SMART ENERGY CRYO-REFRIGERATOR TECHNOLOGY FOR THE NEXT GENERATION VERY LARGE ARRAY

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ABSTRACT

We describe a "smart energy" cryocooler technology architecture for the next generation Very Large Array that makes use of multiple variable frequency cold heads driven from a single variable speed air cooled compressor. Preliminary experiments indicate that the compressor variable flow control, advanced diagnostics, and the cryo-refrigerator low vibration, provide a unique energy efficient capability for the very large number of antennas that will be employed in this array.

Keywords: Cryogenics, Smart Energy, Variable frequency, ngVLA, receivers.

INTRODUCTION

The present baseline design concept for the next generation Very Large Array (ngVLA) envisions a 214-antenna array [1]. This is an increase of approximately 8 times over the number of antennas currently deployed at the Karl Jansky Very Large Array (VLA) in New Mexico, USA. A key requirement of the ngVLA is to minimize its operating cost to within three times that of the VLA. The strategy to accomplish this goal include: 1) reducing the total number of receivers by employing wideband feeds, 2) reducing the total number of dewars employed to cryogenically cool the front-end electronics in each receiver by consolidating receiver bands, and, 3) employing an efficient cryogenic system that optimizes power consumption.

In general, the high degree of control and optimization that is needed in interfacing cryo-refrigerators to receivers requires a careful budgeting of the available cooling power while making the best use of energy. The operational specifications of interest for this application include cooling power, base temperature of the receiver's electronics, vibration levels induced by the cryo-refrigerator, Radiated Frequency Interference (RFI) caused by the helium compressor and associated electronics and, meantime between service cycles. Commercial off the shelf (COTS) cryo-refrigerators appear to be the obvious choice for meeting the cooling requirements of the ngVLA receivers. However, while abating the need for liquid helium, these COTS systems are not known for being energy efficient. For example, the VLA is a radio telescope with eight receivers on each of 27 antennas, that requires continuous full power operation of 81 helium compressors and 216 cryo-refrigerators with a load of 18 KW per antenna. The combined antenna loads for the telescope costs the observatory half million dollars annually in electrical power [2]. Compounding this problem are ever increasing electricity prices that could make the operation of the planned 214 antennas for the ngVLA cost prohibitive in the future [3]. A variable frequency drive (VFD) cryo-refrigerator system for ground based telescopes was previously investigated by Jakob and Lizon [4] using laboratory components. This system however, based on single frequency drive helium compressors was not particularly energy efficient.

In this study, we demonstrate that the key power consumption goals for the ngVLA can be met by employing cryo-refrigerator smart energy technology. This system provides a new capability for a network of 4K and 10 K Gifford-McMahon (G-M) cryo-refrigerators coupled to the wideband receivers to dynamically control the cooling power delivered to the first and second stages based upon the compressor capsule and displacer stroke speeds [5-8].

OVERALL CRYOGENIC DESIGN CONCEPT

The baseline design of the next generation antenna has been proposed to be a receiver-feed configuration concept that involves multiplexing six-bands into two cryocooled dewars [1]. The most efficient configuration for this baseline concept, from a power consumption standpoint is a single helium compressor and one 4 K and one 10 K class G-M cryo-refrigerator running at variable speeds. Figure 1, shows the main components of this proposed system: (1) A variable speed split-air helium compressor installed on a platform outside the antenna, (2) external adsorber, buffer tanks, high pressure lines and manifolds that will be an integral part of the antenna's infrastructure, (3) an intelligent microcontroller to independently control the speed of the capsule in the helium compressor and the speed of (4) two G-M cryo-refrigerators coupled to the two multi-band receivers.

