Array Configuration: Design Description

020.23.00.00.00-0002 DSN

Status: **RELEASED**

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Change Record

Version	Date	Author	Affected Section(s)	Reason
A	2019-07-09	Lear	All	Initial Release
A.01	2021-09-30	All	All	Major updates for Revision D; see ngVLA Memos 82 and 92 for details.
A.02	2022-01-12	Lear	All	Formatting, minor copy edits.
B	2022-01-13	Lear	All	Prepared PDF for signatures and release.
C	2022-08-31	Carilli	All	Updated per CDR-T RIDS
D	2025-08-30	Carilli	All	Update per ECR-0004: Configuration F

Table of Contents

1 Introduction

1.1 *Purpose*

This document describes the ngVLA Array Configuration, Revision F. It covers the design approach, predicted performance, and risks associated with the design. This document will form part of the submission of the ngVLA Preliminary 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 conceptual design:

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

2.2 *Reference Documents*

The configuration design draws extensively from work presented in the ngVLA memo series, available on the ngVLA Memo Series Web page. We refer the reader to these memos for more details on science simulations that relate to the configuration design and characterization of the design. Along with the ngVLA science book, Science with the Next-Generation Very Large Array (2018, ASP), and the recent KSG update from the SAC [RD43], these documents provide much of the provenance for the current configuration design in terms of scientific analyses and simulations verifying performance in key science areas[1].

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[1] Science imaging simulations can be found in: high redshift molecular gas (RD10, 56, 57, 58, 43), proto-planetary disks and movies of planet formation (RD 18,54,55,32,44), high dynamic range imaging of complex objects (RD17, 18,21), sub-milliarsecond imaging of jets from supermassive blackholes, and potentially even the GR shadow of the black hole as part of global VLBI at 90 GHz (RD39), large scale structure in the Milky Way and nearby Galaxies (RD 25, 60, 62), continuum deep fields (RD 09, 56, 59), locating fast transients (RD63), Quasar SZ imaging (RD64), imaging stellar photospheres and movies of mass loss from AGB stars (RD30), SETI (RD31), radio recombination lines (RD38), astrometry of binary supermassive blackholes (RD65), high resolution studies of strong gravitational lensing and the determination of H_o (RD66), radio studies of star clusters (RD67), as well as in the chapters in *Science with the Next-Generation Very Large Array*.

The following documents are cited in the text as providing supporting analysis or context that informed the design of the array configuration:

Ref. 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
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
RD15	Snapshot coverage of the ngVLA: an alternate configuration	ngVLA Memo 49
RD16	Taperability study for the ngVLA and performance estimates	ngVLA Memo 55
RD17	High Dynamic Range Imaging	ngVLA Memo 64
RD18	Demonstrations and Analysis of ngVLA Core + Short Baseline Array for Extended Structure Imaging	ngVLA Memo 67
RD19	A Study of ngVLA Subarray Efficiency: Plains and Fractions of the Core	ngVLA Memo 72

Ref. No.	Document Title	Rev/Doc. No.
RD20	Subarray Selection for the Reference Observing Program	ngVLA Memo 76
RD21	Configuration: Reference Design Rev C.01 Description	ngVLA Memo 82
RD22	The ngVLA Long Baseline Array: Configuration Suggestions	ngVLA Memo 84
RD23	Comparison of Alternative Configurations for the ngVLA Plains Subarray	ngVLA Memo 85
RD24	Imaging Evaluation of Two Mid Configurations	ngVLA Memo 86
RD25	Image Fidelity Study of KSG3	ngVLA Memo 89
RD26	Configuration: Reference Design Rev D Description	ngVLA Memo 92
RD27	Preliminary ngVLA Observing Band Availability Estimate	ngVLA Memo 73
RD28	Seismic study and risk assessment for ngVLA sites	ngVLA Memo 93
RD29	Surface Weather and Atmospheric Measurements at the VLA Site, VLBA Sites, and Relevant Locations in the Southwest US	ngVLA Memo 94 (in prep)
RD30	Evaluation of the Revision D array configuration for stellar imaging	ngVLA Memo 95
RD31	Search for Extraterrestrial Intelligence with the ngVLA	ngVLA Memo 99
RD32	Mapping the Gas Density and Kinematic Structures due to Embedded Protoplanets in Young Disks with the Next Generation Very Large Array	ngVLA Memo 101
RD33	Enhanced Central Condensation Options for the Configuration of ngVLA Mid	ngVLA Memo 102
RD34	Spectroscopy of High Redshift Galaxies with the ngVLA	ngVLA Memo 103
RD35	ngVLA Imaging Science Performance Reference Document	ngVLA Memo 106
RD36	First characterization of Mid locations in Northern Mexico	ngVLA Memo 111
RD37	High Dynamic Range Imaging at 8 GHz at 1mas Resolution	ngVLA memo 112
RD38	Imaging the Radio Recombination Lines from M15's Planetary Nebula K648	ngVLA Memo 116

Ref. No.	Document Title	Rev/Doc. No.
RD39	Imaging the ring and jet in M87 at 85 GHz with the ngEHT and ngEHT+ngVLA	ngVLA Memo 118
RD40	Detrimental Emission Levels for Orbital RFI	ngVLA Memo 119
RD41	Characterization of the synthesized beam with and without Mid antennas in Mexico	ngVLA Memo 122
RD42	Analysis of ngVLA Rev E Mid Sites Using GIS	ngVLA Memo 124
RD43	Key Science Goals for the Next Generation Very Large Array: Update from the ngVLA Science Advisory Council	ngVLA Memo 125
RD44	A Comparison of the Imaging Capabilities of RevF and RevE ngVLA Configurations for Protoplanetary Disk Studies	ngVLA Memo 127
RD45	Transitioning to Rev F: Site Development Considerations	ngVLA Memo 129
RD46	Summary Table of Mid Siting Criteria	020.23.00.00.00-0003 MEM
RD47	Long-Haul Fiber Workgroup Report	020.60.00.00.00-0002 REP
RD48	Rev E Mid Tests: Sensitivity at 7mas Resolution	ngVLA memo 104
RD49	Suggested Changes to ngVLA Long	ngVLA memo 105
RD50	Subarray Study for the Envelope Observing Program	ngVLA memo 121
RD51	Configuration: Rev E Staggered Spiral Tests	ngVLA memo 100
RD52	Imaging the Distribution of Solids in Planet-Forming Disks Undergoing Hydrodynamical Instabilities with the Next Generation Very Large Array	ngVLA memo 57
RD53	Sculpting of the Synthesized Beam and Image Fidelity Study of KSG 1: Imaging of Protoplanetary Disks	ngVLA memo 65
RD54	Imaging the Dusty Substructures Due to Terrestrial Planets in Planet-forming Disks with the Next Generation Very Large Array	ngVLA memo 68
RD55	Testing Photoevaporation and MHD Disk Wind Models Through Future High-Angular Resolution Radio Observations: the Case of TW Hydrae	ngVLA memo 88
RD56	Confusion Limited Surveys with the ngVLA Spiral	ngVLA memo 44

Ref. No.	Document Title	Rev/Doc. No.
RD57	Imaging Cold Gas to 1 kpc Scales in High-Redshift Galaxies with the ngVLA	ngVLA memo 50
RD58	Imaging Cold Gas in High-Redshift Galaxies with the ngVLA	ngVLA memo 83
RD59	Quantifying the ngVLA's Contribution to Exo-Space Weather: Results of a Community Studies Report	ngVLA memo 31
RD60	Short Spacing Issues for Mapping Extended Emission: Milky Way Case Study	ngVLA memo 54
RD61	Relative Integration Times for the ALMA Cycle 1 12-m, 7-m, and Total Power Arrays	ALMA memo 598
RD62	Analysis of ngVLA Core + Short Baseline Array Extended Structure Imaging	ngVLA memo 67
RD63	Fast Transients with the ngVLA	ngVLA memo 77
RD64	Quasar Wind SZ imaging with the ngVLA	ngVLA memo 80
RD65	Toward Astrometric Constraints on a Supermassive Black Hole Binary in the Early-type Galaxy NGC 4472	ApJ 931, 12
RD66	Strong gravitational lensing with upcoming wide-field radio surveys	arXiv:2412.01746
RD67	Proper Motions to Test Radio Source Membership in Galactic Globular Clusters	ngVLA memo 130
RD68	The strength of the core	ngVLA memo 12
RD69	The Total Power Array Concept of Operations & System-Level Requirements	020.27.00.00.00-0001 REQ
RD70	Site Development siting criteria for the ngVLA	020.23.00.00.00-0005 MEM

3 Subsystem Overview

The antenna 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 conceptual design.

The longest baselines set the highest angular 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; PSF), as determined by weighting of the UV-data.

