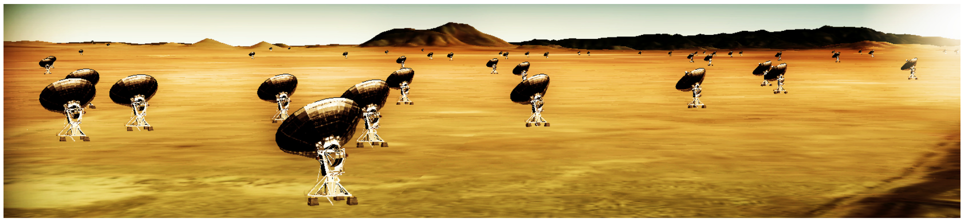

Next Generation Very Large Array Memo No. 92
Configuration: Reference Design Rev D Description

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Abstract

We describe the Rev D configuration, and we delineate the changes since Rev C.01.

1 Introduction

The Rev D configuration will be presented as the configuration group input into the conceptual design review. The review documentation include the design requirements and design description.

We have performed a number of tests and simulations of the science capability in the context of the Key Science Goals and Envelope Observing Program, as documented in the memo series. The configuration builds on the Rev C.01 version, documented in Memo. 82, and we describe the changes relative to Rev C.01. This memo expands upon some of the relevant information from Rev C.01 concerning process, for completeness.

2 Process

2.1 Coordinates Systems and Tools

The initial configuration tables can be in longitude, latitude, and elevation, or in relative distance from a reference point (LOC coordinates). In the latter case, the positions are converted via GIS software (Geographic Information System), into Long, Lat, El, using the reference position. The Long, Lat, El tables are then converted into Earth-centered XYZ coordinates using CASA tools.

We adopt the World Geodetic System 84 (WGS84) for the reference XYZ coordinate system. WGS84 includes correction for the Earth as a oblate spheroid, and is the standard for the GPS system, and for CASA. In this system, the Z axis is along the Earth's rotation axis, passing through the Earth's center of mass, and the X axis is a line passing through the Earth's center of mass and zero longitude and latitude.

When changes have to be made to an antenna position, the longitude, latitude, elevation values are adjusted in GIS. These are then exported as an ascii table. We have written a python script incorporating the standard CASA configuration tool: simutil.long2XYZ, to convert the (long, lat, el) values to Earth-centered XYZ coordinates. We employ CASA tools in order to maintain consistency with the CASA norms, given that our array testing is done in CASA. We have done extensive checks to see that this conversion provides the same XYZ results as was found for the current .cfg files on the ngVLA tool webpage. Agreement is typically much better than a meter. We have python scripts to perform various conversions between XYX, and Long, Lat, El, and LOC, as needed.

2.2 Practicalities of Placements

Within GIS, the Long, Lat, El files are investigated for real-world issues, such as roads, buildings, power, land access, fiber, RFI environment, terrain, and related.

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). In the case of the Spiral array, an overall rotation, and subsequent small shifts to antenna positions on the arms ($\leq 10\%$ of radius, consistent with the random dither), were made relative to Rev C.01, to prioritize placement on public lands. Of the 158 Spiral plus Core antennas on the Plains of San Augustin, 15 are on private land.

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. Sites were chosen to be outside visible flood boundaries and wetlands. In addition, sites were checked for potential landslide risk, specifically in areas affected by wildfires, and for seismic activity (ngVLA memo 93). VLA site performance at 90 GHz has been quantified using existing wind, opacity, and phase monitor data over a 10 year period in ngVLA memos 1, 73, and 94.

For antennas on the Plains of San Augustin, utilities can be accessed directly from those at the VLA site. The spiral form for the 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.

Costing and pathing is being investigated for dark fiber laid and owned by the NRAO in order to service the mid antennas along the five arms, within 300km of the center of the array. Antennas outside of this buffer, as well as the Los Alamos station, will be connected to existing public networks. Under this system 30 of the 46 Mid antennas would be on NRAO run fiber with 16 requiring tie-ins to private company fiber lines.

3 Configuration Components

Table 1 lists the basic parameters for each component of the ngVLA. There are five components of the array, ranging from tens of meter baselines to thousands of kilometers. We envision operation of the ngVLA will involve combinations of the components to achieve the appropriate angular resolution and sensitivity. Sub-arraying, meaning employing, commensally, different array components for science projects requiring different resolutions, will be a normal part of operations (see Memo 72).

We are developing tools for the ngVLA web site that will allow the User to select antennas for a given science simulation. The process can be as simple as concatenating ascii files of configuration components.

We next describe briefly each component, and the changes relative to Rev C.01.