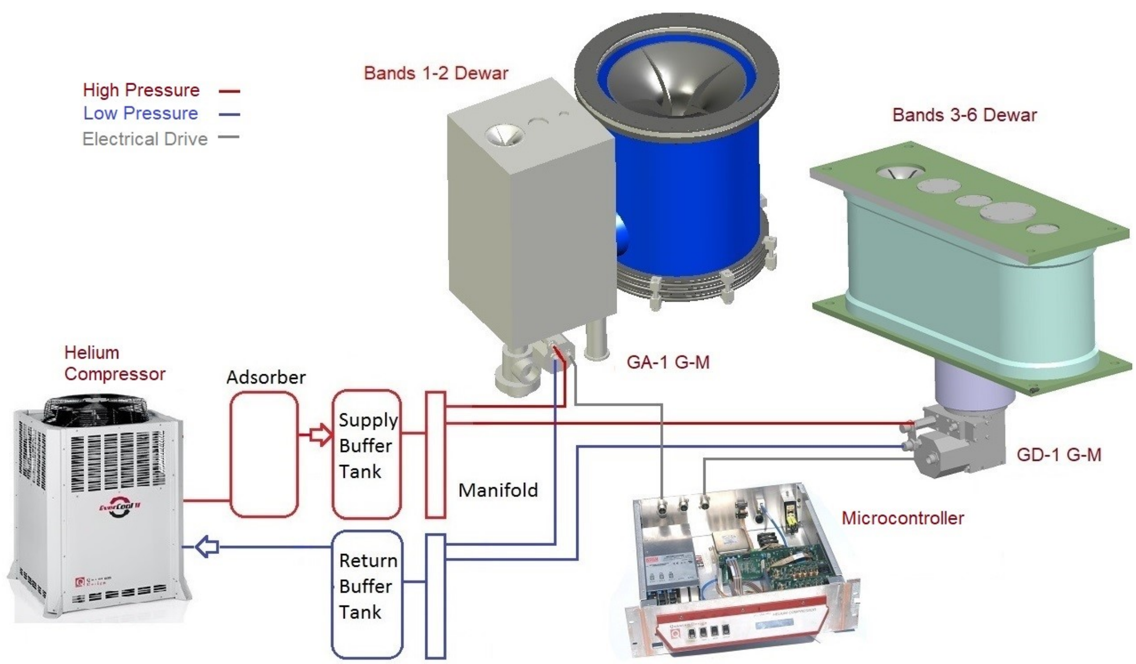

Figure 1 Overview of the proposed smart energy architecture for the ngVLA antennas (for illustration purposes only: not to scale).

VARIABLE SPEED G-Ms

The current baseline receiver configuration envisions a first dewar to house two low frequency receiver bands (1.2 -12.6 GHz). We propose to employ a single 4 K class variable speed G-M cryo-refrigerator model GA-1 to cool the cylindrical band 1 Quad Ridge Feed Horn (QRFH) and the smaller band 2 feeds on the side rectangular dewar. The GA-1 is a two stage cryocooler with first and second stage cylinder dimensions of approximately 46 mm and 20 mm in diameter and 129 mm and 115 mm in length respectively [7-8]. The GA-1 has a nominal cooling power of 0.25 W at 4.2 K and should, with a careful thermal design of the cryostat [9], provide for adequate heat lift off to cool the first and second stages to temperatures below 55 K and 9 K respectively.

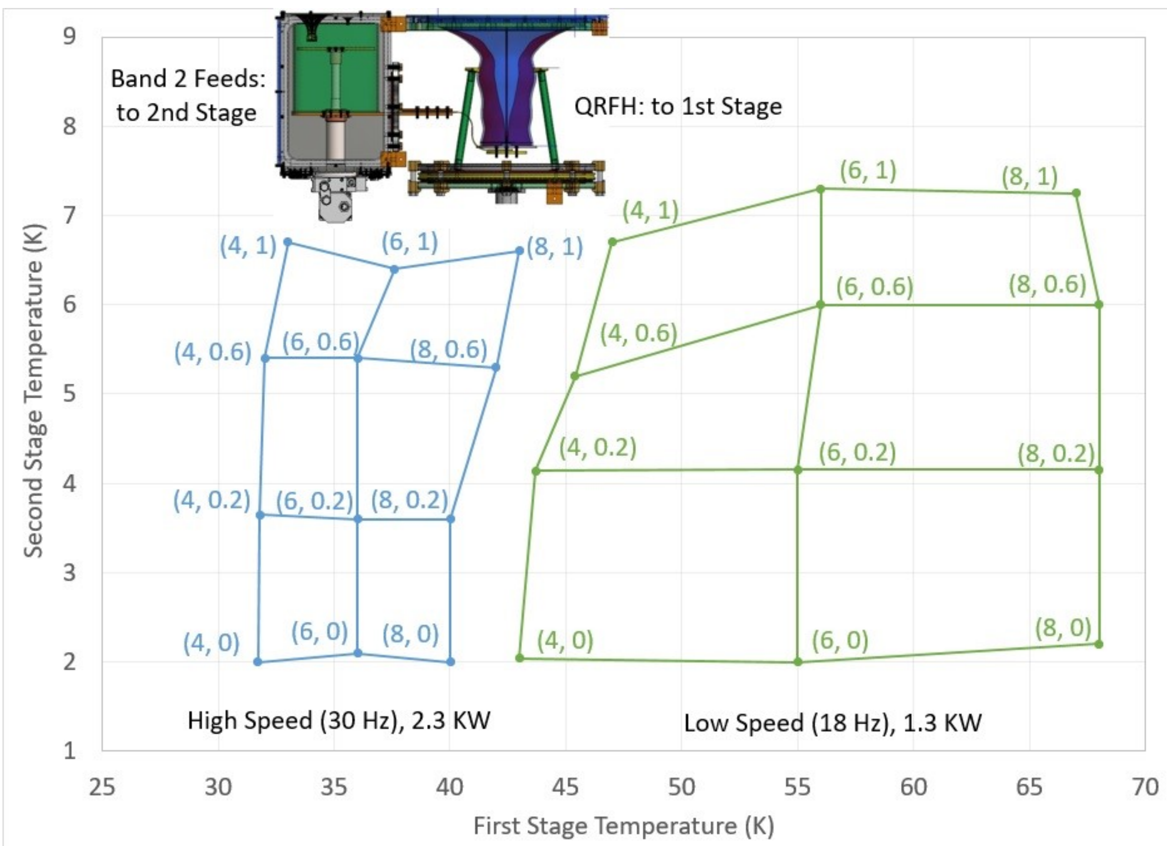

Figure 2 High Temperature load maps for the GA-1 variable speed cryo-refrigerator. (Inset) Cross section of the bands 1-2 cryogenic assembly with a GA-1 variable speed cryo-refrigerator (adapted from [9]).