The array 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 [RD03], in chapter 1 of *Science with the Next-Generation Very Large Array*, and the recent SAC update to the KSGs [RD43]. To perform this broad range of science programs, the array configuration design requires essential capabilities such as[2]:

- High-resolution imaging of sub-pc-scale structures in distant radio jet sources associated with supermassive black holes (SMBH; down to 0.07 mas resolution at 3 mm wavelength), including unique imaging of the connection between the jets and the inner accretion disk as seen as the general relativistic shadow of the SMBH, and astrometric studies of close binary SMBH.
- High-resolution, high-sensitivity observations of exoplanets forming on 1 AU-scales (7 mas resolution at 1 cm).
- High surface brightness sensitivity of 1 kpc-scale structures in the molecular gas in high redshift galaxies (100 mas resolution at 1 cm).
- High surface brightness sensitivity at arc-second resolution for imaging of tens of parsec-scale structures in nearby galaxies in line and continuum emission over a broad range in frequency.
- High dynamic range imaging (up to 10^5) at resolutions from 100 mas to arcsecond scales, for imaging complex radio continuum sources and deep fields over a broad range in frequency.
- Resolved imaging of the structure of stellar photospheres using sub-mas resolution imaging at 90 GHz, including movies of mass loss from end-of-life intermediate mass stars, and deriving the radio Hertzsprung-Russel diagram for stars of all spectral types.

The configuration design reflects the multi-scale demand on the array science case. The sensitivity as a function of resolution will depend on the specific synthesized beam for the science application in question. As a guiding principle, we have adopted the goal of achieving angular resolutions ranging from ~0.3 mas to 1000 mas at 30 GHz with a loss of roughly a factor of two or less in sensitivity relative to natural weighting, over the full resolution range (Figure 12). The array performance for several key science programs has been documented in the memo series and science book, as listed in the reference documents above.

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[2] Quoted resolutions and wavelengths are representative, not exclusive.

4 Site Quality

Locating the majority of antennas in the Main Interferometric Array in the Southwest US and Mexico allows for maximum visibility of the southern sky from the Continental US. The high, dry plains in this area are well suited for observations up to 116 GHz due to generally high elevations (typical elevations of 1500 meters or higher) and low water vapor content. Figure 1 shows an example of the phase stability at the VLA site for observations scaled to 90 GHz. These measurements show that using fast switching calibration provides acceptable calibration results (ϕ_{rms}< 40°) for observations at day or night during most of the year [RD13].

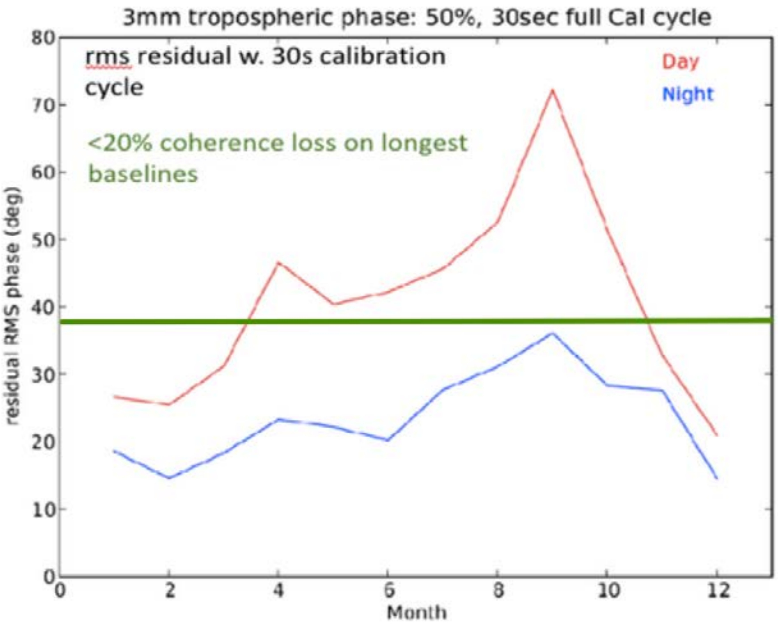


Figure 1: RMS phase residuals after fast switching calibration predicted for the VLA site at 90 GHz based on decades of phase monitoring with the Atmospheric Phase Interferometer (after [RD13]).

As a specific test of whether the location of the array would be suitable for 90 GHz observations, we have done a detailed analysis of what star forming molecular clouds could be observed to satisfy the needs of KSG1 [AD01], given known weather and other assumptions. We assume that the VLA is a good proxy for weather conditions over enough of the array that the results of [RD27] can be used. This should be true for the antennas situated in the Southwest US and Mexico. We use reasonable assumptions regarding calibration overheads. And we use the specific locations on the sky of six nearby star formation regions (Perseus, LkHα 101, Taurus, Orion, Serpens/Aquila, and Cepheus). The results imply a lower limit of roughly 12% of time per year could be devoted to KSG1. Table 1 shows the amount of time per month that is available to observe KSG1. This is a lower limit because we have not included every possible star forming region in this analysis, but a restricted sample of six. If we included more star formation regions the value would go up, because they would cover the sky more completely, so fill in some ranges of time that are not covered in the current analysis. We do note that every star formation region has hundreds of potential targets that could satisfy the needs of KSG1. Note that even if we restrict this to just the

Taurus star formation region, 5.4% of time could be devoted to KSG1, which is far more than is needed to complete the program (60 hours per year).

A calculation of atmospheric opacity at the VLA site (again, a proxy for much of the southwest), based on atmospheric models and weather statistics over a 10-year period, implies the 90 GHz opacity satisfies the '< 10% opacity more than 30% of the time' requirement throughout the year (requirement AAC0501).

A more complete analysis of weather statistics at the VLA site, Southwest US antenna locations, and VLBA sites and how that might affect potential high-frequency observing is forthcoming [RD29].

Table 1: Fraction of time per month during which six nearby star formation regions (Perseus, LkHα 101, Taurus, Orion, Serpens/Aquila, and Cepheus) could be observed in Band 6-lower (70–90 GHz).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All
Fraction (%)	20	12	11	9	12	11	4	3	7	14	20	19	12

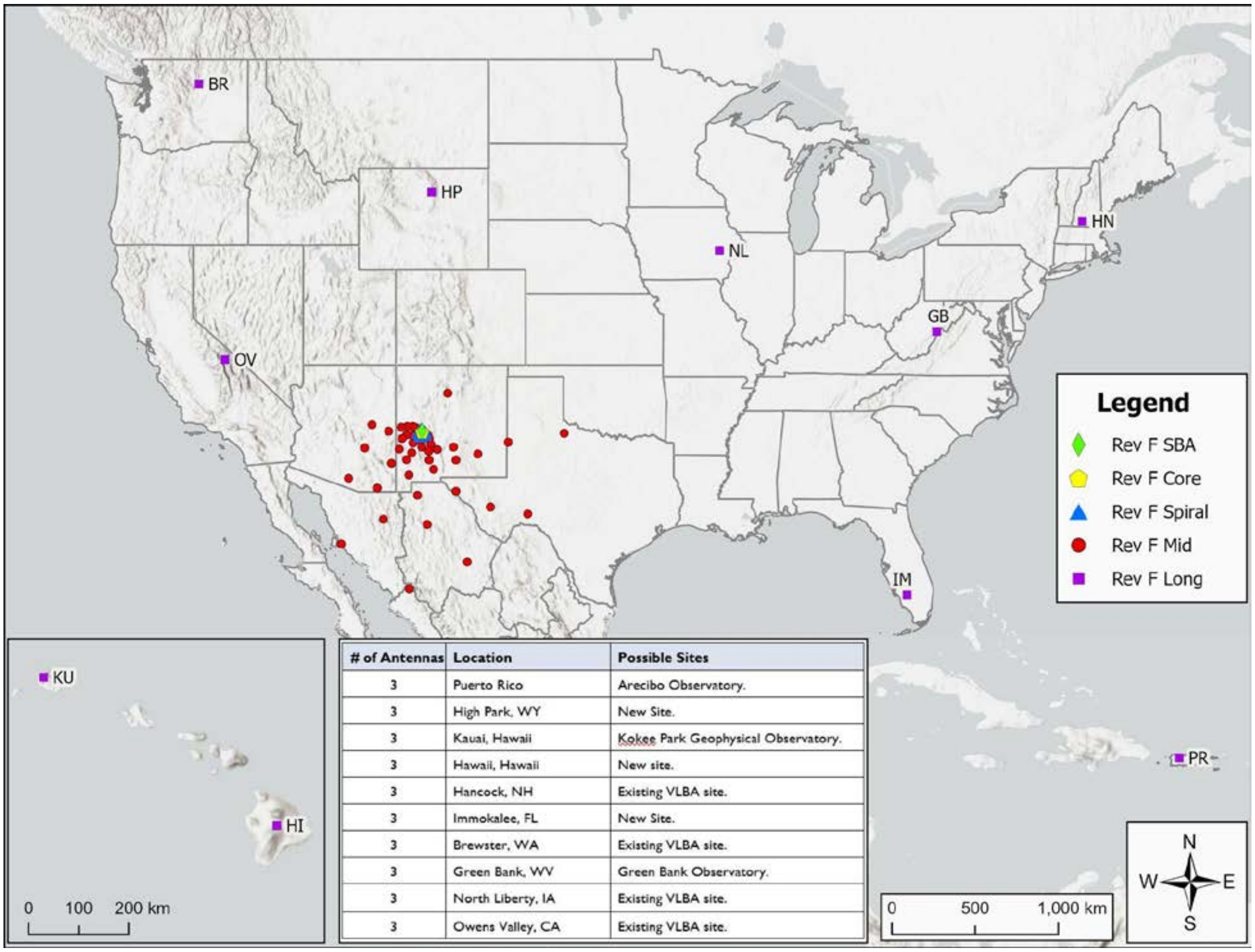
5 Array Configuration Design

5.1 Components of the Array Configuration

Given the ngVLA will not be reconfigurable, the range of angular scales expressed in the broad science program requires antennas distributed over a large range of spatial frequency (baseline length or angular resolution), ranging from 11 m (SBA) to 8600 km (Long). The configuration envisioned consists of three principal components (Figure 2):

- Main Interferometric Array of 214 18m reflector antennas;
- Long Baseline Array (Long) of 30 18m reflector antennas;
- Short Baseline Array (SBA) of 19 6m reflector antennas.