3.1 Short Baseline Array (SBA) and Total Power Antennas (TPA)

Due to mechanical clearance considerations, the ngVLA 18m antennas will not be able to be placed closer together than 38m. However, roughly 25% of identified science use cases require information on spacings shorter than

Table 1: Rev D Configuration Components

Component	Station code	N ants	D_{ant} meters	B_{min} meters	B_{max} meters	Description
Core	cor	114	18	39	4240	radial-random at VLA
Spiral	sp[a-e]	54	18	810	38995	5 arm exponential spiral at VLA
Mid	mid[a-e]	46	18	17050	1068000	5 arm spiral in US SW and Mexico
Long Baseline	stations	30	18	130000 (40)	8794000	10 stations of 3 antennas
Short Baseline	sba	19	6	10.9	59.7	close-packed pseudo-grid

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 x 6m antennas operated as an interferometer to fill spacings between 60m and 11m; basic design considerations are presented in ngVLA memo 43. The short baseline array is an approximate hexagonal grid, with minimum spacing of 11m set by antenna structure. The SBA antennas are delineated with prefix 'sba' in the casa configuration file. The grid is dithered to mitigate grating lobes. The genesis and characterization of the SBA is described in detail in Memos 43, 67, and 82.

Spacings shorter still will be observed by the Total Power Antennas (TPA), a set of 4 18m total power antennas. These SBA and Total Power data were designed to "feather" and/or be jointly deconvolved with observations from the main array core, 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).

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. The integration time ratios needed to match the sensitivity of "adjacent" arrays (SBA/core and TPA/SBA) are 0.6 and 2.13, respectively, computed using the same approach used by ALMA (ALMA memo 598).

Simulations demonstrating the efficacy of the SBA and TPA are presented in ngVLA memo 67. This memo used the previous (Rev.C) antenna configuration, which differs only in very minor respects from the current Rev.D SBA antenna configuration. The primary difference 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 center of the SBA has also been translated to a location in the

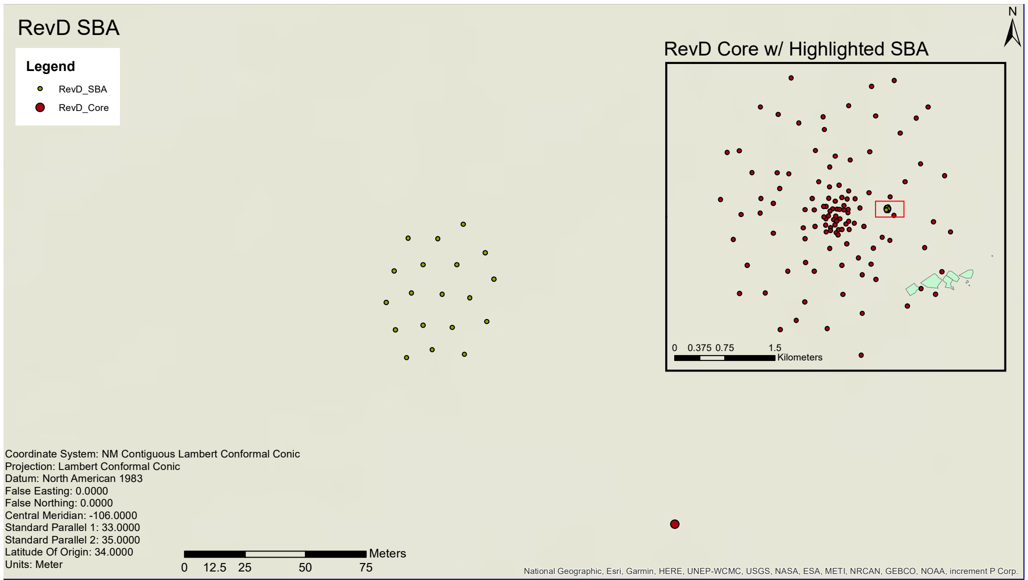

Figure 1: The SBA configuration as green circles. The location of the SBA is 700m east of the Core center, as shown in inset.

Rev.D core which is free of shadowing by 18m antennas, about 700m east of the center of the Core. The SBA has been elongated North-South by 10% to improve PSF performance at low and high declinations.

Figure 1 shows the layout of the SBA antennas. Figures 2 shows the UV plots for snap-shot observations of the different array components, and Figure 3 shows the baseline histogram for the Core+SBA, Core+Spiral (214 18m antennas), and Core + Spiral + LBA (244 18m antennas).

Total Power Antennas: For purposes of Rev.D, it is provisionally assumed that any ngVLA 18m antenna can function as a total power antenna. The TPA would in this scenario be a flexibly allocated logical entity rather than a physically distinct set of antennas. This would allow more or fewer TP antennas as demand and weather conditions require. It is yet to be determined whether the distinctive requirements of total power observing will permit this flexibility in practice, or whether more specifically optimized hardware will be required for the TPA. An ngVLA Total Power Working Group (TPWG) has been charged with addressing this issue. The TPWG deliverables will inform the next iteration of the ngVLA design process leading up to the PDR.

