

Next Generation Very Large Array Memo #89

Image Fidelity Study of KSG 3 (NGA8): Imaging Molecular Gas in Nearby Galaxies

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June 24, 2021

Abstract

In this memo I study the ngVLA imaging performance for Key Science Goal 3 (driving case NGA8): imaging molecular gas in nearby galaxies. I create a representative simulation that combines observations with several components of the ngVLA, i.e., the Plains+Core subarray of the Main configuration, the Short Baseline Array, and the Total Power antennas. The simulations use mosaicking to cover a detailed model of a spiral galaxy that is nearly 2 arcminutes in diameter and an appropriate amount of thermal noise was added to the model visibilities. The high-fidelity image results demonstrate that the ngVLA is capable of meeting the science requirements for this use case.

1 Requirements, Model and Simulations

I explore the capabilities of the ngVLA in order to fulfill the requirements of the key science goal (KSG) 3, driving case NGA8, namely ‘Imaging Molecular Gas in Nearby Galaxies’. The primary goal of this driving case as described in the ngVLA Science Requirements document [2] is:

“The ngVLA shall have the sensitivity to survey cold gas in thousands of galaxies back to early cosmic epochs, while simultaneously enabling routine sub-kiloparsec scale resolution imaging of their gas reservoirs. In doing so, the ngVLA will afford a unique view into how galaxies accrete, process, and expel their gas through detailed imaging of their extended atomic reservoirs and circumgalactic regions. The ngVLA shall also have enough sensitivity to map the physical and chemical properties of molecular gas over the entire local galaxy population. These studies will reveal the detailed physical conditions for galaxy assembly and evolution throughout the history of the universe.”

The NGA8 use case requires imaging molecular gas in nearby galaxies in Band 6b at a tapered and robustly weighted angular resolution of 100 mas. Additionally, a largest angular scale (LAS) of 120 arcsec is needed. The target sensitivity is 0.75 K in a 2 km/s channel.

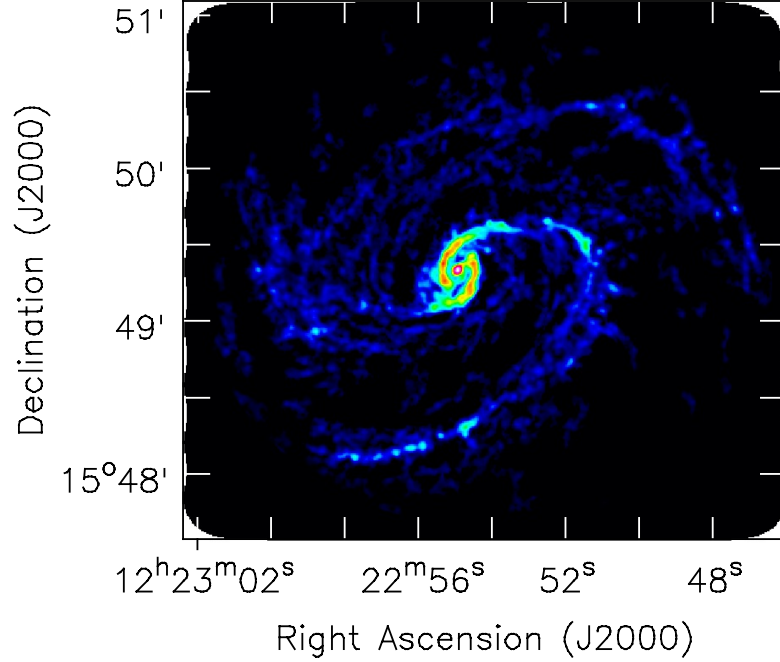


Figure 1: Image of NGC 4321 from the PHANGS-ALMA survey used for making the model image for our study.

For the simulations of the ngVLA observations, I employ the ngVLA Plain+Core interferometric subarray (ngvla-plains-revC.cfg), which is composed of 168 18 m antennas. The LAS of the ngVLA Plain+Core subarray at 115 GHz is ~ 9 arcsec (see ngVLA memo #76 [5] Table 1) and the field of view is ~ 0.5 arcmin. Therefore, in order to properly image the large target galaxies of the NGA8 use case I need to use *mosaic* gridder. Additionally, the LAS of the ngVLA Core subarray is not enough to recover the large scale structures of this science case, prompting the need of the shorter baselines provided by the SBA. The minimum unprojected baseline length of the SBA is $B_{min} = 11$ m corresponding to a LAS at 115 GHz of ~ 24.5 arcsec. This is slightly less than twice the LAS of the ngVLA Core subarray at that frequency but is still not sufficient to meet the LAS requirements stated above. Thus, in addition of the short baselines provided by the Core and the SBA, I require a zero-spacing interferometer given by the total power (TP) response.

1.1 Model Image

For the model I adopt an observation from the PHANGS-ALMA¹ survey of the spiral galaxy NGC 4321 using ALMA at 230.538 GHz. The image used is a moment map with an image size of 474 X 422 pixels, cell size of 0.5 arcsec, and restoring beam of ~ 1.7 arcsec. The diameter of the NGC 4321 galaxy is ~ 230 arcsec, thus nearly filling up the entire image (field of view ~ 3.95 arcmin). In order to use this observation as our model I made the following changes: i) removing the restoring beam, ii) setting the units from K km/s to Jy/pixel; iii) adding a dummy Stokes axis (required by CASA), iv) multiplying the model by an envelope to taper the edges of the image (this taper puts an envelope over the entire image making the edges go to zero, e.g., to help reduce aliasing).