There will also be at least four 18m antennas equipped with instrumentation appropriate to make astronomically accurate measurements of total power.



# of Antennas	Location	Possible Sites
3	Puerto Rico	Arecibo Observatory.
3	High Park, WY	New Site.
3	Kauai, Hawaii	Kokee Park Geophysical Observatory.
3	Hawaii, Hawaii	New site.
3	Hancock, NH	Existing VLBA site.
3	Immokalee, FL	New Site.
3	Brewster, WA	Existing VLBA site.
3	Green Bank, WV	Green Bank Observatory.
3	North Liberty, IA	Existing VLBA site.
3	Owens Valley, CA	Existing VLBA site.

Figure 2: View of Long and the Main Interferometric Array, with 244 18m antennas total. Each Long site is denoted in purple and has 3 antennas. The table lists the locations of the Long stations. The legend specifies the symbols for sub-components of the ngVLA.

Table 2 summarizes the array configuration components. The design is practical, accounting for such logistic limitations as topography, utility access, local RFI sources, and land management/availability (see Section 6).

Table 2: Summary of components within the ngVLA array configuration.

Component Name	Aperture Diameter (m)	Quantity	B_{min} (m)	B_{max} (m)
Long Baseline Array	18	30	495000 (42)[3]	8636000
Main Interferometric Array	18	214	42	1272600
Short Baseline Array	6	19	10.7	59.9
Total Power/Single Dish	18	4[4]	--	--

The Main Interferometric Array itself will have three spatially distinct antenna distributions, referred to as sub-components (Table 3; Figure 3, Figure 4, and Figure 5):

- Core Sub-Component: 114 18m antennas with minimum spacings of 42 m (consistent with antenna design), distributed to a maximum radius of 2.2 km from the center of the Main Array;
- Spiral Sub-Component: 54 18m antennas distributed from a 2.3 km radius from the Main Array center to a maximum radius of 20 km;
- Mid Sub-Component: 46 18m antennas distributed from a minimum radius of 33 km from the Main Array center to a maximum radius of 816 km.

Table 3: Sub-Components of the Main Interferometric Array.

Sub-Component	Min. Baseline (m)	Max. Baseline (m)	Distribution Pattern	# Antennas
Core	42	4272	Constrained random	114
Spiral	812	39270	5-arm spiral	54
Mid	10120	1272600	5-arm spiral	46

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[3] 42 m is the minimum baseline within a Long station. 495 km is the minimum baseline between stations.

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

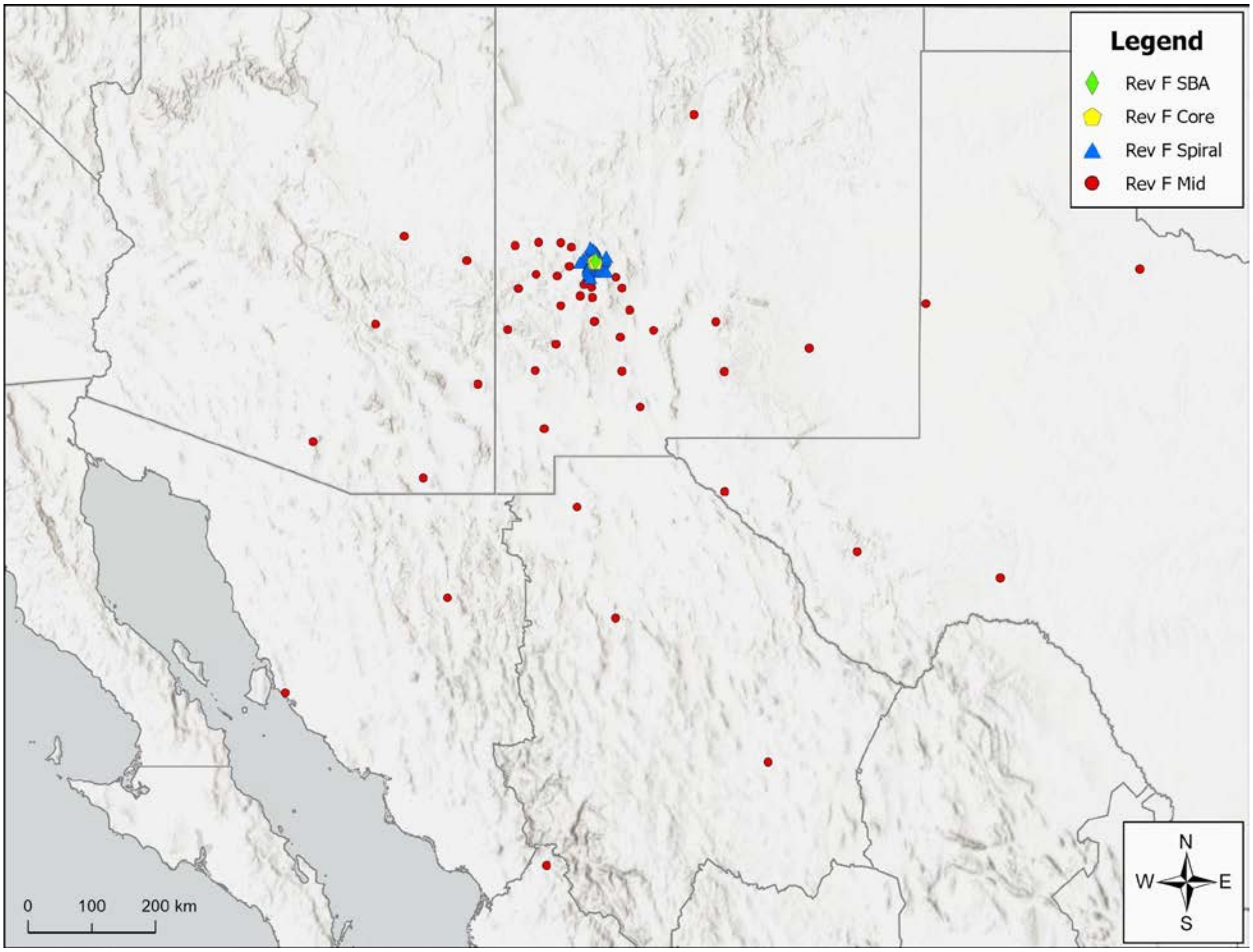

Figure 3: The Mid Sub-Component in the US Southwest and Mexico is shown as red circles. The antennas in the Spiral Sub-Component are shown by blue triangles at the center, for reference.

