Improved Power Efficiency for Cryogenics at the Very Large Array

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ABSTRACT

The National Radio Astronomy Observatory (NRAO) recently completed a major upgrade to the electronics in the Karl Jansky Very Large Array (VLA) telescope, including all eight cryogenic receivers. The focus of development has now shifted toward improving efficiency and reliability to reduce maintenance downtime and power consumption. The cryogenic system in particular requires frequent maintenance by skilled labor, and consumes a considerable fraction of the electrical power supplied to the array. Careful evaluation of the current system and preliminary tests of new techniques have demonstrated significant power savings are possible, along with an overall reduction in maintenance. This paper will describe the application of a Variable Frequency Drive (VFD) for powering the cryogenic refrigerators, to tailor the flow requirement for an individual receiver and extend cold-head life. Additionally, the benefits of Multilayer Insulation (MLI) for the receivers are described and quantified. Combined, these should allow up to a one-third reduction in electrical power consumption, by elimination of one Helium compressor per antenna. Predictions on improvements in reliability and maintenance interval are also given.

INTRODUCTION

The VLA is a radio telescope array with eight receivers on each of 27 antennas, that provide continuous frequency coverage from 1 to 50 GHz. The front end electronics in each receiver are cryogenically cooled by a Gifford-McMahon (GM) refrigerator to minimize thermal noise for maximum receiver sensitivity. Three Helium compressors are currently used on each antenna, which supply gas at ~280 psi for 2 to 3 cold-heads each. All 81 compressors run continuously, the combined 18kW load per antenna costing the observatory almost half million dollars annually in electrical power. In addition, these compressors along with the 216 cold-heads in the array need regular maintenance by a team of experienced technicians.

The NRAO has begun an initiative to reduce power consumption and improve reliability, called the Green Antenna Project (GAP). Our research into more efficient Helium compressors and more reliable refrigerators led us to consider variable-speed operation of both these. As VFD Helium compressors and cold-heads are becoming commercially available, we examined our current system to see how it could be retrofitted with this new technology.

GM refrigerators

All VLA cold-heads are 2-stage units, with a first stage at ~50 Kelvin, and a second stage at ~15 Kelvin. The smallest cold head is designed to run at 200 rpm, while all the other ones run at 72 rpm, for the nominal 60 Hz line frequency. Regardless of the refrigerator size, the electric motor that drives the displacer is an AC-synchronous type with a rotor and stator that have no physical contact. It requires two quadrature-phased AC voltage inputs, which runs the motor at a rate directly proportional to the input frequency. However, the winding impedance varies with frequency, so the supply voltage amplitudes need to be adjusted as the drive frequency is changed, to maintain a constant torque and keep the current below the rated maximum.

Helium compressors

The VLA Helium compressors are the reciprocating (piston) type, and are based on an older model CTI 450 air-cooled compressor. They use the same motor assembly, but were highly modified over the years to reduce construction cost and ease maintenance. During the upgrade, 60 more compressors had to be built to accommodate the increased number of cold-heads. Varying the speed of a reciprocating compressor poses challenges, such as torque pulsation and lubrication problems, which forced us to look at other options.

RECEIVER TEMPERATURE CHARACTERIZATION AT VARIABLE SPEED

VLA receivers span a range of physical size (and cooling requirements), though all except the largest and smallest use exactly the same refrigerator. This would suggest that many if not most of the receiver types have cold-heads that are oversized, at least when run at 60 Hz. To quantify this, laboratory testing of each receiver type was done using a commercial variable-frequency inverter into our standard refrigerator drive unit, and cold stage temperatures were recorded. The measurements were then repeated after the receiver under test was retrofitted with MLI on the first stage radiation shield, and the improvement over the first test recorded.

Test #1: Characterization of VLA receivers at variable motor speeds

After the cold-head motors were verified to be compatible with VFD operation, one of each type of receiver was randomly selected, and run with the inverter over a range of frequencies, from 60 Hz down to 30 Hz. The receiver under test was in a laboratory environment at ambient temperature; the Helium compressor supply pressure was frequently monitored and adjusted to keep it constant. Temperatures on both cold stages were recorded, after allowing enough time between frequency steps for the temperatures to re-stabilize. The temperature data for each stage versus frequency is plotted in Figure 1 and Figure 2 below, for the 8 receiver types tested.