Figure 2 illustrates the primary advantage of the proposed system: the variable speed compressor can be adjusted to reduce power consumption when the cooling power requirements of the antenna are reduced (green trace) after the initial cool down (blue trace) resulting in power savings up to 1 KW. If necessary, the cryo-refrigerator speed could be increased every time the QRFH is observing to achieve lower 1st Stage temperatures. On the other hand, during times when band 1 is not observing the cold head could return to low speed. At low speed the input frequency to the cryo-refrigerator motor decreases from 70 Hz to 50 Hz reducing the reciprocating motion of the displacers. This, in turn reduces the amount of wear in the displacers and valve seals thus extending the mean time between failures.

One of the important design concept for the ngVLA antennas is the offset Gregorian Reflector design. This design provides for unblocked reflector and easy access to receivers at the secondary focus [9]. In this geometry, the two band feeds containing the cryo-refrigerators will be mounted on a rotating platform as already implemented on the Meerkat 64 x 13.5 m array and planned for the SKA 133 x 15 m. Of importance, for this application then, is the ability for the cryo-refrigerator to retain its cooling power regardless of the orientation of the rotation platform. Figure 3 show the cooling power capacity the GA-1 cryo-refrigerator as function of tilt angle. The data indicates that cooling capacity losses of less than 10% for a total rotation of 180 degrees.

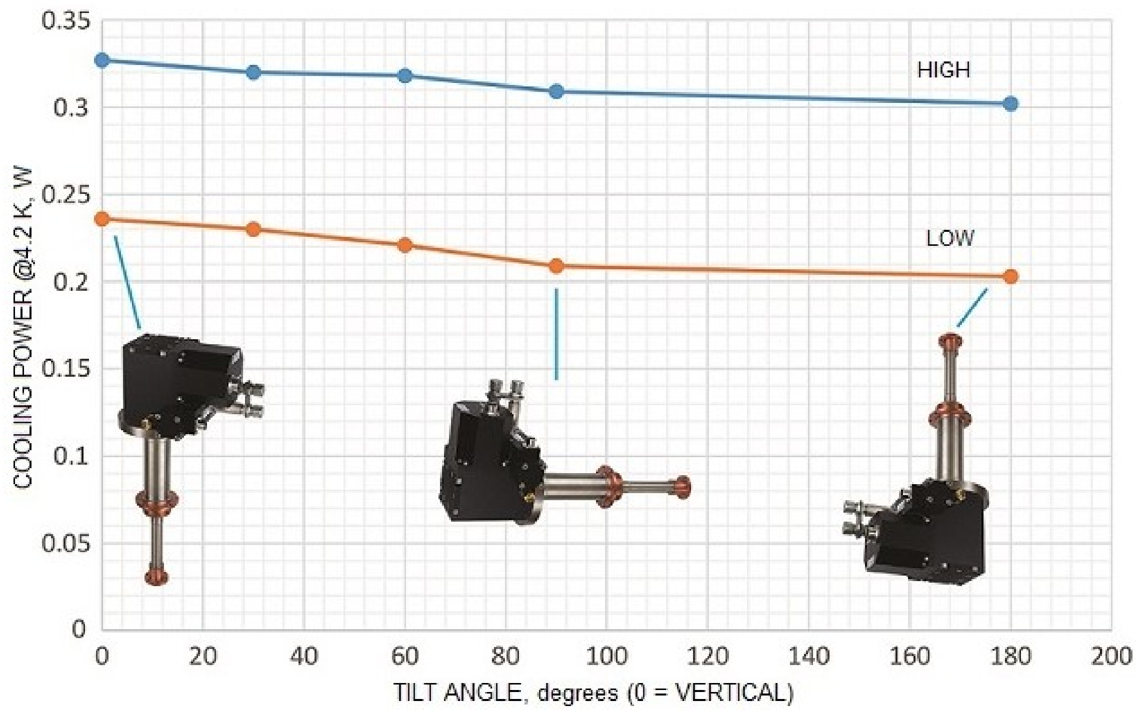

Figure 3 Relationship between 2nd stage cooling capacity and the GA-1 cryo-refrigerator orientation.

The second dewar is envisioned to house four high-frequency receiver bands (12.6 – 116 GHz). We propose these receivers to be cooled by a single 10 K class G-M cryo-refrigerator model GD-1. Specifically designed for this application, apart from the second stage displacer the GD-1 is identical to its 4 K counter-part the GA-1. The commonality of parts between the two refrigerators has several perceived advantages: reduced cost of manufacturing due to economies of scale, common electronic drives, diagnostic controls and software/firmware protocols. Two nearly identical cryo-refrigerators used in the low and high frequency receiver bands will also allow for streamlining of servicing, troubleshooting and assure long term availability of parts for both systems.