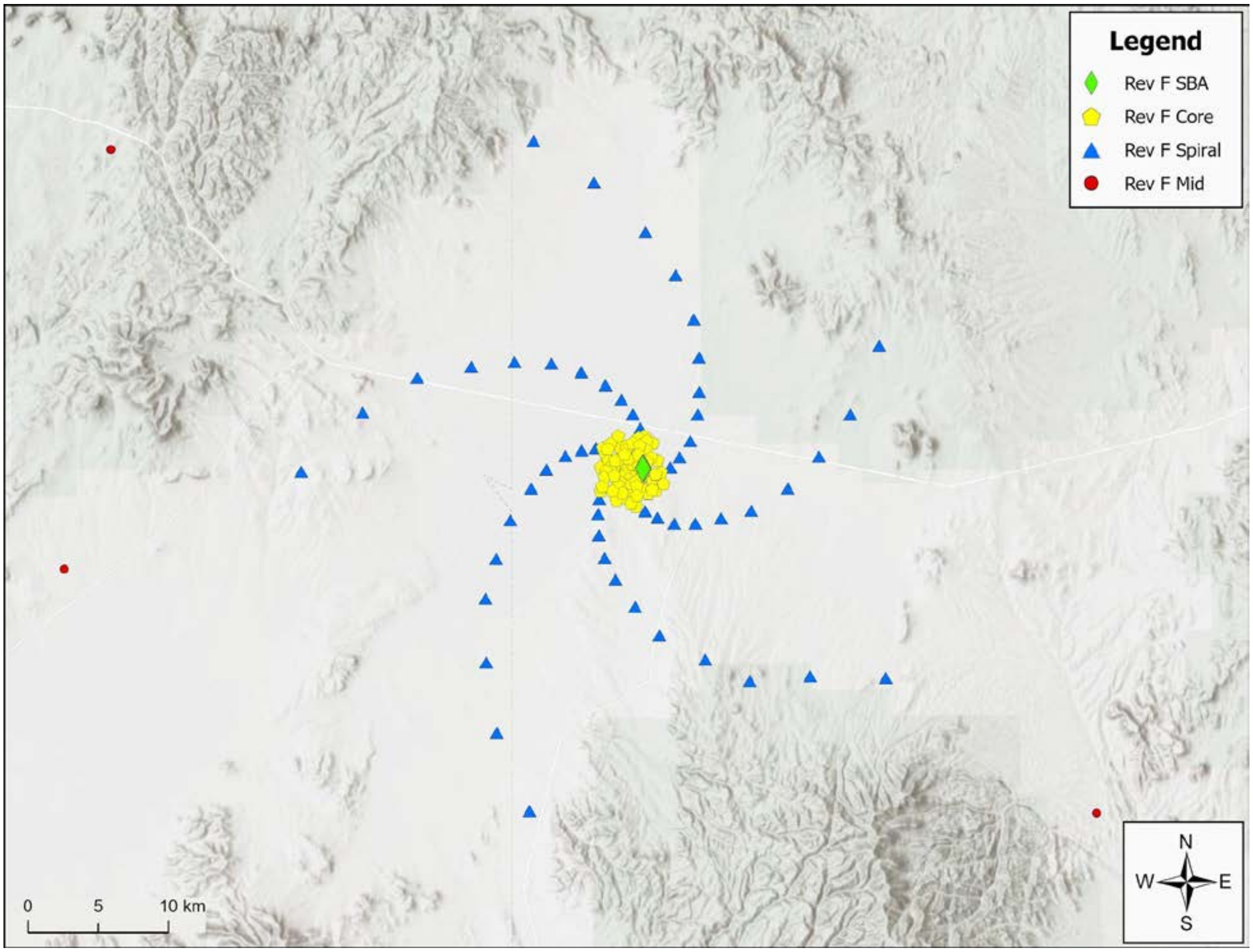

Figure 4: The blue triangles are the antennas of the Spiral Sub-Component on the Plains of San Agustin in New Mexico. The yellow points are the antennas of the Core Sub-Component. Red dots show the inner Mid antennas.

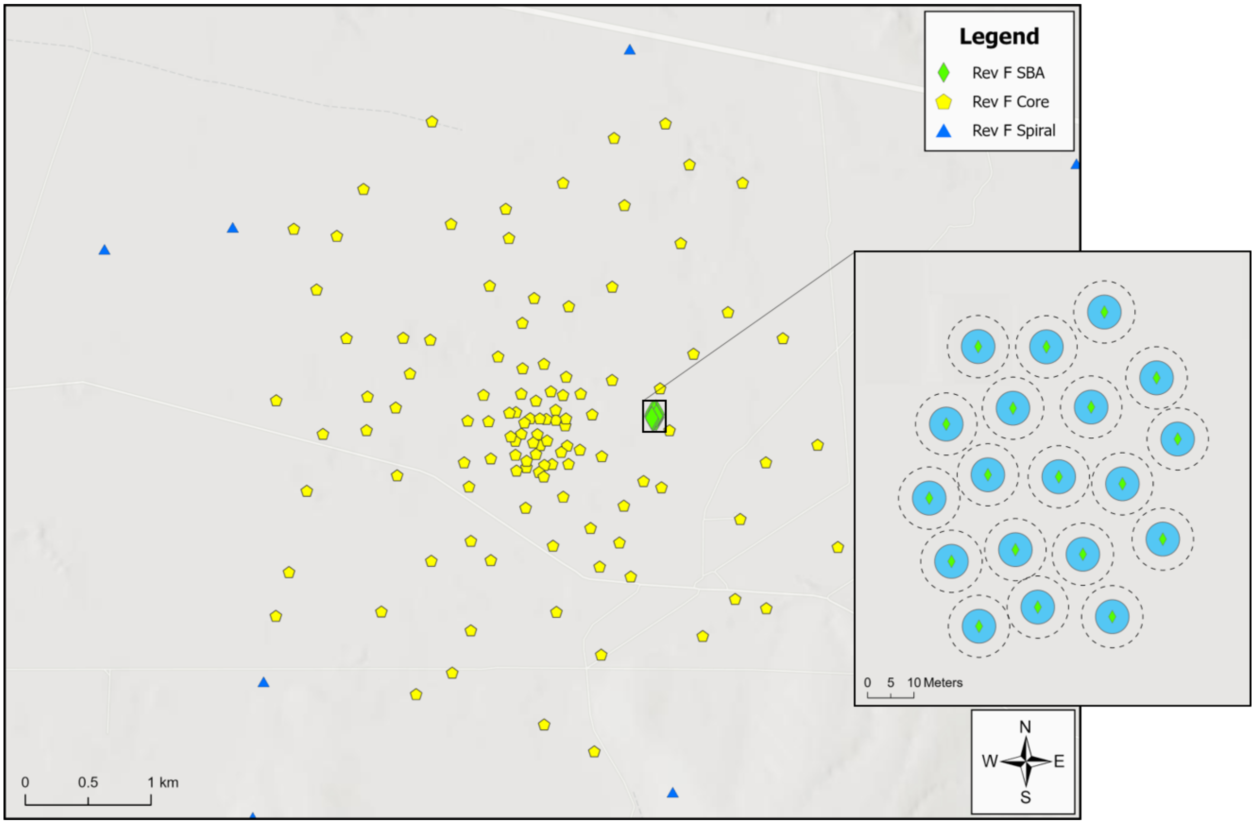

Figure 5: The Core Sub-Component (yellow) and the Short Baseline Array (blue circles are antenna diameter, dashed lines are the safety radii), located near the center of the Spiral Sub-Component on the Plains of San Agustin. The inner antennas of the Spiral are shown as blue triangles.

5.2 *Main Interferometric Array (Main)*

We describe in more detail the Core, Spiral, and Mid Sub-Components of the Main Interferometric Array. We then consider the performance of the Main Interferometric Array in terms of noise and PSF quality with respect to UV-weighting. More detail on general imaging and taperability performance can be found in numerous ngVLA Memos, particularly [RD35], plus studies in [RD37], [RD19], [RD20], [RD23], [RD24], [RD30], as well as memos related to specific science applications.

The ngVLA is designed to routinely support multiple, simultaneous activities through the use of subarrays, including both science observations, testing observations or activities, and other operational tasks. This will necessitate the efficient allocation of observing resources — mainly the antennas themselves — to meet the diverse requirements of specific, often potentially commensal use cases. The ngVLA is being designed such that science can be done with up to 10 sub-arrays commensally. Memos [RD19], [RD20], [RD23], [RD50] provide detailed studies of subarrays and their efficacy in realizing the science program for the ngVLA. The set of subarrays that will be used in operations will be flexible. [RD20] and [RD50] present possible subarray assignments for the Reference Observing Program and the Envelope Observing Program, respectively, along with detailed analysis of the alternatives.

5.2.1 The Core Sub-Component

The antennas of the Core Sub-Component will be located at the current VLA site, in a centrally-concentrated, semi-random array, with minimum baselines of about 40 m (set by antenna design), to a maximum baseline of 4272 m (Figure 5). The configuration has been optimized to capture molecular line imaging programs for nearby galaxies, as given in KSG 3 (see addendum to [RD25]), and generally to perform high fidelity imaging for structures on scales of 0.1” to 1” at 100 GHz (see [RD18], [RD26], [RD35], [RD37]). A detailed description of the design process for the Core can be found in [RD26]. The north-south axis is 10% longer than the east-west axis in order to better support observations of low-declination targets.

The snapshot UV-coverage, baseline distribution, and Naturally weighted point spread function are shown in Figure 6. An analysis of the imaging performance can be found in [RD25] addendum.