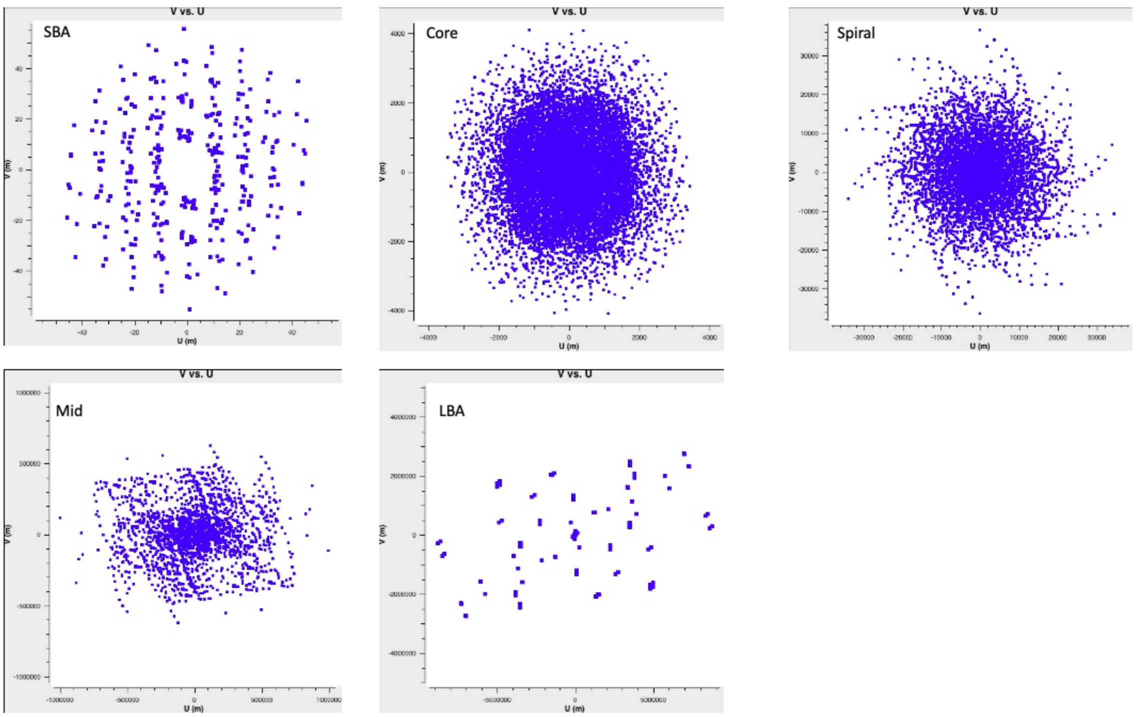

Figure 2: Snap-shot UV-coverage of the five array components individually.

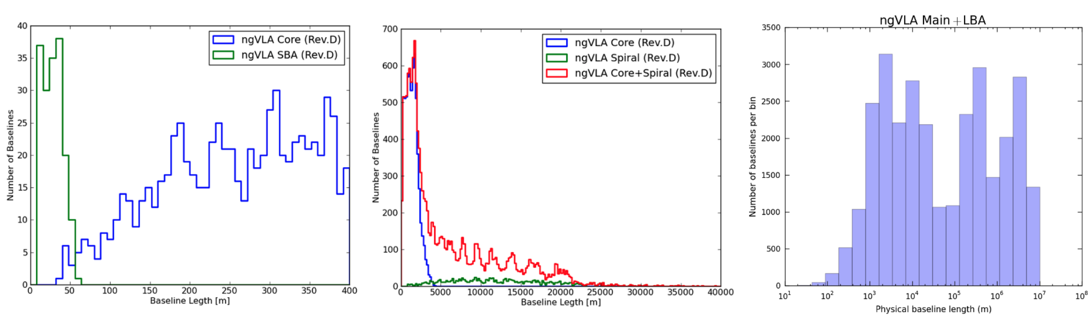

Figure 3: Histograms of the baseline distributions. Left: the inner Core + SBA. Center: Core + Spiral Array (214 18m antennas). Right: Full array, including the LBA (244 18m antennas).

4 Core

The Core is a semi-random antenna distribution of 114 x 18m antennas, from 38m to 2.2km baselines. The Core antennas have 'cor' as a prefix in the CASA configuration files. Figure 4 shows the distribution of antennas. The configuration has been optimized to capture molecular line imaging programs for nearby galaxies, as given in KSG 3 (ngVLA memo 89), and generally to perform high fidelity imaging for structures on scales of 0.1" to 1" in the 80 GHz to 115 GHz band (see ngVLA Memos. 67 and 92).

The Core had the most substantial alterations relative to Rev C.01. Based on a scientific assessment of the high priority key science goals (KSG3, in particular), the semi-random Core was extended to a 2.2 km radius. Four inner antennas from each of the five Spiral arms were incorporated into the Core semi-random distribution.

The details of the development and performance of the Core relative to Rev C.01, can be found in the Appendix 1. In brief, the new Core started with a random, but radially weighted distribution of antennas to 2.2km radius. This distribution was then processed through the AIPS program CONFI, to minimize sidelobes. However, CONFI was found to drive the configuration into a ring at maximum radius. Given the need for good coverage down to the shortest baselines, CONFI was constrained to only move antennas beyond about 600m from the center. Different iterations of CONFI were investigated, and we found a good balance between sidelobe level, while retaining a reasonably flat baseline distribution, could be obtained after 128 iterations.