Additionally, I shrunk the model image from a galaxy diameter of ~ 230 arcsec to ~ 120 arcsec in order to match the LAS requirements. This was done by editing the image header to change the cellsize. Then the (originally rectangular) model image is regridded to a square coordinate system having 12288 pixels per side and with a cell size of 20 mas in order to match the parameters that will later be used during imaging (see section 3). This regridding step also provides substantial zero-padding around the source, which is now 100 arcsec in diameter and centered within an image having a 4 arcmin field of view.

1.2 Simulations

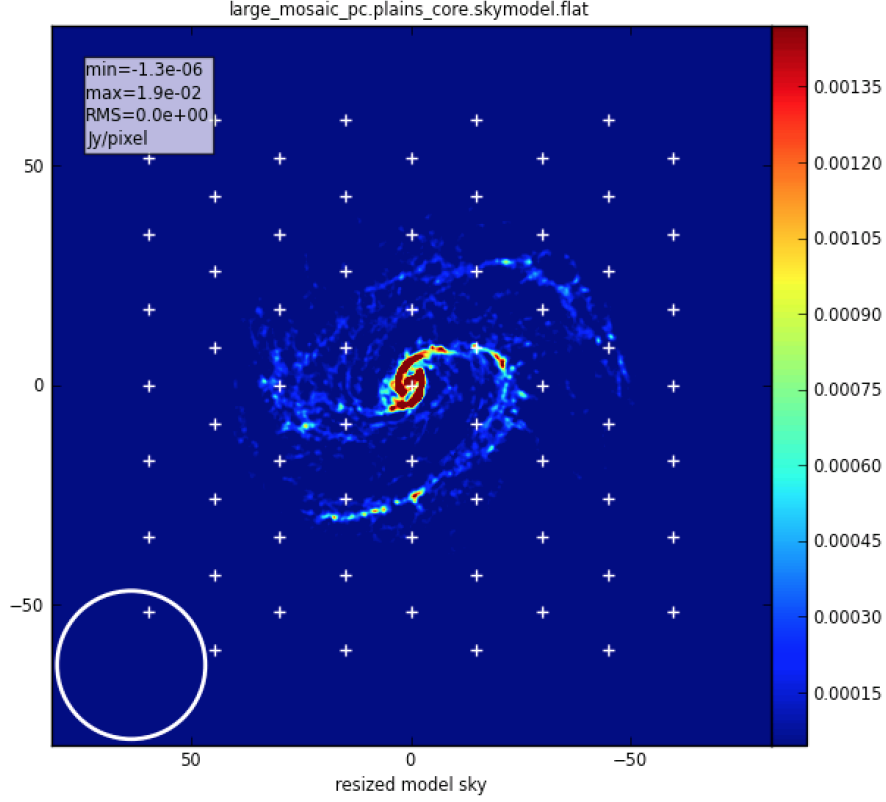
For the simulations, I generated visibilities for the three subarray components used in this study (i.e., Plains+Core, SBA and TP). The simulations used one channel with a center frequency of 115 GHz as a proxy for a single channel of a spectral line cube. `simobserve` alters the original frequency of the observations to the desired one in this case, changing the frequency of the PHANGS image from 230 GHz to 115 GHz. Additionally, the model has been scaled to a representative value of the expected peak flux of the line emission in a (2 km/s channel), in this case in `simobserve` I set `nbright='0.019Jy/pixel'`. This value is estimated from scaling an image of M31 to the distance of Virgo to approximate a typical spiral galaxy for this KSG.

- **Plains+Core:** visibilities generated with CASA task `simobserve` using a 3.9 hr synthesis centered on transit². I used a mosaic of 67 pointings (fields) and an integration time of 10 s³, which corresponds to 21 scans/field.

¹The Physics at High Angular resolution in Nearby Galaxies (PHANGS) using the Atacama Large Millimeter/Submillimeter Array (co-PI: A. Leroy)

²The actual observations would need to be longer to meet the target sensitivity. I selected 3.9 hrs to simplify the simulations, e.g., to avoid a simulation that spans multiple days. The amount of noise (see Section 1.2.2) is scaled such that the final image will have the target sensitivity.

³This is the default value in `simobserve` that I choose for convenience to keep the measurement set files small. Time smearing is not an issue for simulated observations, but this value would need to be reconsidered before scheduling actual observations.