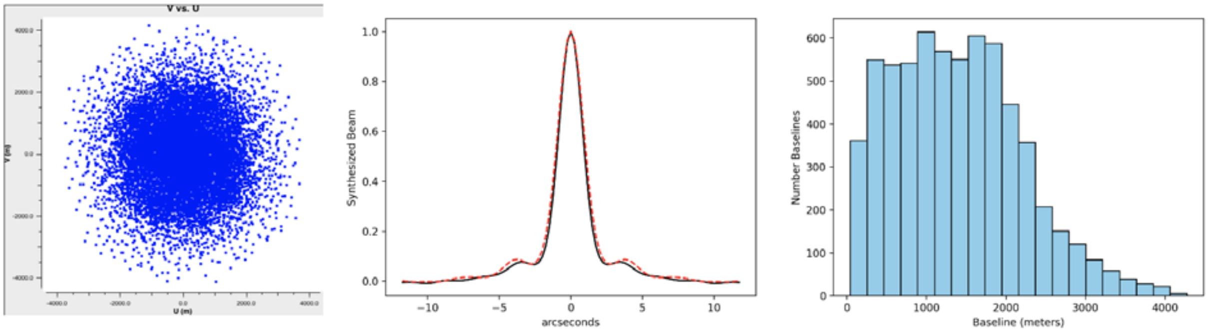

Figure 6: Left: u,v snapshot coverage for the Core sub-component at 10 GHz. Center: East-West (red) and North-South (black) profiles of the NA PSF. Right: histogram of baselines. A Gaussian fit to the Core NA PSF has a FWHM = 2.17” x 1.97”, major axis position angle = 77.7°

5.2.2 The Spiral Sub-Component

The Spiral Sub-Component consists of 54 18m antennas with baselines starting at a radius of 2.3 km, and extending to a 20 km radius (Figure 4). The antennas are distributed in a 5-arm spiral. The spacings along the arm are an exponential function, as defined in SKA Design Document WP3-050.020.000-R-002, and described in [RD21]. We include a 10% of radius dither of each antenna to broaden the UV-distribution. The Spiral has been rotated and shifted to optimize public land usage, and individual antennas have been moved from obvious terrain or structure conflicts (see Section 6). The Spiral has also been elongated 10% North-South to improve the PSF at low and high declinations.

The snapshot UV-coverage and baseline distribution and Naturally weighted point spread function are shown in Figure 7. An analysis of a 5-arm spiral imaging performance can be found in [RD10], [RD51].

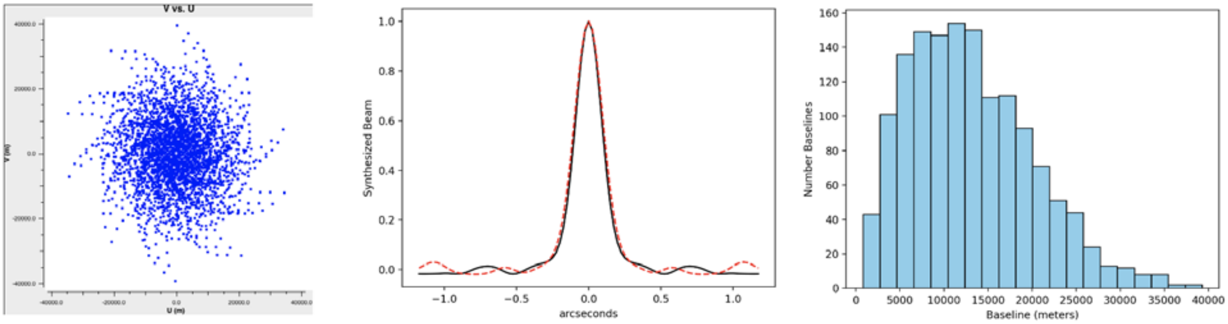

Figure 7: Left: u,v snapshot coverage for the Spiral sub-component at 10 GHz. Center: East-West (red) and North-South (black) profiles of the NA PSF. Right: histogram of baselines. The spiral has a NA PSF FWHM = 0.23" x 0.21" major axis position angle = 73.5°

5.2.3 The Mid Sub-Component

The Mid Sub-Component consists of 46 18m antennas from 33 km to 1273 km radius from the ngVLA center (Figure 3). The antennas are distributed along a rough 5-arm exponential spiral, extending predominantly toward the South, and taking into consideration terrain and other practicalities (see Section 6). There are 6 antennas in Mexico, 6 antennas in Arizona, and 5 in Texas. Included in Mid are the current VLBA sites at PT, KP, LA, and FD. The Mid provides excellent UV-coverage for few mas-scale observations at 30 GHz to 100 GHz for proto-planetary disks, as well as providing intermediate baseline coverage down to tens of km for higher-resolution Long imaging of complex objects.

The snapshot UV-coverage of Mid, baseline distribution and Naturally weighted point spread function are shown in Figure 8. The imaging performance of Mid is considered in [RD33], [RD48].

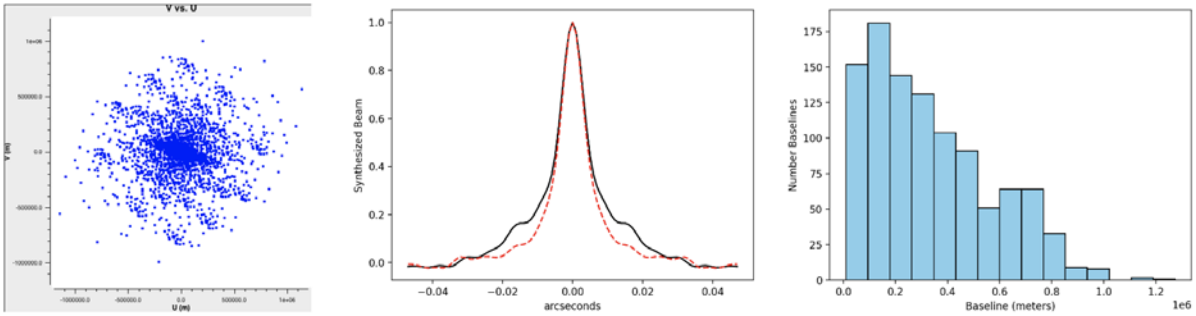

Figure 8: Left: u,v snapshot coverage for the Mid sub-component at 10 GHz. Center: East-West (red) and North-South (black) profiles of the NA PSF. Right: histogram of baselines. The Mid has a NA PSF FWHM = 9.14 mas x 8.20 mas, major axis position angle = 9.7°

5.3 Long Baseline Array (Long)

The Long baseline array is composed of 30 18m antennas at ten different sites or stations (Figure 2). Clustering antennas at each station is a cost-effective way to increase the array's sensitivity while sharing the operations infrastructure per site. Clustering also enables unique science capabilities, including:

- Simultaneous observations of the science target and the calibrator for paired-antenna phase calibration,
- Simultaneous frequency coverage across the same set of baselines for temporal-spectral variable source studies, and
- Use of sites individually, as small phased arrays for "single dish" observations, such as pulsar timing or fast transient searches.

The Long by itself provides reasonable UV-coverage on scales from a few hundred to ~9000 km baselines, in particular for longer synthesis observations, while incorporating the Mid Sub-Component fills in baselines to tens of km. For the outermost sites, the Long has a second site within a few hundred km, to improve flux scale calibration (see [RD22] and [RD49]). The UV-coverage, baseline distribution and Naturally weighted point spread function are shown in Figure 9.

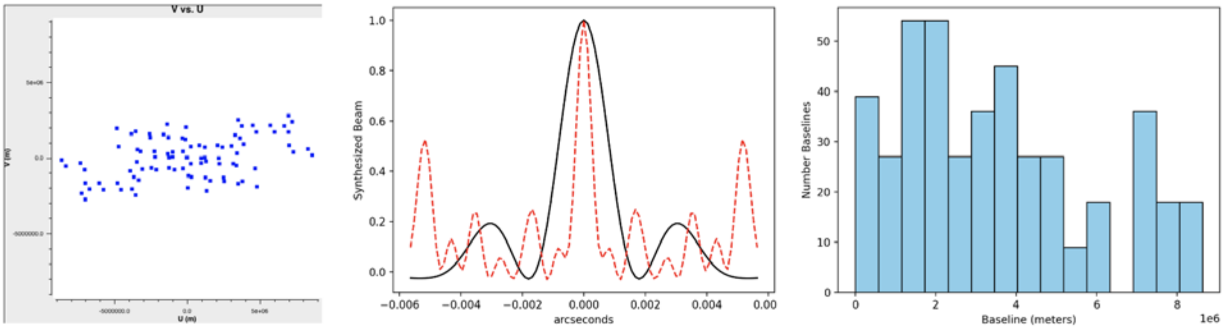

Figure 9: Left: u,v snapshot coverage for the Long sub-component at 10 GHz. Center: East-West (red) and North-South (black) profiles of the NA PSF. Right: histogram of baselines. Long has a NA PSF FWHM = 1.88mas x 5.60mas with major axis position angle = -9.0°

5.4 ngVLA (Main+Long) Performance

Figures 2–5 show the Long and the Main Array's antenna distribution for each of its sub-components. This configuration has been designed to satisfy the broad requirements in resolution vs. sensitivity for the ngVLA science program. The distribution of baseline lengths for all 244 18m antennas included in the Main + Long sub-components is shown in Figure 10. The consequence of having a relatively dense distribution of antennas on scales of a few km, then baselines extending to almost 9000 km, leads to a naturally weighted PSF for the 244 18m antenna distribution with three very different scales (see Figure 11):

- a narrow spike with high resolution (~0.3 mas at 30 GHz) due to the Long + Mid antennas,
- a first skirt extending to 100 mas at 30 GHz at the 50% to 20% power level of the PSF due to the Spiral antennas,
- a second, broader skirt due to the Core antennas extending to 1000 mas at 30 GHz in the 20% to 10% power 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, numerous 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 PSF. [RD16] describes the process of adjusting standard imaging parameters (Briggs weighting, UV-taper, cell and image size) to obtain an adequate synthesized beam shape for high quality imaging. The ngVLA 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. Moreover, the ngVLA project has shown that sub-arraying, meaning using multiple subsets of antennas in parallel, with different baseline coverage, can perform commensally a variety of science programs with little to no loss of performance (PSF and sensitivity; [RD50]).