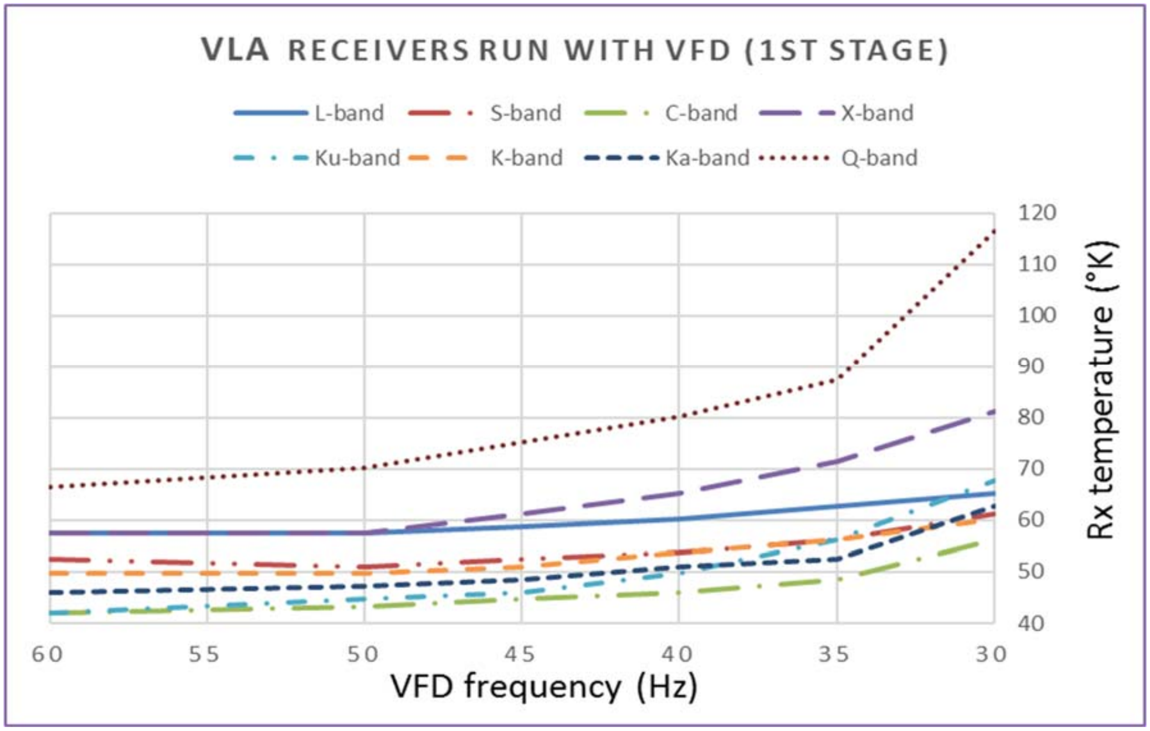

Figure 1: VLA receivers 1st stage temperatures when run with VFD

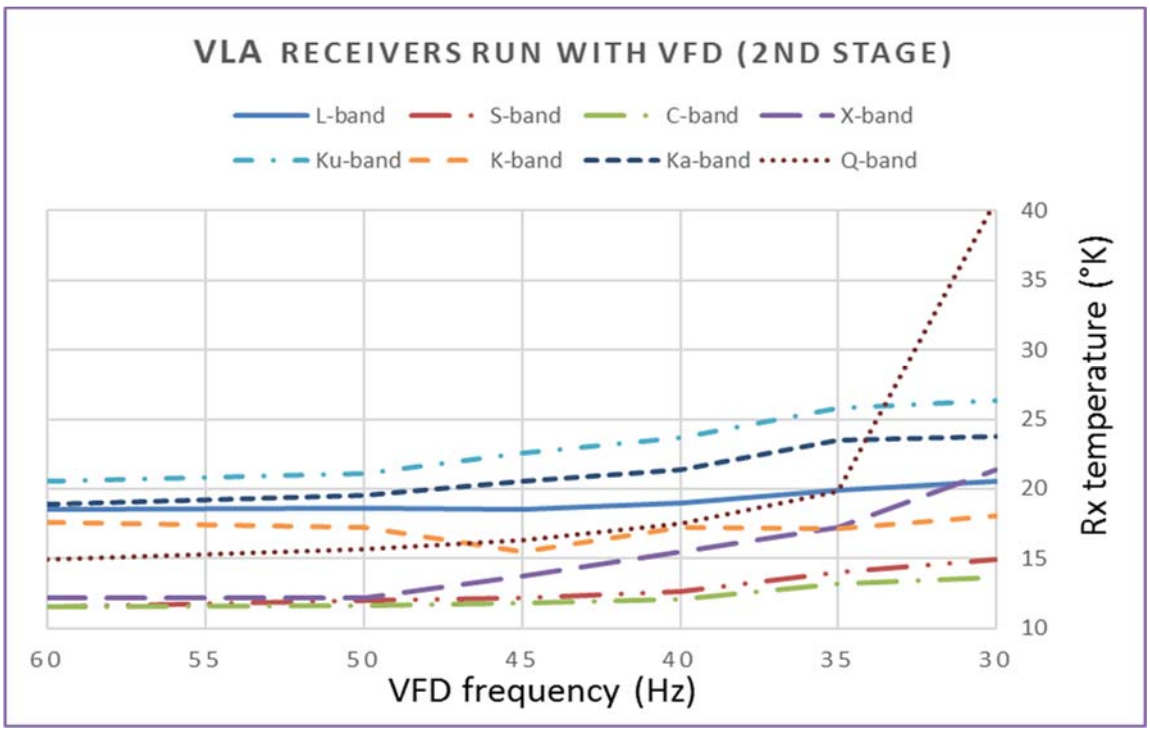

Figure 2: VLA receivers 2nd stage temperatures when run with VFD

The plotted results are revealing. For both the L-band and S-band receivers, it's clear they can be run down to two-thirds the nominal speed (40 Hz), with near-negligible temperature rise on the critical second stage where the low-noise amplifiers are mounted. The first stage temperature was also nearly flat for both of them, and for the ka-band the second stage temperature actually *decreased* slightly at 45 Hz, then returned to the original temperature at 40 Hz. The C-band shows as well a flat temperature response on both stages down to 40Hz.

Conversely, the X-band, Q-band and Ku-band receivers all show a significant proportional increase in temperature on both stages as the drive frequency drops from 60 to 30 Hz, indicating the cold head thermal loading is closer to the rated capacity. The Q-band does have the small cold head, which could account for the rise; likewise, the first stage radiation shield area on the X-band and Ku-band are relatively large compared to the remaining three receivers.

Overall, the relative increases on the first and second stages for all receivers appear to be correlated. This very likely indicates radiative loading on the first stage as the dominant contributing factor, which the next test is intended to confirm.

Test #2: Addition of MLI to the first stage (~50K) radiation shield