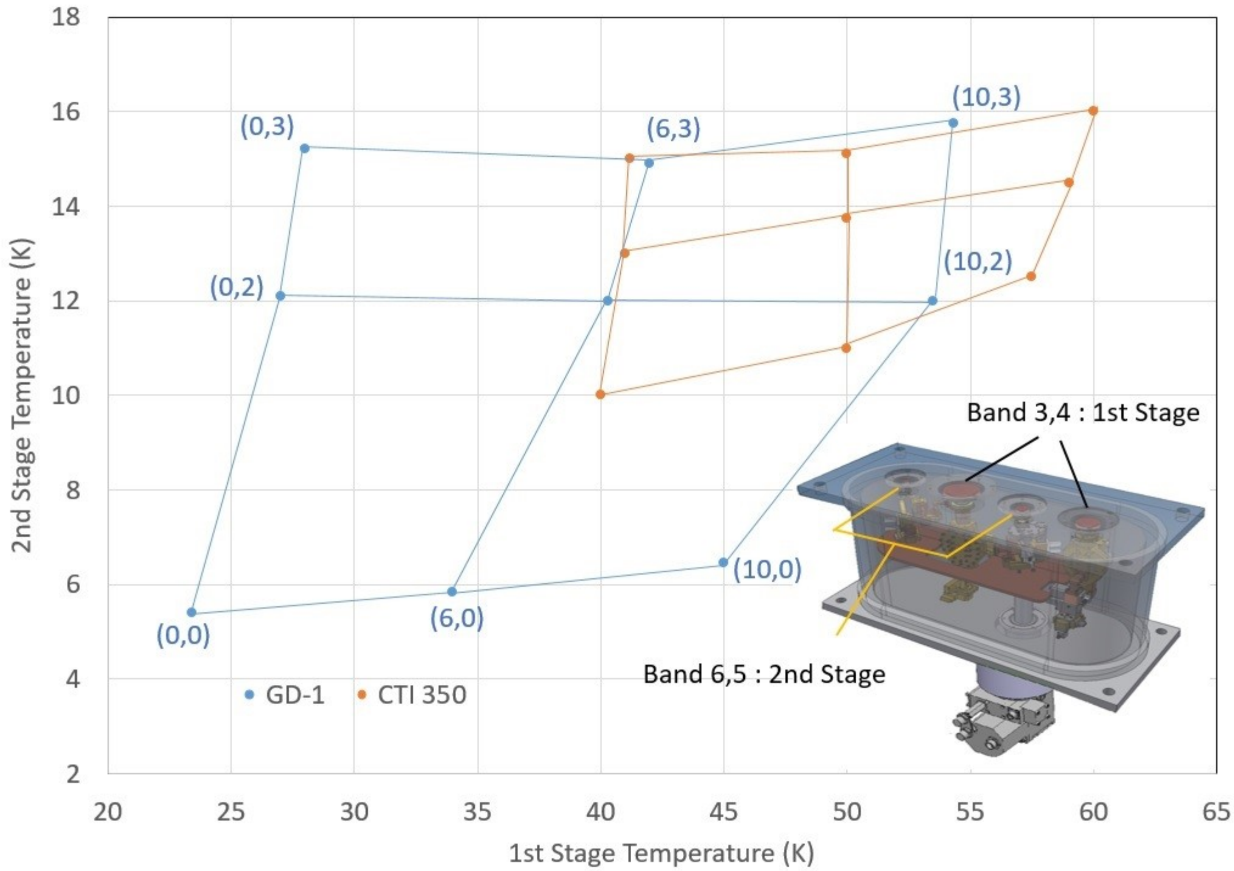

Figure 4 High Temperature load maps for the GD-1 variable speed cryo-refrigerator. (Inset) Cross section of the bands 2-6 cryogenic assembly with a GD-1 variable speed cryo-refrigerator (adapted from [1]).

The GD-1 cryo-refrigerator is envisioned to be used in place of the legacy CTI 350 cooler. Initial experiments on a test receiver Dewar indicate that the second stage reached 6.5 K and the first stage 38.5 K with just the radiation and conduction heating due to the wiring in the Dewar. Figure 3 (left) shows a favorable comparison of the cooling power of the GD-1 at high speed when compared to the CTI 350. For a given heat load the GD-1 outperforms the CTI 350 with lower 1st and 2nd stage temperatures. Analogous to the low frequency band receivers, if necessary, the cooling strategy for the high frequency bands could involve speeding the cryo-refrigerator to achieve lower first stage temperatures when bands 3 and 4 are observing.

VARIABLE SPEED COMPRESSOR UNIT

Figure 4 is a schematic of the HAC 4500-LV split air cooled compressor that will be used in this study as the starting point for the ngVLA “smart energy” design. Because of the uncertainty that still exists regarding the number of receivers and cryostats that will be employed in the ngVLA we should point out that, the compressor employed in this study might need to be sized down in the future, depending on the number of cryo-refrigerators that the final design will use. Preliminary experiments conducted for the “Green Antenna” initiative have demonstrated that the HAC 4500-LV compressor is capable of driving with variable frequency controls as many as 2 test receivers dewars equipped with CTI 350 cryo-refrigerators and 3 test receiver dewars equipped with CTI 22 cryo-refrigerators. This compressor first became commercially available in 2012 as part of the Quantum Design Physical Property Measurement System (PPMS) Evercool II [10]. The HAC 4500-LV is designed around an inverter rated 3-phase 6 horsepower Hitachi Scroll Capsule S603DH.

