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 (**Fig.6**) is retained, as it can readily cool to temperatures below 20°K, as required for optimum receiver noise performance. Other advantages of this type of refrigerator is the relative insensitivity to physical orientation**,** 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 refrigerator 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 what is required for ngVLA. The **Fig.1** and **Fig.2** below show some of the measurements done on a mid-size helium compressor under development in Allentown, PA by Sumitomo SHI.

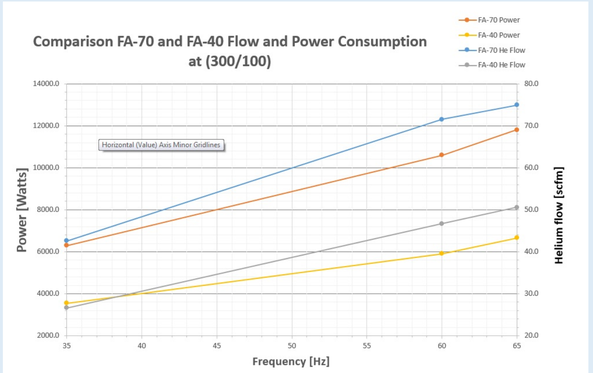


Figure 1: Comparison of the large capacity FA-70 compressor with the mid-size FA-40S. It is important to note that where their Helium flows overlap the smaller compressor use 1kW less power

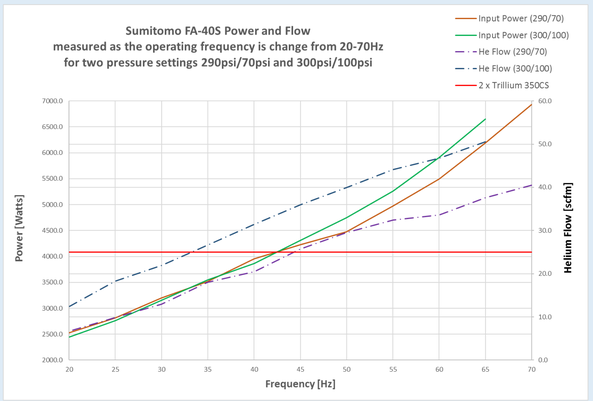


Figure 2: Sumitomo FA-40S Power and Helium Flow vs VFD frequency for two different pressure settings.

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 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: Sumitomo FA-40 Helium compressor selected for the reference design

Figure 6: Trillium 350CS refrigerators used for the reference design

ngVLA Cryogenics Reference Design Specifications

Scroll Compressor : Sumitomo FA-40L	
Variable Speed Drive	30-70Hz
Power Consumption	max 6 kW @ 60Hz
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: Trillium 350CS	
Variable Speed Drive	30-70Hz
1st Stage Cooling Capacity	20 W @ 80°K
2nd Stage Cooling Capacity	5 W @ 20°K
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

Considering the fact that the ngVLA front end reference design has only two receivers, NRAO has funded a design study with Sumitomo SHI for a mid-size Air cooled Scroll compressor operating at variable speed. Sumitomo SHI will use their current FA-40L air cooled compressor (**Fig.5**) model that runs on 3 phase 200V 60Hz power as the base for the study. The compressor will be equipped with a Variable Frequency Drive (VFD) to allow the speed of the Scroll capsule to be adjusted, the Helium flow and power consumption will be measured at various operating frequencies and pressure settings. (**Fig.2**) The prototype compressor will then be sent to NRAO Socorro to be tested in the VLA reverberation chamber for RFI emissions, the control electronics and power electronics shielding requirement will be derived from the measurement. A second phase of the study (to be funded in 2019) will be the integration of the FA-40 inside a FA-70 outdoor enclosure with shielded electronics as a field ready ngVLA prototype.

References

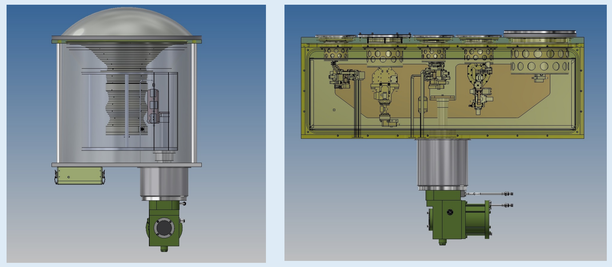
- L. D'Addario "Advanced Cryocoolers For Next Generation VLA" ngVLA Memo No. 24
- J. Gardiner, et al. "Smart Energy Cryo-Refrigerator Technology for the Next Generation VLA" ngVLA Memo No.23
- D. Urbain et al. " Improved Power Efficiency for Cryogenics at the Very Large Array" Cryocoolers 19, Proc. Of 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)

Thermal Analysis And Possible Technical Development Study

The GM type of refrigerator selected for the reference design is not the most efficient, other more advanced cryocooler developed for Millitary and Space application have higher efficiency and require a lot less maintenance. However, space-qualified cryocooler like the Raytheon 2-stage Sterling Pulse-tube (**Fig.4**) have limited cooling capacity and are usually very costly. Before NRAO decides to explore this alternative type of cryocooler, it is essential to know if their cooling capacity is adequate for the two ngVLA FE cryostat concepts.

A detailed mechanical model of both receivers concept is being developed, and NRAO has contracted an outside expert firm (Callisto in France) to do an accurate thermal analysis of both assemblies. It is well understood that at this stage of the project, there are many unknowns and a lot of elements (IR filters for example) that will need further development.

The band 2-6 receiver model was recently analyzed by Callisto, and the calculated heat load for an ambient temperature of 20°C gave: 18.4W at 50°K on the first stage and 4.3W at 15°K on the second stage. A similar analysis was done on the band 1 receiver for the same environmental conditions and the heat loads calculated were 9.81W at 50°K on the first stage and 3.14W at 15°K on the second stage. Base on this first run, we will make some changes to both models and will run a second simulation. The results of the second thermal analysis is one of the critical piece of information that NRAO will evaluate to decide if an advanced cryocooler study could be of interest for ngVLA and should be funded.

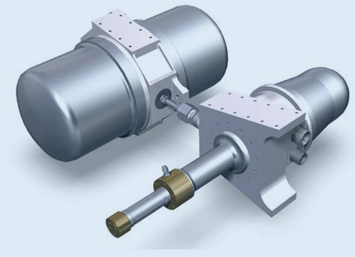


Image from Schaefer 2014 Cryocoolers 18

Figure4: Raytheon LT-RSP2 Hybrid Cryocooler with Sterling 1st stage and Sterling pulse tube 2nd stage. The compressor (left) is common to both stages. Cooling capacity 10W at 60°k and 2W at 20°K for 550W of input power.

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