ngVLA Memo # 17

ngVLA Reference Design Development & Performance Estimates

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Revised: April 30th, 2018: *Corrections to T_B in Table 1.*

Abstract

The ngVLA reference design continues to converge towards a single coherent concept. This memo summarizes recent developments towards the current concept and estimates system sensitivity at multiple angular scales. It reflects the design iteration from cost estimation (Kern, Selina), configuration design (Greisen, Owen), synthesized beam weights (Carilli), and system noise and bandwidth estimates (Grammer).

1 Introduction

The ngVLA concept is rapidly converging post the June 2017 ngVLA Science and Technology Workshop[1].

In a complex and evolving project, it is inherently difficult to keep tools and estimates consistent since multiple parts of the design progress in parallel. However, in such an environment it is also essential to provide snapshots of performance for first-pass calculations, and to permit parallel development of the technical concept and science case.

This memo attempts to produce a snapshot of the estimated performance of the current array concept resulting from the workshop and recent work by the team. Iteration is expected to continue as the configuration design matures and its performance is simulated.

2 Design Description

The design resulting from the workshop includes a number of points of convergence in both the requirements and a matching concept. The design is described here only to the degree necessary to understand the performance estimates in Section 3. A number of design options are omitted for the sake of brevity, and to highlight the choices that support the performance estimates.

The array configuration (Figure 1) has a minimum extent of 300 km (E-W) by 500 km (N-S), not yet accounting for long-baseline science cases such as astrometry and geodesy. The array collecting area is

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[1] https://science.nrao.edu/science/meetings/2017/ngvla-science-program/index

distributed to provide high surface brightness sensitivity on a range of angular scales spanning from approximately 1000 to 10 mas. In practice, this means a core with a large faction of the collecting area in a randomized distribution to provide high snapshot imaging fidelity, and arms extending asymmetrically out to 500 km baselines, filling out the (*u,v*)-plane with Earth rotation and frequency synthesis.

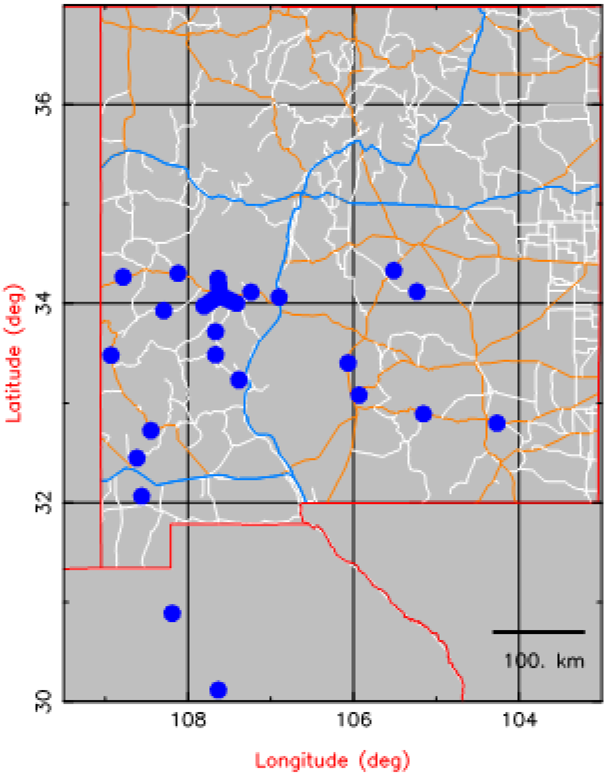

Figure 1 - Stations in the present ngVLA configuration (Greisen, Owen). The compact core is located at the apex of the present VLA, and antennas are populated along the VLA arms. Long baseline stations radiate primarily south and east from the VLA. The locations of the long baseline stations are approximate, but account for land ownership and available infrastructure including roads, electrical distribution lines, and fiber optics networks.

The present concept is a homogeneous array of 214 18m apertures. The selection of the number of apertures and the antenna diameter is supported by parametric cost estimation, using the ngVLA Quantitative Exchange Model (a.k.a. 'Cost Model') version 3.07. The antenna locations are fixed, with no reconfiguration capability. All antennas are outfitted with front ends that provide access to the atmospheric windows spanning 1.2 GHz to 50.5 GHz and 70 GHz to 116 GHz.

The available spacings between the 18m apertures recover all angular scales of interest in approximately 75% of identified use cases. Therefore, there is still a need to recover total flux for sources large relative to the shortest baseline fringe, using either a single dish, or a short spacing array plus total power antennas. The detailed requirements and supporting concept to meet this need require further analysis.

