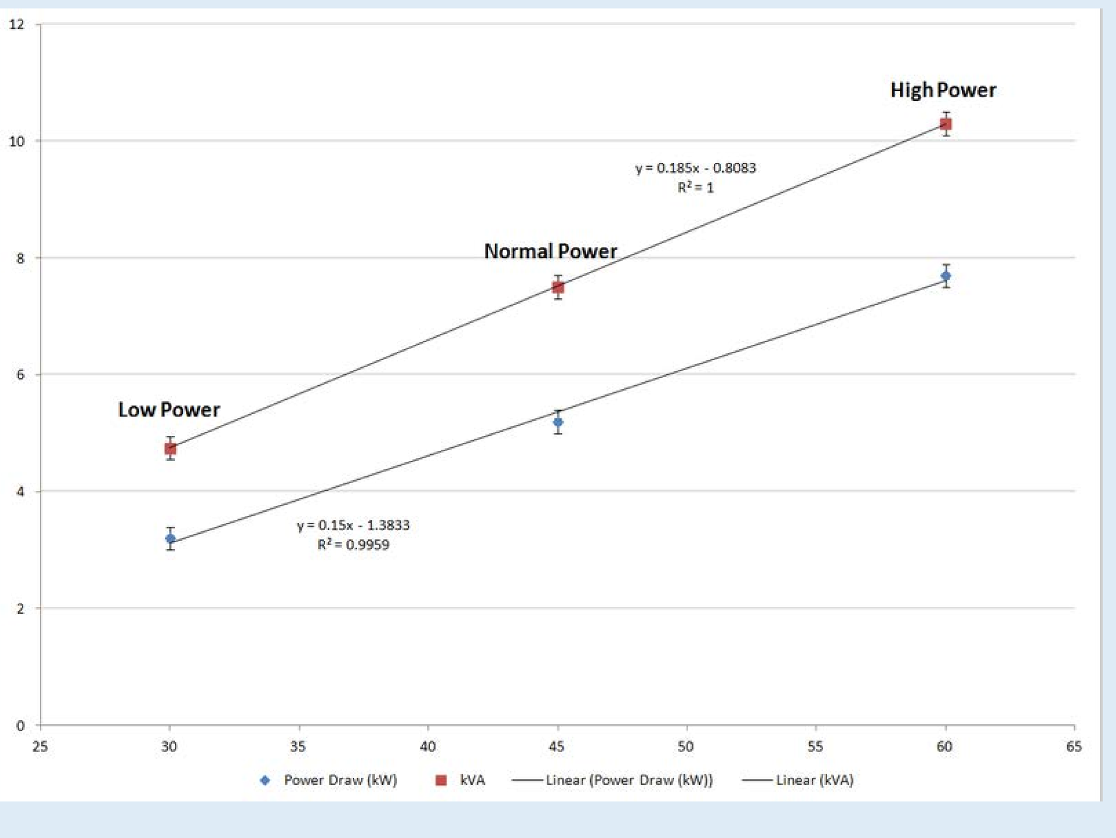


Figure 2: HAC4500 power consumption vs VFD frequency.

Abstract

The next generation VLA (ngVLA) will have 214 antennas with a diameter of 18m, and will have a core centered at the current location, but will extend in to neighboring states and northern Mexico. Operations cost are a driving concern for ngVLA, and the goal is not to exceed 5% of the capital/construction cost annually ($75M/yr. in 2016 dollars).

Using the VLA as a reference, the cryogenic subsystem (**Fig. 5 and 6**) dominates the electrical budget, and is a source of frequent maintenance visits to the antennas. Scaling this system for an array of 214 antennas will be prohibitively expensive, in terms of energy cost and upkeep. Our objective with the ngVLA is a redesigned cryogenic equipment that minimize per-antenna power consumption and maximizes reliability, in order to keep the overall operating cost within the assigned budget.

Figure 5: Helium compressors Mounted on VLA antenna

Figure 6: CTI refrigerators currently used at the VLA

ngVLA Cryogenics Reference Design Specifications

Scroll Compressor	
Variable Speed Drive	Yes
Power Consumption	max 4.5kWatts
Mean Time Between Maintenance	>35,000 hours
Electronics RFI Shielding	Meet VLA Emission Requirements
Cooling	Air
Operating Temperature Range	-30°C to +45°C
Cold Start (remote start-up in sub zero temperatures)	< 2 hours
GM Refrigerator	
Variable Speed Drive	Yes
1st Stage Cooling Capacity	10 Watts (TBC)
2nd Stage Cooling Capacity	0.5 -1 Watt (TBC)
Mean Time Between Maintenance	Goal 35,000 hours
Electronics RFI Shielding	Meet VLA Emission Requirements
Operating Temperature range	TBD (Within an environmental enclosure)
Orientation	Can operate in any direction with small variation in cooling capacity.

