ngVLA Memo 43

The ngVLA Short Baseline Array

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v1 - 2 April 2018: first draft.

v2 - 13 April 2018: incorporate RS comments, add discussion of other ngVLA configurations including Spiral-214 Rev.B

v3 - 18 April 2018: add histogram of baseline lengths & release

Abstract

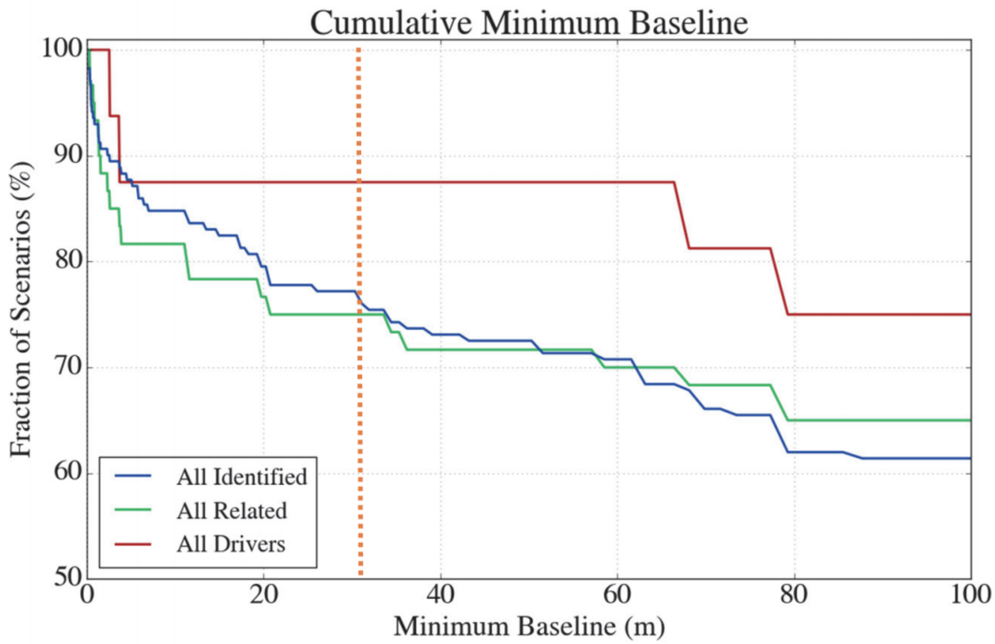
We present the reference design for an ngVLA Short Baseline Array (SBA) comprising 19 6m antennas and 4 18m total power antennas. Under the most conservative assumptions the SBA interferometer will provide good supporting data for the ngVLA with total integration times 2.8× those of the ngVLA itself, and with total power integration times 4.9× those of the main ngVLA array. We also consider stand-alone total power options, and find that other things being equal a 50m-100m single dish can provide similar supporting data as the SBA as a whole in comparable integration times: 2.2× to 4.9× the ngVLA main array integration time. Given reasonable expectations of the distribution of requested science use cases these approaches are viable options to provide the larger spatial scale information that are required by $20\% - 30\%$ of identified ngVLA science use cases.

1 Introduction

The ngVLA reference design (NGVLA Memo 17) calls for 214 antennas, each with a diameter of 18 meters. This design is driven by the sensitivity requirements of Key Science Use Cases (NGVLA Memos 18 & 19) subject to cost constraints. These science cases require sensitivity on a range of spatial scales, and an interferometer can only provide accurate information up to some Largest Angular Scale (LAS). This largest scale θ_{LAS} is usually expressed as $\theta_{LAS} = k\lambda/B_{min}$, where λ is the wavelength being observed, B_{min} is the shortest well-sampled baseline length, and k is a constant of order unity. The shortest possible spacing is often in turn set by the requirement that antenna elements not collide; for ngVLA $B_{min} \sim 1.65\,D = 30$m. Approximately 25% of identified science use cases require information on larger spatial scales than this (see Figure 1). This information can be obtained by adding data from a single dish telescope, from a more compact interfereometer, or from a combination of the two (as is the case for the ALMA Compact Array). A minimum criterion for the instrument providing the short spacings is it provide continuous uv coverage to shorter spacings from B_{min}. If the short spacing instrument is a single dish, this implies the antenna diameter $D > B_{min}$. If the short spacing instrument is an interferometer, it must have baselines at least as long as B_{min}. It is also necessary for the short spacing instrument to provide relevant sensitivity in integration times that are feasible.