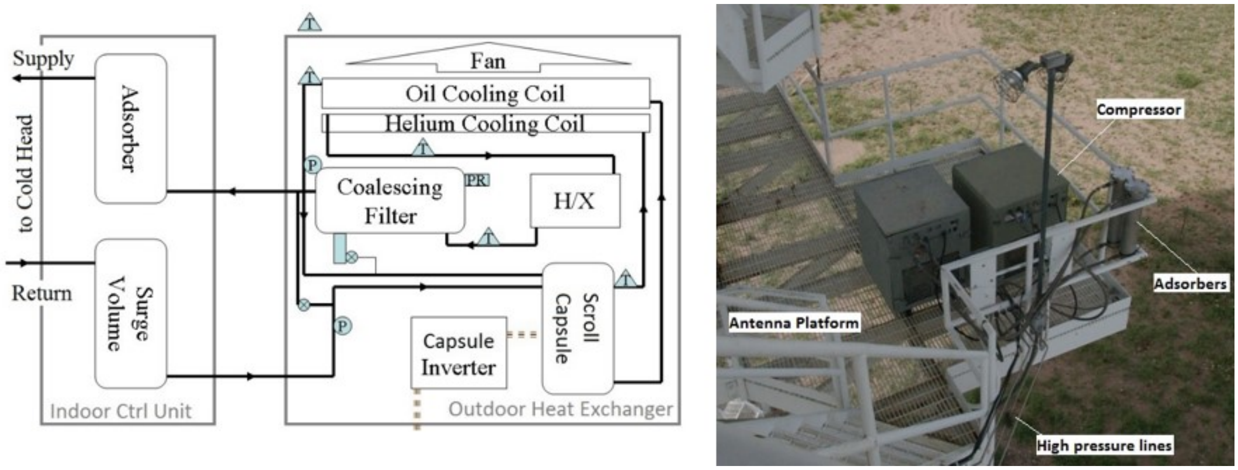

Figure 5 Schematic of the HAC 4500 (left). Captions T=Thermistor, P=Pressure Sensor, PR= Pressure Relief Valve, H/X Heat Exchanger. Current compressor location and configuration at the Karl Jansky Very Large Array (VLA) in New Mexico, USA (right).

A Hitachi WJ series inverter is used for driving the scroll capsule while a 5-phase hybrid stepper motor electronic control board is used for each of the cryo-refrigerator drives. Ambient air is drawn from the sides of the outdoor heat exchanger where it cools the helium and oil flowing through their respective cooling coils. An important aspect of a variable speed compressor is the proper oil management for cooling the scroll capsule not only at high speed but also at low and intermediate speed. To this end, we have designed a dynamic oil drain system comprised of an oil sump, level meter and a solenoid valve that opens when the sump is filled. In the standard configuration used in Quantum Design’s cryogenic laboratory instruments the adsorber, surge volume, and microcontroller electronics together with the user interface controls are housed in an indoor Compressor Control Unit (Figure 5, left). On the other hand, it is envisioned that in the ng-VLA the adsorber and surge volumes will be part of the antenna infrastructure (Figure 5, right) and a separate microcontroller has been designed to provide all the controls and data taking electronics of the system as shown in Figure 1. The microcontroller, will be housed in a standard 17” rack mounted shielded box for ease of installation into the Vertex room.

The compressor environmental temperature is a critical factor in the proper operation of any helium compressor. The HAC 4500-LV is a split air cooled compressor, which is designed to be resistant to harsh environments. The outdoor unit is coated with two special coatings which make it resistant to coastal, industrial salty and corrosive environments. Washable grilles on the outdoor unit make it easy to maintain the heat exchanger clean and free of particulates which might degrade its efficiency. In addition, a slow start in subzero temperature allows to be brought up to speed gradually to allow the oil to liquefy and flow throughout the system. Figure 6 (left) is a picture of a typical HAC 4500 compressor installation in a snowy environment such as the one at the University of Troitsk, Russia where the average temperature in January is −14 °C (7 °F), and +20 °C (68 °F) in July. The data shown on the right a "slow start" of a compressor at the University of Minnesota, USA where the outdoor temperature can reach as low as -10 °C (labelled "Output temperature"). The compressor was started remotely from a computer to finely control the capsule speed and allow for the viscosity of the oil to gradually change to a lower value and the oil to flow and properly cool the capsule motor. The data (Figure 6 - right) shows that the capsule motor input frequency is kept at 15 Hz to allow for the temperature of the capsule motor to raise from -10 °C to about 60 °C. When this occurs a proper flow of the oil is observed with the oil level meter showing an increase in the oil sump below the coalescer which implicates an increase in oil flow in the system which will keep the capsule motor operating safely. Once capsule speed of 25-30 Hz is reached the oil flow can be seen to be cycling as expected from a low value of 35% to about 80% at which point the oil drain valve opens to the capsule to drain the oil accumulated in the coalescer. To our knowledge this is the only system commercially available that can be started remotely without the use of external heaters by a "slow start" protocol.