5 Spiral

The Spiral is comprised of 54 antennas from about 2.2 km radius to 20 km radius, arranged in a 5 arm, exponential spiral, as described in Memo 82. The Spiral antennas have the prefix 'spX' in the CASA configuration files, where X corresponds to the arm of the spiral (a through e). Figure 5 shows the Spiral configuration.

The primary changes for the spiral relative to Rev C.01 were:

- Remove 4 inner antennas from each arm and incorporate them into the semi-random Core;
- Rotate the array, and make small adjustments to individual antennas, to maximize locations on Government owned land, or to avoid serious

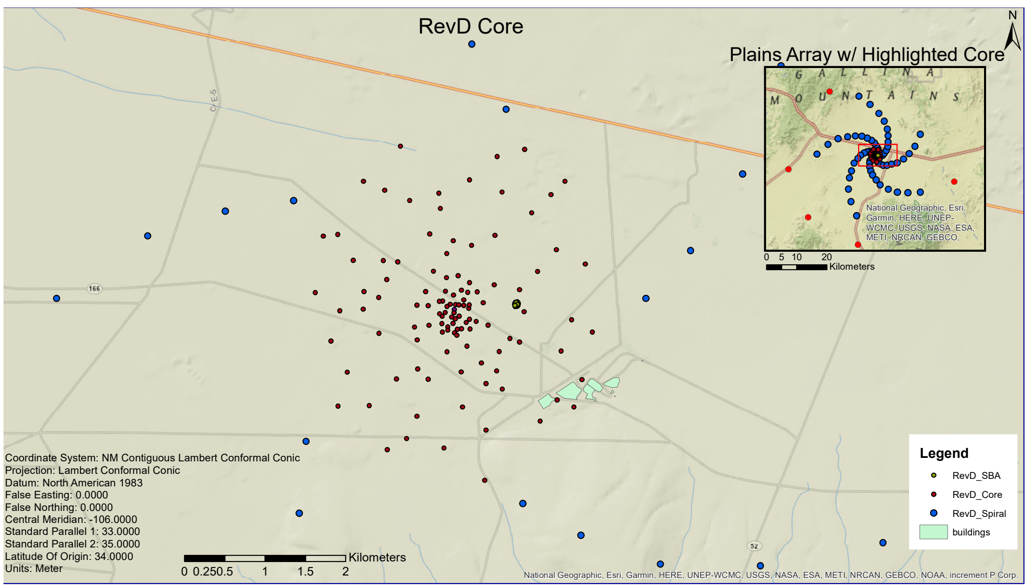

Figure 4: The Core configuration shown as light red circles. The inner spiral antennas are shown as blue, to demonstrate the relationship. The SBA antennas are shown as darker green, about 700m east of the Core center. Also shown in this, and subsequent, figures is the terrain, and some of the roads and buildings.

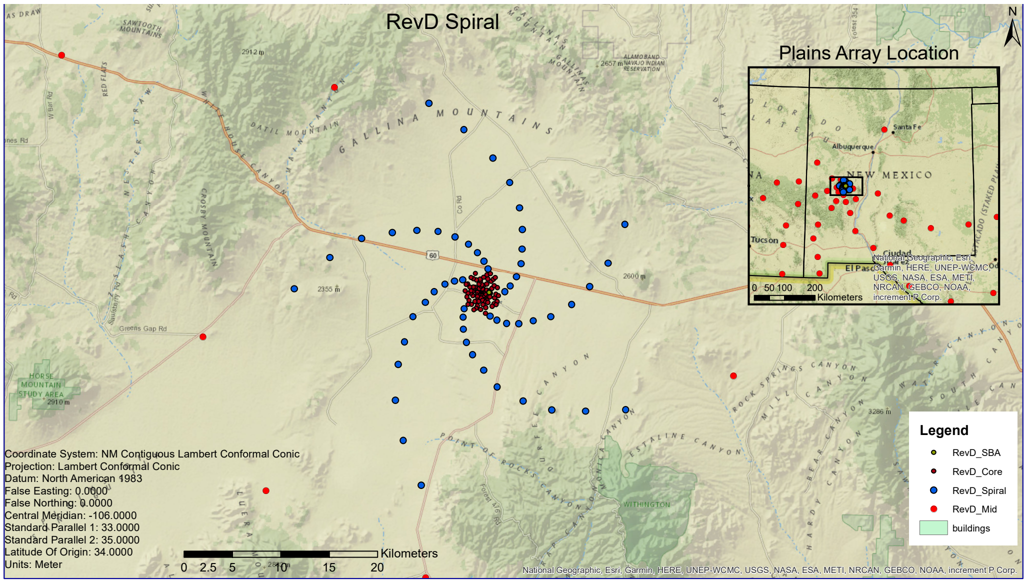

Figure 5: The Spiral configuration shown as blue circles. The Core antennas are shown as dark red, to demonstrate the relationship. Inner Mid antennas are shown as light red.

terrain or infrastructure restrictions;

- Elongate the array 10% North-South for a rounder beam at high and low declinations.

6 Mid

The Mid configuration has 46 antennas from 20 km radius to 500 km radius, extending as a rough spiral from the center, mostly to the south (Figure 6). The antennas are designated as 'mdX' in the CASA files, where X is the arm of the spiral (a through e).

