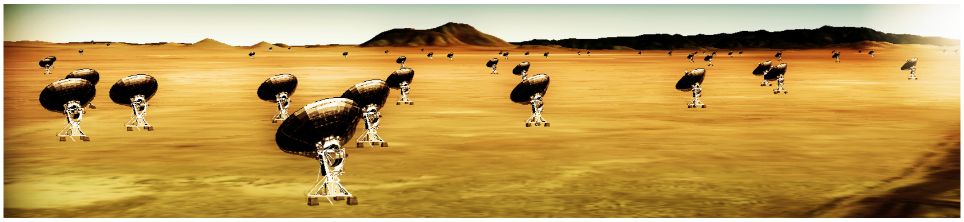

Next Generation Very Large Array Memo No. 12

The Stength of the Core

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Abstract

I consider the performance of a idealized 300 element array extending to 150km radius, with differing core-concentrations: 20% vs. 40% of the antennas in a 0.6km radius core. I consider two performance metrics: (i) the noise penalty due to visibility weighting that is required to achieve both high angular resolution and high fidelity imaging, relative to natural weighting, and (ii) the 'mapping speed' for the compact core, based on the point source sensitivity (total collecting area) for the array out to a given baseline length, combined with the field of view of the antenna. The naturally weighted beam in both cases is clearly not appropriate for high fidelity imaging at high resolution. The analysis suggests that the noise penalty to achieve both high angular resolution and a reasonably behaved PSF is a factor 1.9 and 2.4, for the 20% vs. 40% core, respectively. In terms of mapping speed, the 40% core ngVLA configuration is a factor 2.8 faster than the most compact ALMA configuration (ALMA-out01), and a factor 13 times faster than the ALMA-out09 configuration. The same factors for the 20% core configuration are 0.6 and 4.2, respectively. I do not consider reconfiguration, which will greatly improve the performance on short baselines, but comes at a cost. The issue of restoring spacings shorter than the antenna diameter, and in particular, the zero spacing total power measurement, will be considered elsewhere.

1 Introduction

I consider the question of the impact of the core fraction on imaging for a large element array. I consider an idealized 300 element array with baselines out to 300km. I adjust the array for 20% and 40% of the antennas to be within a core of 0.6km radius, and investigate the impact on the PSF and noise for high fidelity, high resolution imaging, and the mapping speed of the core itself, including a comparison to the most compact JVLA and ALMA configurations.

I present only relative sensitivities, not true sensitivities at a given resolution for a given observation. The latter has been done to a some degree in the current ngVLA memo series (Carilli et al. 2016, ngVLA Memo. 11), but needs to be investigated in much great detail in the context of a given science goal. Such investigations are most appropriate for the community design studies.

The configuration files are designed for ease of use with the CASA SIMOBSERVE task. The format also allows for simple configuration adjustments using standard programming languages (ie. x,y positions in meters with respect to array center).

Note that the array is idealized in the sense of involving no consideration for real-world constraints, like topology, land accesss, etc... Nor do I espouse ring configurations vs. eg. spirals. I simply investigate the imaging performance of one manifestation of a large N array, with varying core concentration. Hopefully, the conclusions presented herein on gross performance with respect to core dominance are fairly generalizable to a range of configurations with 300 antennas extending out to 300km baselines.

2 Configurations

I start with the idealized outer ring configuration, as described in Clark & Brisken, modified to 300 antennas and 300km maximum baseline. This configuration was shown to perform adequately for high fidelity, high resolution imaging of protoplanetary disks on tens of milliarcsec scales, using simulated models and CASA mock observations (Carilli et al. 2016; Barge et al. 2017, in prep). For lack of a better term, I call this configuration 'Original'. This configuration has 20% of the antennas within a 0.6km radius of the array center.

I then modified the configuration by semi-randomly moving antennas from the outer array to the inner kilometer. I tried to maintain the overall balance across the outer array dictated by the original configuration. The resulting array has 40% of the antennas within a 0.6km radius of the array center. I designate this configuration 'Core'. In both cases, the shortest baseline is 18m (the nominal antenna diameter).

Figure 1 shows the antenna distribution for the Core array on four scales: out to radii of 0.5km, 3.0km, 30km, and 150km. Figure 2 shows the same plots for the Original configuration.

