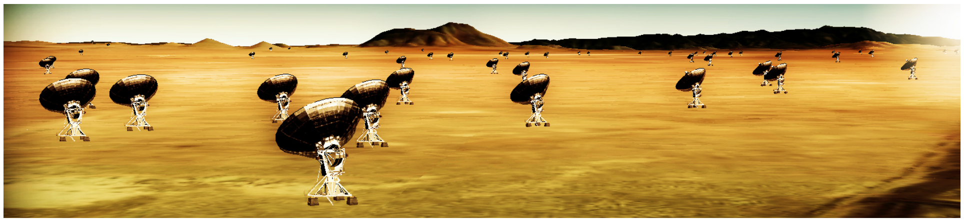

Next Generation VLA Memo. 41

Initial Imaging Tests of the Spiral Configuration

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Abstract

We investigate the imaging performance of the Spiral214 array in the context of two key science programs for the ngVLA. The constrained Spiral array performs adequately for the two models explored. A reasonable synthesized beam, and imaging results, can be obtained for a given target resolution between 10mas and 1" at $\sim$ 30Ghz, with a loss of sensitivity relative to Natural weighting between a factor 1.6 and 2.9.

1 Introduction

We perform initial image tests of the Spiral configuration for the ngVLA. We test the imaging capabilities using two of the models that have appeared in previous ngVLA memos using the original (Y-based) configuration. These models are part of the key science program envisioned for the ngVLA (Memo 19).

The Spiral214 configuration entails 214 antennas of 18m diameter, to baselines of a few hundred km: 168 of these antennas are on the Plains of San Augustin on baselines out to about 30km, and 94 of these are in the Core with baselines to about 1km (Figure 1). The locations have preliminary real-world constraints included in placement. The main difference with the previous SW214 configuration is that the antennas on baselines of a few km to 30km are in a Spiral pattern on the Plains of San Augustin, and not on the linear VLA-Y distribution. A more detailed description of the configuration will be forthcoming.