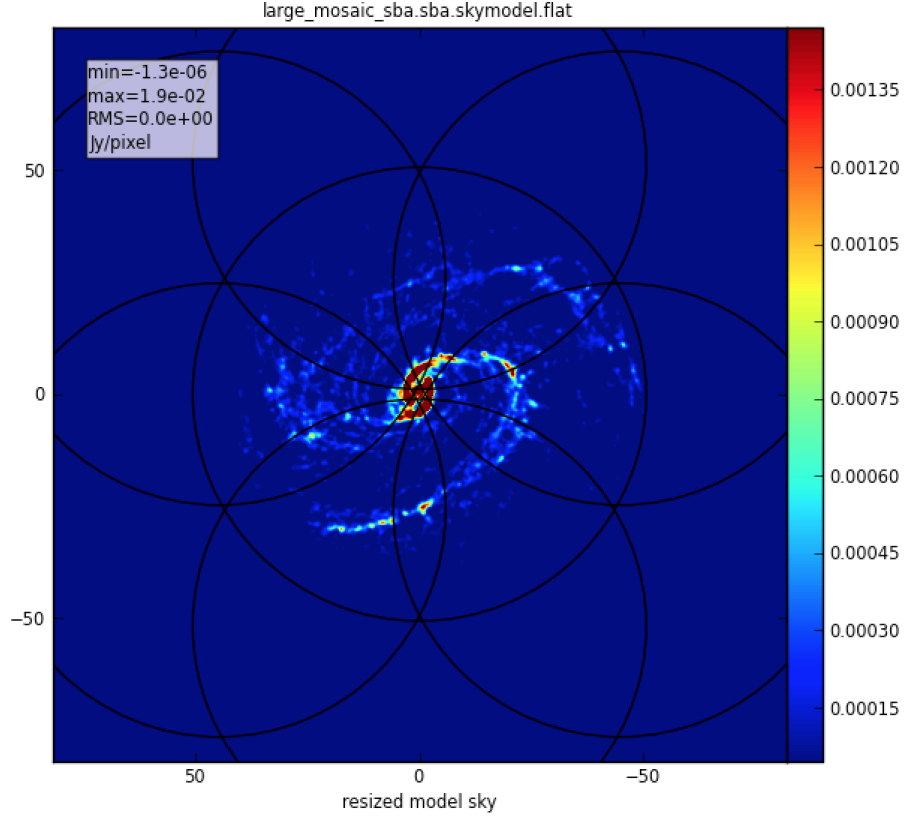


Plains+ Core mosaic simulation. The white crosses are the 67 pointing centers and the white circle in the lower left shows the FWHM of one primary beam.

- **SBA:** visibilities generated with CASA task `simobserve` using a 8.6 hr⁴ synthesis centered on transit. I used a mosaic of 7 pointings (fields) and an integration time of 10 s, which corresponds to 442 scans/fields.
- **Total Power:** In this case, I directly made the simulated image by running the CASA task `imsmooth` on the model image. The resolution of the simulated image is 38.64 arcsecs, which is close to the expected primary beam size of one of the 18m total power antennas (and takes into account other parameters such as blockage diameter, etc).

More information about setting up the simulations and imaging using the SBA subset (together with the Core subarray) using `simobserve` can be found in ngVLA memo #67 [1]. Specifically, I referenced the procedures discussed in memo #67 for construction of custom voltage patterns and imaging of heterogeneous arrays.

⁴This is equivalent to an integration time ratio $t_{sba}/t_{core} = 2.2$ which was used in ngVLA memo #67 [1].

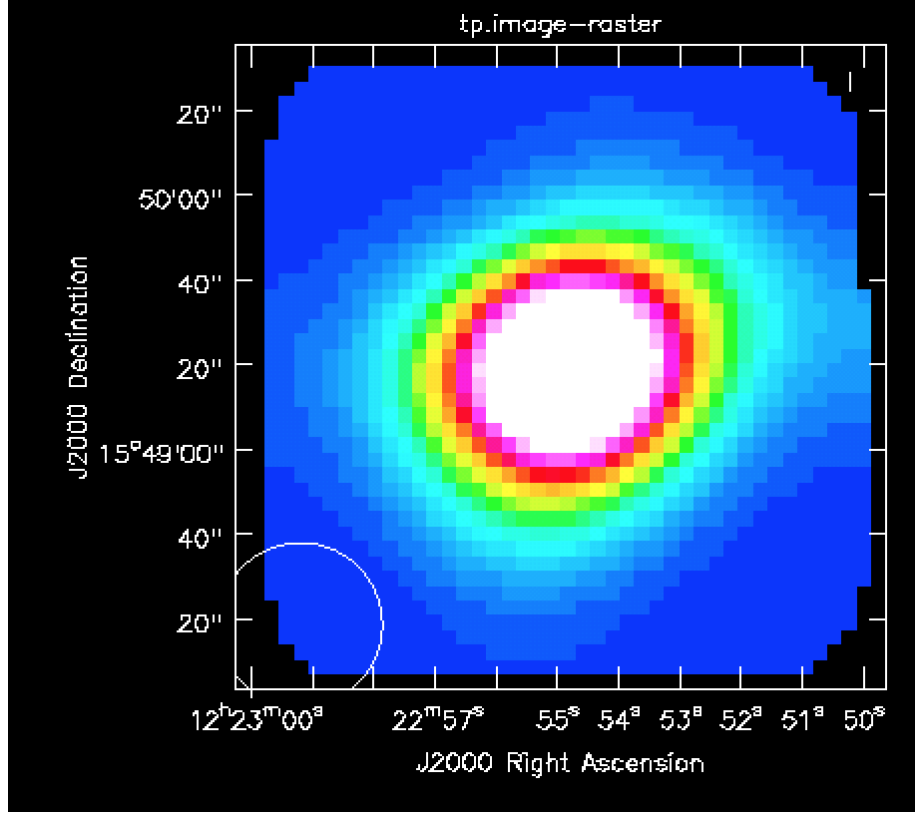


***SBA mosaic simulation.** The black circles show the FWHM primary beam for each of the 7 pointing centers.*

1.2.1 Predicting the visibilities

CASA has several ways to predict the visibilities (e.g., `im.ft`, `sm.predict`, `tclean`) by providing either an image or a component list. The prediction in this study has been made using `simobserve`⁵ and supplying the model image discussed in the above section. The `simobserve` task calls `sm.predict` when predicting the visibilities. Additionally, I use `vp` manager to custom set the primary beam for the 18 m and 6 m antenna interferometers (i.e., `vp.setpbairy(telescope='NGVLA1', dishdiam=dishdiam, blockagediam=0.0)`, where `dishdiam` is the dish diameter in meters and the telescope name should be the same one given when creating the simulation).

