Array Configuration: Reference Design Description

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PREPARED BY	**ORGANIZATION**	**DATE**
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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2018-07-06	Carilli	All	Reference Design Review
02	2018-07-09	Selina	All	Updates throughout; Cleaned up template, some format fixes, etc.
03	2018-07-17	Mason	4.3	Updated Fig. 3
04	2018-07-17	Murphy	Various	Minor editorial corrections
05	2018-07-17	Rosero	All	Editorial corrections; updated figures using Rev B; reference figures within the text; updates in section 4.1; added Table 1; edited section 4.6
06	2018-07-23	Erickson	4.5	Added content
07	2018-09-17	Rosero	4	Updated/added figures and text using current configuration (Spiral 214 + LBA); added Fig. 8
08	2018-11-30	Carilli, Rosero, Erickson	4	Revised to address RIDS from Reference Design Review
09	2019-05-31	Selina	5	Minor edits and corrected figure locations
A	2019-07-09	Lear	All	Prepared document for approvals & release

Table of Contents

1 Introduction

1.1 Purpose

This document describes the ngVLA Array Configuration reference design. It covers the design approach, predicted performance, and risks associated with the reference design. This document will form part of the submission of the ngVLA Reference Design documentation package.

1.2 Scope

The scope of this document covers the design of the array configuration, specifically, the configuration design and its key constituents. It does not include specific technical requirements, which are addressed separately in [AD04].

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents inform this reference design:

Reference No.	Document Title	Rev / Doc. No.
AD01	Science Requirements	020.10.15.00.00-0001-REQ
AD02	Preliminary System Requirements	020.10.15.10.00-0003-REQ
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD04	Array Configuration Preliminary Technical Requirements	020.23.00.00.00-0001-REQ

2.2 Reference Documents

The configuration reference design draws extensively from work presented in the ngVLA memo series. We refer the reader to these memos for more details on science simulations that relate to the configuration design and characterization of the design. These memos provide much of the provenance for the reference configuration in terms of scientific analysis and simulation verifying performance in key science areas.

The following documents provide additional supporting analysis or context that informed the reference design of the array configuration:

Reference No.	Document Title	Rev / Doc. No.
RD01	ngVLA Science Use Case Parameterization Spread Sheet	2017-06-20 V24
RD02	ngVLA Reference Design Development & Performance Estimates	ngVLA Memo #17
RD03	Summary of the Science Use Case Analysis	ngVLA Memo #18
RD04	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19
RD05	Image Capabilities: High Redshift CO	ngVLA Memo #13
RD06	Investigating the Early Evolution of Planetary Systems with ALMA and the Next Generation Very Large Array	ngVLA Memo #33
RD07	More on Synthesized Beams and Sensitivity	ngVLA Memo #16
RD08	ngVLA Dynamic Range	ngVLA Memo #30

Reference No.	Document Title	Rev / Doc. No.
RD09	Deep Fields at 8GHz	ngVLA Memo #35
RD10	Initial Imaging Tests of the Spiral Configuration	ngVLA Memo #41
RD11	Resolution and Sensitivity of ngVLA-revB	ngVLA Memo #47
RD12	The ngVLA Short Baseline Array	ngVLA Memo #43
RD13	Fast Switching Phase Calibration at 3mm at the VLA Site	ngVLA Memo #1
RD14	Possible Configurations for the ngVLA	ngVLA Memo #3

3 Subsystem Overview

The array configuration is a basic property of the array. It is an abstraction, defining the locations of antennas within the array. The cost of the antennas and supporting infrastructure is included within other packages of the reference design.

The longest baselines set the ultimate resolution of the array, while the shortest determine the largest-scale structures that can be imaged. The antenna distribution then sets the sensitivity as a function of spatial resolution and the shape of the synthesized beam (point spread function), as determined by weighting of the uv-data.

The array reference design will not be reconfigurable, yet it must perform a broad range of science programs with a wide range in spatial resolutions as a function of frequency, as summarized in ngVLA Memo #18. To perform this broad range of science programs, the array configuration design requires essential capabilities such as:

- very high resolution (10 mas at 30 GHz) for sensitive observations of exoplanets forming on AU-scales;
- high surface brightness sensitivity observations at 100 mas of molecular gas in distance galaxies; and
- imaging of large-scale structures in nearby galaxies at ultra-low surface brightness at 1000 mas resolution.