The antenna optical configuration favors unblocked apertures, with an Offset Gregorian feed-low design offering synergy with the front-end concepts under consideration, while additionally accounting for maintenance and operational concerns. The antenna surface error will be limited to of order 160 um RMS, ensuring that the antenna Ruze efficiency is better than 50% at the 116 GHz upper operating limit.

The front-end concept will use single pixel feeds. Multi-pixel designs will not be further considered for the reference design exercise. The baseline concept employs six receiver bands in two dewar packages (see Figure 2). By employing wide illumination angles, of order 55-deg. half angle, both corrugated horn and quad-ridge (QR) feed designs are viable and all feeds can be cooled in modestly sized dewars. Even the 1.2 to 3.9 GHz feed can be accommodated within a dewar measuring less than 50 cm in diameter. Wideband 3.25:1 QR feeds would be used to span the 1.2 to 12.6 GHz frequencies in two bands. Above 13 GHz, waveguide front ends will provide 1.67:1 bandwidths with optimized noise performance. The latter is a necessity to provide the spectral line sensitivity demanded by the driving science use cases.

Band #	***Dewar***	***f_L GHz***	***f_M GHz***	***f_H GHz***	***f_H: f_L***	***BW GHz***
1	**A**	**1.2**	**2.2**	**3.9**	3.25	**2.7**
2	**A**	**3.9**	**7.0**	**12.6**	3.23	**8.7**
3	**B**	**12.6**	**16.3**	**21**	1.67	**8.4**
4	**B**	**21**	**27.1**	**35**	1.67	**14.0**
5	**B**	**30.5**	**39.2**	**50.5**	1.66	**20.0**
6	**B**	**70**	**90**	**116**	1.66	**46.0**

Figure 2 - ngVLA Baseline Receiver Band Definition (Grammer).

The digitization, data transmission and correlator systems will be capable of processing up to 20 GHz of instantaneous bandwidth, with full polarization. Flexible tuning will be required within the band, permitting mixed spectral line and continuum modes, preferably at variable bit-depth.

The correlator is an FX design, possibly with a distributed F-engine. The correlator will support a high-data rate to multiple back-ends, providing tunable spectral resolution over approximately 64k channels, and up to 1 ms time resolution.

3 Performance Metrics

The predicted performance of the array is summarized in Table 1. While the values are more representative of the current design than those previously reported (e.g., ngVLA Memo 5), the table is by necessity a simplification. As the configuration and our understanding of its performance evolve with design refinements and modeling, most factors in this table can be expected to change as future work on the imaging performance of the array continues.

A sensitivity calculator is currently being developed based on such investigations and will eventually supersede the values included in Table 1.

Table 1: Next Generation VLA Key Performance Metrics

Parameter [units]	**3 GHz**	**8 GHz**	**17 GHz**	**28 GHz**	**41 GHz**	**93 GHz**	**Notes**
Band Lower Frequency, f_L [GHz]	1.2	3.9	12.6	21.0	30.5	70.0	a
Band Upper Frequency, f_H [GHz]	3.9	12.6	21.0	35.0	50.5	116.0	a
Field of View FWHM [arcmin]	19.5	7.3	3.4	2.1	1.4	0.6	b
Aperture Efficiency [%]	0.75	0.75	0.77	0.75	0.72	0.53	b
Effective Area, $A_{eff,}$ x 10^3 [m^2]	40.8	40.8	41.9	40.8	39.2	28.9	b
System Temp, T_{sys} [K]	18	22	21	31	48	87	a, f
Max Inst. Bandwidth [GHz]	2.7	8.7	8.4	14.0	20.0	20.0	a
Antenna SEFD [Jy]	265.7	324.8	302.0	457.7	738.2	1817.5	a, b
Resolution of Max. Baseline ($\theta_{\max}$) [mas]	**69**	**26**	**12**	**7**	**5**	**2**	**c**
Resolution FWHM @ Natural Weighting [mas]	**130**	**49**	**23**	**14**	**10**	**4**	**c, d**
Continuum rms, 1 hr [μJy/beam]	0.30	0.21	0.20	0.23	0.31	0.76	d
Line Width, 10 km/s [kHz]	100.0	266.7	566.7	933.3	1366.7	3100.0	
Line rms, 1 hr, 10 km/s [μJy/beam]	49.9	37.3	23.8	28.1	37.5	61.3	d
Resolution ($\theta_{1/2}$) [mas]	**1000**						
Continuum rms, 1 hr, Robust [μJy/beam]	0.61	0.45	0.45	0.56	0.77	2.01	e
Line rms 1 hr, 10 km/s Robust [μJy/beam]	100.1	81.7	55.4	68.0	93.2	161.6	e
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	0.0823	0.0086	0.002	0.0009	0.0006	0.0003	e
T_B rms line, 1 hr, 10 km/s, Robust [K]	13.53	1.55	0.23	0.11	0.07	0.02	e
Resolution ($\theta_{1/2}$) [mas]	**100**						
Continuum rms, 1 hr, Robust [μJy/beam]	0.48	0.36	0.37	0.46	0.64	1.69	e
Line rms 1 hr, 10 km/s Robust [μJy/beam]	79.0	65.9	45.3	56.1	77.4	135.7	e
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	6.4955	0.6927	0.1566	0.0710	0.0463	0.0238	e
T_B rms line, 1 hr, 10 km/s, Robust [K]	1067.33	125.12	19.06	8.70	5.60	1.91	e