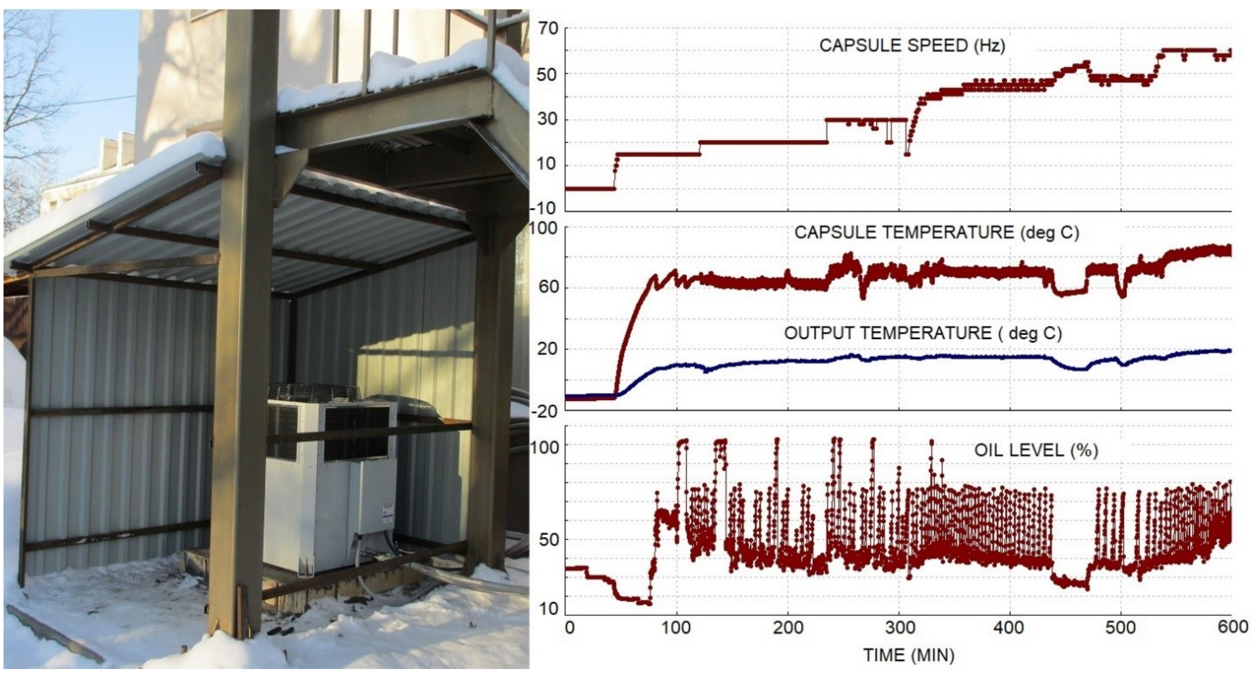

Figure 6 HAC 4500 installed at the University of Troitsk in Chelyabinsk, Russia (left), data variable speed cold start from -10 °C from the University of Minnesota, USA (right).

MAINTENANCE CONCEPT

In general, the official recommended interval between head refurbishments is 10,000 hours for most commercially available G-M cryo-refrigerators. This is only 14 months and refurbishing costs are typically several thousand dollars. This is one of the reasons, we propose to operate the cryo-refrigerators at reduced drive levels. It has been our experience that these heads will typically run substantially longer than the prescribed period, even at standard drive levels. We have looked at the typical wear patterns of several G-M cryo-refrigerators and found several common themes. The greatest wear usually happens in the warm end of the refrigerator, not on the displacer seals.

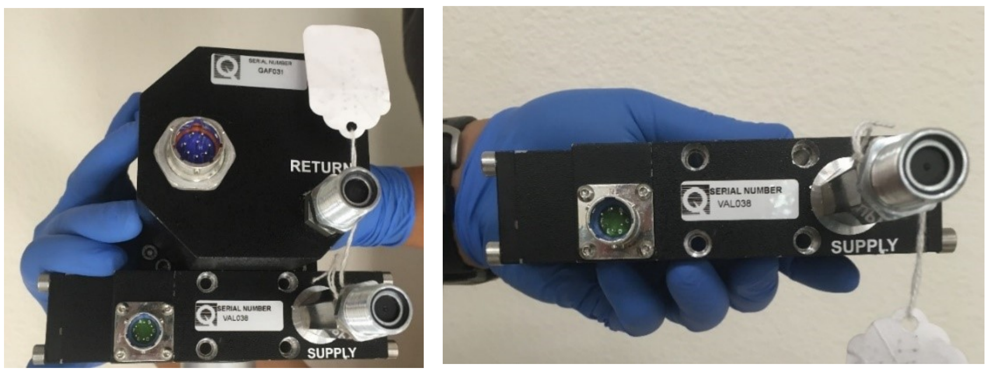

Figure 7 Replacement of the valve mechanism in GA-1 is accomplished by simply venting the system and unbolting four bolts.

The plastic bushing on the motor eccentric (that drives the scotch yoke) in classic G-Ms shows the highest wear of all parts and this directly creates a loud clacking noise in the head. The next major wear items are the slide-bushings that constrain the scotch yoke to move vertically. As these wear, the drive rod moves transversely and tears up the gas seal that is riding on it. In the GA-1 all the gas seals have been designed to provide a minimal amount of friction during operation. In addition, one of the benefits of an independent valve assembly that is not mechanically linked to the displacer motion is the ease in which it can be serviced. Figure 7 shows the removal of the GA-1 spool valve by venting the cryo-refrigerator and un-bolting four bolts that mate the valve to the main housing. Table 1 compares the maintenance costs, assuming a comparable cost of overhaul, for a single speed and a variable speed cryo-refrigerator. Over a period of ten year of ownership, the variable speed cryo-refrigerator can yield savings more than $60,000 per antenna when operated at medium and low speed. Under these conditions, the cost savings for the future ng-VLA observatory over the same period could approach nearly $ 13 million dollars.

Cryo-refrigerator Type	Service Interval (hr)	Unit Rebuild Service Cost ($)	Service interval in a 10 year period	Service Cost in a 10 year period
Single speed	10,000	4500	8.76	$39,420
Variable speed, low vibration	44,000	4500	1.99	$8,959

Table 1 Comparison of service costs between cryo-refrigerator types.