The reference design reflects the multi-scale demand on the array science case. The ultimate sensitivity as a function of resolution will depend critically on the specific synthesized beam for the science application in question. As a guiding principle, we have adopted the goal of roughly a factor two loss in sensitivity relative to natural weighting, for spatial resolutions ranging from ~0.3 mas to 1000 mas at 30 GHz. The array performance for several key science programs has been documented in the memo series, as listed in the reference documents above.

4 Array Configuration Design

4.1 *Sub-Components of the Array Configuration*

The range of angular scales that the array must be sensitive to cannot be accessed with any practical homogeneous array. A heterogeneous array is therefore required, consisting of four main components (Figure 1):

- Main Interferometric Array of 214 18m reflector antennas (also referred as the Spiral 214 array),
- Long Baseline Array (LBA) of 30 18m reflector antennas,
- Short Baseline Array (SBA) of 19 6m reflector antennas, and
- Total Power Array of four 18m reflector antennas (included as part of the Spiral 214 main array).

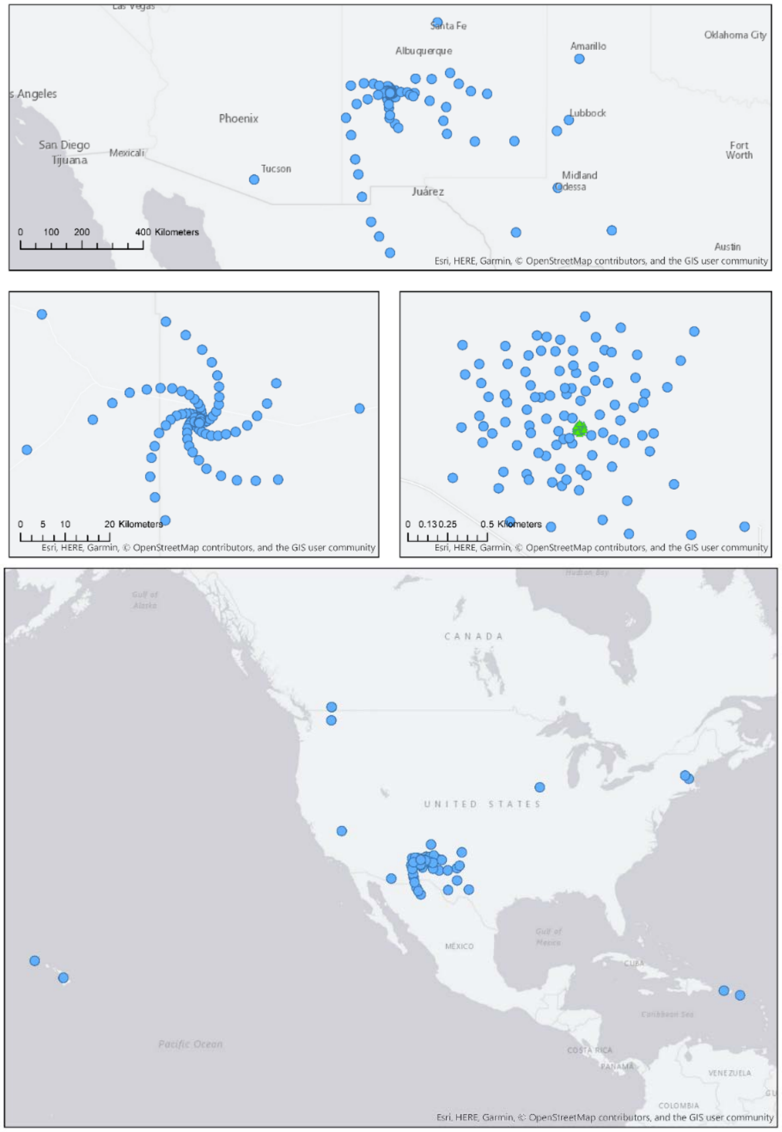

Figure 1 - Top three panels: main interferometric array (Spiral214) composed of a compact core (top right; short baseline array antennas are shown in green), a five-arm spiral spanning the Plains of San Agustin (top left), and a rough spiral that extends to Texas, northern Mexico and Arizona (top). Bottom: view of the main array and the long baseline array (244 18m antennas total). Each LBA station has two or more antennas.

