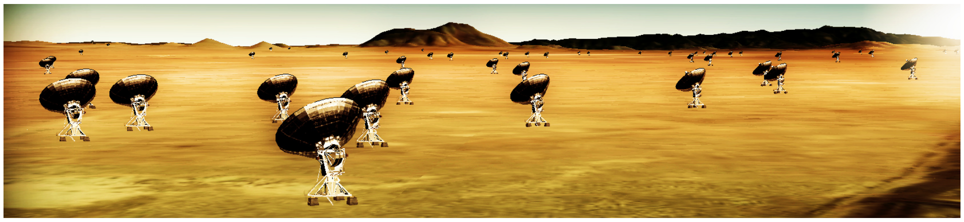

Next Generation Very Large Array Memo No. 104

Rev E MID Tests: Sensitivity at 7mas Resolution

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Abstract

I investigate different MID configurations to determine the sensitivity loss for larger versions of MID in the context of imaging of protoplanetary disks at 1 AU resolution at 140 pc (KSG1), at both 33 GHz and 115 GHz. The MID versions, taken from Walker (ngVLA memo 102), include: (i) the most extended exponential spiral (max baseline = 1230 km), (ii) two smaller exponential spiral configurations with different inner spacing distribution (max baseline = 828 km), and (iii) the Rev D configuration (max baseline = 1068 km). In all cases, Rev D performs the worst with respect to sensitivity and synthesized beam shape. At 33 GHz and at the target resolution of 7 mas, comparing the two more compact exponentials MID39 and MID29, with the larger exponential 28MOD, MID29 performs best, with a lower rms by 5.4% and lower negative sidelobes by 30% relative to 28MOD. At 115 GHz and 7 mas resolution, MID39 performs best, with a lower rms by 7.7% and lower negative sidelobes by 26% relative to 28MOD. The sensitivity losses can be recovered through modest increases in integration times. We feel the benefit of the extra resolution in the larger 28MOD configuration, when needed (a capability that is lost for MID39 and MID29), and the better baseline continuity between MID and LONG for 28MOD, outweigh the added integration times needed for KSG1. Further simulations of specific science goals are in progress to test the detailed imaging performance in both cases.

ADDENDUM July 2024: The RevF MID configuration has been added to the analysis, with no substantial performance differences with respect to 28MOD.

1 Introduction

A primary science goal for the ngVLA is imaging planet formation at a scale of 1 AU, both in dust continuum emission at 33 GHz through 115 GHz, and in molecular line emission up to 115 GHz (KSG1; ngVLA memo 19). The nearest star forming regions, including Taurus and Ophiuchus, are at a distance of $\sim$ 140 pc, and contain hundreds of protoplanetary disks over a range in masses, for which 1 AU then corresponds to 7 mas.

An angular scale of 7 mas requires baselines out to 300 km at 33 GHz and 84 km at 115 GHz. The Rev D MID configuration was designed as a power-law distribution of 46 antennas along five rough spiral arms, with a maximum baseline of 1068 km (ngVLA memo 92). While simulations with Rev D showed that the goals of KSG1 were attainable, the idea was proposed of making MID moderately less extended, with more short baselines on scales relevant to KSG1. However, this shortening comes at a price: loss of the longest MID baselines and hence loss of higher resolution capabilities with MID, as well as a poor match for more uniform baseline coverage between MID and LONG. The longer MID baselines become relevant in imaging studies of eg. stellar atmospheres (ngVLA memos 66, 95; ngVLA Science Book p. 369).

Walker recently presented alternatives to the power-law Rev D MID configuration with exponential antenna placements along the five arms (ngVLA memo 102). He presents both an extended 28MOD configuration that has a maximum baseline of 1230 km, and two more compact configurations, MID39 and MID29, for which the longest baseline is 828 km, with the difference being the distribution of the shorter baselines.