Of the eight VLA receiver types, only two (L-band and S-band) currently incorporate MLI on the first stage radiation shield. In this phase, MLI was added over the radiation shields of the remaining 6 receiver types in the test group, and the testing above was repeated on these receivers to quantify the effect of thermal loading on the refrigerator.

A brief summary of the results is given in the **Table 1** below, showing the temperature reduction after MLI installation on each temperature stage for the 6 bands, at the nominal 60 Hz drive frequency. The addition of MLI dropped the temperature of the first stage by several degrees, with a corresponding smaller drop on the second stage. The 10K reduction seen on the Ku-band second stage was questionable, so another Ku-band receiver was tested to confirm the results. The second receiver initially had a warmer first stage and colder second stage compared to the first receiver. But after adding MLI the final temperatures for both receivers were almost identical.

	C Band	X Band	Ku Band	K Band	Ka Band	Q Band
KT 1st stage	5.2K	14.1K	6.5K/33.2K	3.8K	7.8K	23K
KT 2nd stage	0.4K	0.9K	10K/4.9K	0.5K	0.9K	1.8K

Table 1 - Temperature Reduction with MLI, at 60 Hz drive

The next **Table 2** shows the temperature increase on both stages relative to the 60 Hz result, as the drive frequency is lowered in steps to 30 Hz. Again, the data was recorded after sufficient time had passed for the temperatures to re-stabilize, when the drive frequency was changed.