Table 1 summarizes the ngVLA array configuration elements. The design is practical, accounting for such logistic limitations as topography, utility access, local RFI sources, and land management/availability.

Component Name	Aperture Diameter (m)	Quantity	B_{min} (m)	B_{max} (km)
Long Baseline Array	18	30	32.6	8856
Main Interferometric Array	18	214	30.6	1005
Short Baseline Array	6	19	11.0	0.06
Total Power/Single Dish	18	4[1]	--	--

Table 1 - Summary of elements within the ngVLA array configuration.

The main interferometric array will have three discrete components (see Table 2). A compact, dense core (extent ~1.3 km) will have roughly ~45% of the antennas. Another ~35% of the antennas on the Plains of San Agustin will extend about ~15 km from the core for about 36 km maximum baselines. The remaining ~20% of the antennas will be in mid-baseline stations extending to maximum baselines of ~1000 km.

Component Name	Max. Baseline (km)	Distribution Pattern	# Antennas
Core	1.25	Random	94
Plains	36	5-arm spiral	74
Mid-Baselines	~1000	~3-arm spiral	46

Table 2 - Main interferometric array components.

The main array location in the Southwest US and Mexico is well suited for observations up to 116 GHz due to generally high elevations and low water vapor content. Figure 2 shows an example of the site quality for observations at 90 GHz. These tests show that using fast switching calibration provides acceptable calibration results ($\phi_{rms}<40°$) for observations at day or night during most of the year.

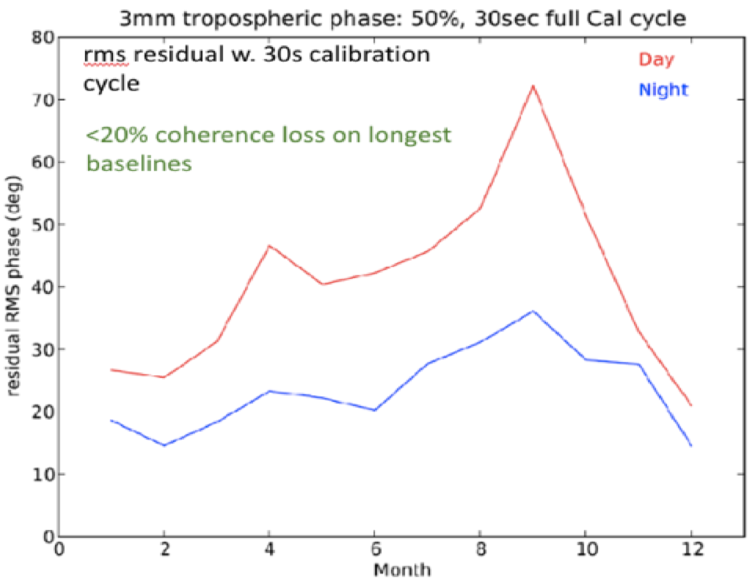

Figure 2 - RMS phase residuals after fast switching calibration predicted for the VLA site at 90 GHz based on decades of phase monitoring with the Atmospheric Phase Interferometer (ngVLA memo 1).

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[1] The four total power antennas are a subset of the 214 antennas of the main array.

4.2 Main Interferometric Array

The core of the main interferometric array will be located at the current VLA site, in a dense configuration optimized for image quality, with maximum baselines of ~1.25 km. The Plains array is comprised of a five-arm spiral to ~15 km radius from the VLA center. This spiral is also optimized for quality imaging (see ngVLA memos 30, 41, and 47). The outer antennas of the main array that expand from ~15 km out to ~1000 km baselines are distributed in a rough three-arm spiral, extending mostly south into Mexico and Texas.