In this memo, I address the question: what is the sensitivity loss between these configurations when trying to achieve an angular resolution of 7 mas at 33 GHz and 115 GHz? The full ngVLA is employed (Core + Spiral + MID), as per all the science simulation studies of protoplanetary disks and planet formation to date (ngVLA memos 11, 33, 57, 65, 68, 101). In this case, 'beam sculpting' is required via tapering to achieve a synthesized beam that has the desired FWHM, while not being dominated by broad wings due to the large Core contribution to the configuration (also known as 'taperability'; ngVLA memos 3, 16, 55, 65, 78). The metric adopted in these studies for the wings of the synthesized beam to achieve reasonable imaging performance is a value of $\sim$ 10% at a radius $\sim$ FWHM of the synthesized beam. This metric has been verified in numerous high fidelity imaging simulations of the ngVLA to date.

2 Process and Results

The configurations employed are described in detail in Walker, ngVLA memo 102, and I refer the reader that memo for details.

To achieve a resolution of 7 mas with a reasonable synthesized beam (ie. suppressed wings), I employ Briggs weighting with R = -2, corresponding to Uniform weighting. I then adjust the uv-taper to achieve a synthesized beam FWHM of $\sim$ 7 mas, as determined by a Gaussian fit in CASA TCLEAN. The uv-cell size is adjusted to sample the longest baselines, and the image size is large to avoid gridding the entire core into a single cell (ngVLA memo 16, 55, 65, 78). The sensitivity loss relative to natural weighting in all cases was about a factor two, consistent with previous taperability studies (ngVLA memo 16, 55, 65, 78).

One set of simulations is done at 33 GHz for thermal continuum emission from dust. This lower frequency is adopted to correspond to studies of very dense protoplanetary disks, where dust opacity effects can become relevant on AU-scales even at 115 GHz (ngVLA memos 11, 33, 57, 68, 88). For these simulations, we adopt a cell size of 0.5 mas, and an image size of 16k. A bandwidth of 8 GHz was assumed for the noise calculation. The second set of simulations is at 115 GHz, corresponding to CO 1-0 emission (ngVLA memo 101). For these simulations we adopt a cell size of 0.3 mas and an image size of 16k. We assume a channel width of 120 MHz for the noise calculation. In both cases, a four hour synthesis is simulated. Note that only relative sensitivities between configurations are relevant in this analysis, but we include 'realistic' noise values for completeness.

2.1 Tapering and Sensitivity

I first consider the loss of sensitivity given the required tapering to get to 7 mas resolution with a reasonable synthesized beam shape.

Table 1 summarizes the results. Column 2 gives the required Gaussian uv-taper parameter to achieve the target beam size. Column 3 lists the resulting beam FWHM from Gaussian fitting in TCLEAN, and column 4 lists the resulting rms noise.

At 33 GHz, MID29 has the lowest noise. The sensitivity loss between MID29 and 28MOD is 5.4%. Rev D is substantially higher noise, by 13% relative to MID29.

At 115 GHz, MID39 has the lowest noise. The sensitivity loss between MID39 and 28MOD is 7.7%. Again, Rev D is substantially higher noise, by 14% relative to MID39.

Table 1: Beam Sizes and Sensitivities

Configuration	UV Taper mas	Beam FWHM mas	RMS μJy beam^{-1}	Wings R=FWHM N, E Percent	Negative Sidelobe Percent
33 GHz					
RevF	5.50	7.12 x 6.86 at +5.2^o	0.446	13.3, 10.8	-5.4
28MOD	5.45	7.23 x 6.91 at -59.0^o	0.444	11.2, 11.3	-5.7
MID39	5.40	7.20 x 6.89 at -48.2^o	0.436	11.4, 11.3	-5.6
MID29	5.52	7.08 x 6.84 at -45.5^o	0.420	10.2, 9.4	-4.0
Rev D	6.40	7.42 x 6.60 at -14.1^o	0.483	16.1, 5.7	-8.0
115 GHz					
RevF	6.17	7.18 x 6.77 at 54.8^o	25.0	9.5, 13.0	-4.7
28MOD	6.34	7.10 x 6.85 at 79.3^o	24.6	7.3, 9.8	-3.8
MID39	6.27	7.19 x 6.89 at 84.9^o	22.7	6.7, 9.1	-2.8
MID29	6.57	7.07 x 6.83 at 74.0^o	24.2	8.2, 10.4	-3.6
Rev D	5.37	7.33 x 6.69 at 89.8^o	26.4	11.6, 9.9	-8.3

2.2 Synthesized Beams

Figure 1 shows the synthesized beams at 33 GHz, and Figure 2 shows the beams at 115 GHz. Table 1 column 5 and 6 list the values of the beam wings at a radius of 7 mas for the North and East directions. Column 6 lists the peak negative sidelobe.