	C Band		X Band		Ku Band		K Band		Ka Band		Q Band	
Frequency	K1st in K	K2nd in K	K1st in K	K2nd in K	K1st in K	K2nd in K	K1st in K	K2nd in K	K1st in K	K2nd in K	K1st in K	K2nd 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 2 - Temperature Rise with Decreasing Drive Frequency, MLI Installed

The most striking result from the test is that all the receivers can be run at 40 Hz, and still maintain lower temperatures with MLI than at 60 Hz without MLI. This assumes the receivers tested are representative of the majority in the VLA. Retrofitting these receivers with MLI is relatively inexpensive and straightforward, but the refrigerator drives currently in the VLA are fixed at 60 Hz. Without a VFD, the benefits of reduced power consumption and longer life cannot be achieved. This will be the topic of the next two sections.

Change in compressor configuration

A cold-head that runs at a lower speed requires less Helium flow from the compressor, effectively allowing a smaller unit to be used. A compressor capable of variable-speed operation would be ideal, as it can be adjusted to precisely match the required flow. Unfortunately, the VLA compressors are fixed-speed, and cannot easily be modified for variable-speed operation.

However, another solution is possible, if all three compressors on an antenna can be adapted to feed a single supply manifold common to all 8 receivers, rather than having separate circuits. This could allow selective remote shutdown of a compressor, when the total demand is low enough to allow it. In steady-state operation (all receivers cold), running the cold-heads at 40 Hz should reduce the required flow by a third, which would allow one compressor to be shut off. When more flow is required, such as during receiver cool-downs, the third compressor could be brought back online. While such an arrangement isn't as flexible as varying the compressor speed, it could still allow a substantial power savings, given the extra capacity will be needed for only a very small percentage of the time.

Implementation of new compressor configuration

Combining multiple compressors on a single circuit present risks, and a few precautions must be taken. In order for the flow from one compressor not to enter or interfere with that of another, a one-way valve must be placed at the output of each. If a compressor is shut down, its supply and return pressures must equalize, and be isolated from the rest of the circuit. When a compressor is turned off, the static pressure is ~200 psi, so the one-way valve is adjusted to allow flow at a slightly higher pressure (~230 psi). Therefore, Helium will only flow from a compressor into the supply input manifold if the compressor is actually running. In a like manner, a second one-way valve set to ~70 psi is placed on each compressor's return port, to prevent back flow and set a minimum return pressure.

The output from all compressors feed into a 20-liter stainless-steel buffer tank through an input manifold. The tank is equipped with a relief valve for safety, and a transducer to measure the pressure. An identical buffer tank and manifold arrangement are used on the return side, to combine the return flows from the cold-heads and on to the individual compressors.

Finally, an adjustable orifice is added to connect the two buffer tanks, providing a bypass for excess flow. The orifice is set to provide a return pressure of 75 psi when all the cold-heads are not running.

Figure 3 below shows a diagram of the overall system, with Helium supply paths as solid lines, and the return paths as dashed lines.