Resolution ($\theta_{1/2}$) [mas]	**10**						
Continuum rms, 1 hr, Robust [μJy/beam]	-	-	-	0.36	0.51	1.37	e
Line rms 1 hr, 10 km/s Robust [μJy/beam]	-	-	-	44.2	61.5	109.8	e
Brightness Temp (T_B) rms continuum, 1 hr, Robust [K]	-	-	-	5.5945	3.6781	1.9216	e
T_B rms line, 1 hr, 10 km/s, Robust [K]	-	-	-	685.18	444.94	154.35	e

(a) 6-band 'baseline' receiver configuration.
(b) Reference design concept of 214 18m aperture antennas. Unblocked aperture with 160um surface.
(c) 'South West' Configuration by E. Greisen. Resolution in E-W axis.
(d) Using Natural Weights, dual pol, and all baselines.
(e) Using Weights as described in ngVLA Memo #16, scaled by frequency.
(f) Averaged over the full band. Assumes 6mm PWV and 45 deg. elev. on sky.
For the latest performance estimates please visit the ngVLA website: ngvla.nrao.edu/page/refdesign

Table 1 - ngVLA Key Performance Metrics.

The spot frequencies chosen for the columns of Table 1 correspond to the center frequencies of the baseline receiver band definition. Values for the sensitivity of the naturally weighted beam are provided as a ceiling on sensitivity. More representative values are given at 1000, 100 and 10 mas, with tapered and robust weighted beams.

The largest uncertainty in these estimates is in the weights required to produce useful synthesized beams. The weights chosen above are scaled from the analysis in ngVLA Memo #16 (C. Carilli), and do not reflect active work on the configuration since the June 2017 Science Workshop.

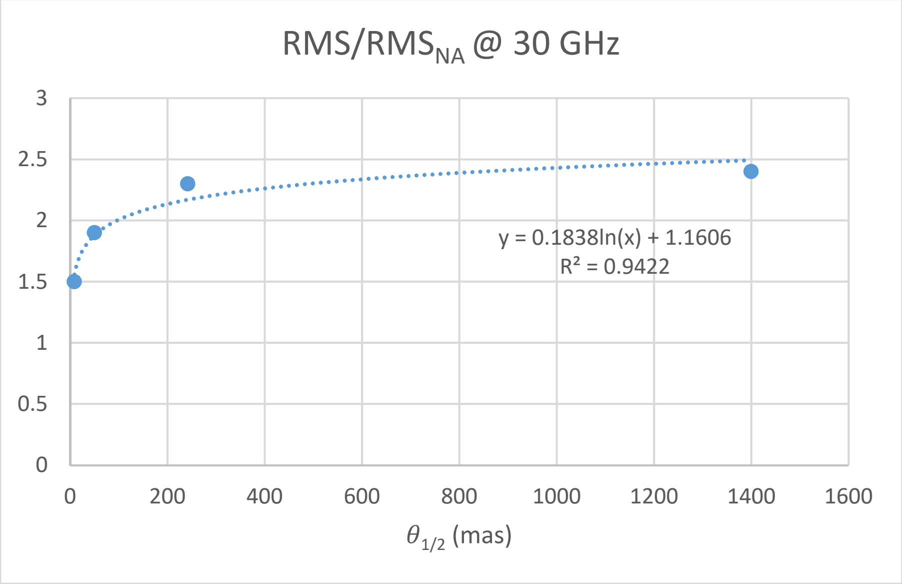

Figure 3 - Simple model of system noise at different angular resolutions (FWHM of synthesized beam), relative to system noise of naturally weighted beam. Values are computed at 30 GHz, then scaled by frequency.

A simple model was fit to the values in Table 1 of ngVLA Memo 16 to allow easy parameterization of the expected loss in sensitivity relative to natural weights as we vary angular resolution and/or frequency. Values that scale outside the range explored in Memo 16 (e.g., 1000 mas at 97 GHz) may be specious.

This degree of abstraction was required for simple parameterization, but further work is clearly needed using differing robust weights, taper, and cell size, as well as investigations with more sophisticated algorithms such as multi-scale CLEAN. Beam qualities will also need to be quantitatively parameterized. Such work should use the in-progress configuration update to better represent the performance of the array.

However, even with these caveats, the values reported are likely representative.

4 Acknowledgments

This memo builds upon the work of a number of ngVLA project team members. It reflects the design iteration from cost estimation (Kern, et. al), configuration design (Greisen, Owen), synthesized beam weights (Carilli) and system noise and bandwidth for a representative front-end design (Grammer).

This memo also builds upon the work of the associated community studies by Chalmers, Fleming, Weinreb, Soriano and others.

5 Appendix: Formulas

The following formulas are used to derive the values in Table 1.

The full width half maximum (FWHM) of the antenna beam is calculated assuming a Gaussian illumination pattern with -16dB of taper, consistent with the aperture efficiency computation:

$$\Theta_{1/2} = 1.02\ \frac{\lambda}{D}$$

The taper coefficient of 1.02 was computed as described in Essential Radio Astronomy[2]. Note that -16dB of taper corresponds to an amplitude ratio of 0.158 between the center and edge of the dish.

$$K = \frac{\sqrt{-8\ln(2)\ln(0.158)}}{\pi} = 1.02$$

We note that the assumption of a Gaussian illumination pattern is only representative for approximating the FWHM of the main lobe of the beam and is *not* appropriate for describing the actual beam shape or sidelobe levels (e.g., see Condon and Ransom 2016).

The resolution (FWHM) of the longest baseline (B_{max}) is computed as:

$$\theta_{max} = \lambda / B_{max}$$

The System Equivalent Flux Density ($SEFD$) of a single antenna is computed as:

$$SEFD = 2\ k_B\, T_{sys} / (\ \eta_Q \eta_A\, A\ )$$

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[2] http://www.cv.nrao.edu/~sransom/web/Ch3.html

where k_B is Boltzmann's constant, η_Q is the digitizer quantization efficiency, η_A is the antenna efficiency, and A is the antenna's geometric collecting area.

The naturally weighted point source RMS sensitivity is computed as:

$$\sigma_{NA} = SEFD \;/\; (\,\eta_C \sqrt[2]{N_{pol}\,\Delta\nu\; t\; N_{ant}\,(N_{ant}-1)}$$

where η_C is the correlator efficiency (0.98), N_{pol} is the number of polarizations (2), $\Delta\nu$ is the bandwidth, t is the integration time in seconds, and N_{ant} is the number of antennas (214). Bandwidth used is either the 'Max Instantaneous Bandwidth' for continuum cases or the 10 km/s channel width for spectral line RMS.

The weighted point source sensitivity is computed as:

$$\sigma_{rms} = \eta_{weight}\,\sigma_{NA}$$

where the efficiency factor applied to the natural RMS is approximated with the formula from Figure 3:

$$\eta_{weight} = 0.1838\,\ln(\theta_{1/2} * \nu_{GHz}/30\,GHz) + 1.1606$$

The line width is computed as:

$$\Delta\nu = \Delta v/c$$

where the velocity resolution, Δv, and speed of light in a vacuum, c, are both in m/s.

Brightness temperature, in Kelvin, is computed as:

$$\sigma_{T_B} = 1.216\,\sigma_{rms}\,/\,\theta_{1/2}^2/\,\nu^2$$

where σ_{RMS} is the point source sensitivity in µJy/bm, $\theta_{1/2}$ is the resolution (FWHM) of the synthesized beam in arcseconds, and ν is the center frequency in GHz. This is a simplification of:

$$\sigma_{T_B} = \left({c^2}/{2\,k_B\,\nu^2}\right)\left({\sigma_{rms}}/{\Omega_B}\right)$$

where $\Omega_B = \left({\pi}/{4\ln(2)}\right)\theta_{1/2}^2$ is the beam solid angle.

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