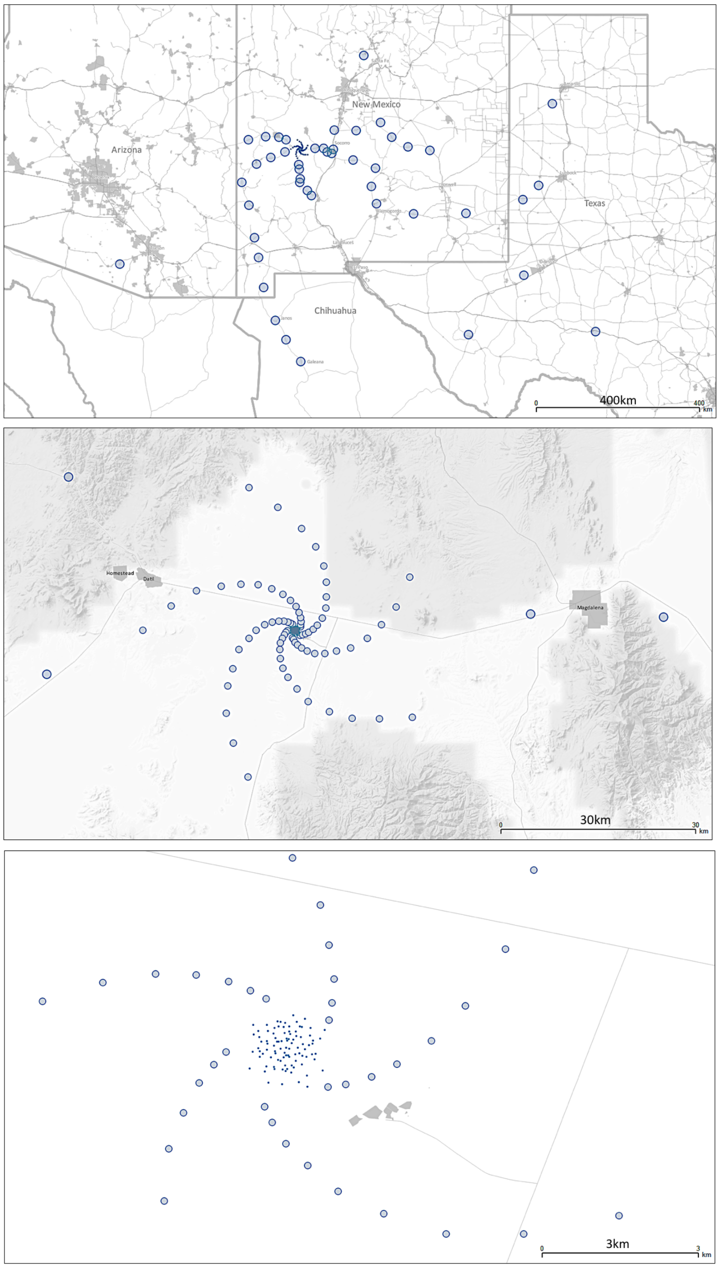

Figure 1: Antenna placements for the constrainted Spiral214 array on three scales. All the antennas are of 18m diameter.

2 Spider Web Galaxy Model

The Spider Web galaxy is a very massive, forming galaxy at $z = 2$ (Emonts et al. 2017). The system has multiple sub-galaxies distributed over about 100kpc, in the process of merging to form a giant elliptical galaxy. VLA and ATCA observations have discovered CO 1-0 emission distributed across the system, with a total gas mass of $1.5 \times (\alpha/4) \times 10^{11}$ $M_\odot$.

We employ a model for the integrated CO 1-0 emission from a system analogous to the Spider Web galaxy, based on numerical simulations of massive galaxy formation in the early Universe by Narayanan et al. (2015, Nature, 525, 496), scaled to the size and luminosity of the Spider Web system (Emonts et al. 2018, in prep). The simulated galaxy has a dominant merging galaxy system on a scale of about 3" $\sim$ 27kpc, plus a diffuse halo of CO emission on a scale roughly twice that.

We then run the model through the CASA simulator, using a configuration comprised of the Core and Plains antennas out to baselines of 30km (168 antennas total). The observing frequency is 38GHz (CO 1-0 at $z = 2$), and the velocity integrated flux in the model is 0.21 Jy km s^{-1}. We simulated a 48 hour observation, made up of twelve 4 hour syntheses. We are considering the velocity integrated CO emission, so the model is 'collapsed' in frequency to a single channel with a width of 71 km s^{-1} (9MHz). We use this channel width for the noise calculation, since along any given line of sight, the line width is probably of order this width. Future simulations in 3D will consider the large scale velocity structure.

We calculate the theoretical thermal noise with Natural weighting for the array using the array parameters listed in Memo 17 (interpolated between 28 GHz and 41GHz):

- Theoretical rms using NA weighting, for full SPIRAL (214 antennas) ~ 1.8 μJy beam^{-1} in 48 hours, 9MHz channel at 38GHz.
- Theoretical rms using NA weighting, for core + plains array (168 antennas) $\sim 2.3\mu$Jy beam^{-1}

We generate noise-only images and iterate on the 'simplenoise' parameter in SETNOISE to obtain the noise per visibility (120sec per vis), which gives the image noise values above. The process is described in the CASA ngVLA simulations instructions. The empirically determined value per visibility is 4.2 mJy. This value matches within 20% the theoretical noise per visibility calculated using the system temperature and aperture efficiency from Memo 17.