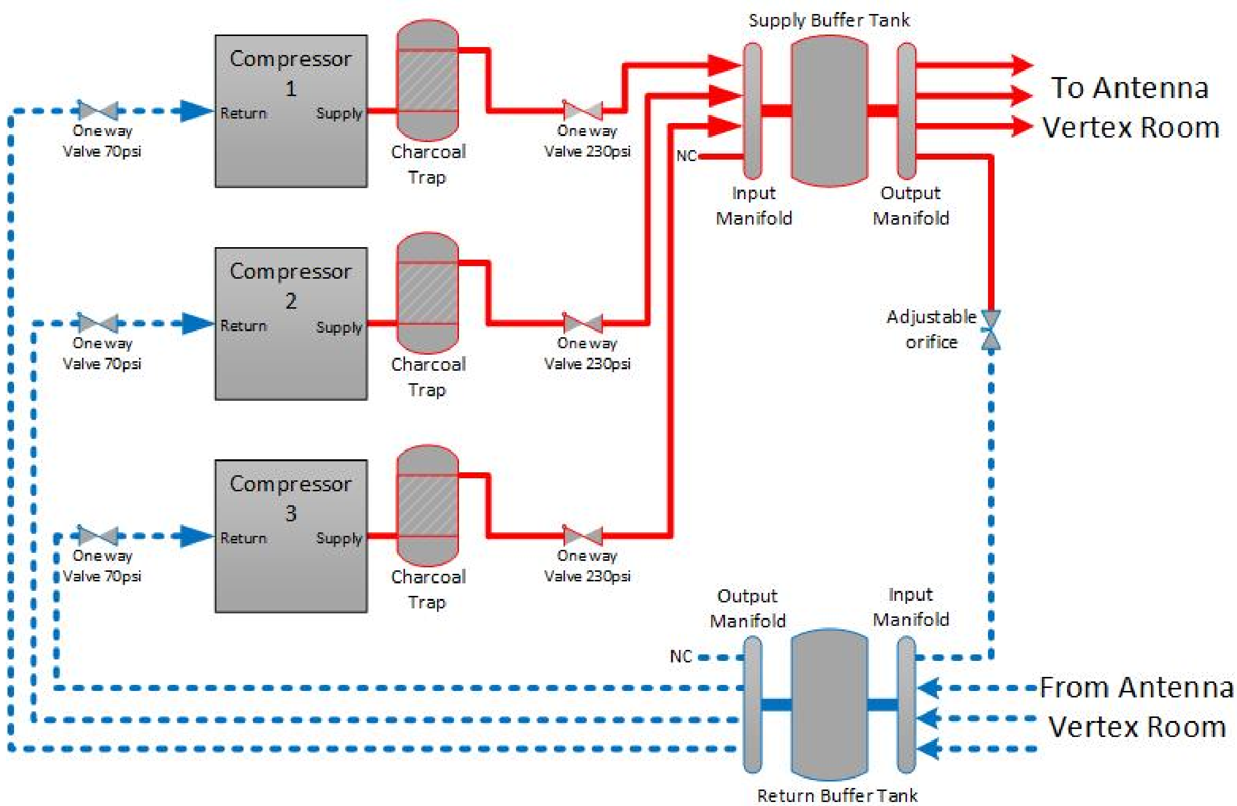

Figure 3: Green Antenna cryogenics block diagram

CURRENT DEVELOPMENT STATUS AND FUTURE PLANS

Design of custom VFD electronics

The variable-speed tests on receivers in the lab used a commercially-supplied line frequency inverter to drive a standard VLA refrigerator power supply, for simplicity and expedience. However, in the implementation for the antenna a custom inverter will be designed. The new inverter will generate two quadrature-phase supply voltages, without the bulky and expensive transformers currently used. Output amplitudes will be adjusted automatically with changing frequency, to keep the motor torque constant and limit the current.

Figure 4 below shows a block diagram of the VFD electronics for a single cold-head. An FPGA is utilized to digitally synthesize the quadrature-phase waveforms. A 16,384-point representation of as sine wave is stored in a dual-port ROM, and sampled at 31.25 kHz with an incrementing address input. The frequency f (Hz) of the sinusoid is changed by adjusting the address increment N used to step through the table, where

$$f = (31{,}250 / 2^{14}) \times N \approx 1.90735 \times N \quad ; \; N < 8192$$

Hence for ~40 Hz output, N would be set to 21. The sawtooth waveform generator and comparators are used to generate pulse-width modulated outputs at 62.5 kHz, each with a duty factor (ratio of pulse width to period) directly proportional to the sampled output values from the dual-port ROM. A second lookup table adjusts the sawtooth amplitude with the selected drive frequency, in order to maintain a constant motor torque. These pulse train outputs are amplified and filtered to produce two analog sinusoidal voltages for direct motor drive.

A bench prototype has been thoroughly tested with a cold-head motor, validating the design approach. We are currently focused on harmonic mitigation, to minimize potential RFI and to insure smooth motor operation throughout the drive frequency range. Future work will be design of an advanced prototype unit suitable for installation and test in an operational VLA antenna.