Figure 1 shows the reference design configuration of the multi-scale array, which has a naturally weighted beam with three very different spatial scales:

1. a narrow spike with high resolution (~0.3 mas at 30 GHz),
2. the first skirt due to the Plains array extending to (100 mas at 30 GHz) at the 50% to 20% level, and
3. the second skirt due to the core extending to (1000 mas at 30 GHz) in the 20% to 10% range.

The challenge for imaging is to optimize uv-data weighting to obtain a reasonable synthesized beam while maintaining sensitivity. For a reasonable synthesized beam, several numerical simulations have shown that high dynamic range imaging can be obtained by keeping the broad skirt to below 10% at a radius from the beam peak = FWHM of the beam. The project is performing a broader suite of simulations to quantify this metric, while algorithmic development is ongoing to optimize the imaging and science return for multi-scale arrays in general.

The ngVLA Main Array reference configuration has the interesting property that the core, with 45% of the antennas, is located at the northern extremity of the configuration, as Figure 1 shows. Hence, the behavior of sensitivity and beam shape with uv-weighting is very different than ALMA or the VLA. Tests show that, as the uv-data weighting is varied to obtain resolution from ~0.5 mas to 1000 mas at 30 GHz (see Figure 4), the sensitivity remains roughly constant and within a factor of about 2 of Natural weighting.

This behavior is predictable, in retrospect, since at 1000 mas one is using just the core, which has 45% of the collecting area, while at 0.5 mas one is correlating the long baseline antennas to all the core antennas, thereby obtaining high resolution without a dramatic sacrifice of sensitivity.

4.3 SBA and TP array

The ngVLA Short Baseline Array (SBA) comprises 19 6m antennas and 4 18m total power antennas (included as part of the main 214-antenna array; see Figure 3). This array was designed to adequately “feather” or be jointly deconvolved with the main array core (i.e. matched surface brightness sensitivity on scales of the shortest core baselines). This also improves sensitivity to large structures, up to 70 arcsec at 90GHz, for the SBA alone, and raster imaging of even large structures with the total power antennas.

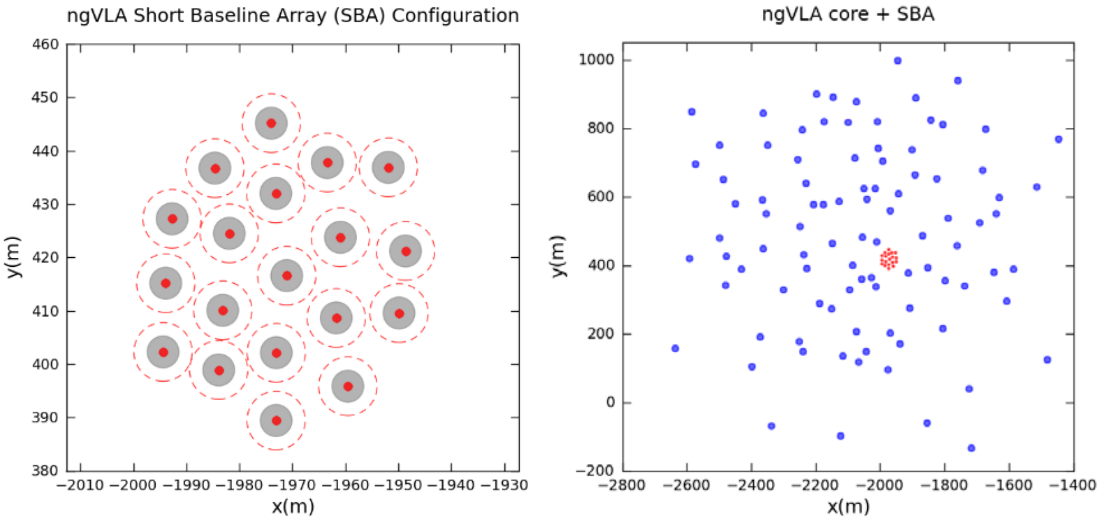


Figure 3 - SBA reference design (left) and notional placement within ngVLA core revB (right). SBA antennas are shown by red solid lines, with their clearance zones shown by red dotted lines. ngVLA 18m antennas are shown by blue solid dots.