The Mid had major changes from Rev C.01. The changes follow along the lines of those proposed in Memos 49 and 86, to obtain a more uniform, rough 5 arm spiral structure. Mid now has 5 antennas in Mexico, 9 antennas in Arizona, and 6 antennas in Texas.

An initial GIS investigation of terrain, access, power, roads, radio environment, and Fiber has been made (see Section 2.2). A more detailed investigation, in particular into the Fiber access and costing, is underway.

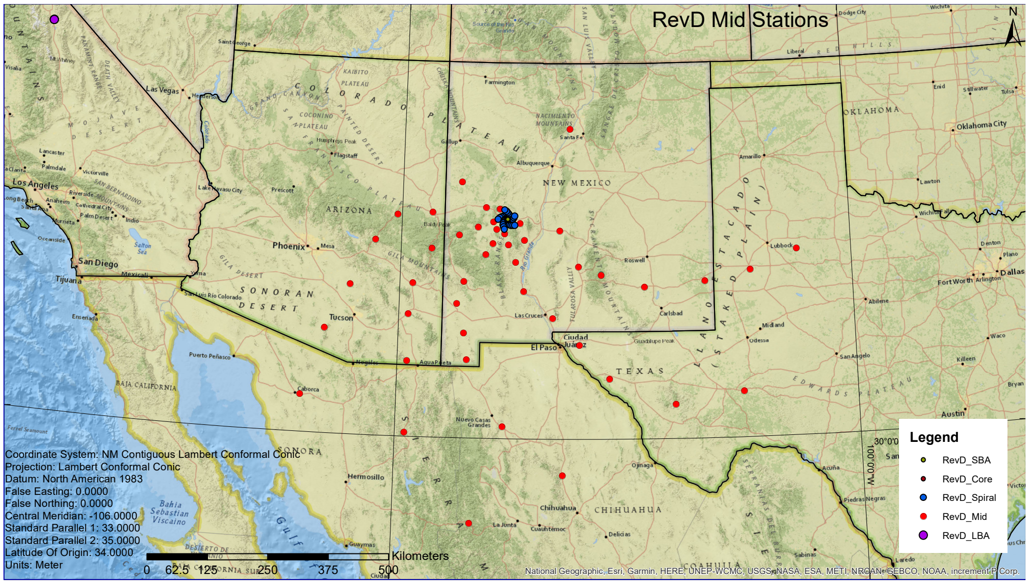

Figure 6: The Mid Array with antennas labeled, as orange circles. The spiral array is also shown as blue circles.

The practicalities of the Mexican stations have not been looked at in detail. This is being considered as part of the Mexican collaboration contribution.

The baseline distribution for the Full array shows a modest gap at ~ 40 km to 150 km. This gap is due to the separation of the inner Mid antennas from the outer Spiral antennas. We are investigating how to best fill this gap, likely by moving the starting points of Mid arms inward.

7 Long Baseline Array (LBA)

The LBA consists of 10 stations of 3 antennas each, from Hawaii to Saint Croix (Figure 7). Half of the installations are at existing VLBA sites. The others are arranged to improve UV-coverage, in particular when including some of the Mid stations. Note that a few of the existing VLBA stations (Pie Town, Los Alamos, Kitt Peak, Fort Davis), are included in the Mid configuration.

The addition of multi-antenna stations will help in calibration, including the capability of paired-antenna calibration, where calibration transfer is done continuously between an antenna pointing at the target, and the neighboring antenna pointing at the calibration source (Carilli & Holdaway,

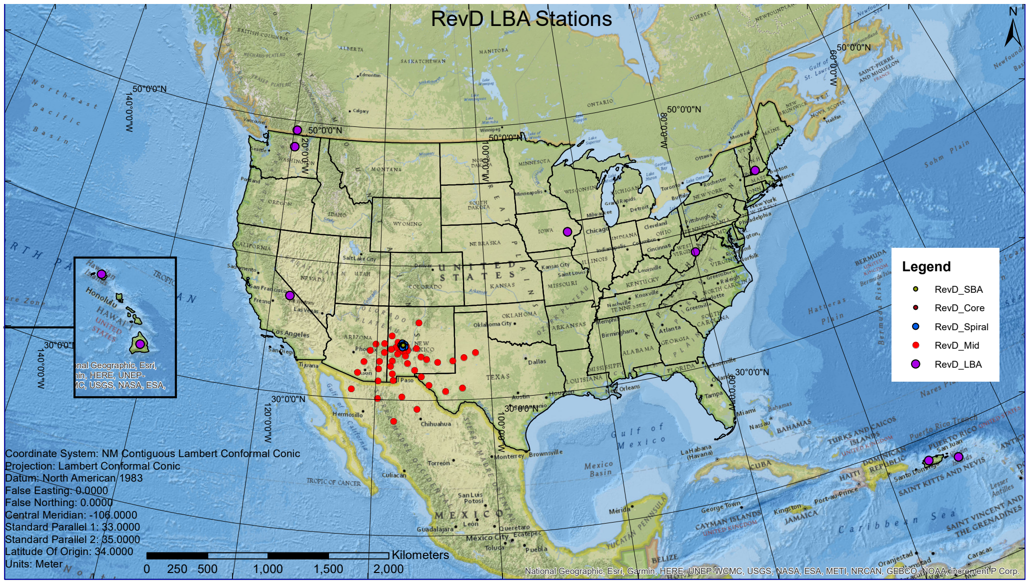

Figure 7: The Long Baseline Array with antennas labeled, as light green circles. The Mid array is also shown as orange, with the spiral as darker green.