Figure 3 shows the visibility distributions for a snapshot observation (10min) at zenith for the Core array. Three scales are shown: out to 300km baselines (full array), out to 15km baselines, and out to 0.6km baselines. Figure 4 shows the same for the Original array.

3 Comparisons

Figure 5 shows the cummulative number of visibilities for a snapshot observation at zenith for the full Core and Original arrays, out to 300km baselines. Figure 6 shows the cummulative number of visibilities for the inner part of the arrays, out to 1km baselines. Also shown in Figure 6 are the distributions for two configurations of ALMA, and for the VLA-D configuration.

For ALMA, I chose two configurations from the set of 'final' (50 antenna) configurations available in CASA. One configuration is the most compact configuration, ALMA-out01. This configuration has a maximum baseline of 160m, and a resolution at 30GHz of 12", and 4" at 90GHz.

The second ALMA configuraiton is ALMA-out09. This configuration has a maximum baseline of 700m, and a resolution at 30GHz of 2.7", and 0.9" at 90GHz. I investigate this array, since reaching a resolution of 1" at 90GHz was deemed critical for the study of the ISM in galaxies in the local group, and possibly out to the Virgo Cluster, by Science Working Group 2.

Table 1 shows the numbers of visibilities out to a given baseline length for the different arrays. From Fig. 6, we see that the Core ngVLA has a factor 1.26 more spacings out to 160m than the most compact configuration of ALMA-out01, and dramatically more than Original, ALMA-out09, and VLA-D. Out to 700m, ngVLA Core has a factor 6 more visibilities than ALMA-out09, a factor 3.1 more than Original, and a factor 22 more than VLA-D. At 700m, the ngVLA Original configuration has a factor 1.9 more visibilities than ALMA-out09, and a factor 7.2 more than the VLA-D. Of course, the increased number of inner spacings for Core comes at the expense of a less well filled-in array at longer spacings, as seen from Figure 5.

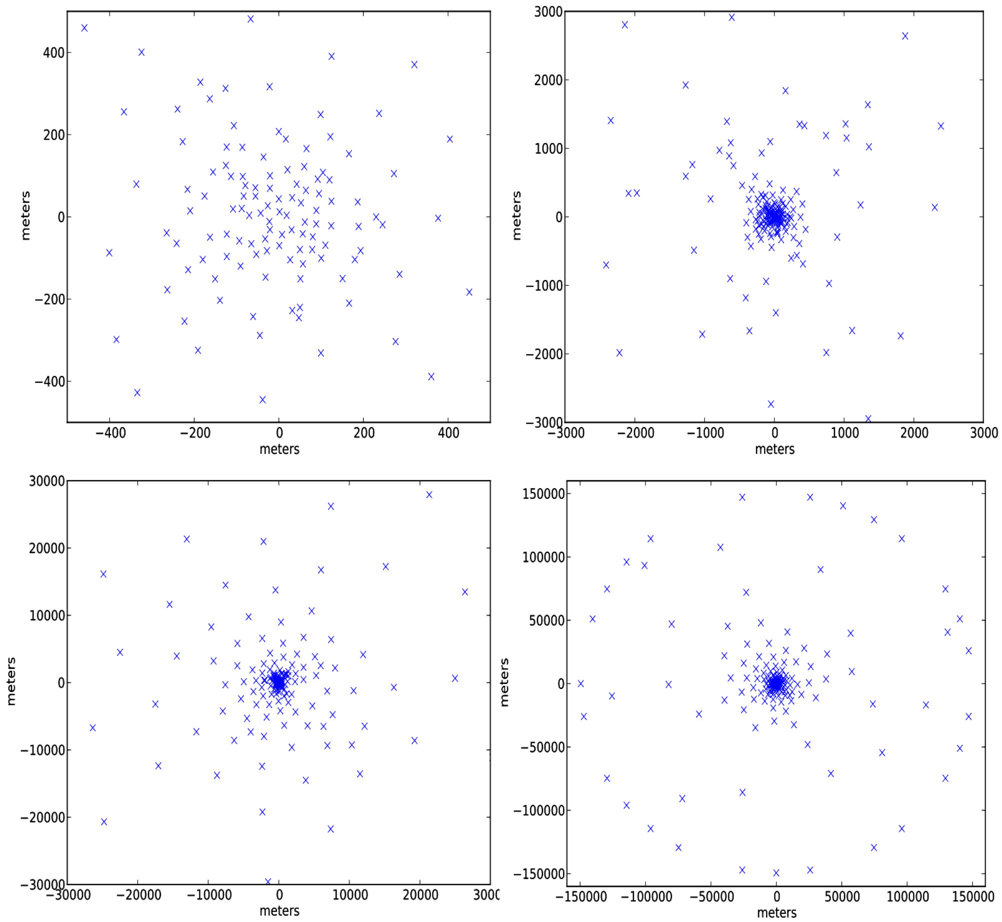

Figure 1: Antenna positions on four different scales for the ngVLA 'Core' configuration, in which 40% of the antennas are within 600m radius of the array center.