Simulations show that the SBA interferometer will provide good supporting data for the ngVLA with total integration times 1.3x those of the ngVLA main array, and total power integration times 2.3x those of the main ngVLA array (ngVLA Memo 43). Given reasonable expectations of the distribution of requested science use cases, these approaches are viable options to provide the larger spatial scale information required by 20% to 30% of identified ngVLA science use cases.

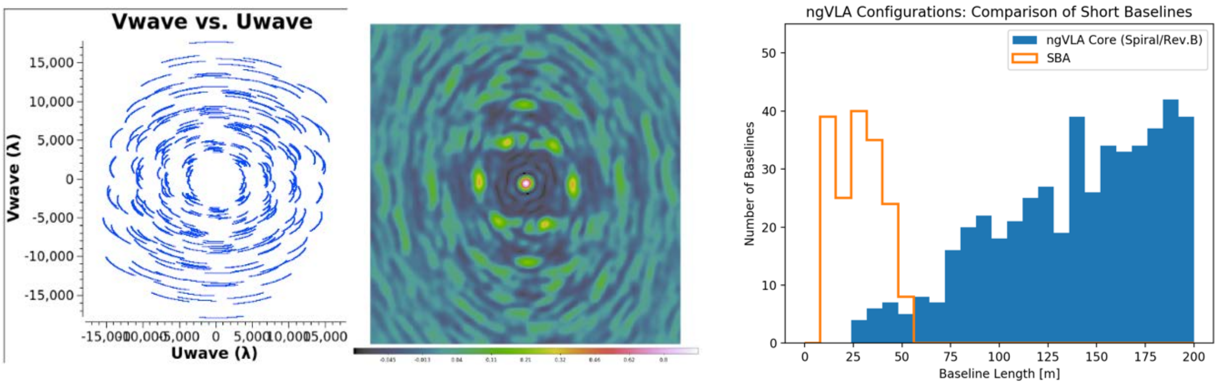


Figure 4 - Left: uv-coverage of the SBA at 100 GHz for a 1000 s observation at Dec = –17° along with the resulting synthesized beam. Center: the NA weighted synthesized beam, with a FWHM = 10". Right: the number of baselines in the core and the SBA vs. baseline length.

4.4 Long Baseline Array

The long baseline array is composed of 30 additional 18m antennas at ten different sites (see Table 3). Clustering antennas at each site is a cost-effective way to increase the array's sensitivity while sharing the operations infrastructure per site. Clustering also allows unique capabilities such as simultaneous observations of the scientific target and the calibration source or simultaneous frequency coverage across the same set of baselines. Additionally, the clusters could be used individually as small phased arrays for "single dish" observations such as pulsar timing.

The LBA by itself provides several spacings such as continental scale (B_{max} ~8860 km) baselines, intermediate scales of ~1000 km and short spacings of ~30 m within the sub-array, making it suitable for both astrometry and imaging projects and enabling the LBA to function effectively as a standalone array or as an integrated part of the main array.

Antenna Quantity	Location	Reference Design Site
3	Puerto Rico	Arecibo Observatory
3	St. Croix	VLBA Site
3	Kauai, Hawaii	Kokee Park Geophysical Observatory
3	Hawaii, Hawaii	NOT on Mauna Kea. New site.
2	Hancock, NH	VLBA Site
3	Westford, MA	Haystack Observatory
2	Brewster, WA	VLBA Site
3	Penticton, BC	Dominion Radio Astrophysical Observatory
4	North Liberty, IA	VLBA Site
4	Owens Valley, CA	Owens Valley Radio Observatory

Table 3 - Reference design antenna sites of the ngVLA long baseline array.

4.5 Array Performance

Figure 5 shows the distribution of number of baselines versus baseline length, and the collecting area as a function of baseline length for the main array plus the LBA. The distribution of collecting area shows the preponderance of the core, tapering smoothly to lower values to 1000 km distances. The resulting baseline distribution is relatively uniform from 100 m to a few thousand kilometers.