Radio Science, 34, 817). For the longest baselines, the design incorporates a relatively nearby station, within a few hundred km. Experience shows that having a relatively close station helps to anchor the gain calibration for the longest baselines.

Relative to Rev C.01, the main changes are:

- Make all stations three antennas, with no internal station baselines longer than 200m.
- Move the Massachusetts (Quabbin) station in RevC.01 to Green Bank.
- Check each station for terrain limitations

8 Characterization

The heterogeneous ngVLA configuration has been designed to satisfy the broad requirements in resolution vs. sensitivity for the ngVLA science program. 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

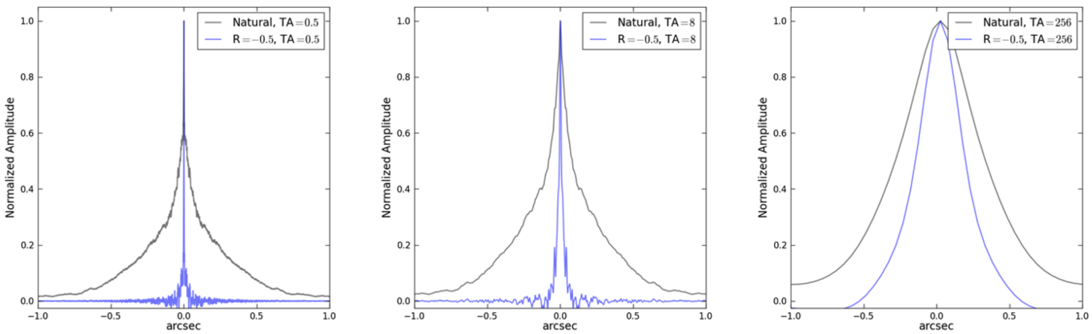

Figure 8: Simulated 30 GHz PSFs for the present ngVLA reference array (Rev D), including all 244 18m antennas, over a range of resolutions, showing the effect of different imaging weights (TA: uv-taper in mas, R: Briggs robust parameter). The PSFs are a selection of the data presented in Figure 9. The FWHM of a Gaussian fit to the beams are, from left to right for the NA curves (black) are: 2.3, 36.6, and 549 mas; the values for the Robust weighted curves (blue) are: 1.4, 14.3, and 326 mas. These examples illustrate how combinations of robustness and tapering allow for a beam of much higher quality, i.e., greatly reduced beam skirts, but at the expense of sensitivity (see Figure 9).

a Naturally weighted PSF for the entire set of 244 18m antennas with three very different scales (see Figure 8):

- A narrow spike with high resolution (FWHM $\sim$ 0.3 mas at 30 GHz) due to the LBA antennas.
- A first skirt extending to 100 mas at 30 GHz at the 50% to 20% level due to the Spiral antennas.
- A 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. Considering 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. 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.

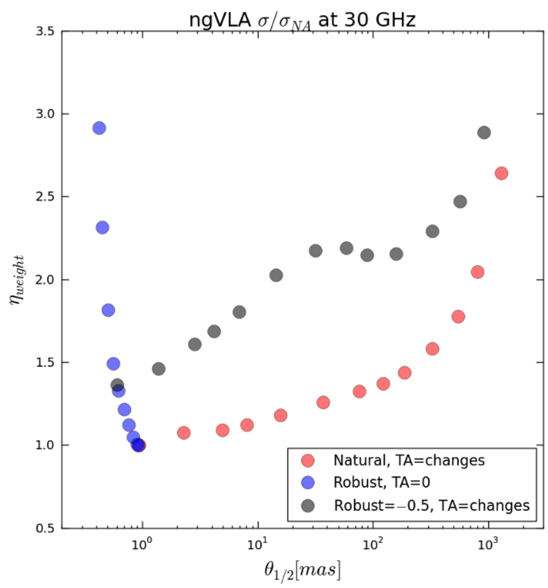

Figure 9: Image noise (rms) at different angular resolutions (FWHM) achieved by varying the imaging weights, simulated at 30 GHz using the 18-m 244 antenna array configuration (see ngVLA memo 55 for details of the process). The noise has been scaled relative to that of the naturally weighted image (σ_{NA}). 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 8).