POWER DRAW EXPERIMENTAL RESULTS

The HAC 4500 compressor was run with several cold heads and flow impedance fixtures, with a static pressure of 1.5 MPa at various speeds while cooling down and at base temperature. The cold head speed was kept at an input frequency of 60 Hz to the motor. The actual power draw of the compressor was measured with a Fluke 437 power meter. Figure 8 shows that the power draw of the HLC 4500 compressor varies greatly depending on the compressor capsule speed and differential pressure (Supply Pressure – Return Pressure) of the compressor. During cool down at a given speed, the differential pressure typically was about 0.5 MPa larger than the differential pressure once the system was cold at base temperature leading to a power reduction of about 0.6 KW.

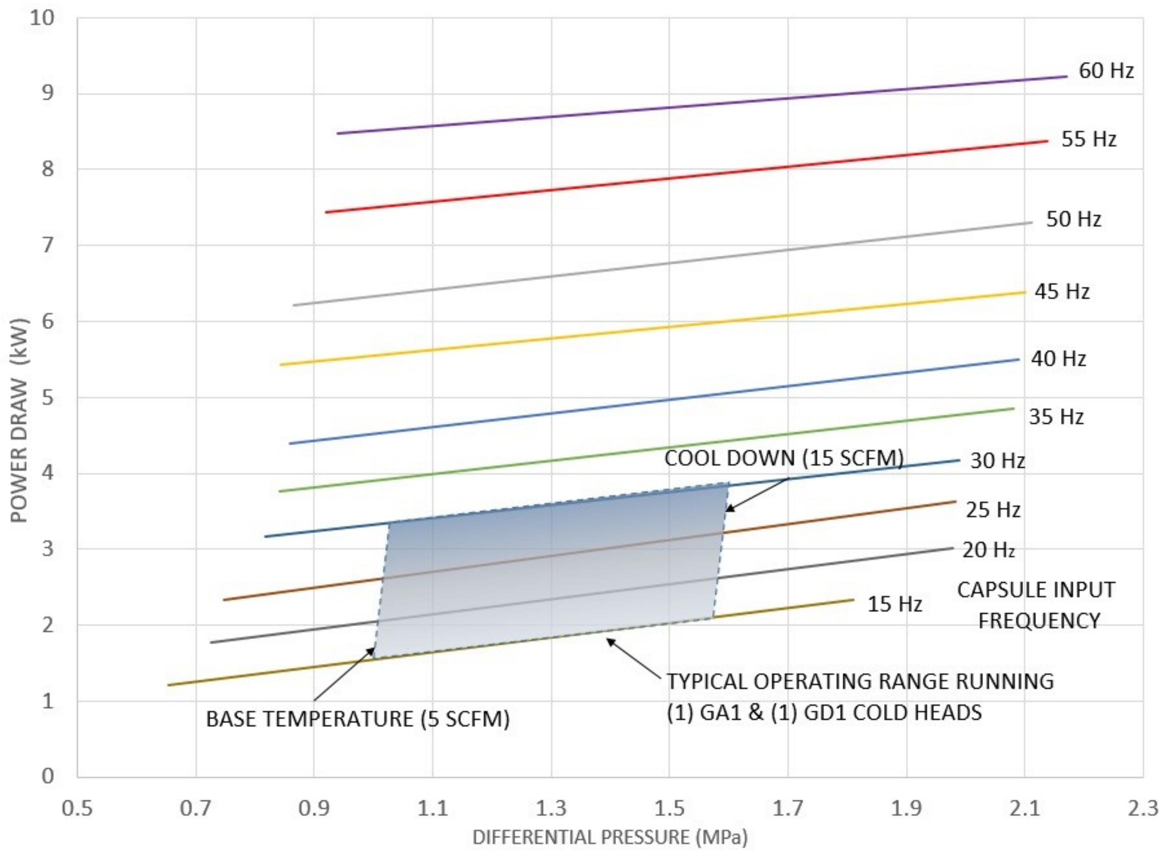

Figure 8 HAC 4500-LV compressor actual power draw at various speeds.

This data clearly shows the HAC 4500-LV to offer substantial operational cost reduction for the antenna over systems that use constant power frequency compressors. In general, three distinct regions of power consumption can be identified in the graph: 1) low power with input frequency up to 15 Hz, this range will be typically employed in the "quiescent" or "stand-by" mode that require minimal amount of cooling power delivered to the cold head, 2) medium power with input frequencies between 20 and 25 Hz for intermediate thermal heat loads and, 3) high power mode with frequency at or above 30 Hz for initial system cool down.

The smart energy features of the compressor we propose to employ in the ngVLA are key for making it a "low power" telescope. Planned antenna deployments include remote locations that lack utility power, and thus must be powered by alternative means. The variable frequency drive employed in these compressors allows the system to slowly "ramp up" the speed of the capsule during system start up. This avoids the large "in-rush" current associated with single speed motors which employ a startup winding. This is especially important, if a smaller single phase compressor was used instead of the HAC 4500, since the in-rush current typically requires the power source to be oversized by a factor of four just to satisfy the compressor's starting current requirements. When such a device is to be powered from an inverter, generator, or UPS, this equates to a power source which is larger and more costly than that required for normal running conditions. The use of a variable speed drive can eliminate the need for over-sizing the power source. In the case of the ngVLA, an advanced concept design (Figure 9) would be to power the cryo-refrigerator system solely with solar cells. As with any solar installation, minimizing the end load is critical not only for minimizing the number of solar panels required, but also for reducing the capacity of the energy storage system. The variable capacity refrigeration system might require the system to operate at "full observation mode" when solar energy is available then "in reduced observation mode" during periods when solar energy production is minimal or non-existent.