Compressor Development

The reference design uses a large-capacity compressor that produces enough flow to run up to four or five refrigerators. The ngVLA front end concept has only two receivers, therefore a smaller compressor would be more appropriate. In the forthcoming year, NRAO is considering funding the development of a smaller outdoor variable-speed compressor that will be optimized in terms of capacity, power consumption and durability for ngVLA. This smaller compressor could save an additional 700 watts representing a savings of 15-20% in power consumption over the current reference design.

References

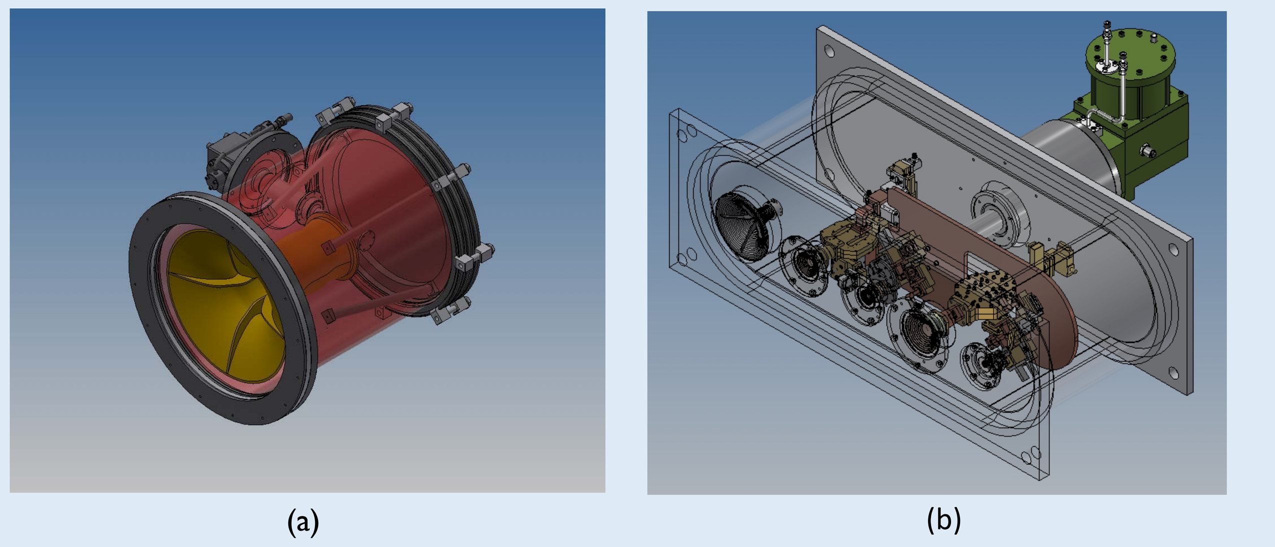
- L. D'Addario "Advanced Cryocoolers For Next Generation VLA" ngVLA Memo No. 24
- J. Gardiner, et al. "Smart Energy Cryo-Refrigerator Technology for the Next Generation VLA" ngVLA Memo No.23
- D. Urbain et al. " Improved Power Efficiency for Cryogenics at the Very Large Array" Cryocoolers 19, Proc. Of 19th International Cryocooler Conf., 2016
- W. Grammer et al. "ngVLA Receiver/Feed Summary" US Radio/Millimeter/Submillimeter Science Futures III, Berkeley CA, 2-4 August 2017

Front End (FE) Concept

The ngVLA Front End concept offers continuous frequency coverage from 1.2 to 116GHz, with a gap between ~50 to 70 GHz due to atmospheric absorption. The FE reference design will implement this in six separate receiver bands, with the lowest (Band 1) occupying one cryostat (**Fig.3a**), while the remaining five higher-frequency bands share a second cryostat (**Fig.3b**).

The window diameter for each band is inversely proportional to (Θ f_{min}) where f_{min} is the lowest frequency for that band and Θ is the antenna illumination angle as seen from the feed. The ngVLA antenna optics will be designed for a wide illumination angle (Θ ~110 degrees), compared to of order 18 degrees for the VLA. Having smaller feeds allows the integration of most of the receiver bands into a common cryostat, and even the feeds themselves can be cooled, further improving receiver sensitivity.

With tight mechanical integration of the receivers into a pair of compact cryostats, combined with variable-speed cryocoolers and compressor, there will be considerable saving in the per-antenna operations cost for the cryogenic system, relative to the VLA.



(a) (b)

Figure 3: ngVLA two cryostat FE concept, (a) Band 1 (1.2-3.5GHz), (b) Band 2-6 (3.5 -116GHz)

Technical Development Study

The proposed reference design for ngVLA cryogenics is based on currently-available equipment and readily-tested technology. While more advanced cryocoolers have been developed for military and space applications, very often the cost and size of these cryocoolers are incompatible with the requirements and budget of an array like the ngVLA. However, Raytheon has developed a 2-stage Stirling pulse-tube cryocooler (**Fig.3**) that might have enough cooling capacity (**Fig.4**) to meet the ngVLA front end needs. This unit is more efficient than the GM cryocooler proposed in the reference design and could offer significant reductions in power consumption and required maintenance. However, space-qualifed cryocoolers like this one are made in very small quantities and are usually very costly. These cost tradeoffs need to be well understood even before an alternative to GM cryocoolers is considered.