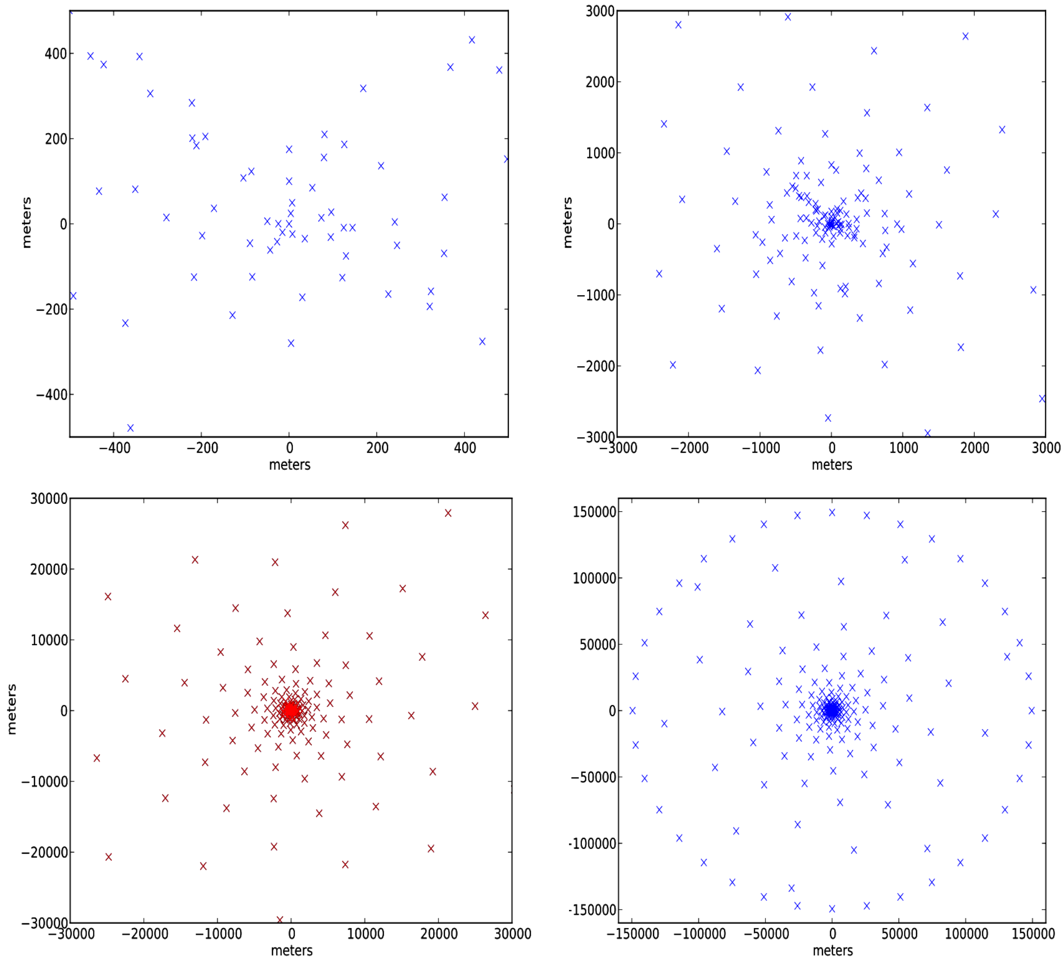

Figure 2: Antenna positions on four different scales for the ngVLA 'Original' configuration, in which 20% of the antennas are within 600m radius of the array center.