⁵Alternatively, the complete analysis made in this memo was made using `tclean`, to predict the visibilities. The `tclean` task saves the model to the `MODEL_DATA` column of the measurement set (MS) when providing a start model image and using the option `savemodel="modelcolumn"`. The final results of the image fidelity using both methods are equivalent.



TP simulated image.

1.2.2 Adding thermal noise

Thermal noise was added, based on the science requirements of KSG 3 (NGA8), using the `sm.setnoise` function of the `sm` toolkit⁶. For the calculations I used the requested rms sensitivity of 0.75 K, which is equivalent to $\sigma_{NA} = 81.6 \mu\text{Jy}$ when using a central frequency of $\nu = 115 \text{ GHz}$ and a resolution of 100 mas. The RMS noise (σ_{NA}) in an untapered, naturally-weighted Stokes I image⁷ will be approximately:

$$\sigma_{NA} \sim \frac{\sigma_{simple}}{\sqrt{n_{ch} n_{pol} n_{baselines} n_{integrations}}} \quad (1)$$

where σ_{simple} is the simplenoise parameter in `sm.setnoise` and corresponds to the noise per visibility, n_{ch} is the total number of channels across all spectral

⁶For more on estimating the expected rms noise in an untapered, naturally-weighted Stokes I image and adding thermal noise to a MS see https://casaguides.nrao.edu/index.php/Simulating_ngVLA_Data-CASA5.4.1

⁷See setnoise function https://casa.nrao.edu/casadocs/casa-5.4.0/global-tool-list/tool_simulator/methods

windows, n_{pol} is the number of polarizations used for Stokes I (typically 2) and $n_{integrations}$ is the number of correlator integration times in the MS (i.e., total on-source time / integration time). The number of baselines $n_{baselines}$ is $N(N-1)/2$ where N is the number of antennas in the array.

Solving for the scaling parameter σ_{simple} in equation 1 and taking into account the mosaicking, the calculation is the following:

$$\sigma_{simple} \sim \sqrt{(1.75)} \sigma_{NA} \sqrt{n_{ch} n_{pol} n_{baselines} n_{integrations}} \quad (2)$$

where the factor of 1.75 corresponds to the overlap of the beams in the mosaic⁸. For the **Plains+Core** subarray, $N=168$ and therefore $n_{baselines}=14028$. The $n_{integrations}=21$ (number of loops), the total number of channels is 1 and the number of polarizations is 2. The estimated σ_{simple} factor is then $\sigma_{simple \text{ PC}} \sim 82.86 \text{ mJy}$, which is equivalent to an image noise of $81.6 \mu\text{Jy/beam}$.

Now for the **SBA** subset, we can scale the target $\sigma_{NA} = 81.6 \mu\text{Jy}$ by area $((D_{subarray}/D_{SBA})^2 = (18/6)^2)$, by the number of antennas ($N_{subarray}/N_{SBA} = 168/19$) and by time ($\sqrt{t_{core}/t_{sba}} = \sqrt{(1/2.2)}$). Thus, for this specific example, a single pointing of the SBA should have a target noise of $\sigma_{NA} \times 53.65$. The σ_{simple} factor for the **SBA** subset is then in general:

$$\sigma_{simple \text{ SBA}} \sim 6.07 \sigma_{simple} \frac{N_{subarray}}{19}, \quad (3)$$

where $N_{subarray} = 168$ for this study (since I am using the Plains+Core subarray). For the **SBA** subset, $N=19$ and therefore $n_{baselines}=171$. The $n_{integrations}=442$ (number of loops), the total number of channels is 1 and the number of polarizations is 2. The estimated σ_{simple} factor is then $\sigma_{simple \text{ SBA}} \sim 2.25 \text{ Jy}$, which is equivalent to an image noise of 4.4 mJy/beam .

1.2.3 Concat

In order to concatenate the Plains+Core with the SBA measurement sets I run the `concat` task and scale the relative weights based on the diameter of the dishes (i.e., `visweightscale = [1., 0.01234]`; where the second value is given by $(6/18)^4$), thus reflecting the sensitivity of the visibilities.

2 Determination of Imaging Parameters

A fundamental requirement of KSG 3 NGA8 is to achieve a spatial resolution of 100 mas at 115 GHz. Therefore, in order to investigate what combination of imaging parameters will produce such resolution, I made a grid of PSFs using a range of Briggs weighting and uv-tapers. I vary the robust value from uniform

⁸I use a value similar to the one from the ALMA pattern.

($R = -2$) to natural ($R = 2$) in steps of 0.4 (for a total of 11 values of robust) and use values of uv-taper from 0 to 200 mas in steps of ~ 8 mas (for a total of 25 values of uv-taper) resulting in a grid of 275 images. The imaging was done using CASA task `tclean` and all the simulated images have an image size of 12244 px. Figure 2 is a color contour representing the achieved resolutions⁹ of the resulting PSFs from our grid using different Briggs robust values and uv-tapers. The combinations of Briggs robust and uv-taper values that result in a resolution of 100 mas is represented by the white solid line and the dashed lines indicate the combination of parameters that yield resolutions between 80 and 120 mas. I also found it desirable to set the `mosweight` parameter to False in order that robust weighting better downweighted the shorter baselines.