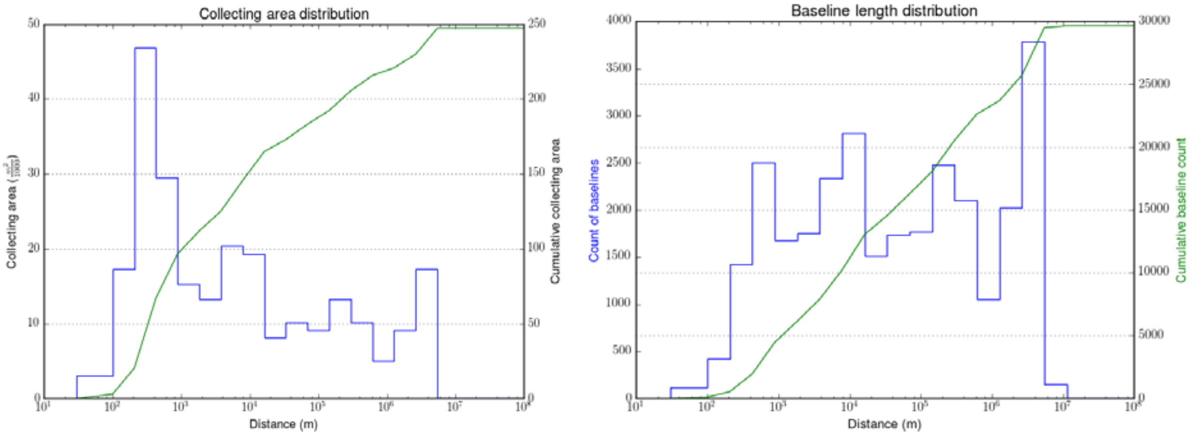


Figure 5 - The left graph shows collecting area versus radial distance from the core center, with log bins (blue). The green line is the cumulative distribution. The right graph shows the number of baselines versus baseline length for the full 18m ngVLA reference design (main+LBA) array, using logarithmic bin sizes (blue line). The green line is the cumulative distribution.

Imaging sensitivity will depend on the required resolution and imaging fidelity. Figure 6 and Figure 7 show the effects of adjusting imaging weights to vary resolution and PSF quality. These figures are based on a four-hour simulation at 30 GHz using the 244 antenna array configuration, for a source at +24° declination observed during transit. The reported beam size is the geometric mean of the major and minor full width at half maximum (FWHM) of the synthesized beam as parameterized by Gaussian fitting in the CASA tclean task.

To account for the sensitivity change due to use of imaging weights (relative to the naturally weighted rms σ_{NA}), we adopted an efficiency factor η_{weight} such that expected image rms after weighting is $\eta_{weight}\ \sigma_{NA}$.

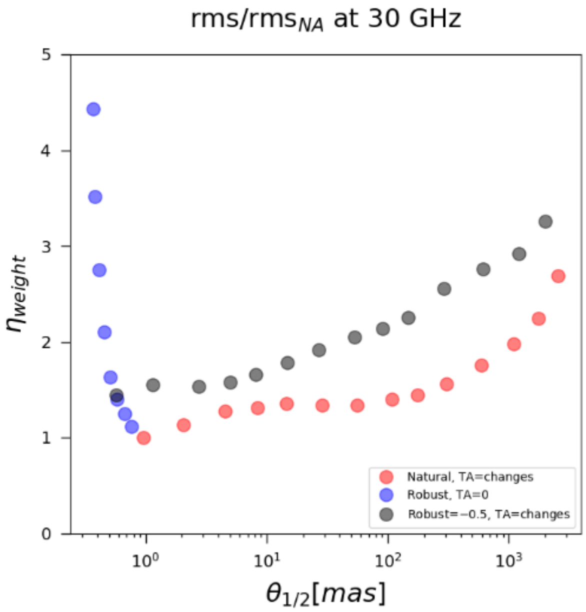


Figure 6 - Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz using the 244 antenna array configuration. The noise has been scaled relative to that of the naturally weighted image (rms$_{NA}$). The red symbols correspond to use of a uv-taper and natural weights, and the blue symbols to Briggs robust weighting without a taper. The gray symbols are for Briggs robust = –0.5 and a varying uv-taper, which has a large effect on beam quality (see Figure 7).