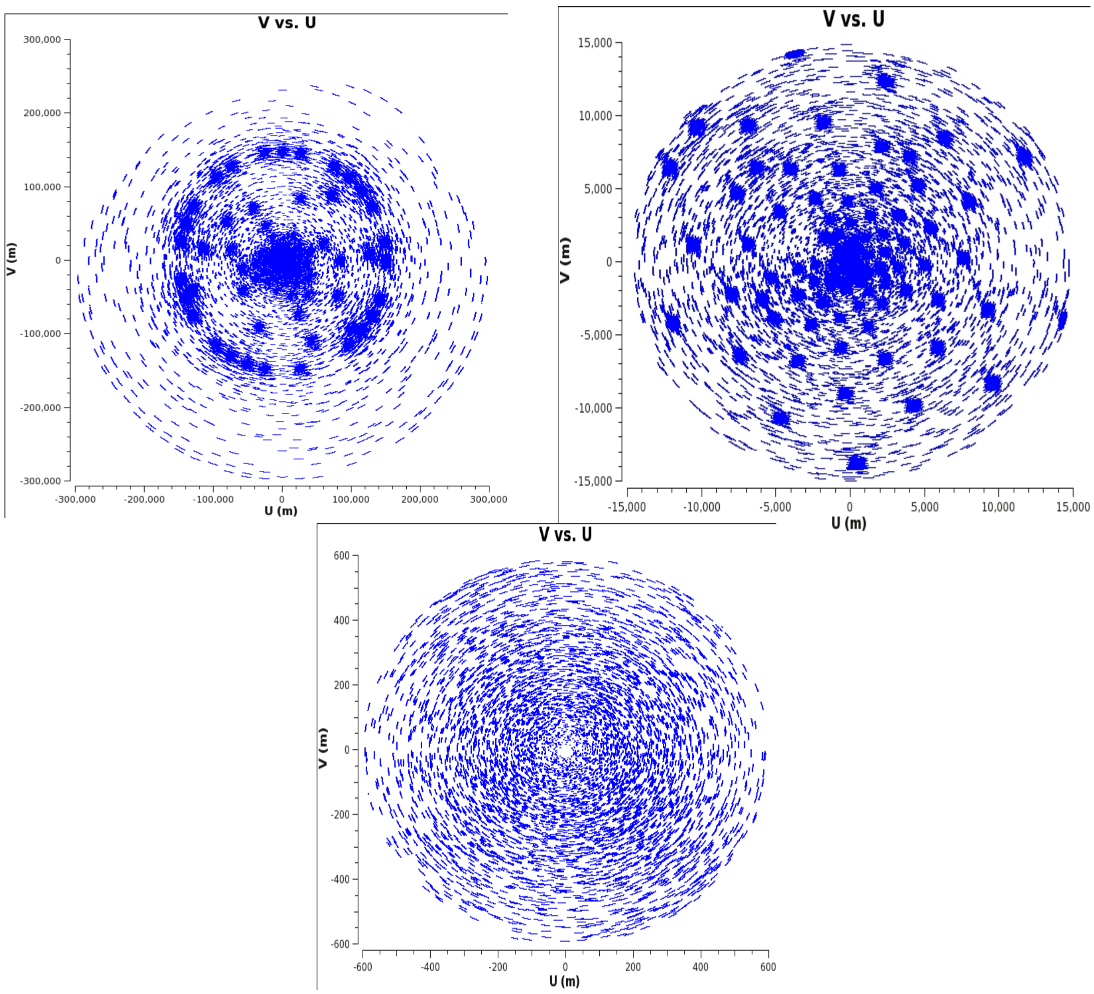

Figure 3: UV coverage on three different scales for the ngVLA 'Core' configuration, in which 40% of the antennas are within 600m radius of the array center. Upper left is full array (300km max baseline), upper right is for baselines out to 15km, and lower is baselines to 600m. Note that CASA PLOTMS does not plot the Hermitian conjugate of a given baseline, as is done in AIPS.