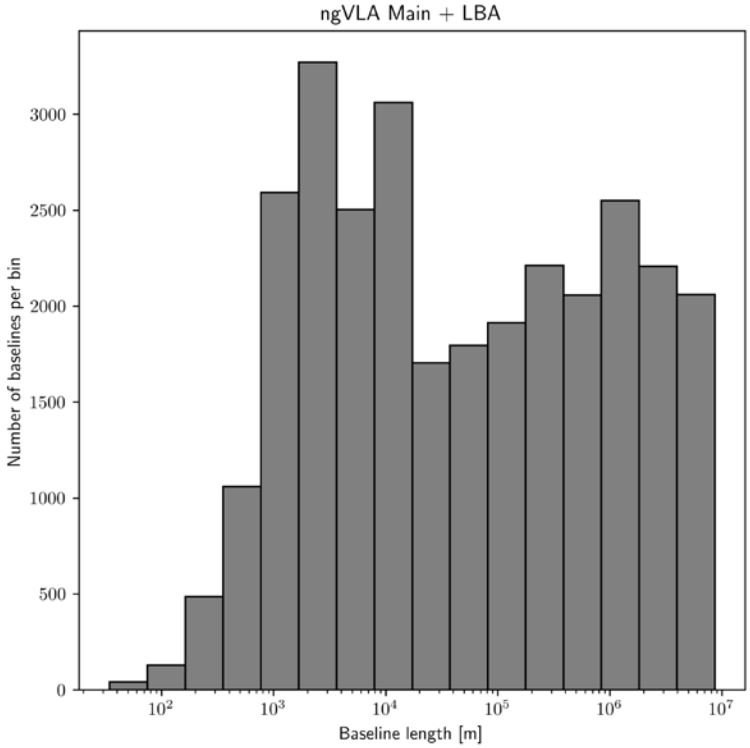

Figure 10: Number of baselines versus the baseline length for the 244 18-m antenna ngVLA (Main+Long), using logarithmic bin sizes.

Image sensitivity will depend on the required resolution and imaging fidelity. Figure 11 and Figure 12 show the effects of adjusting UV-weights to obtain a target spatial resolution, while maintaining a PSF shape adequate for quality imaging [RD16]. These figures are based on a four-hour simulation at 30 GHz using the 244 18m antenna configuration, for a source at +24° declination observed during transit.

To account for the sensitivity change due to the use of UV-weights to obtain a quality PSF for imaging, we adopted an efficiency factor, η_{weight}, defined such that the image rms after weighting is: [$\eta_{weight} \times \sigma_{NA}$], where σ_{NA} is the naturally weighted rms thermal noise. The process entails adjusting the taper and robust to obtain a well behaved PSF for a target spatial resolution (in particular, low skirt-levels), while optimizing sensitivity [RD16]. In Figure 12, the gray points show the η_{weight} values for quality imaging at a desired resolution. The η_{weight} values range between a factor 1.5 and 2.2 higher than NA weighting (red points), in the resolution range of 5 mas to 500 mas. We re-emphasize that the red symbols for NA weighting yield PSF shapes that have extremely broad skirts which preclude high-quality imaging (Figure 11).

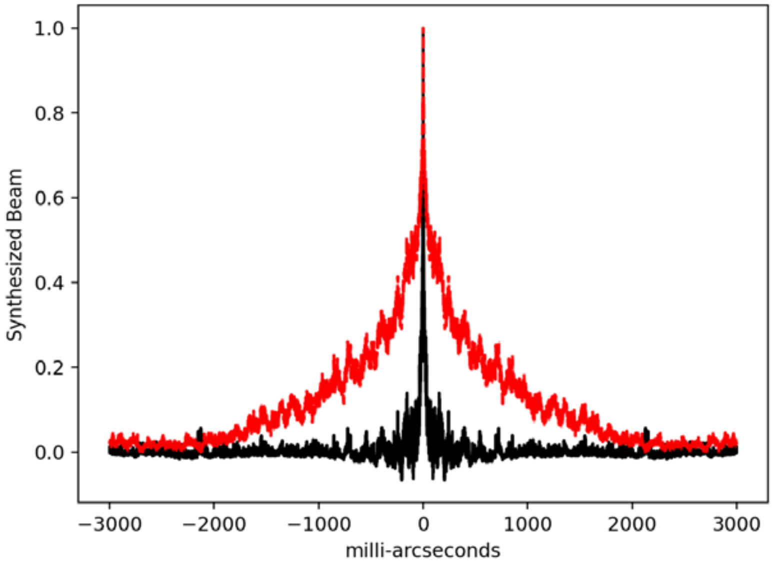

Figure 11: Simulated 10 GHz synthesized beam in one dimension (east-west) for the ngVLA configuration Rev F (Main + Long 244 18m antennas) using Natural weighting (red) and Uniform weighting (black). This figure demonstrates that when using the full range of baselines from tens of meters to thousands of km in the ngVLA, natural weighting cannot be used due to the many short baselines in the array leading to very wide and bright 'skirts', with widths of 10 to 100 times larger than the nominal resolution of the longest baselines. Some combination of robust weighting and subarraying provides for the most efficient use of the ngVLA for imaging experiments to obtain a reasonable sensitivity with a well-behaved synthesized beam (Section 5.4 and [RD16] and [RD50]).

Science simulations have verified that the current configuration and existing imaging tools in CASA, with appropriate weighting schemes, are adequate to perform the Key Science programs defined to date, such as imaging protoplanetary disks on scales down to 1 AU ([RD32], [RD44], [RD52], [RD53], [RD54], [RD55]), CO in high redshift galaxies ([RD10], [RD56], [RD57], [RD58], [RD34]), radio continuum deep fields ([RD59], [RD09], [RD56]), and large scale structures in nearby galaxies ([RD60], [RD18], [RD25]). Algorithmic studies of multi-scale information recovery with an array with extremely high spatial dynamic range (of order 1e6 for the ngVLA), are a priority for the project in the coming year, which may improve performance beyond the current suite of imaging tools.

Several Python software tools have been developed in order to characterize the performance of the ngVLA, e.g., end-to-end pipelines that automate the process of creating and analyzing simulated observations for any given revision of the configuration reference design. For example, the *taperability* pipeline allows one to compare different antenna configurations, and the imaging performance pipeline allows the study of the requirements for the driving cases (e.g., PSF-level, image fidelity). A Python command-line ngVLA sensitivity calculator is available at https://ngect.nrao.edu/. A CASA guide has also been established to assist in simulating and imaging ngVLA datasets:

https://casaguides.nrao.edu/index.php/Simulating_ngVLA_Data-CASA6.7.0

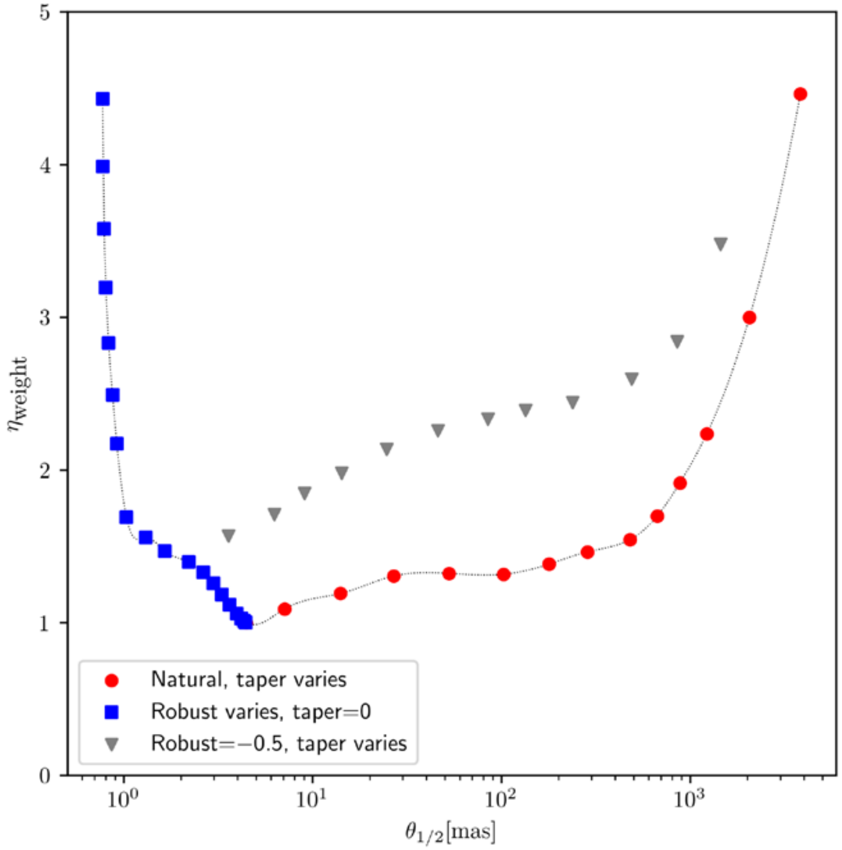

Figure 12: Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz using the 18-m 244 antenna configuration. The noise has been normalized by the noise of a naturally weighted image with no taper (σNA), i.e. the thermal noise for a 244 antenna array. 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 is required to obtain a synthesized beam adequate for quality imaging (see Figure 11 and RD16). For the blue points, the robust values go from -2 to +2 in steps of 0.2.