Imaging sensitivity will depend on the required resolution and imaging fidelity. Figure 8 and Figure 9 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 18m antenna configuration, for a source at $+24^o$ declination observed during transit. The reported beam sizes in the caption are 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 the expected image rms after weighting is: $[\eta_{weight} \times \sigma_{NA}]$. The process entails adjusting the taper and robust to obtain a well behaved PSF for a desired resolution (skirt sidelobes levels less than 10% level at radius = FWHM, as prescribed for high quality imaging through science simulations), while optimizing sensitivity (see ngVLA memo 55 for details). The values of η_{weight} are shown as gray symbols Figure 9. These η_{weight} values are between a factor 1.5 to 2.2 for resolutions from 5 mas to 500 mas at 30 GHz. These η_{weight} values are used in the ngVLA sensitivity calculator when specifying a desired resolution. Note that the red symbol NA-weighted sensitivites in Figure 9 are not viable for imaging, since the resulting PSFs have very broad, highly non-Gaussian skirts at very high levels which preclude quality imaging science (see Figure 8).

9 Appendix 1: 4km Core

The major revision from RevC.01 was to extend the Core distribution from 0. km radius to 2.2 km. Again, the configuration has been optimized to capture molecular line imaging programs for nearby galaxies, as given in KSG 3 (ngVLA memo 89), and generally to perform high fidelity imaging for structures on scales of 0.1" to 1" at 100 GHz (see ngVLA Memos. 67 and 92).

We incorporated the inner 5 antennas from each spiral arm to get 114 antennas total in the 4km Core, leaving 54 antennas in the Spiral. We generated 25 semi-random antenna position distributions with different random number seeds and spatial density distributions and selected one which qualitatively provided good coverage. The selected density distribution truncates at r=2.2km (D=4.4km) and has a functional form: $p(r) = 1/(1+(r/600m)^2)$. Several antennas were manually relocated to fill holes in the uv-coverage, including achieving good coverage down to the central 38m hole.

We then used CONFI in AIPS to minimize PSF sidelobes (Kogan 2000, ASPC, 217, 348; MMA memo 171). We adopted most of the default CONFI parameters, with a few exceptions.

We ran three different numbers of iterations (APARM(1)): 128, 512, and 2048. 128 was chosen as roughly 'let the optimization move each antenna twice' (while this is not really how the optimization works, it can be thought of that way), then increasing by factors of 4 to get to 2048. By 2048 the optimization had converged – the maximum sidelobe level was not going down.

We found that after optimization, the PSF tended to be round at zenith, which is not desired – the preferred configuration has a BMAJ/BMIN ratio of 0.85 at zenith to give a rounder beam toward the South. The final CONFI outputs were manually stretched in Y direction to get that factor back.

Our investigation showed unconstrained CONFI pushes all antennas to an annulus at maximum radius, leaving too few short baselines for low surface brightness work. Hence, we pursued a constrained CONFI by fixing the inner 50 antennas (radii $\leq$ 600m), and adjusting the outer antennas with 128 and 512 iterations of CONFI. We then compared the baseline distribution, PSF, and noise vs. uv-taper.

The imaging and sensitivity simulations entailed:

- 10min observation at 8 GHz, 114 antennas
- Original Mason 4km core, and after 128, 512 constrained iterations of Confi

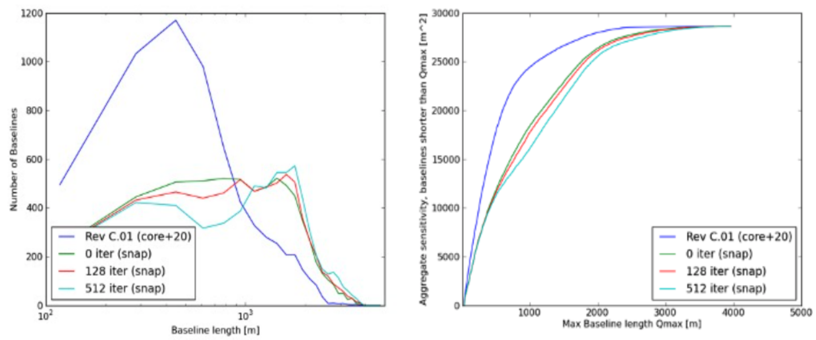

Figure 10: Left: Baseline histogram for the 114 antenna Core (RevC.01 shows core + the corresponding inner spiral antennas). Right: cumulative collecting area distribution.

- These were stretched to get 10% N-S elongation and GIS adjustments made to 1 or 2 antennas
- NA = natural weighting, plus a UV Taper get to FWHM $\sim$ 6” and 12”
- Noise was added per visibility based on Selina et al. (2018).

Table 2 shows the beam FWHM, rms noise in the image, and the peak sidelobe of the PSF. We find the RMS noise varies by $\leq$ 7% between configurations, which is probably within the systematics of the simulation and noise realizations. The NA Confi versions have higher resolution, but that could be changed by a simple scaling. The peak sidelobes are similar to 1%.

Figure 10 shows the baseline histograms and Figure 11 shows the PSFs for NA weighting of the Mason 4km, and after the constrained Confi with 128 and 512 iterations, while Figure 12 shows the antenna distributions. It is clear that Confi tends to force the antennas out towards a ring at maximum radius, as can be seen in the more prominent PSF ring at $\sim$ 4” radius with increase CONFI iterations. All the PSFs have $\sim$ 10% maximum sidelobes, and Gaussian Cores at the $\geq$ 15% level.