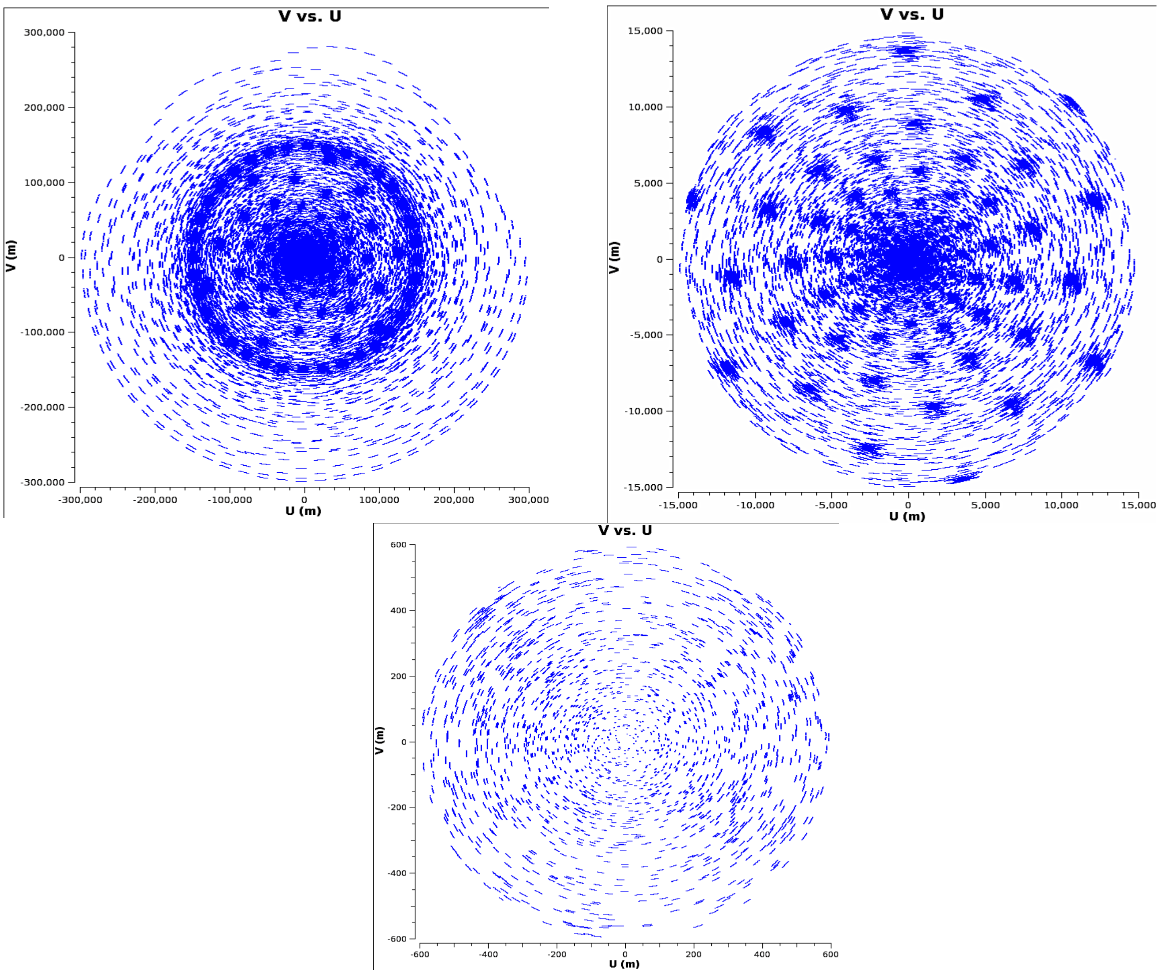

Figure 4: UV coverage on three different scales for the ngVLA 'original' configuration, in which 20% of the antennas are within 600m radius of the array center. Upper left is full array (300km max baseline), upper right is for baselines out to 15km, and lower is baselines to 600m. Note that CASA PLOTMS does not plot the Hermitian conjugate of a given baseline, as is done in AIPS.

Table 1: Number Vis within Baseline Length

B_{max} meters	Core kVis	Original kVis	VLAD kVis	ALMA-out09 kVis	ALMA-out01 kVis
160	37.1	7.3	1.7	9.6	29.4
700	170	55	7.6	29.4	–
1000	192	85	8.4	–	–
3000	317	193	–	–	–
10000	501	345	–	–	–
30000	690	523	–	–	–
90000	841	739	–	–	–
300000	1076	1076	–	–	–

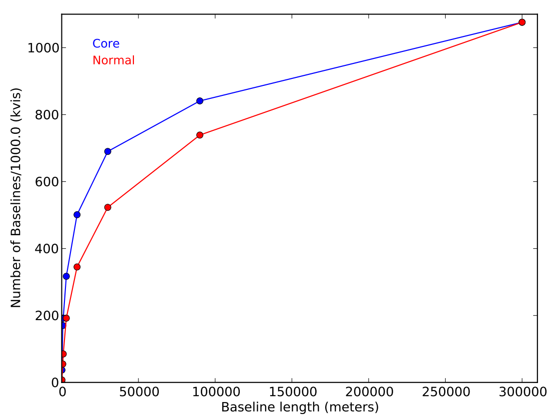

Figure 5: Cummulative number of visibilities (in units of 1000), versus baseline length for the Core and Original configurations for a snapshot observation at zenith.