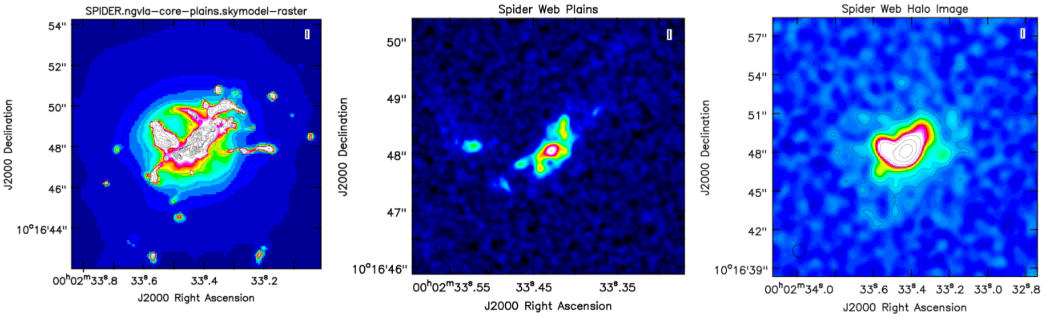

Figure 2: Images of the velocity integrated CO 1-0 emission from a $z = 2$ massive forming galaxy system analogous to the Spider Web galaxy (Emonts et al. 2016, Science, 354, 1128, Narayanan et al. 2015; Casey et al. 2015, ngVLA Memo 8, Emonts et al. 2018 in prep.) The observing frequency is 38GHz. Simulations assume 48 hours observing with the ngVLA. Left: The input model. The emission is squashed over velocity, with an effective velocity width is 71 km s^{-1} = 9MHz. Center: the emission from the main merging galaxy system at 0.126" resolution (1kpc). The peak surface brightness is 0.1 mJy beam^{-1}, and the rms is 3.0 μJy beam^{-1} per channel. Right: the emission on large scales at 1.0" resolution. The contour levels are a geometric progress by a factor 2, starting at $\pm 3\sigma = 10\mu$Jy beam^{-1}. The peak is about 1mJy beam^{-1}, and the rms is 3.5 μJy beam^{-1} per channel.

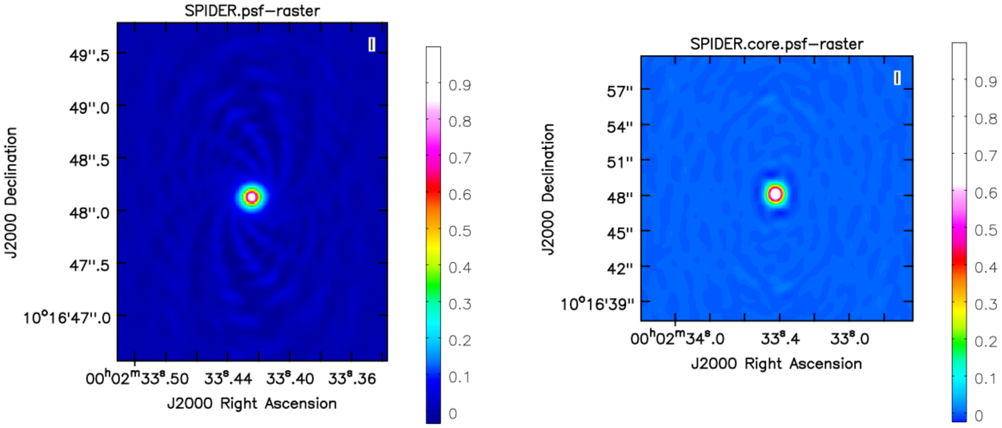

Figure 3: The synthesized beams for the 0.126" resolution simulation ('plains'), and for the 1.0" resolution simulation ('core'), at 38GHz.

We consider the Briggs robust parameter, cell size, and uv-taper, to obtain synthesized beam sizes of 0.12" (1kpc) resolution to image the main galaxy, and 1" resolution to observe the extended halo. The search over parameter space was not exhaustive, but the following parameters provided reasonable synthesized beams, meaning beams in which the skirts of the beam drop below 10% at a radius $\sim$ FWHM of the synthesized beam (see Memo 35). We determined the noise in the resulting image made from the noise-only model, for the parameters given below:

- Taper = 0.09", robust = 0: FWHM = 0.126", rms = 3.0 μJy beam^{-1}. This taper provides resolution relevant to the Plains array, while down-weighting the Core. Note that we do not include spacings longer than 30km in the configuration.
- Taper = 0.85", robust = 0.5: FWHM = 1.0", rms = 3.5 μJy beam^{-1}. This taper provides resolution relevant to the Core array, and down-weights the longer spacings.

The resulting images for the input model, the Plains array, and the Core array, are shown in Figure 2.