At 33 GHz, MID29 has the lowest negative sidelobe (in absolute value): 30% lower than that for 28MOD. Rev D has the highest negative sidelobe, a factor two higher than MID29.

At 115 GHz, MID39 has the lowest negative sidelobe: 26% lower than that for 28MOD. Rev D has the highest negative sidelobe, a factor three higher than MID39.

3 Conclusions

The sensitivity loss when targeting the 7 mas resolution of KSG1 for imaging protoplanetary disks between the more compact exponential configurations MID29 and MID39, and the more extended exponential 28MOD, is 5.4% at 33 GHz and 7.7% at 115 GHz (with MID29 performing better than MID39 at 33 GHz and vice verse at 115 GHz). These would then require 11% and 15% longer integration times, respectively. We feel these extra integration times are acceptable in order to retain the longer baseline capabilities of MID for eg. stellar atmospheric imaging, and for better continuity in baseline coverage to LONG.

In terms of beam shape, the more compact configurations have modestly cleaner beams (lower peak negative sidelobes by $\sim 30\%$). Science simulations are currently underway to determine image quality in the relevant key science areas for these configurations.

In all metrics, Rev D performance is decidedly worse, and will not be considered further.

4 Addendum July 2024

I have repeated the exact same analysis for the RevF configuration. RevF has given more attention to the practicalities of the array configuration, such as fiber and power cost, and road access. The new results are in Table 1.

The primary point of comparison is with 28MOD, which has become the current standard for the MID configuration. For the 33 GHz simulation, the Gaussian core fit by CASA tclean is slightly rounder for RevF than for 28MOD, while the broad wings are slightly higher for RevF, at least N-S. The noise is similar, as is the peak negative sidelobe. In all cases, the differences are less that a few percent.

For the 115 GHz simulation, the Gaussian core fit by CASA tclean is slightly rounder for 28MOD than RevF, while the broader wings are a few percent higher for RevF. The noise is similar. The peak negative sidelobe is a bit higher for RevF.

Overall, the performance differences between RevF and 28MOD are small enough that we expect there will be no impact on the primary science driver for MID, namely, imaging proto-planetary disks. For completeness, PP disk imaging simulations are in progress as a final check on the performance.

Considering declination dependence, to first order, the North-South synthesized beam shape all of the configurations will scale similarly as 1/cos(zenith angle), at least until the northern-most antennas can no longer see the source.

