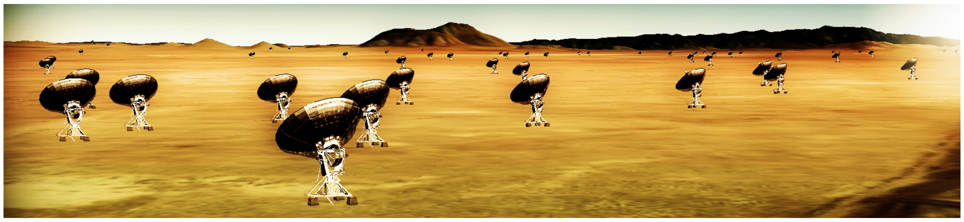

Next Generation Very Large Array Memo No. 16

More on Synthesized Beams and Sensitivity

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Abstract

I present further calculations on synthesized beams and sensitivities for the ngVLA. Adjusting basic imaging parameters, including cell size, robust, and uv-taper, in CASA CLEAN, I find that reasonably well behaved synthesized beams can be generated at resolutions ranging from 0.01" to 1.4" at 30GHz. The loss of sensitivity relative to pure natural weighting increases steadily from a factor 1.5 at 10mas resolution, to a factor 2.4 at 1.4" resolution. This study is certainly not exhaustive with respect to parameter space, simply representative, using tools currently available. The results are likely conservative in terms of ultimate array performance, pending future imaging algorithmic development for complex arrays such as the ngVLA.

1 Calculations

I have investigated the change of sensitivity when trying to achieve a given resolution with the ngVLA. The three-tiered VLA configuration under consideration, from the dense core, through the VLA-scales ($\leq$ 30km), out to 500km baselines, challenges imaging algorithms when trying to obtain a given spatial resolution with a reasonably well behaved synthesized beam. Moreover, the output beam shapes in CASA CLEAN are a complex function of the imaging parameters, including: cell size, image size, uv weighting (Robust, Natural (NA), Uniform (UN)), and uvtaper (TA).

The Robust parameter, cell size, and uv-taper affect the resulting synthesized beam size. The Robust and uv-taper parameters act through the uv-weighting function and gridding. The cell size[1] becomes relevant if a value is chosen that is much larger than will allow for Nyquist sampling of the effective resolution of the longer spacings. The basic effect of a large cell size is to truncate the uv-distribution at baseline lengths that cannot be sampled by the selected cell size, ie. removing the longest baselines.

Considering ALMA, the dependence on the robust parameter is less of an issue, since each configuration is designed such that changing from UN to NA only changes the resulting PSF and rms noise at the $\sim 20\%$ level or so. For the JVLA, the centrally condensed, logarithmic spacings lead to about a factor two change in beam size and rms noise going from UN to NA weighting.

The current working model for the ngVLA configuration has its own idiosyncracies. I employ the same 'southwest configuration' of Greisen & Owen, as used in ngVLA memo 13, and the CASA simulator. This configuration is unique in that the 40% core is located on the northern extremity of the array. Hence, even the most distant antennas correlate to the full core, ie. the longest baselines retain significant sensitivity via the core.

The three-tier distribution of antennas for the southwest configuration, with roughly 40% of the antennas within 1km, another 40% on VLA scales of 30km, and the rest to 300km, leads to a Naturally weighted PSF that has three tiers. I present this in detail below.

In my calculations, I adjust the robust parameter, cell size, and uv-taper, to obtain the desired resolution while retaining reasonable sensitivity relative to NA, and avoiding the very broad, 3-tier skirts inherent in the ngVLA NA beam.

A critical point to keep in mind is that, when trying to get close to the full resolution of the array's longest baselines, one cannot just fix the robust parameter to some high value that gives good sensitivity (ie. toward NA), then adjust the cell size and taper to get a given resolution. The resulting beam Gaussian fit will never get to the target 10mas resolution at 30GHz, due to the large number of short spacings in the array. Obtaining a given PSF requires a more involved consideration of all parameters.

Another important point is that the main metric for assessing the quality of the resulting PSF is not the 'peak sidelobe'. The more relevant issue is the magnitude of the skirts to a given distance. In this study, I adopt a criterion to obtain a skirt of $< 10\%$ to a radius of about four times the size of the synthesized beam FWHM. Based on the imaging simulations of high

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[1] Cell size herein corresponds to the image pixel size, as per CASA and AIPS imaging input parameters.

redshift molecular gas and protoplanetary disks (see ngVLA memos 11, 12, and 15), I believe that, for imaging problems that require modest dynamic range ($\sim 10^3$), these beam shapes are adequate.

I simulate ae 4hour synthesis for a single narrow channel at 30GHz. Note that bandwidth synthesis for continuum observations will greatly improve 'holes' in the uv-plane, but it may not change the magnitude of the skirts of the PSF for a given weighting. I have explored various combinations of cell size, robust parameter, and uv-taper. I present four examples that achieve a resolution ranging from 0.01" to 1.4", increasing in steps of five to six, and yielding a reasonable PSF while retaining sensitivity.

The input model is a very large image with a small pixel scale (2mas and 16k × 16k pixels), with zero intensity in all pixels. After generating the measurement set using SIMOBSERVE, I add unit noise to each visibility, and then reference the resulting noise for the different cell sizes and robust factors to the Naturally weighted noise for the full array.

2 Results

I start with the reference NA beam. This is generated using natural weighting with a very large image and small pixel scale to avoid truncating the longest baselines. I use a cell size of 1.7mas to sample the longest baselines, and a very large image (25k × 25k pixels), to facilitate gridding that may be relevant for structure on scales approaching the primary beam[2].

Figure 1 shows the NA beam. The plot shows the 3-tier beam for this core-dominated configuration and NA weighting. The longest baselines lead to a narrow spike on 10mas scales. The VLA-scale baselines then give the first skirt out to a scale of ~ 0.2", at a level between 20% and 50%. The dense core then leads to the very wide skirt at the level of 20% to 5%, out to ~ 1.5".

Next, I explore the parameters space for imaging to different resolutions. Table 1 lists the cell sizes, robust parameters, and uv-tapers, used to achieve a given resolution and a reasonable PSF. Column 1 has the Briggs robust parameter, cell size, and taper. Column 2 lists the resulting FWHM of the synthesized beam, as parameterized via Gaussian fitting in CLEAN. Column 3 shows the rms noise in the image relative to the NA image. Note that many other combinations were tried, and these gave the best results.

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[2] I have found that total image size has less of an effect on the PSF as the above parameters, but is clearly paramount if one is interested in imaging a large source.

Table 1: Beams and noise levels at 30GHz

Robust, cellsize, TA mas	FWHM mas	RMS/RMS$_{\rm NA}$	Cont. rms, T$_B$ μJy, K in 4hr	Line rms, T$_B$ μJy, K in 4hr, 10km s^{-1}
Natural, 1.7, 0	13.0×17.0	1.0	0.14, 0.85	20, 121
R$= -0.2$, 1, 4	8.7×11.4	1.5	0.21, 2.9	30, 408
R$= 0.2$, 6, 25	50×62	1.9	0.27, 0.12	38, 16
R$= 0.5$, 30, 100	242×244	2.3	0.32, 0.0074	46, 1.1
R$= 1$, 140, 500	1400×1390	2.4	0.34, 0.00024	48, 0.033

Figure 2 shows the resulting beams. At the highest resolution, there remains a remnant of a skirt to the 10% level at 40mas. This could be reduced by adjusting to a lower robust parameter, at the expense of higher noise. In general, some of the beams may not appear particularly Gaussian in shape. However, imaging simulations of eg. proto-planetary disks, suggest that departures from Gaussianity may not be debilitating for moderate dynamic range imaging.

The noise relative to NA weighting (Table 1, column 3), increases steadily, from 50% higher at 10mas resolution, to a factor of 2.4 at arcsecond resolution. This reflects that the lowest resolution only uses the core baselines (40% of the array), while the higher resolution is still using most of the spacings between the outer antennas to the core, since the core is situated at the northern extremity of the antenna distribution.

Lastly, Columns 4 and 5 show the 'real' noise of the array based on standard performance parameters, for an array with 10 times the effective collecting area of the current JVLA at 30GHz, and a 4hr integration, as per the simulation (see ngVLA memo 5). The NA noise is calculated using the radiometer equation, and the noise values for different imaging parameters are then scaled by the noise increase relative to NA, as listed in column 3. We assume a 20GHz bandwidth for continuum observations, centered at 30GHz, and a 10km s^{-1} channel width for line obserations at 30GHz (channel width = 1MHz).

I emphasize that obtaining optimal sensitivity, with a well behaved PSF, at a given resolution, is going to be a long-standing study in algorithmic development. The results will also depend critically on the final adopted configuration. The results presented herein are just representative of the magnitude of changing noise factors at different resolutions, derived using the tools currently available in CASA. These results are likely conservative, pending future developments in imaging algorithms for complex arrays, such as the ngVLA.

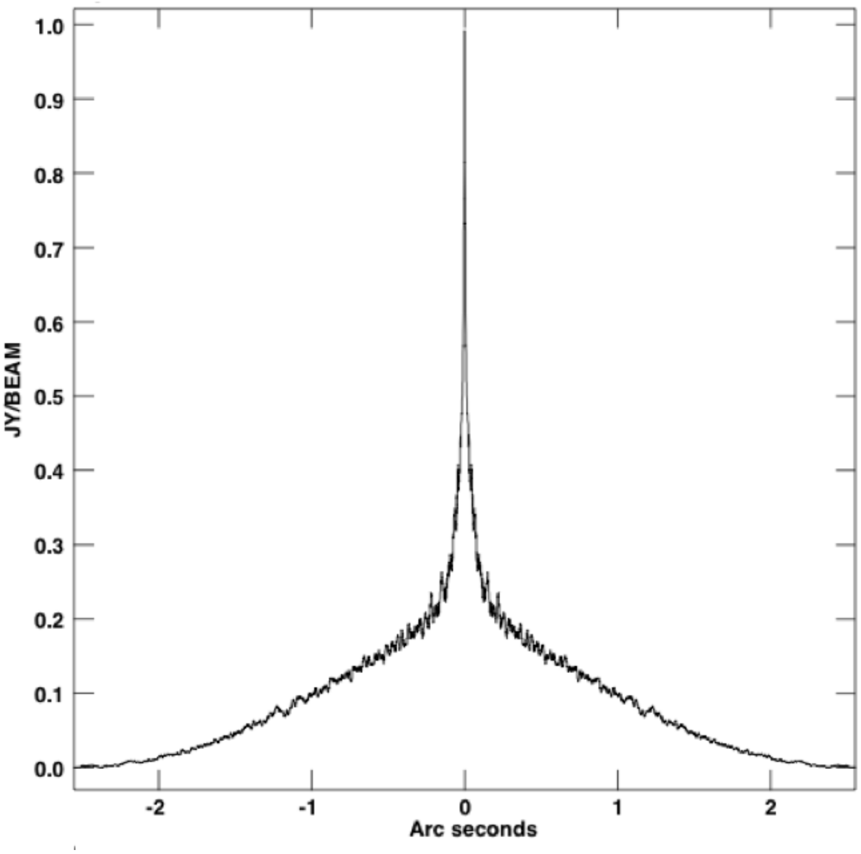

Figure 1: The Naturally weighted PSF in a N-S slice using a small cell size (1.7mas) and a very large image (25k × 25k).

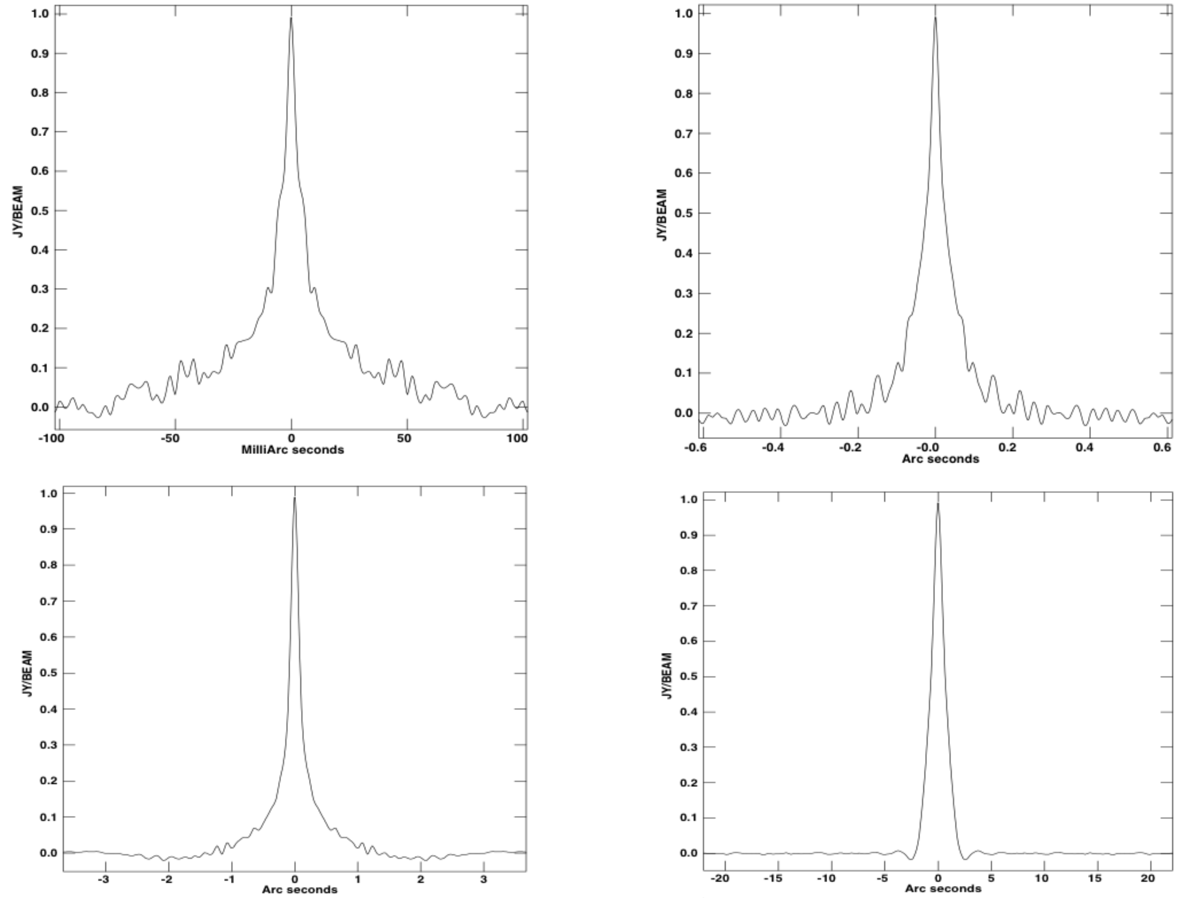

Figure 2: The resulting PSF profiles (North-South) of the synthesized beams for the ngVLA. Upper left: R=-0.2, cell size = 1mas, TA = 4mas, resulting in FWHM = 8.7 × 11.4 in mas. Upper right: R=0.2 and cell size = 6mas, TA = 25mas, resulting in FWHM = 50 × 62 in mas. Lower left: R=0.5 and cell size = 30mas, TA = 100mas, resulting in FWHM = 242 × 244 in mas. Lower Right: R=1 and cell size = 140mas, TA = 500mas, resulting in FWHM = 1390 × 1400 in mas.

The National Radio Astronomy Observatory and Green Bank Observatory are facilities of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work was supported by awards AST-2034328 (MSIP Prototype Antenna) and AST-2334267 (ngVLA Design Activities); NRAO related activities are funded under award AST-1647378 (NRAO Operations/Development).

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