At 0.126" resolution, the image reproduces well the structure in the main galaxy, with a resolution corresponding to a physical scale of 1kpc. The observed brightness temperature limit (3σ) = 0.5K. The minimum gas mass (H_2) for individual clumps (3σ) = 5.6×10^8 M$\odot$.

At 1.0" resolution the halo is detected to 3σ surface brightness (10μJy beam^{-1}) to a radius of about 3" (27 kpc). The corresponding observed brightness temperature is 9mK.

For completeness, in Figure 3, we show the PSF for the two tapered images. Again, in each case the skirt of the synthesized beam drops below 10% at a radius of about the FWHM of the synthesized beam.[1] For this weighting scheme, the maximum negative sidelobe is 2% for the Core and 3.5% for the Plains arrays.

3 Disk Model

We employ the Spiral array (Spiral214) to image the proto-planetary disk model for an HL Tau analog with a forming Jupiter at 6AU and Saturn at 13 AU (see Memo 6).[2] This model corresponds to the dust emission at 25GHz

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[1] For reference, a Gaussian falls to about 3.3% at this radius.

[2] This simulation did not include the single antenna at Kitt Peak.

for a 1Myr old, Solar mass proto-star, and a 0.1 Solar mass dusty disk, at a distance of 140pc. The total flux density in the model at 25GHz is 4mJy. We compare the results to the previous SW214 (with the Y on the plains) configuration. We perform a limited exploration of Briggs weighting.

The sensitivity is set assuming a 100 hour observation made up of a series of 4 hour syntheses (25 days). We calculate a sensitivity relevant to a 10GHz bandwidth, although the model is not a spectral data cube, and hence we cannot employ bandwidth synthesis. Multi-frequency synthesis will improve the imaging capabilities by filling-in the uv-plane. However, MFS also adds a new parameter to the imaging, namely, the source spectrum. Future simulations will explore MFS with a spectral model as input.

We have explored various combinations of robust weighting, tapering, and cell size to obtain a synthesized beam of $\sim$ 10mas FWHM, while maintaining enough sensitivity to image the disk. In our modest exploration of imaging parameter space, we found a combination of robust = -0.75, Taper = 4mas, and a cell size of 1.2mas yielded a synthesized beam of 10×8mas for both configurations, with an rms of about 88nanoJy beam^{-1} for Spiral214, and 92nanoJy beam^{-1} for SW214. For reference, the Naturally weighted rms for the 214 array in this case is about 30nanoJy beam^{-1}. The loss of sensitivity is due to the down-weighting of the core baselines, and inner Plains baselines, to get to the high resolution of the full array.

Figure 4 shows three images: (i) the input model, (ii) the ngVLA simulation using the new Spiral214 array, (iii) the ngVLA simulation using the original SW214 configuration. The color scale is the same in both simulated images.[3] The two rings are detected, as well as emission from the accretion onto the outer planet, and possibly the inner planet.

While the rms and beam size are similar for Spiral214 and SW214, in terms of rms and beam size, the spiral array image shows fewer artifacts that one might associate with imaging errors, such as the broad stripe across the SE part of the disk, and a more mottled structure, in SW214. The inner ring is also more apparent in Spiral214, although it is somewhat blurred with the inner disk, possibly due to 'skirts' in the PSF, which very between $\sim$ 10% and 30% at a radius of $\sim$ FWHM of the synthesized beam. More detailed studies are in progress to optimize the ngVLA imaging performance in the context of planet formation (Ricci in prep).

Lastly, Table 1 lists some of the relevant synthesized beam and image properties as a function of robust weighting parameter in imaging, for the