An accurate thermal model for the ngVLA proposed receivers will be developed in the near future to calculate the thermal loading in both cryostats. If the loads are close to the capability of the Raytheon cryocooler, NRAO may consider funding an advanced cryocooler study to determine whether this type of refrigerator can be manufactured at a cost compatible with the ngVLA proposed budget while still maintaining their durability.

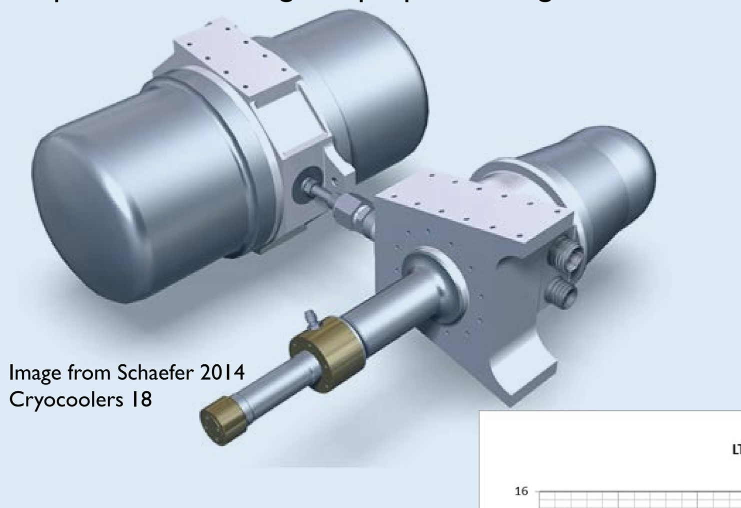


Image from Schaefer 2014 Cryocoolers 18

Figure 3: Raytheon LT-RSP2 Hybrid Cryocooler with Sterling 1st stage and Sterling pulse tube 2nd stage. The compressor (left) is common to both stages.

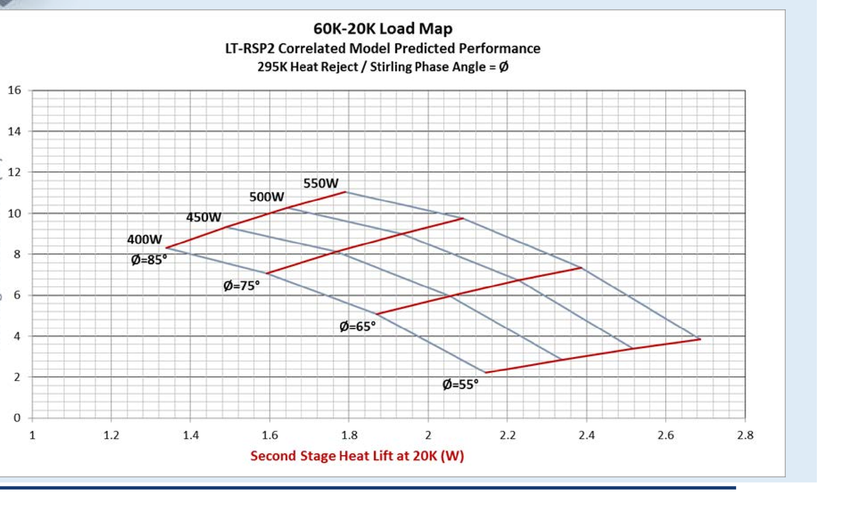
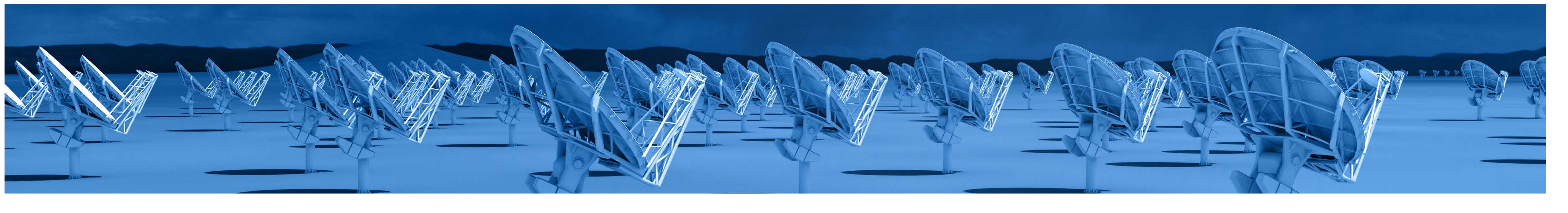


Figure 4: Cooling power on each stage of the LT-RSP2 cryocooler at fixed Temperature vs. compressor input power.



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