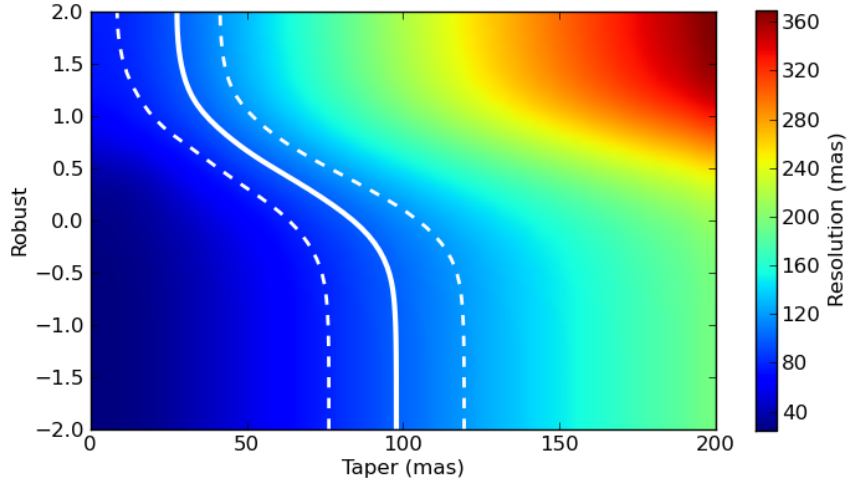


Figure 2: Resolution as a function of the robust and uv-taper values. The color scale shows the size of the clean beam as fit with the CASA `tclean` task. The solid white line are the combination of robust and uv-taper values that will result on a resolution of 100 mas, and the dashed lines delimit the resolutions from 80 to 120 mas.

⁹The plotted resolutions correspond to the geometric mean of the minor and major beam FWHM of the synthesized beam, as parameterized by Gaussian fitting inside the CASA `tclean` task.

2.1 Images with the Desired Resolution

The results from Section 2 show that there are many combinations of robust and uv-taper that will produce a 100 mas clean beam. Although different combinations will formally result in the same resolution, other properties of the resulting PSFs may be very different. Different combinations of robust and uv-taper will also affect the image sensitivity.

For this study, I create new simulated images (from the concatenated MS with modified weights) using only combinations of Briggs weighting and uv-taper which will give 100 mas resolution. I vary the robust value from uniform ($R = -2$) to natural ($R = 2$) in steps of 0.2 in order to have a suite of 21 equally spaced values. I pair each robust value with a uv-taper based on interpolation of the white solid line shown in Figure 2. Table 1 shows the imaging parameters and statistics, where columns 1 and 2 are the robust and uv-taper, respectively. Column 3 gives the geometric mean of the minor and major beam FWHM of the synthesized beam. Column 4 is the standard deviation (σ) scaled relative to that of the naturally weighted image (i.e., σ/σ_{NA}). All the simulated images have an image size of 12244 px and cell sizes of 20 mas.

Each of the 21 new images listed in Table 1 have a resolution that matches the target resolution of the KSG driving case, as parameterized by Gaussian fitting in the CASA `tclean` task. We can see how combinations of robust and uv-taper values will allow for beams of much higher quality (i.e., more Gaussian), but at the expense of sensitivity. To describe the PSF quality I use ‘metric 2b’ which refers to a measure of the level of the PSF at a radius of one FWHM (e.g., ngVLA memo #65 [4], #76 [5]).

Table 1: Parameters and statistics of the images with resolutions ~ 100 mas.

Robust	Taper	Resolution	σ/σ_{NA}
	[mas]	[mas]	
-2.0	97.83	100.00	1.912
-1.8	97.82	100.00	1.912
-1.6	97.82	100.00	1.912
-1.4	97.79	100.00	1.911
-1.2	97.72	99.99	1.908
-1.0	97.61	100.03	1.903
-0.8	97.23	100.03	1.888
-0.6	96.26	99.97	1.856
-0.4	93.82	99.57	1.791

Table 1 – Continued on next page

Table 1 – Continued from previous page

Robust	Taper	Resolution	σ/σ_{NA}
	[mas]	[mas]	
−0.2	90.32	99.97	1.690
+0.0	83.85	100.00	1.563
+0.2	74.19	99.39	1.428
+0.4	64.52	100.33	1.305
+0.6	53.23	99.62	1.191
+0.8	43.57	99.25	1.102
+1.0	37.10	100.12	1.047
+1.2	32.26	99.92	1.018
+1.4	29.73	100.00	1.006
+1.6	28.37	99.83	1.001
+1.8	27.93	99.96	1.000
+2.0	27.74	100.00	1.000

Figure 3 is the resulting ‘*sculptability*’ curve from the analysis of the 21 constant resolution images. This figure shows the level of the PSF skirt (as measured with metric 2b; solid blue line) versus the Briggs robust parameter. They also show the inefficiency factor (η_{weight} ; solid green line) which is the factor by which the sensitivity increases over natural weight and no uv-taper. A PSF level of 10% (dashed blue line) and corresponding inefficiency factor for the robust-taper combination that yields this PSF level (dashed green line) are also shown.

3 Imaging

The imaging was done using the CASA task `tclean` on the MS produced by `concat` (i.e., the concatenation of the Plains+Core and the SBA datasets). The input model was spatially correlated on scales of $1.7''$ ¹⁰ and so the resulting image at 100 mas resolution will have a high degree of smoothness. Due to the amount of extended emission, cleaning required a very large number of minor cycle iterations in order that the residuals approached the thermal noise level ($> 500,000$ iterations).