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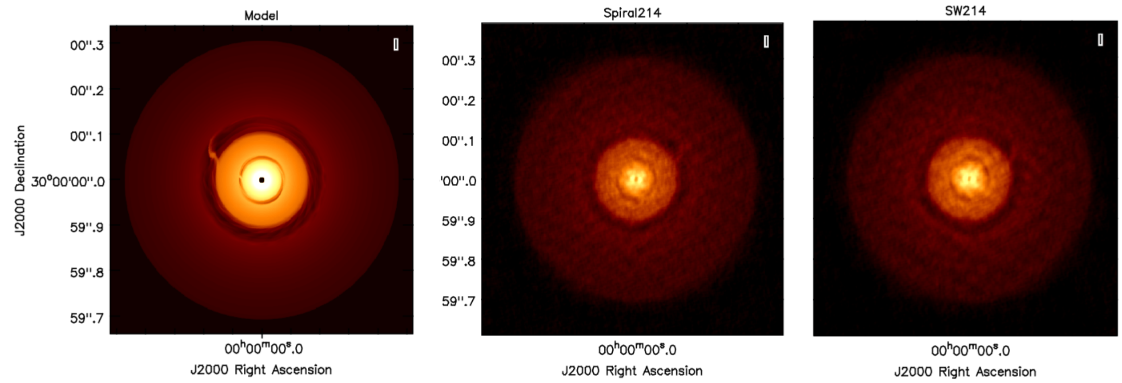
[3] The RA pixel size was erroneously set to positive delta in the input FITS model, so that the images get inverted East-West relative to the model.


Model

Spiral214

SW214

Figure 4: Images of an HL tau analog proto-planetary disk at 25GHz. The model has a forming Jupiter at 6AU and Saturn at 13AU. Left is the input model. Center is the ngVLA simulation using the Spiral214 array, using robust = -0.75, a Taper of 4mas, and a cell size of 1.2mas. Left is the same for the SW214 configuration. The peak surface brightness is about 7 μJy beam^{-1}, and the rms is about 90nanoJy beam^{-1}, in both cases, and the resolution is about 10×8mas.

two arrays. For R $\geq$ 0.5, the imaging is not reliable, due to the broad wings of the PSF. In this case, the PSF is definitely not well fit by a Gaussian, in particular due to the very broad, high skirts, such that the rms becomes hard to define in a small field.

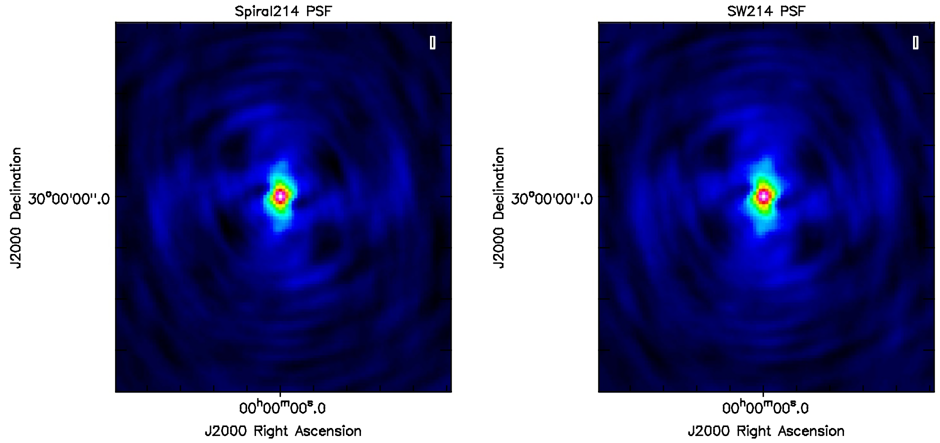


Figure 5: The synthesized beams for the HL tau simulations at 25GHz. Left is for the SW215 configuration, and right is the Spiral214. The PSFs look similar due to the fact that the antennas positions beyond the Plains are identical between configurations.

Table 1: Synthesized Beam Parameters at 25GHz

Array	Robust	FWHM mas	RMS nanoJy beam^{-1}	Skirt: Radius=50mas %	Skirt: Radius=300mas %
Spiral214	-1	5.5 × 5.3	96	0	0
Spiral214	-0.5	9.7 × 7.5	74	6	0
Spiral214	0	13.5 × 11.0	64	22	0
Spiral214	0.5	16.1 × 13.4	–	33	4
SW214	-1	7.2 × 5.7	94	0	0
SW214	-0.5	10.4 × 7.7	72	8	0
SW214	0	13.7 × 11.1	66	22	0
SW214	0.5	15.9 × 13.1	–	32	4

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