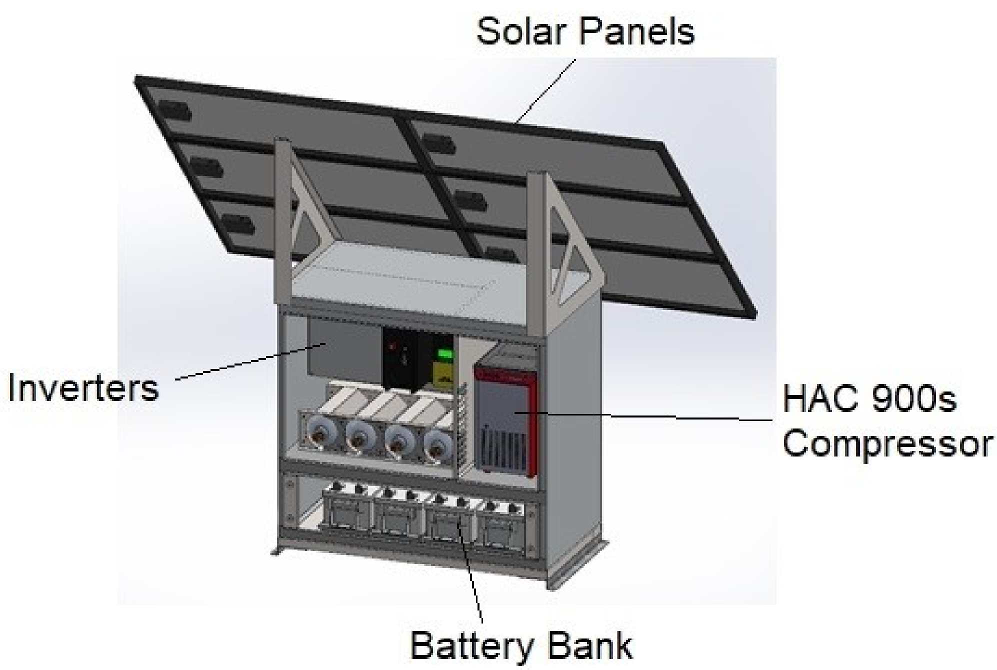

Figure 9 Concept for an advanced compressor and solar power enclosure concept employing the Quantum Design HAC 900s air cooled compressor (courtesy of GWR).

COST OF OWNERSHIP AND LONG TERM AVAILABILITY ANALYSIS

Table 2 compares estimates of the total yearly cost resulting from electrical consumption for the current VLA and the ngVLA array proposed in this study. The reduction of cryostats coupled with more powerful cryo-refrigerator that are smart energy efficient allow for the proposed cryogenic concept developed in this work to reduce the cost of operation of the observatory over the current VLA despite its significant larger size.

	Current VLA configuration	ngVLA Baseline configuration (this work)
Number of cryostats	8	2
Number of 25 m antennas	27	214
Number and type of cryo-refrigerators per antenna	1 x CTI22, 6 x CTI350,1 x CT1050	1 X GA-1, 1 x GD-1
Number of cryo-refrigerators on the array	216	428
Variable speed drive	No	Yes
Cumulative Helium flow (scfm) per antenna	121	5
Number of Helium compressors per antenna	3	1
Number of compressor on the array	81	214
Variable speed drive	No	Yes
Cumulative electrical power consumption (kW) per antenna	**18**	**1.7**
Yearly electrical cost per antenna	$17,345	$1,638
Total yearly electrical cost for the array*	**$468,310**	**$350,557**

*Using the average residential electricity rate in New Mexico of 0.11 $ /kWh

Table 2 Comparison of total electrical cost for the array between the VLA and ngVLA.

The ngVLA will come online and be in operation for the next decades. As such it should be designed with modern components and devices whose long-term availability (20 years or more) is secure allowing long-term planning and leading to the un-interrupted operation of the telescope. The product life time of the cryo-refrigerator technology used to cool the front-end electronics in the antennas of the ngVLA should be an important factor in determining its adoption in a design that is expected to last for the next 20-30 years. Technical support, long term availability of spare parts, serviceability know-how and, warranty from vendors should be carefully reviewed as part of the qualification of the cryo-refrigerator technology adopted in the ngVLA. Remarkably, many of the cryo-refrigerators and helium compressors in use or being considered for adoption in future telescopes are based on designs such as the Displex drive technology first introduced by CTI in the 1960s. Piston type compressors, cryo-refrigerators with synchronous motors and classic scotch yoke drive mechanisms are inherently limited and their performance and power efficiency is currently being challenged by newer technologies that have come to the market. As such, these legacy cryo-refrigerator systems will presumably be entering their "End Of Life" (EOL) phase soon. While optimistically this phase might still be 5 to 10 years long, assuming the risk of lack of support, technical improvement in the form of hardware and firmware upgrades and, availability of spare parts in a not too distant future should not be taken lightly.

CONCLUSIONS

In this study, we have begun investigating the feasibility for adopting a smart energy cryo-refrigerator technology for the receivers that will be employed in the ngVLA. The ability for independently controlling the cooling power delivered to the receivers and the slower movement of the displacers result in energy savings and increased mean time between service intervals for the cryo-refrigerators. The system described, has been ruggedized for outdoor operation and can be started remotely even in extreme environmental conditions. The key operating cost goal for the ngVLA can be easily met by employing the overall smart energy technology concept proposed in this study.

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