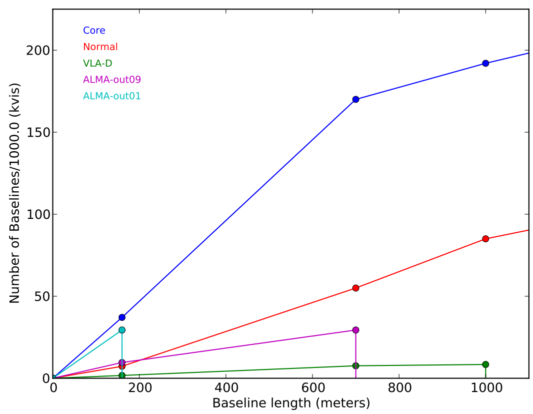

Figure 6: Cummulative number of visibilities (in units of 1000), versus baseline length for the Core and Original configurations, compared to the VLA-D configuration, and two final ALMA configurations (50 antennas), out01 = most compact configutation, and out09 = configuration that gives roughly 1" resolution at 90GHz. Again, these are for a snapshot observation at zenith.

4 Mapping speed relative to ALMA

These filling factors can be turned into a 'mapping speed', in combination with the antenna diameters. Mapping speed in interferometry is complicated by the issue of the shortest spacing (see below), and the distribution of spacings relative to the spatial structure on the sky. I adopt a simple metric based on the point source sensitivity (total collecting area) for the array out to a given baseline length, combined with the field of view of the antenna. I compare ngVLA Core and Original to ALMA-out09 and ALMA-out01, Again, these ALMA configurations lead to resolutions of 0.9" and 2.7" at 90GHz, respectively.

The mapping speed will increase linearly with the number of visibilities on relevant scales. The mapping speed also needs to be scaled for the primary beam in two ways. First, the area mapped increases linearly with the Field of View, implying an increase in mapping speed as (antenna diameter)$^{-2}$. The time required to reach a given sensitivity also decreases with the (antenna area)^2, implying an increase in mapping speed with (antenna diameter)^4, assuming the same bandwidth, antenna efficiency, and system temperature. The relative mapping speed is the product of these

Table 2: Core mapping speed wrt ALMA

ALMA Config	Resolution at 90GHz arcsec	Core factor	Original factor
Out09	1”	13	4.2
Out01	4”	2.8	0.6

two diameter dependencies, and the number of visibilities: Mapping speed $\propto$ ($\mathrm{Nvis}_1/\mathrm{Nvis}_2$) $\times$ ($\mathrm{Diameter}_1/\mathrm{Diameter}_2)^2$. I adopt a diameter for the ngVLA of 18m, hence $(\mathrm{Diameter}_{ngVLA}/\mathrm{Diameter}_{alma})^2 = (18/12)^2 = 2.25$.

Table 2 shows the relative mapping speed, according to this metric and using the number of visibilities out to a given baseline length from Table 1. For programs requiring $\sim$ 1” resolution at 90GHz, both Core and Original clearly out-perform ALMA-out09 by factors of 13 and 4.2 in mapping speed, respectively. For mapping at lower spatial resolution (4” at 90GHz), Core still out-performs ALMA-out01 in mapping speed by a factor 2.8, but Original is slower than ALMA-out01 by a factor 0.6. Again, I have not considered reconfiguration in the context of the ngVLA. Clearly, any reconfiguration of the inner part of the array will improve performance on the shortest baselines, but has an associated cost.

There remains the issue of the shortest spacing. For the Core and Original, the shortest spacing is 18m. For ALMA, the value is 12m for the main array in the most compact configuration, and 7m including the ACA. In all cases, a hole remains. Hence, smaller antennas mitigate, but do not solve, the short spacing problem. ALMA also includes total power on a few antennas to address the zero spacing. The ngVLA project is considering various options for the very short spacing issue for the ngVLA, including an ALMA-like solution, or large cameras on big single dishes. These type of calculations are well suited for Community design studies.