5.5 Short Baseline Array and Total Power Antennas

Due to mechanical clearance considerations, the ngVLA 18m antennas cannot be placed closer together than 38m. In practice, we have designed Core with a minimum baseline of 42m, to ensure reasonable safety and access margins. However, roughly 25% of identified science use cases require information on spacings shorter than this. In order to address this need, the ngVLA includes a short baseline array as well as a total power capability.

The ngVLA Short Baseline Array (SBA) consists of 19 6m antennas in an approximately hexagonally close-packed configuration operated as an interferometer to fill spacings between 60 m and 11 m (Figure 5); basic design considerations are presented in [RD12]. Spacings shorter still will be observed by the Total Power Antennas (TPA), a set of ~4 18m antennas capable of measuring total power accurately (see below). The SBA and TPA were designed to "feather" and/or be jointly deconvolved with observations from the Core Sub-Component of the Main Array, improving sensitivity to spatially large structures (up to 70 arcseconds at 90 GHz for the SBA alone, with TPA raster scans enabling recovery of much larger scales). Figure 13 shows the u,v coverage, NA PSF, and baseline histogram for the SBA.

The number and distribution of antennas in the SBA was selected to provide good surface brightness sensitivity, while also providing comparable surface brightness sensitivity to the shortest, overlapping baselines measured by the Core. A histogram of the baseline lengths for the SBA and Rev F Core is shown in Figure 14. The formalism for calculating the integration time ratios needed to match the sensitivity of "adjacent" arrays computed, as developed for ALMA, is presented in [RD61].

Simulations demonstrating the efficacy of the SBA and TPA are presented in [RD18]. These memos used a previous (Rev C) SBA configuration, which differs only in very minor respects from the current Rev F SBA antenna configuration. The primary difference, as described in [RD21], is that the array orientation has been rotated by 30 degrees in order to reduce shadowing for low and high declination sources. For a 1hr 15min track on Sgr A* this rotation reduces shadow-flagged data by a factor of almost 5 down to only 6.4%. The locations of the SBA antennas have also been translated to a location in the Rev F Core which is free of shadowing by 18m antennas. The SBA has been elongated North-South by 10% to improve PSF performance at low and high declinations.

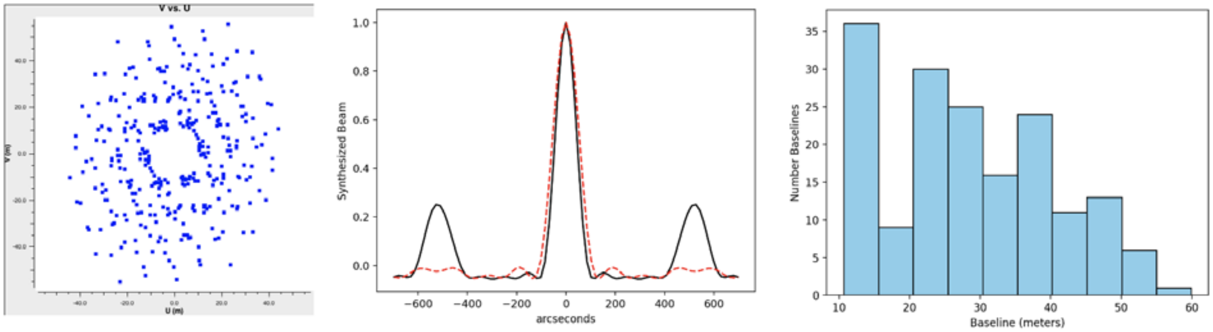

Figure 13: Left: u,v snapshot coverage for the SBA sub-component at 10 GHz. Center: East-West (red) and North-South (black) profiles of the NA PSF. Right: histogram of baselines. The SBA NA PSF has a FWHM = 115.7" x 91.3", major axis position angle = -73.9°

Total Power Antennas: The requirements and system concept for the ngVLA Total Power Array were described in [RD69]. For purposes of Rev F it is provisionally assumed that there will be 4 Main array antennas that are optimized for good total power performance, including excellent spectral baseline stability and sufficiently clean primary beams for total power mapping. These antennas can also be used for interferometric observations. Whether the antennas are actually different from other Main array antennas— mechanically or electrically— is under consideration. It is also possible that other 18m antennas could be used for total power observations, perhaps with inferior performance for some applications, thereby simplifying maintenance and increasing operational flexibility.

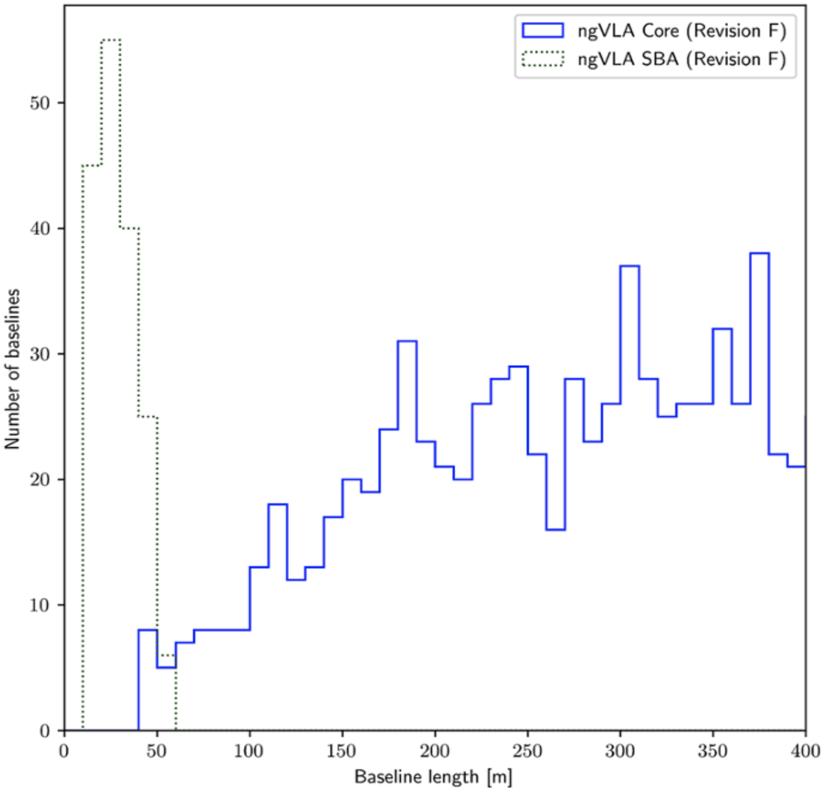

Figure 14: Histogram of baseline lengths for the Short Baseline Array (SBA) and the Rev F Core Sub-Component. Note that Core baselines extend to 4,213m.

6 Practical Considerations for Antenna Locations

Antenna sites must be vetted for practical considerations and feasibility prior to construction. Initial vetting of sites began in Rev D by considering access to roads, power, and fiber, land status ([RD26]; [RD33]), and seismic hazards [RD27] as well as general science and project requirements. A major change was made to the Rev D MID design with the intermediate Rev E configuration, moving to a rough 5-arm spiral, which required a reanalysis of real-world constraints [RD33]. Part of this analysis was to establish a standard set of siting criteria, with attention to science, engineering, and site development. Many of these site selection criteria, which apply to all components of the ngVLA configuration, can be found in [RD42]; [RD46]. A comprehensive project document has been established that will maintain the master list of siting criteria [RD70].

Beyond scientific performance, the siting criteria can be grouped, for the most part, into a number of general areas. These include:

- Power and Fiber availability (eg. within 2km miles of power and fiber)
- Road access (eg. within 2km)
- Site geography and geology (eg. gradient < 10.5%, soil)

- Land acquisition (eg. private, public, protected)
- Weather (preferred high and dry sites; low wind)
- RFI avoidance (eg. no line of sight transmitters, 6 km from high voltage power lines), and/or terrain shielding
- Minimized disturbance of local infrastructure, ecology, geology, commerce
- Environmental considerations
- Hazard evaluation/avoidance

The Long Haul Fiber Workgroup Report [RD47] details the use of fiber across the ngVLA. The report recommends that all stations beyond a 300 km radius from the center of the array should be serviced by partnerships with local ISPs. Los Alamos, while within the 300 km radius, would also be served by a local ISP. All sites inside of the 300 km radius would be served by dark fiber (Figure 15).