The imaging parameters that I used are the following:

- `multiscale` imaging with a range of scales to improve the speed and

¹⁰This scale corresponds to the pixel size of the PHANGS model; thus there is no detail on any smaller scales except for the added thermal noise.

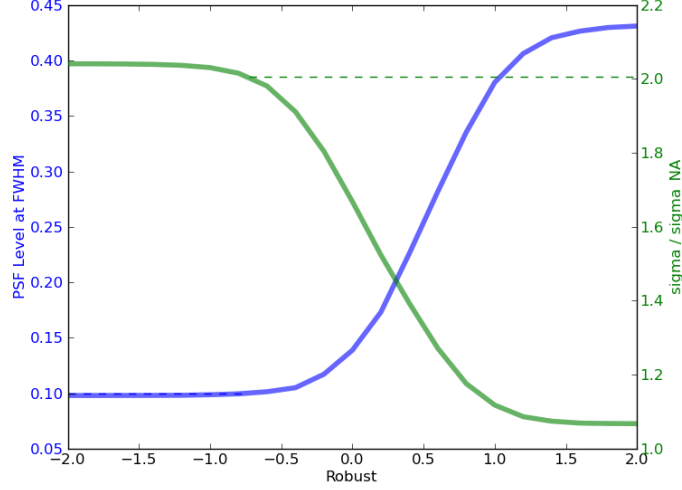


Figure 3: PSF skirt level (as measured with metric 2b; solid blue line) and inefficiency factor (solid green line) versus the Briggs robust parameter. A PSF level of 10% (dashed blue line) and corresponding inefficiency factor for the robust-taper combination that yields this target level (dashed green line) are also shown.

quality of the deconvolution (which also helps with the smoothness of the input model)

- **robust=0** together with a **taper=83.85 mas**; combination that yields a beam of 100 mas, a PSF level 14% and a loss in sensitivity of ~ 1.6
- Interactive masking; to adjust the mask each major cycle, largely to avoid cleaning negative regions created by PSF sidelobes
- Image size of 12288 pixels; to achieve a field of view that includes the entire primary beam of the outer mosaic pointings, which minimizes aliasing
- Cell size of 20 mas; to oversample the restoring beam by a factor of 5

3.1 Feather

I combined the interferometric image with the total power simulated image using the CASA task **feather**, based on the following procedure:

- The TP image was multiplied by the primary beam of the interferometric mosaic and used as the low-resolution input to **feather**
- The interferometric image, before primary beam correction, was used as the high-resolution input to **feather**

- The **feather** task was run with default values for the remaining input parameters, i.e., `sdfactor`, `effdishdiam` and `lowpassfiltersd`
- The feathered image was primary beam corrected by dividing by the interferometric image's PB

The resulting image is shown in Figure 4. The spiral galaxy model is reconstructed well with no readily apparent artifacts. The large-scale noise seen outside the galaxy matches the amplitude and spatial scale of the noise added to the SBA simulation, and the small-scale noise corresponds to the noise added to the Plains+Core simulation. The primary beam correction has boosted the noise around the edge of the image.

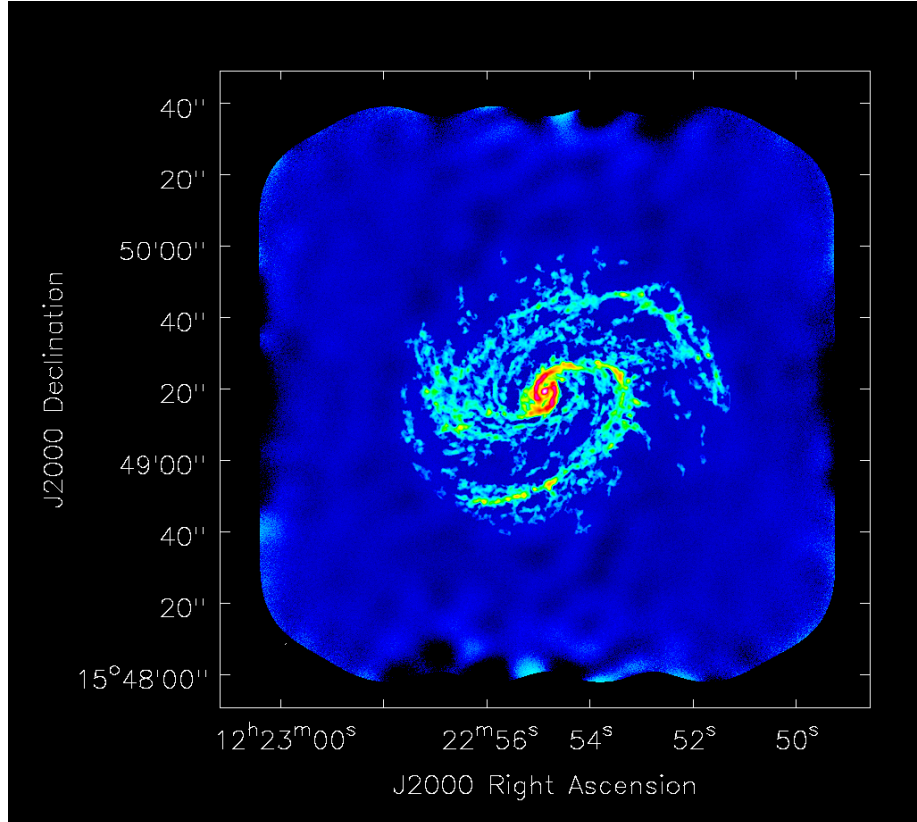


Figure 4: The final image after feathering.