5 Briggs weighting and relative performance

I have investigated the relative performance of the Core and Original arrays under different assumptions for Briggs Weighting in the gridding of the visibilities. I investigate a range in Robust parameter from R=2, 0, -2, ranging from close to Natural weighting (full sensitivity), to close to Uniform (high spatial resolution), respectively. This test was done using SIMOBSERVE, with a zero input image plus unit noise added per visibility (simplenoise=”1Jy” in setnoise in CASA). Again, I do not investigate the true noise of the array, just the relative performance of the arrays assuming a unit noise parameter per visibility.

Table 3 shows the results for array performance parameters: Synthesized beam FWHM (Gaussian fit to PSF), noise with respect to Natural weighting, and first and second sidelobe response of the PSF. Figures 7 and 8 show images of the PSF for each instance.

As expected for arrays with a substantial core, the PSF for R=2 ($\sim$ naturally weighted) beam is highly non-Gaussian. The nominal fit to the PSF gives a FWHM = 21" for the Core array, and 16" for the Original array, but the fit is poor. In particular, there are very bright inner rings in the PSF at 14" and 28" radius, at the level of $\sim$ 50%, plus a broad plateau extending down to the 10% level out to radii of 20 or more synthesized beams from the center. Clearly, Natural weighting will not be useful for high resolution, high fidelity imaging of complex structure.

Going to R=0, the PSF fits have FWHM = 15" for the Core array, and 10" for the Original array. The inner rings are reduced by a factor two or more relative to the R=2 beam, and the plateau is effectively removed. Still, the Core configuration inner ring remains substantial (44%). The noise relative to 'natural' weighting is increased by 20% in both cases.

Going to R=-2, the PSF fits have FWHM = 8" for both the Core array and the Original array. The inner rings are reduced to $\sim$ 10% or less, and again, the plateau is effectively removed. The noise relative to 'natural' weighting is increased by a factor of 1.9 for the Original array, and a factor 2.4 for the Core array.

The parameters in Table 3 are representative for the moment. The real test of performance for Core dominated vs. more distributed configurations will come through the Community Design studies of particular high profile science applications. Still, it is encouraging that the noise penalty using close to Uniform weighting to achieve high angular resolution and a reasonably behaved PSF is only roughly a factor two.

6 Discussion

I analyze the performance of two idealized configurations for the ngVLA. One configutation (Original) has 20% of the antennas within a core of 0.6km radius. This configuration has already been shown to produce high fidelity, high resolution images in the context of protoplanetary disks and imaging CO from high redshift galaxies, using suitable weighting of the visibilities. The second configuration (Core) has 40% of the antennas in the 0.6km radius

Table 3: Imaging Capabilities vs. Robust Weighting

Configuration	Robust	FWHM milliarcsec	RMS $\sigma/\sigma_{R=2}$	1st Sidelobe at 14"	2nd Sidelobe at 28"	10% Plateau radius arcsec
Original	2	16	1.0	0.49	0.37	0.3
Original	0	10	1.2	0.24	0.11	none
Original	-2	8	1.9	0.08	0.02	none
Core	2	21	1.0	0.64	0.54	0.7
Core	0	15	1.2	0.44	0.29	none
Core	-2	8	2.4	0.14	0.06	none

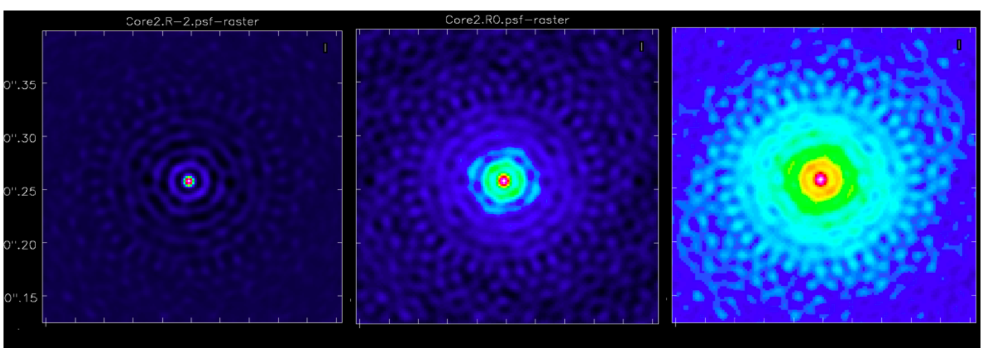

Figure 7: Synthesized beams for different robust weighting schemes for the Core configuration using all baselines. The area shown is 0.25" on a side. Left has R = -2, center R = 0, and right R = 2, so approximately Uniform to Natural weighting. Values for the inner sidelobes are given in Table 3. Color scales are the same in each plot, with the magnitude of the first and second sidelobe given in table 3. Note the R=2 beam has a bright plateau that fills the region shown.

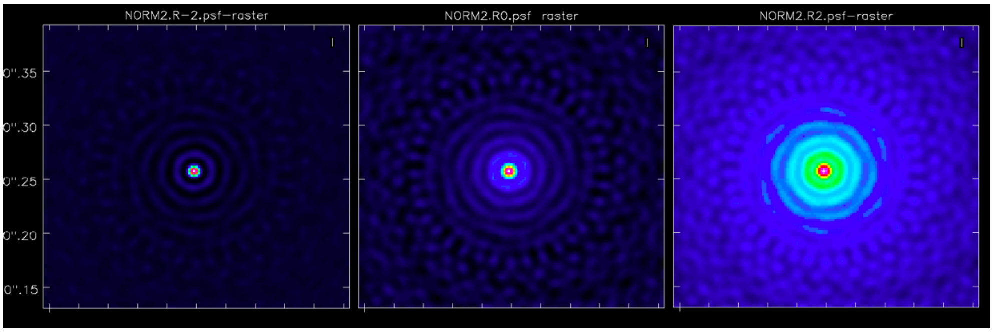

Figure 8: Synthesized beams for different robust weighting schemes for the Original configuration using all baselines. The area shown is 0.25" on a side. Left has R = -2, center R = 0, and right R = 2, so approximately Uniform to Natural weighting. Values for the inner sidelobes are given in Table 3. Color scales are the same in each plot, with the magnitude of the first and second sidelobe given in table 3. Note the R=2 beam has a bright plateau that fills the region shown.

core.

While the Naturally weighted beam in both cases is clearly not appropriate for high fidelity imaging at high resolution, it is encouraging that the noise penalty, when using close to Uniform weighting to achieve both high angular resolution and a reasonably behaved PSF, is only a factor 1.9 for the Original configuration, and 2.4 for the Core configuration.

I have not considered tapering of the gridded visibilities in parallel with robust weighting. The real test of performance for Core dominated vs. more distributed configurations will come through the Community Design studies of particular high profile science applications. Design studies should investigate optimal strategies for weighting and tapers.

I have presented mapping speeds of fields larger than the primary beam, for these configurations relative to two ALMA configurations: the most compact ALMA configuration (ALMA-out01), giving a resolution of 4" at 90GHz, and the ALMA-out09 configuration that gives 1" resolution at 90GHz. A resolution of ~ 1" was deemed critical by SWG2 in the study of the ISM of nearby galaxies (Leroy et al 2016, ngVLA memo. 6). I adopt a simple metric based on the point source sensitivity (total collecting area) for the array out to a given baseline length, combined with the field of view of the antenna. The ngVLA Core and Original configuration have faster mapping speeds relative to the ALMA-out09 by factors of 13 and 4.2, respectively. Compared to the most compact ALMA configuration, Core is still faster than ALMA by a factor of 2.8, while Original is slower by a factor 0.6.

I have not considered reconfiguration for the inner array of the ngVLA. Clearly, reconfiguration will have a great impact on these numbers, but comes at a construction and operations cost.

I have not considered the issue of filling-in the shortest spacings of the array. This could be done through a combination of an array of smaller antennas, total power on some antennas, and/or wide field cameras on a large single dish.

Lastly, I have also not considered subarrays. For arrays with highly concentrated cores, the notion of subarrays becomes a particularly intriguing area of investigation. For instance, science programs that require the full resolution of the array, plus good image fidelity, may employ data weighting schemes that down weight the core spacings substantially. In these cases, the array performance for the high resolution program may be adequate using only some fraction of the core antennas. The rest of the core antennas could then be used in a subarray to perform a science program that relies on short baselines, such as wide field imaging of diffuse emission, or time domain monitoring.

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