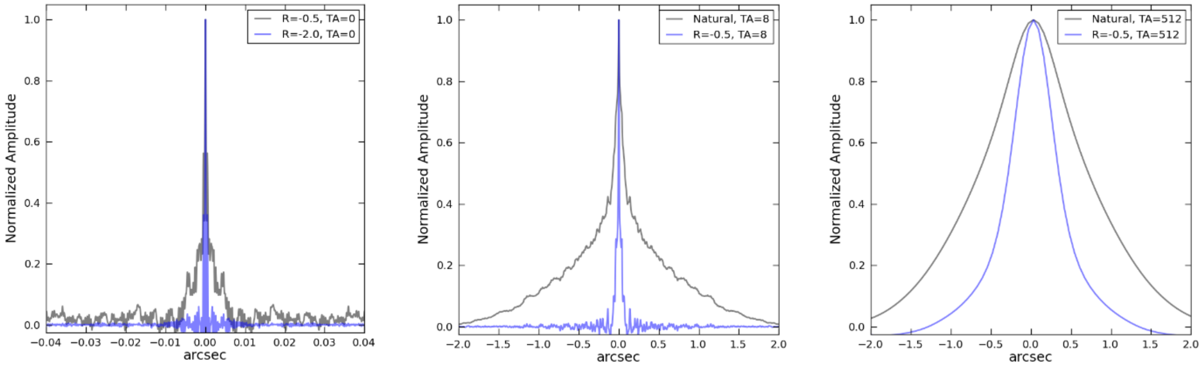


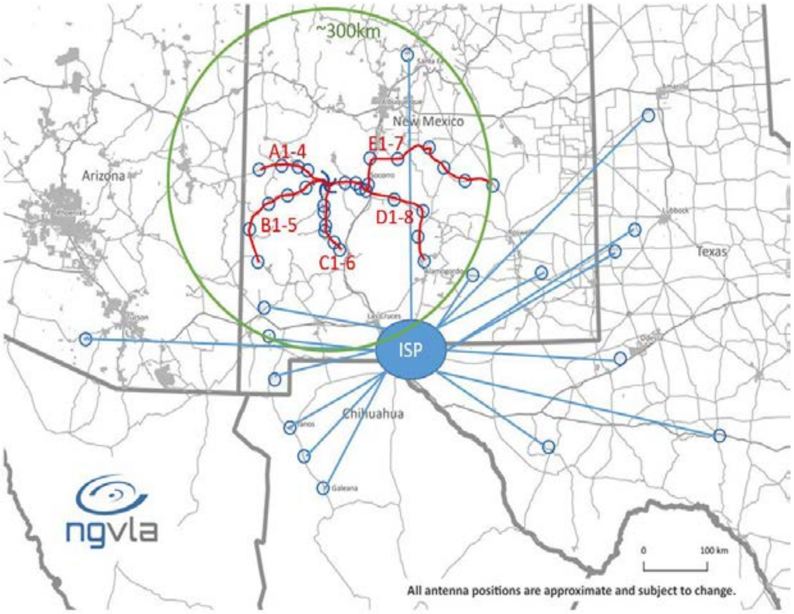
Figure 7 - Simulated 30 GHz PSFs for the present ngVLA reference array over a range of resolutions, showing the effect of different imaging weights (TA: uv-taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 6. These examples illustrate how combinations of robustness and tapering allow for a beam of much higher quality, meaning, greatly reduced beam skirts, but at the expense of sensitivity (see Figure 6).

We emphasize that the current study is preliminary, with weighting schemes that are adequate to perform some of the Key Science programs defined to date, such as imaging protoplanetary disks on scales down to 1 AU (Memos 13, 41), CO in high redshift galaxies (Memos 13, 41), and radio continuum deep fields (Memos 30, 35). A more in-depth study of imaging performance and sensitivity versus spatial resolution is in progress, including a wider exploration of the parameter space of imaging algorithms. The results will be presented in the Imaging Performance Reference Document in 2019.