4 Analysis of Image Fidelity

Here I measure and analyze the resulting image fidelity for the image produced by feather. By fidelity I refer to the comparison of the model with the resulting image, such that a high fidelity image has smaller residuals after subtracting the model from the image.

In this work I use the definition of fidelity given in equation 4, as defined in ngVLA memo #67 [1] and also presented in the ngVLA Science Requirements document [2]:

$$F = 1 - \frac{\sum_i [\beta_i W_i * (|I_i - M_i|)]}{\sum_i \beta_i^2 W_i} \quad (4)$$

where I is the resulting image and M is the model. Additionally, β_i is defined to be $\max(|I_i|, |M_i|)$ and W_i is a ‘window function’ which defines the region where the fidelity is evaluated ($W_i = 0$ outside and $W_i = 1$ inside). For more details about this image fidelity definition see ngVLA memo #67 [1].

In order to subtract the model from the image we first need to convert to model to brightness units of Jy/beam. This is done by convolving the model by the same restoring beam that appears in the image’s header. I also create model and image cutouts using a region that matches the size of the original PHANGS image. This region includes all non-zero pixels of the model image but avoids the areas of model zero-padding, which in the image appear as noise-like regions which are enhanced near the edge of the mosaic by the primary beam correction. The use of cutouts replaces the need for the window function in the fidelity calculation, i.e., $W_i = 1$ everywhere inside the cutout.

The final fidelity calculated using Equation 4 is 0.9898, representing the weighted average of the difference between the final image and the input model. Figure 5 shows an image of the fundamental term in the fidelity calculation prior to weighting and averaging, i.e., image minus model. The image area corresponds to the size of the cutout region. The residuals over most of the galaxy are characteristic of the residuals created by multi-scale clean, and are of the same order of magnitude as the thermal noise. Larger magnitude residuals are present at the position of the galaxy’s core and the bright, inner portions of the spiral arms. At these locations the intensity of the final image is $\lesssim 1\%$ higher than that of the convolved model, so while the absolute error causes these regions to stand out, the relative error does not seem unusual. Figure 6 shows an image of the fundamental term in the fidelity calculation prior to weighting and averaging, i.e., image minus model divided by model. You can think about this image as the fidelity per pixel. The unmasked pixels in Figure 6 have a standard deviation of 0.032 and a median value of -0.01 .

Figure 7 shows the accuracy with which flux is recovered as a function of angular scale in each simulated image (see ngVLA memo #67 [1] for more details

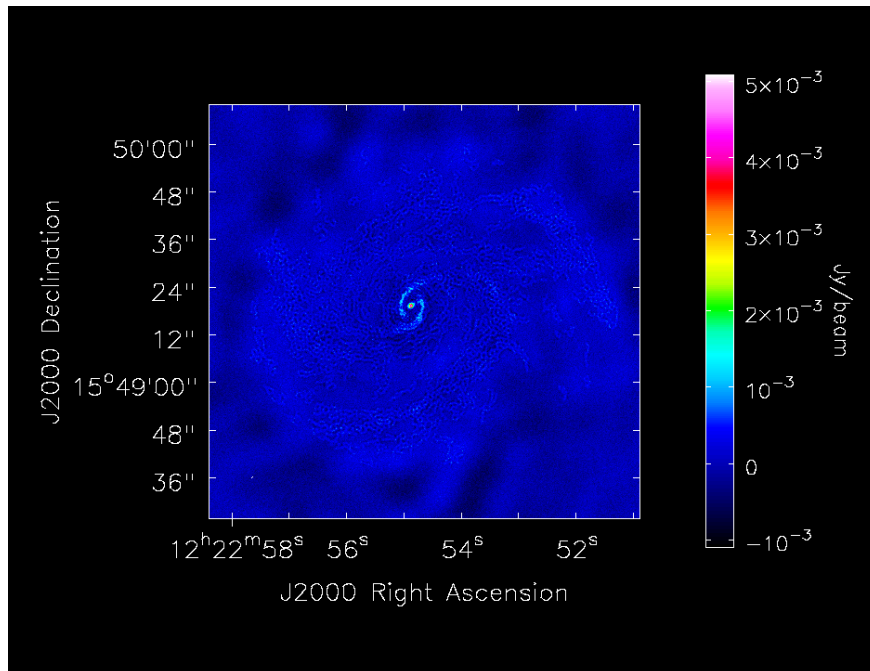


Figure 5: Image of the convolved model subtracted from the final image.

about the used heuristic), and calculating the median fraction of integrated flux recovered in a circular aperture compared to the simulation input image as a function of aperture radius. The final image after feathering using all the considered arrays recover the input flux to better than 5% at all scales.

5 Summary

These results demonstrate that the ngVLA is capable of producing high fidelity images that meet the requirements for Key Science Goal 3 (driving case NGA8). The fine details of the spiral galaxy structures are recovered well due to the large number of antennas in the Plains+Core subarray. The resulting ~ 4 hour synthesis produces a large number of visibilities that provide excellent u-v coverage, producing a PSF with low sidelobes and allowing for accurate deconvolution. The SBA is highly effective in providing shorter baselines that significantly fill in the central portion of the u-v plane that could not be measured with the larger diameter antennas of the Main array. This allows for a good recovery of extended emission on larger scales, e.g., the galaxy's spiral arms. Finally the total power map was important to accurately measure the integrated flux of the galaxy and to recover diffuse emission on the largest scales, i.e., the galaxy's diameter.