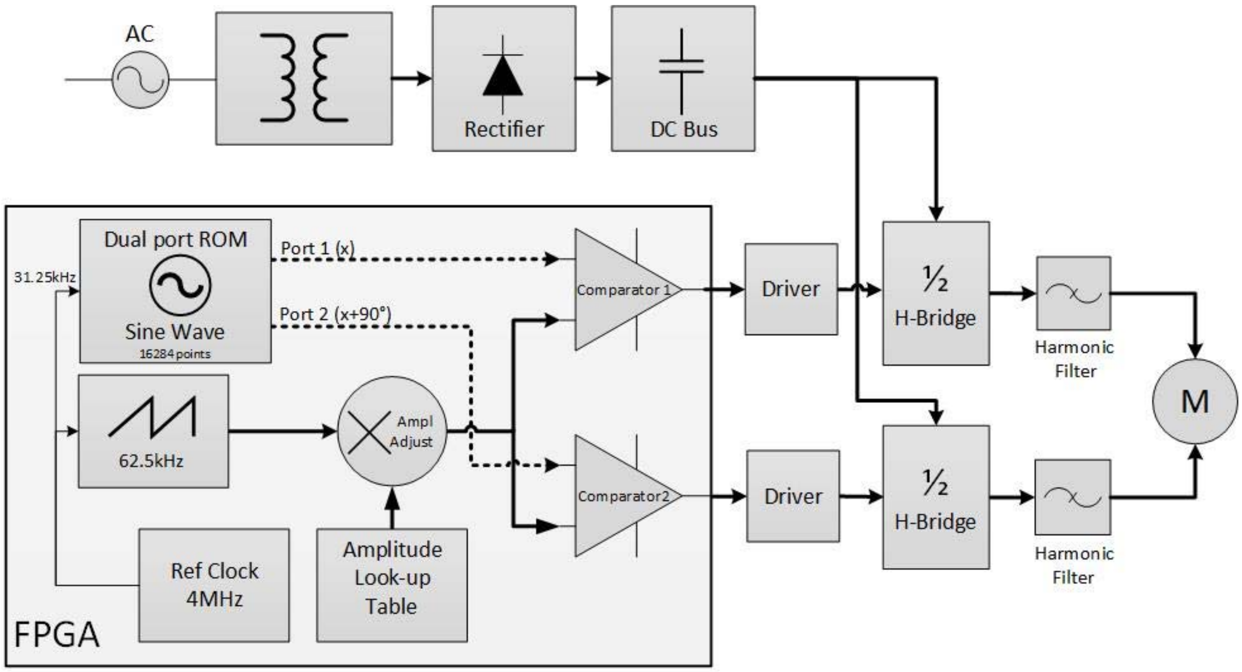

Figure 4: VFD block diagram

Buffer tank assembly

Two 20-liter stainless steel buffer tanks have been fabricated as well as the input and output manifolds. The one way valves were adjusted to the respective pressure before being mounted to the manifold. Before completion of the assembly both tanks and the four manifolds will have to pass the hydrostatic pressure test. Once completed both assemblies will be leak-tested, before being charged with high-purity Helium for system testing with actual compressors.

Prediction on improvements in reliability and maintenance interval

Analysis of maintenance history for the VLA cryogenic equipment shows the service interval for a cold head is directly proportional to the speed of the displacer. For example, a model 22 that runs at 200 rpm has to be serviced almost three times more often than a model 350 that runs at 72 rpm. Based on this information, we can expect an increase in the maintenance interval proportional to the decrease in cold-head speed. The collected data show as well that most of the compressor problems are due to cooling fan failure. When the fan stops working, the compressor heats up and shuts down requiring human intervention to connect the spare compressor to the proper Helium circuit. Having three compressors on a single circuit will allow us to shut down a failing compressor while starting up the standby unit, entirely remotely and without interruption.

CONCLUSION

We have demonstrated that adding MLI on the radiation shield of our receivers allows a 33% reduction in running speed on the cold-heads, with essentially no increase in cold stage temperatures. Receiver sensitivity will be unaffected, while allowing ~30% in overall power savings from the compressors. The slower movement of the cold-head displacers should result in a lower wear rate and longer maintenance interval, with attendant savings in labor and material costs.

The Green Antenna Project is a test bed for more energy-efficient technologies and techniques that can be implemented on the present VLA, but also a pathfinder for advanced cryogenic systems needed for a next-generation VLA telescope.

ACKNOWLEDGMENTS

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