4.6 Practical Considerations for Antenna Locations

Antenna locations, in particular for the antennas outside the Plains, incorporate the practical considerations of land access, roads, power, fiber, interference environment, safety, and security. Where possible, antennas have been placed on public land. Public land areas were chosen that are contiguous with nearby primary roads to allow convenient utility access and that are large enough to place the antenna some distance from the road to reduce the impact of radio frequency interference (RFI). Because public land comprises a minority of the current VLA site, antennas on the Plains of San Agustin were placed primarily on land of the same ownership as that of VLA antennas.

Though roads are significant sources of RFI, antennas have generally been placed within 1 km of existing primary roads to allow easier access to both utilities and service vehicles. Some access roads may require surface enhancement and improved drainage management. Sites were selected for several geographic features. In general, antenna sites are shielded by distance or terrain from easily identifiable RFI emitters such as urban centers, airports, radar installations, and large transmitter towers. Most antenna lines of sight are within ten degrees of the horizon. Sites were chosen to be outside visible flood boundaries and wetlands. Sites with provision for non-bedrock anchoring were selected over nearby bedrock-only candidates. While much of the array is sited in and near the seismically active Rio Grande rift zone, some effort was made to avoid sites affected by fault features visible in satellite imagery.



All antenna positions are approximate and subject to change.

Figure 8 - Model of the proposed fiber architecture for the inner array (<300 km). The wiring scheme for the dark fiber (shown in red) is arranged in five arms (A to E; number scheme increases from the inner to the outer end of the arm). This arrangement will allow for good LO timing, minimizing transmission costs and framing overhead (see Long Haul Fiber Report, Doc No. 020.60.00.00.00-0002).

For outlying antennas, proximity to primary roads allows access to fiber optic lines and power (Figure 8). For antennas on the Plains of San Agustin, utilities can be provided from those at the VLA site. The spiral form for arms was chosen for the Plains antennas not only for imaging performance but also for convenient emplacement of utilities. Each spiral arm can host utility trenches and access roads. Designs for electrical infrastructure provide power distribution systems that are redundant along each arm so that preventive maintenance (PM) or faults need not significantly affect UV coverage.

The arms are centered about 1 km northwest of the VLA array center to reduce physical conflict between a still-operational VLA and ngVLA during ngVLA construction, and to reduce RFI effects between the instruments. For the randomly-sited antennas in the array core, a suitable set of access roads and utilities distribution will be planned, with attention to graceful degradation of performance for PM and faults.

4.7 Future Work and Optimization

The Array Configuration Reference Design is expected to go through additional iterations based on further testing and feedback. One current consideration is how to improve the snapshot uv-coverage when using the longest baselines. A new configuration has been explored in ngVLA Memo #49 which involves moving the 46 outer antennas of the main interferometric array to be configured in a 5 arm spiral within the same maximum baseline of Rev. B (i.e. ~1000 km).

This proposed configuration offers a better snapshot UV coverage than Rev. B while maintaining or improving upon the long-track UV coverage. Further study is also required to optimize the location of the antennas to carefully take into consideration factors such as high frequency observations (e.g., atmospheric conditions), physical infrastructure and the difference in costs with respect of Rev. B.

Remaining work will also include

- Defining PSF imaging metric: Memo with simulations and metrics in preparation for early 2019.
- Imaging simulations of the performance of the SBA and the LBA for their Key Science Programs.
- Multi-scale weighting scheme: new algorithms for optimizing recovered information as a function of angular scale on complex celestial objects, for a multi-scale configuration such as that of the ngVLA. Experimental and ongoing.
- Multi-frequency synthesis simulations: current simulations are based on a single channel.
- Finding a better fit for the "efficiency" weight (eta_weight in Figure 7, right) applied to the rms; model currently uses interpolations.
- Integrating fiber and utility data.

5 Appendix

5.1 Abbreviations & Acronyms

Acronym	Description
AD	Applicable Document
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NSF	National Science Foundation
RD	Reference Document
RF	Radio Frequency
SBA	Short Baseline Array
TBD	To Be Determined
TP	Total Power
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer