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Front End Concept for the Next Generation Very Large Array

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Abstract

The next-generation Very Large Array (ngVLA) Front End will consist of six cryogenically-cooled, dual polarization receivers, each with an integral feed horn. The upper five bands (2–5) are modular units co-located within a single compact cryostat, while the lowest-frequency band (1) occupies a second cryostat of similar volume and mass. Waveguide-bandwidth (~1.66:1) receivers are used above 12 GHz for optimum performance. Below 12 GHz, wideband (~3.6:1) receivers are used to reduce the volume, total mass, and cost, with modest trades in sensitivity. Simulations of sensitivity (A_{EFF}/T_{SYS}) versus frequency and antenna elevation are given, based on modeled or estimated performance of the receiver components and antenna optics.

1. Introduction

The ngVLA science goals require continuous frequency coverage from 1.2–116 GHz in multiple receiver bands, with a gap at the atmospheric absorption band between ~50–70 GHz [1]. Maximizing overall sensitivity in each receiver band, while minimizing the total operating cost, are primary design goals. Thus, receivers will be cryogenically cooled, with multiple bands integrated into a common cryostat where feasible. The use of feed horns with broad bandwidth and high aperture efficiency is also key to meeting the goals.

Mass and volume are also important concerns, given the Front End will be atop a movable platform on the antenna feed arm, rather than at a fixed location under the main reflector as in the VLA. Compact feeds are preferred, as they can be integrated into the cooled receiver assemblies, further reducing the system noise.

2. Concept Description

2.1 Subsystem Overview

The Front End subsystem is mounted on the feed arm at the secondary focus of a dual-offset Gregorian antenna. A pair of enclosures (Receiver, Auxiliary) provide a protected and temperature-controlled environment for the cryostats and ancillary equipment. The Receiver Enclosure contains the two receiver cryostats along with the downconverter and digitizer modules, while the Auxiliary Enclosure houses a vacuum pump for initial evacuation of the cryostats, and other support electronics not integrated into the cryostats. Total mass of both enclosures is ~600 kg.

A conceptual rendering of the subsystem enclosures is shown in Figure 1. Other associated elements (not shown) include the cryocooler helium lines, vacuum and glycol lines, and associated cable wraps.

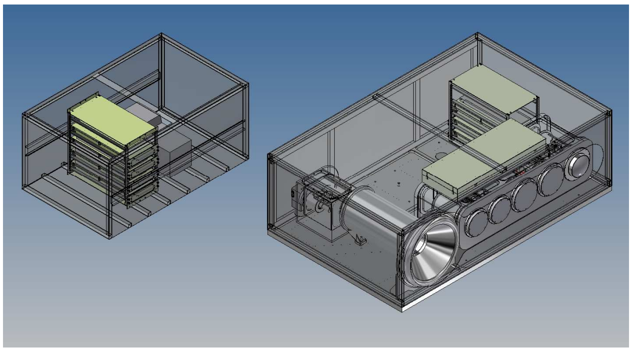

Figure 1. Receiver and Auxiliary Enclosures.

2.2 Cryostats

The ngVLA Front End concept is implemented in six independent receiver bands, each with an integral feed horn. The upper five (Bands 2–6) are housed inline within a single, moderately-sized cryostat (B), while the lowest (Band 1) occupies a second cryostat (A). Due to the wide opening angle used in the optics design [2], all feeds except on Band 1 are sufficiently compact to be cooled to 20 K, reducing losses ahead of the low-noise amplifiers (LNAs). On Band 1, the flared horn section is at ambient, while the remainder of the feed can be cooled to 80 K. A two-stage cryocooler with ~5W of cooling capacity on the 20 K stage is used on each cryostat. Approximate masses of cryostats 'A' and 'B' are 49 kg and 95 kg, respectively.

Conceptual renderings of both cryostats, showing some of the internal layout details, are given in Figure 2 and Figure 3. The arrangement and orientation of all six feeds allow any band to be moved into the secondary focus by lateral translation of the Receiver Enclosure.

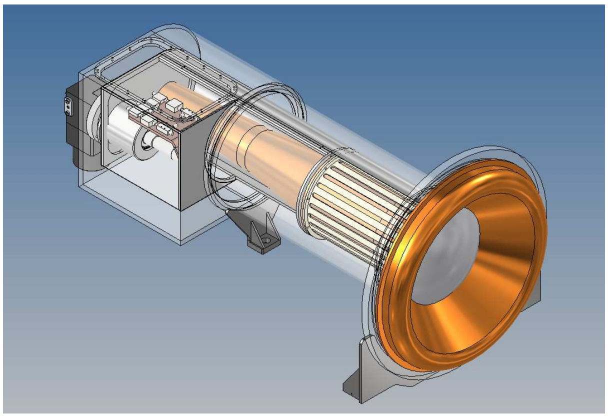

Figure 2. Cryostat ‘A’ (Band 1)

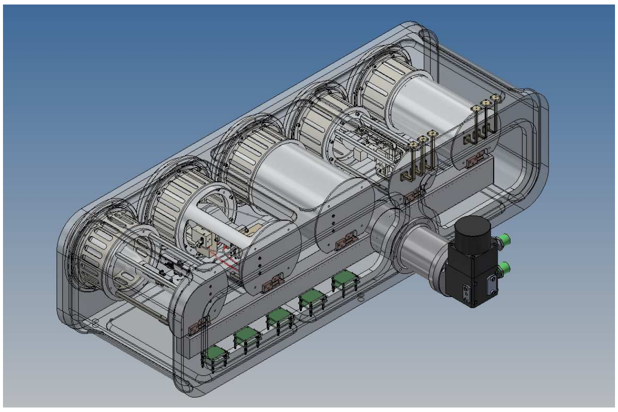

Figure 3. Cryostat ‘B’ (Bands 2–6).

2.2 Receivers

Frequency limits and bandwidths of all six receiver bands are given in Table 1, and block diagrams in Figure 4. Output polarizations on all receivers are orthogonal linear, rather than left/right circular as on the VLA. This simplifies the receiver design, reduces the receiver noise, and permits a larger ratio bandwidth in the all-waveguide receivers of Bands 3–6. No frequency conversion is performed on any of the bands in the Front End portion of the system.

Table 1. ngVLA Receiver Frequencies and Bandwidths.

Band #	Dewar #	f_L GHz	f_M GHz	f_H GHz	$f_H : f_L$	BW GHZ
1	A	**1.2**	**2.0**	**3.5**	2.92	2.3
2	B	**3.4**	**6.5**	**12.3**	3.62	8.9
3	B	**12.3**	**15.9**	**20.5**	1.67	8.2
4	B	**20.5**	**26.4**	**34**	1.66	13.5
5	B	**30.5**	**39.2**	**50.5**	1.66	20
6	B	**70**	**90**	**116**	1.66	46

Each receiver also contains a calibrated noise injection path ahead of the LNAs for self-calibration during observing. This is shown with a splitter and pair of directional couplers. The noise source drive has an adjustable output level, and could be located outside or within the cryostat, but at ambient temperature.

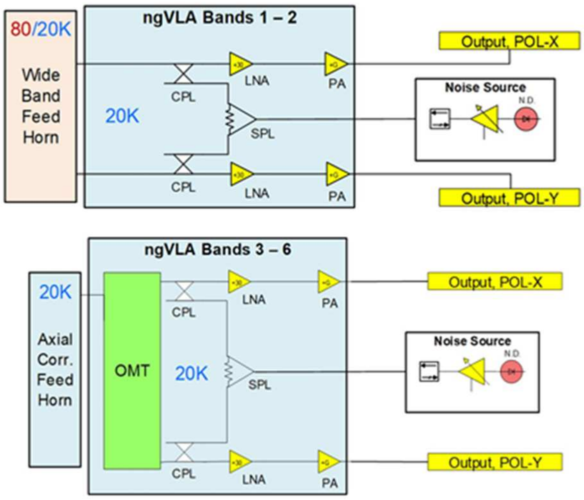

Figure 4. ngVLA Front End receiver block diagrams, Bands 1 & 2 (top) and Bands 3–6 (bottom).

Individual receiver bands in Cryostat ‘B’ are designed as modular units to better optimize Front End production and to simplify servicing. These cylindrical receiver modules (‘cartridges’) are installed through the front of the cryostat.

Conceptual rendering of a representative receiver cartridge body, into which the receiver feed and other components are installed, is shown in Figure 5. The intent is to have one or two standardized cartridge body sizes across the five bands, to allow use of a common test cryostat design for receiver production. Each cartridge will have an integral vacuum window, radiation shield, cold stage attachment points, and a thermal gap assembly for mechanical support and alignment of the feed horn.

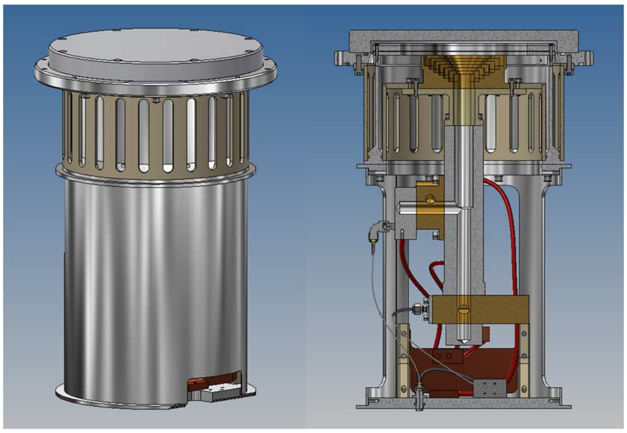

Figure 5. Receiver Cartridge, Cryostat ‘B’. Band 3 model is shown, fully assembled and in a cutaway view.

A side panel on the cryostat provides access for securing thermal straps from the cold stages, connecting the receiver to its support electronics, and attaching the cryostat interface coax cables or waveguides to the ports of the receiver cartridge.

3. Simulated Performance

3.1 Receiver Noise

A cascade gain and noise analysis was performed for each of the six bands, using simulated data on key components (LNAs, polarizers) and estimates for the other components (feeds, windows, couplers, cables, waveguides) based on a simplified analysis and on past experience [3]. A uniform temperature of 20 K was assumed for the cooled receiver components in the signal path including the feeds, except in Band 1 where the feed was assumed to be at 80 K. The calibration path was assumed to be at ambient, except for the power splitter which was at 80 K. Component-level mismatch and associated ripple were omitted for this simplified analysis. These will be added in the future, when component selection and design have advanced and simulated or measured S-parameter data is available.

Simulated receiver noise temperatures across frequency are plotted in Figure 6. As might be expected, they increase steadily at higher frequencies, but are also slightly elevated in Bands 1 and 2. This is due to the use of coaxial rather than waveguide components in these wideband receivers.

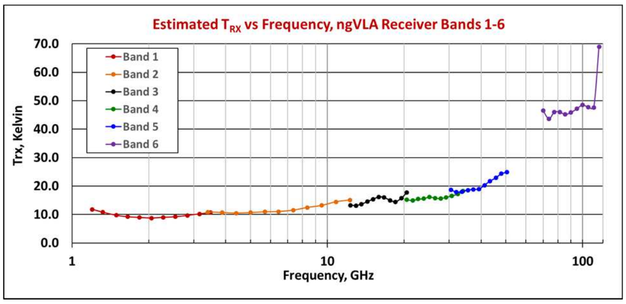

Figure 6. Receiver noise temperature, ngVLA Bands 1–6.

3.2 Antenna Sensitivity

Using collected estimates of feed + antenna aperture efficiency, combined with the estimated overall system temperature T_{SYS}, the sensitivity metric A_{EFF}/T_{SYS} is calculated for a single ngVLA antenna [2, 3]. The results are plotted in Figure 7, over the full range of frequency and at different elevation angles. The following are assumed:

• Unblocked dual-offset Gregorian antenna, 18-meter primary aperture, shaped optics, no antenna deformation.
• Reflector surface roughness of 160 microns RMS.
• Precipitable water vapor (PWV) of 6 mm for Bands 1–5, and 1 mm for Band 6 alone.
• Nominal VLA site elevation of 2120 meters.

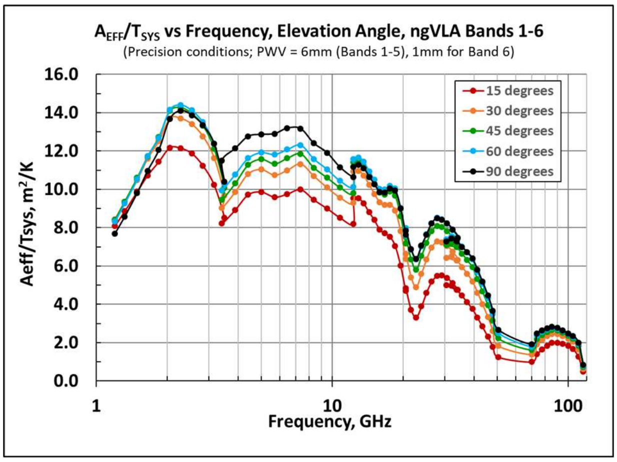

Figure 7. Relative sensitivity for a single ngVLA antenna vs. frequency and elevation angle, ngVLA Bands 1–6. There is no data between 50.5 and 70 GHz.

The roll-off at the lowest frequencies is mainly due to the decreased feed efficiency combined with higher spillover. Roll-off at the higher frequencies is due to a combination of increasing receiver and sky temperatures (especially at low elevation) and decreasing aperture efficiency from the reflector surface roughness. Gravitational deformation of the optical surfaces is not modeled here, but will have a significant effect over elevation and at high frequencies.

References

[1] E. J. Murphy et al., "The ngVLA Science Case and Associated Science Requirements," *Science with a Next-Generation Very Large Array,* ASP Conference Series, Monograph 7, 2018, pp. 3-14.

[2] R. Lehmensiek and D. I. L. de Villiers, "An Optimal 18 m Shaped Offset Gregorian Reflector for the ngVLA Radio Telescope," *IEEE Trans. Antennas Propag.*, vol. 69, no. 12, pp. 8282-8290, December 2021. doi: 10.1109/TAP.2021.3090827.

[3] https://ngvla.nrao.edu/page/tools