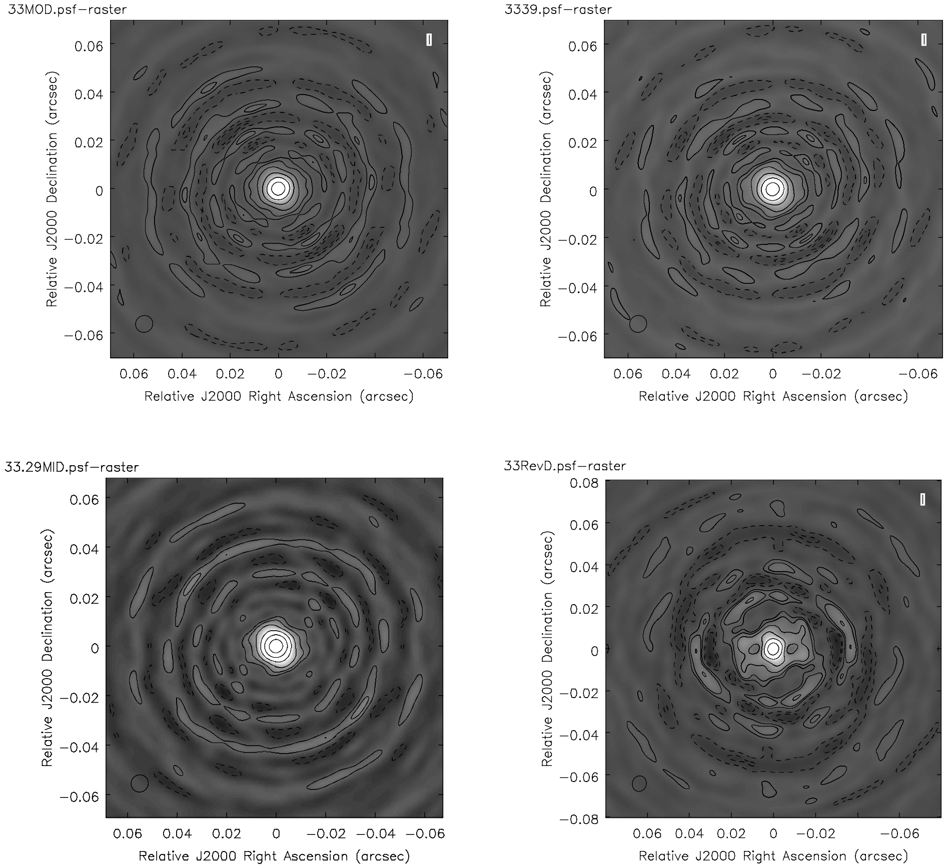

Figure 1: Synthesized beams for a 4 hour integration at 33 GHz with tapering as given in Table 1. Contour levels are a geometric progression in factor two, starting at ±0.02. Upper left is for MOD28, Upper right MID39, Lower left MID29, and Lower right Rev D.

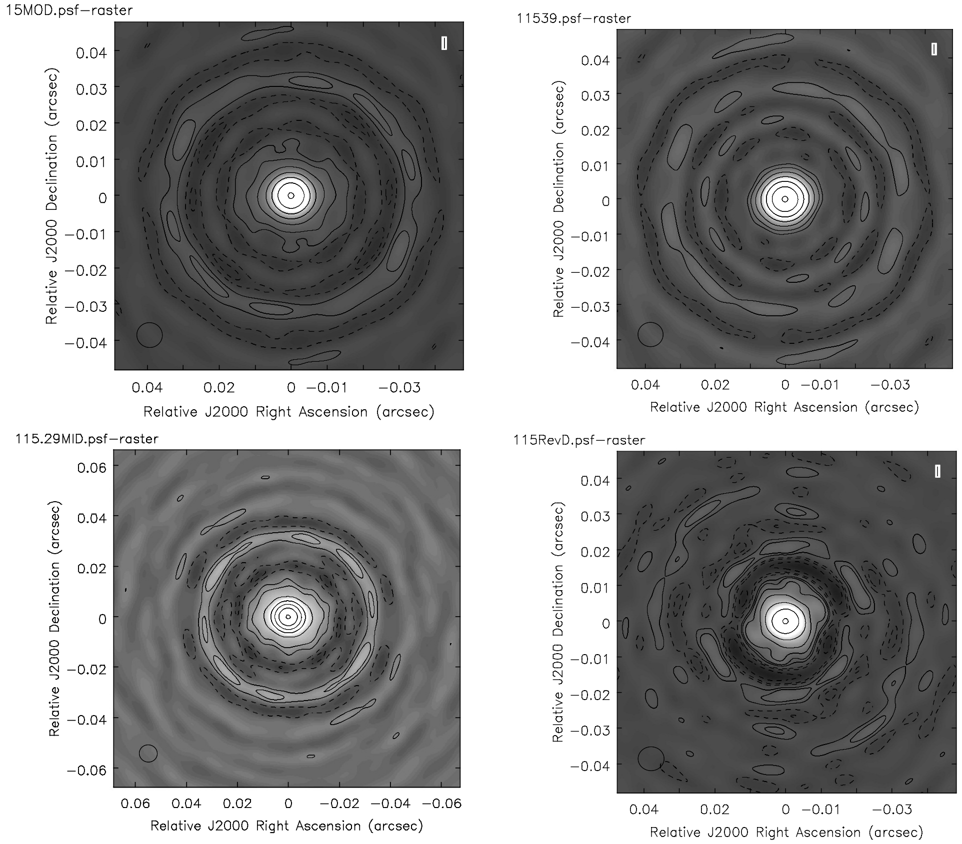

Figure 2: Synthesized beams for a 4 hour integration at 115 GHz with tapering as given in Table 1. Contour levels are a geometric progression in factor two, starting at ±0.015. Upper left is for MOD28, Upper right MID39, Lower left MID29, and Lower right Rev D.