In summary considering the Core:

- 512 constrained CONFI leads to large gap between outer donut + compact core: drop in N baselines at 0.6 to 1km is sensitivity lost on those scales that cannot be recovered via tapering, and hence undesirable.

Table 2: Rev D Instantiations

Configuration and Weight	FWHM	rms μJy beam^{-1}	Peak Sidelobe
Mason 4km NA	2.98” $\times$ 2.68”	5.4	10%
128 NA	2.79” $\times$ 2.53”	5.4	10%
512 NA	2.54 $\times$ 2.28	5.3	10%
Mason 4km TA=5.2”	6.2” $\times$ 5.8”	8.2	8%
128 TA=5.0	6.3” $\times$ 5.8”	8.1	7%
512 TA = 4.8”	6.2” $\times$ 5.9”	8.7	8%
Mason 4km TA=11.7”	12.3” $\times$ 11.7”	13.6	8%
128 TA=11.2”	12.3” $\times$ 11.7”	13.2	8%
512 TA=10.6”	12.4” $\times$ 11.7”	13.7	8%

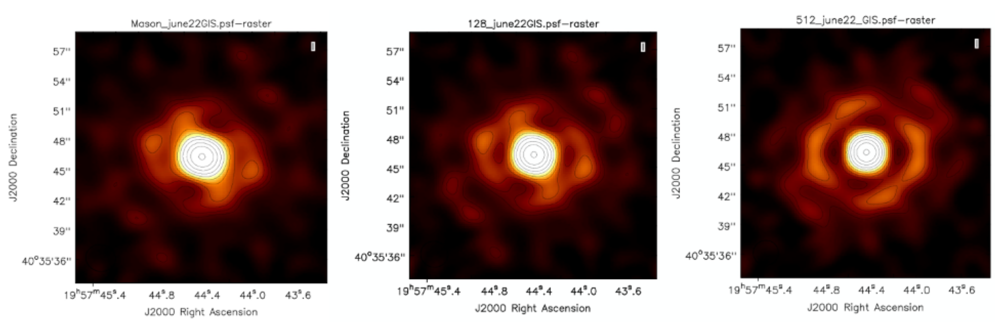

Figure 11: PSF with NA weighting for Mason Big Core, 128, 512 Constrained Confi iterations. Contours are a geometric progression in square root 2, starting at 0.03 (every two contours is factor 2 in response).

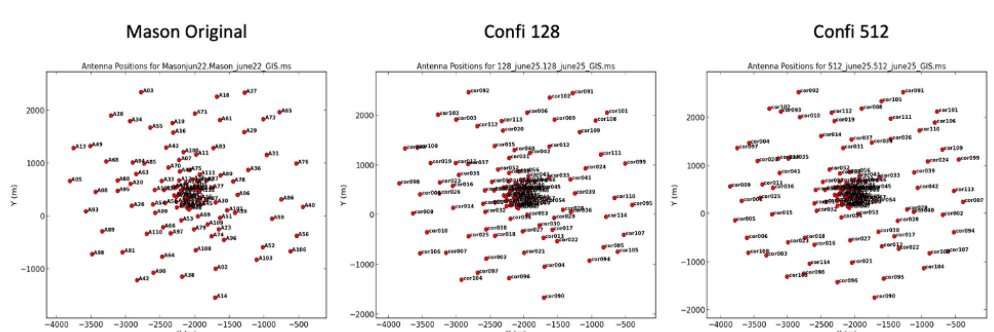

Figure 12: Antenna placements for the different Core realizations.

- The reduction in sidelobes that CONFI generates is primarily done by means of reducing the "skirt" (i.e. the number of short baselines). This tendency is both desirable (for PSF quality) and undesirable (for sensitivity to larger spatial scales).

- 128 interastions produces the flattest baseline distribution, down to about 100m baselines.

- All three had similar noise and PSF values vs. tapering.

Based on the analysis, we favor the constrained CONFI with 128 iterations, since it gives the flattest baseline distribution to short baselines, and good sensitivity and PSF behavior vs. uv-tapering on scales relevant to the KSGs. The final adopted Core also had a GIS check on infrastructure, with a few small adjustments made.

10 Appendix 2: Future Work

General

- 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.

- Multi-frequency synthesis simulations.

- Continued investigation of terrain restrictions and RFI sources, in particular for outer Mid antennas, including Mexico, and some LBA sites.

- Quantify site atmospheric quality for sites at lower elevations.

- Evaluate LAS for RevD subarrays (especially core); compute SB sensitivity as a function of taper for different subarrays.

Spiral

- Stagger arm starting points to smooth out the saw-tooth pattern in the baseline histogram.

Mid

- Fill-in paucity in baseline histogram at 50 km to 100km between Spiral and Mid by staggering arm start-points.

LBA

- HN station does not have obvious land available even for three close antennas.
- Baselines between PR and SC, and between PN and BR, are short – less than 200km. This leads to a lot of redundancy in the UV-plot (see paired points in Figure 2). Better UV coverage could be obtained by separating these sites by about 500km or so.