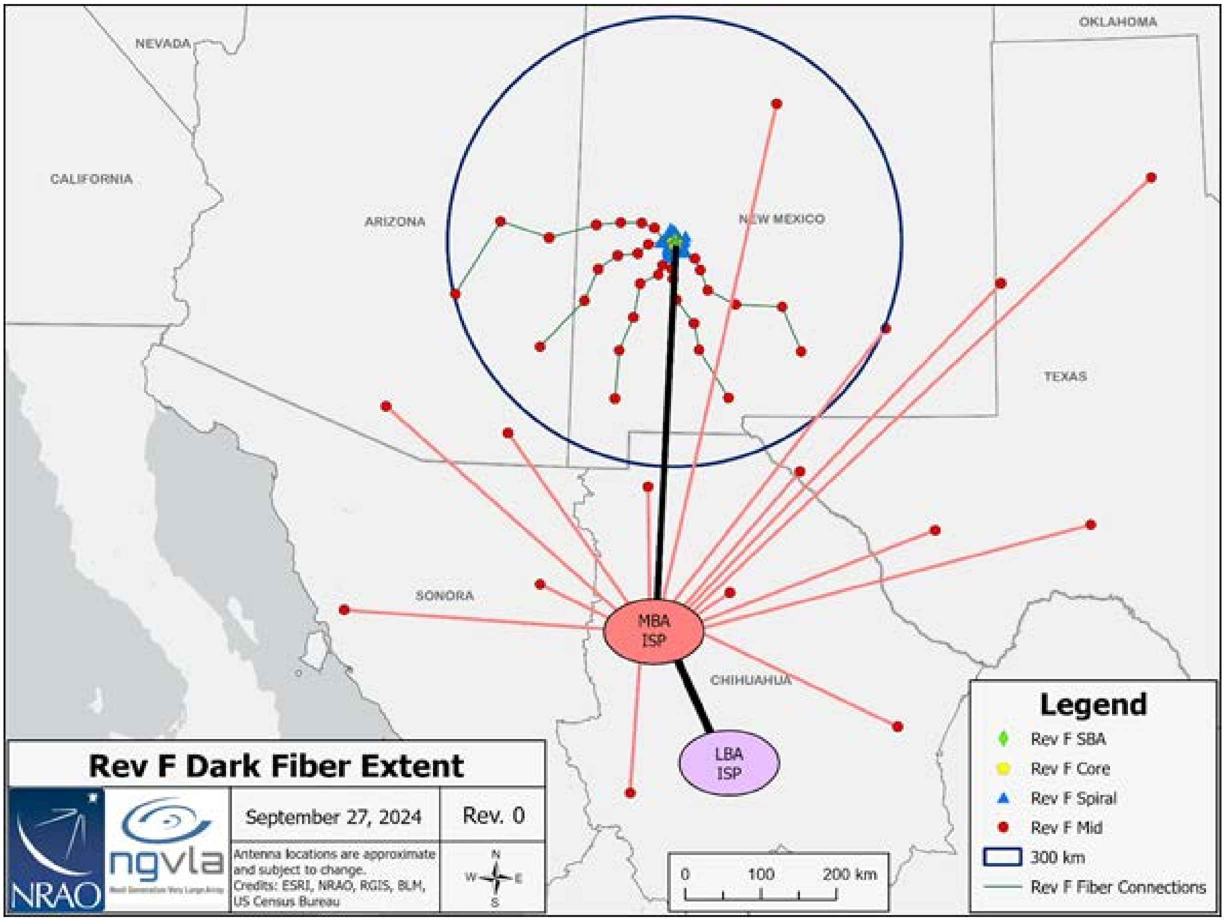

Figure 15: Map from the long Haul Fiber Workgroup Report showing approximately 168 antennas are located on the Plains of San Agustin, and 15 antennas are outside the 300km configuration [RD47].

Site analysis was performed in ArcGIS using publicly available data sources. Availability of data for site analysis varied between jurisdictions, primarily at the state and country levels. In the US, information typically maintained at the state level such as infrastructure, land, grazing, and right-of-way information often existed but was presented in different formats and with varying levels of detail. Data maintained at the federal level were mostly consistent across state boundaries. The largest discrepancy in GIS data availability was between the US and Mexico: Data available for the US was not always available in Mexico, and data for Mexico was not always available in the US.

Specifics to the sites in Northern Mexico

[RD36] demonstrated clearly the importance of having antennas in Northern Mexico, particularly for high resolution PSF performance at lower declination (declination zero and below). Initial consideration of Mexican sites focused on terrain and weather constraints, with some consideration of infrastructure. In [RD49] for Rev F, more detailed consideration has been given to issues of fiber, power, remoteness, and land access and availability (eg. avoid socially owned lands and nature preserves). Sites beyond the nominal 10% dither range were included in the investigation for completeness. In the near future we expect to get insight on fiber expansion from the largest fiber provider (TELMEX), which can be used to find more potential sites for each antenna location.

MOUs have been signed with the larger universities in Northern Mexico, including Universidad de Sonora (UNISON) and Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), and (in the near future) Universidad Autónoma de Chihuahua (UACH). These agreements are critical to the project development in Mexico, as they support site visits, and provide much improved acquisition of regional information, such as power, fiber, land ownership, social conditions, risk assessment, etc. Connection is being made to regional communities through contact with community colleges.

Site visits were made to potential locations near two antennas, mde009, mdd008. These visits have already revealed restrictions, such as land ownership by the mining industry. Site visits will continue and we expect to visit all preferred and potential sites for all antennas in Mexico in the near future.

Genesis

We summarize briefly the genesis of Rev F. The design has been developed with the goal of optimal performance on the key science goals, as documented in the memo series, and includes practical considerations on siting logistics. [RD26] summarizes the tools used in generating configurations, and the adopted coordinate systems (WGS84).

- The first configurations ranged from nested rings to fractals to random distributions, and others ([RD14], [RD68], [RD08], [RD10]). Rev B settled on a 5 arm spiral on VLA-scales, plus Mid antennas to a few hundred km radii, with a 1 km diameter core [RD10].
- Rev C included the 1km diameter dense core, and codified the 5 arm exponential spiral based on the SKA design [RD21].
- Rev D extended the core to 4.5 km diameter to optimize imaging of nearby galaxies; the Mid was altered to an approximate 5 arm spiral as well [RD26], and extended in diameter. Initial GIS study of the site practicalities was performed. Long stations were all changed to 3 antennas. Rev D was costed and baselined for the CoDR.
- Rev E: the primary change was to go to an exponential Mid antenna distribution vs. the previous power-law, to improve shorter spacings and the transition from the Spiral to Mid, and to extend the Mid maximum baseline modestly. Also, two LONG stations were moved to improve the intermediate baseline coverage and for calibration purposes ([RD34], [RD48], [RD49]).
- Rev F: the Core had a few antennas relocated to provide better transition to Spiral; the Mid exponential distribution is essentially the same as Rev E (MOD28), but a much more detailed

consideration was made by the Site Dev group on siting practicalities and potential cost impacts ([RD42], [RD45]).

7 Future Work and Optimization

The Array Configuration is expected to go through additional iterations based on further testing, siting, and feedback. Likewise, it is possible that algorithmic developments may change the approach to multi-scale imaging in the future. Further, the ngVLA project remains cognizant of the science developments in the community, and configuration optimization can and will consider new science opportunities that arise in the coming years.

Future studies will be considering site characteristics to the next level of detail, possibly including site visits and RFI testing. Areas of continued work include:

- Outreach: the distributed nature of the ngVLA across the USA provides excellent opportunities for community engagement and education at all levels. Agreements have already been established with Texas Tech and the University of Florida to explore such possibilities at the Long sites in those states, including detailed assistance with local siting. Further discussions are on-going with institutions of higher learning in other states hosting ngVLA antennas.
- Outreach: similar outreach to local institutions are being established in Mexico.
- Further imaging simulations are in progress of the science performance of the SBA and the Long for their Key Science Programs.
- Long station design: optimal layout of the 3-antenna stations is under examination, balancing potential novel calibration techniques against shadowing.
- Multi-scale weighting: 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.
- Continued investigation of Site Dev requirements including fiber, power, roads, terrain restrictions, RFI sources, and land ownership/access; Site visits may commence.
- Quantify site quality for sites at lower elevations using historical weather data and possibly local monitoring.

8 Appendix

8.1 Abbreviations & Acronyms

Acronym	Description
AD	Applicable Document
AIPS	Astronomical Image Processing System
AU	Astronomical Unit
CASA	Common Astronomy Software Applications
FWHM	Full Width at Half Maximum
HRSA	Horizontal Spectral Response Acceleration
KSG	Key Science Goal
LBA	Long Baseline Array (*deprecated*)
M&C, M/C	Monitor and Control
NES	Near Earth Sensing
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PM	Preventive Maintenance
PSF	Point Spread Function
RD	Reference Document
RFI	Radio Frequency Interference
SBA	Short Baseline Array
TBD	To Be Determined
TPA	Total Power Antenna
USGS	United States Geological Survey

VLA	Jansky Very Large Array
VLBA	Very Long Baseline Array
WVR	Water Vapor Radiometer