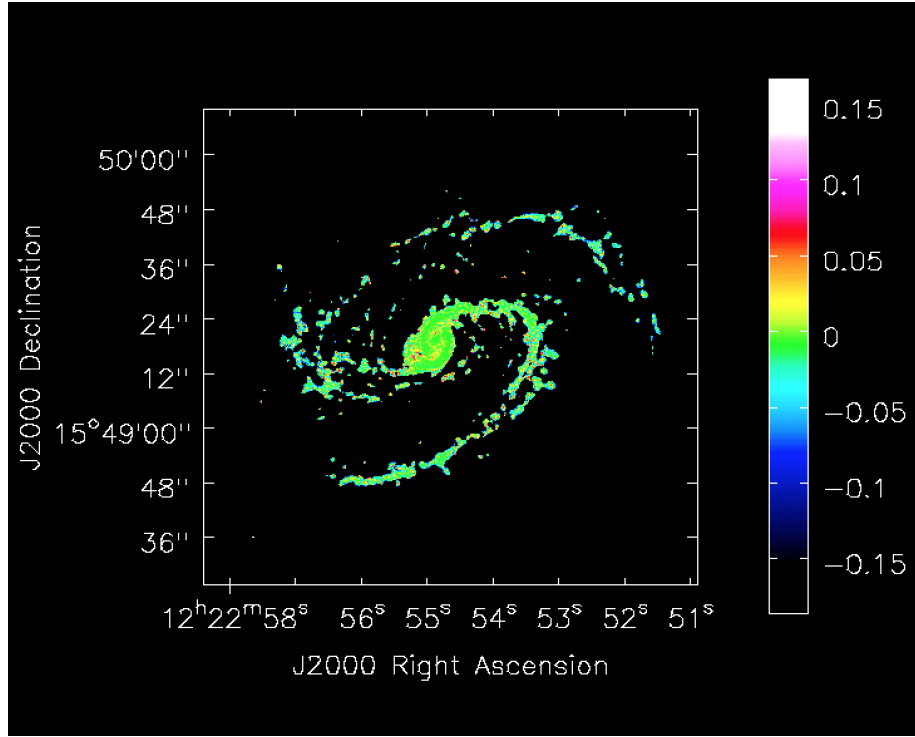


Figure 6: Image of the relative residuals, i.e., $(\text{model-image})/\text{model}$. The image is masked where the convolved model is fainter than 5 mJy/beam.

Acknowledgments

Many thanks to Brian Mason and Chris Carilli for very useful discussions and insights, specially for helping to choose representative values for making the simulations. This project made use of some of the codes available here: <https://github.com/teuben/dc2019/tree/master/scripts/ngVlaSbaSims>. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

References

- [1] Mason, B., *Next Generation Very Large Array Memo No. 67 Demonstration & Analysis of ngVLA core + Short Baseline Array Extended Structure Imaging*.
- [2] Murphy E., Selina R., ngVLA SAC, *ngVLA Science Requirements document 020.10.15.00.00-0001-REQ*.

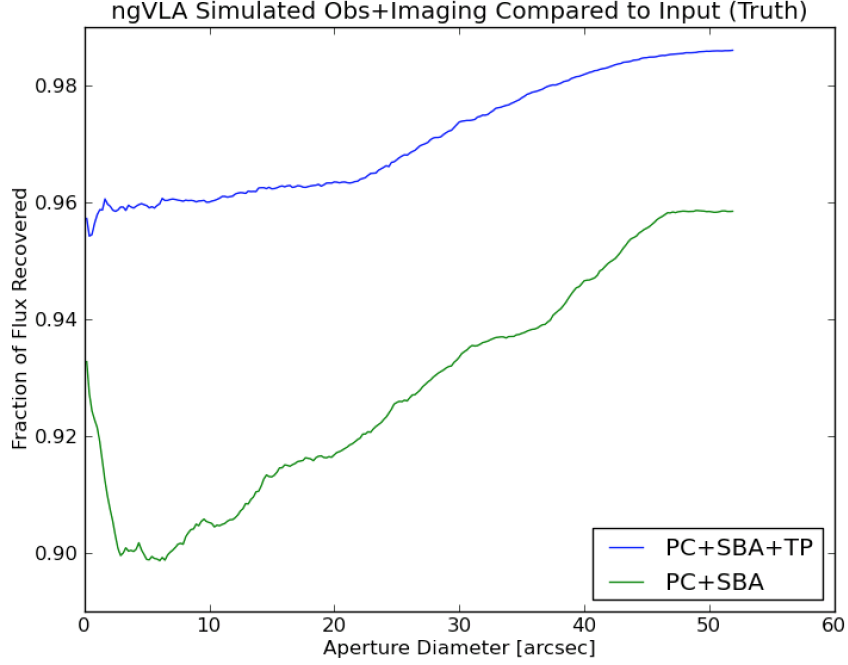


Figure 7: Median fraction of spatially integrated flux density recovered as a function of aperture diameter for the image made from the concatenated data set (Plains+Core plus SBA) and from the same image after feathering with total power.

- [3] Rosero, V., *Next Generation Very Large Array Memo No. 55 Taperability Study for the ngVLA and Performance Estimates.*
- [4] Rosero, V., *Next Generation Very Large Array Memo No. 65 Sculpting of the Synthesized Beam and Image Fidelity Study of KSG 1: Imaging of Protoplanetary Disks.*
- [5] Rosero, V., *Next Generation Very Large Array Memo No. 76 Subarray Selection for the Reference Observing Program.*