In this memo we present a conceptual design of a system to provide larger spatial scale information for ngVLA observations. This system comprises an interferometric array of small antennas, plus a few ngVLA 18-meter antennas operated in total power mode. We calculate the integration time that these instruments would require in order to complement ngVLA main-array observations. We also consider the alternative approach of complementing the ngVLA main array by a larger, stand-alone single dish.

For the sake of specificity many of the calculations and simulations in this memo are done at a reference frequency of 100 GHz ($\lambda = 3.0$ mm). We use the ngVLA reference configuration `nudged-30m-SWcore.cfg`, which is essentially the core of the "South West 214" configuration (Greisen 2017) available on the ngVLA web site. This configuration has 114 18m ngVLA antennas within the central $D = 1.5$ km. As this memo was being completed, a new ngVLA configuration has emerged (Spiral-214 Rev.B, Carilli 2018). This configuration has a slightly smaller core— 94 18m antennas within 1.3 km— and $\sim \sqrt{2}\times$ less surface brightness sensitivity on scales relevant to the SBA. This and other ngVLA configurations are discussed in § 6.



v25

Figure 1: The cumulative shortest baseline required for identified, key ngVLA science cases (from ngVLA memo 18). The dashed, vertical, orange line shows the ngVLA main array minimum baseline; this is the minimum physical baseline, not necessarily the largest well-reconstructed spatial scale. If a largest useful angular scale $\theta_{LAS} = 0.5\lambda/B_{min}$ is adopted (see § 2) then fully 30% of identified science use cases require capability not provided by the ngVLA 18m array.

2 Largest Angular Scale, Spatial Frequency Overlap, and Field of View

The largest spatial scale that an interferometer can measure is determined by its shortest baseline, and it is often said that an interferometer is sensitive to sky brightness components of size up to λ/B_{min}. It is typically the case, however, that practical performance at these largest scales is not very good. For instance, Wilner & Welch (1994) point out that a baseline of length B_{min} will only measure 3% of the total flux density of a Gaussian component of FWHM λ/B_{min}. No clear consensus exists in the literature as to how a Largest Angular Scale (LAS) θ_{LAS} is to be defined, and indeed it dependens on the signal-to-noise ratio, uv-coverage and sky image characteristics in question. Using the parameterization $\theta_{LAS} = k\lambda/B_{min}$, the VLA adopts values of either $k = 0.6$ or $k = 0.8$, depending on the configuration. ALMA adopts $k = 0.6$, which is the largest uniform disk for which simulated observations using ALMA configurations recover 10% of the total flux density. Wilner & Welch (1994) tabulate the values of k for which observations of a Gaussian component of FWHM $k\lambda/B_{min}$ on a baseline of length B_{min} recover 50% ($k = 0.44$), $1/e \sim 37\%$ ($k = 0.54$), and 10% ($k = 0.80$) of the total flux. In this memo, we adopt $k = 0.5$ unless otherwise stated, yielding

$$\theta_{LAS} = \frac{1}{2}\frac{\lambda}{B_{min}} \tag{1}$$

For the `nudged-30m-SWcore.cfg` ngVLA configuration the shortest baseline is 30.3 m, corresponding to an LAS by this defintion $\theta_{LAS} = 10''.2$ at 3mm.

An instrument designed or selected to "fill in" the missing spatial frequencies below B_{min}/λ should measure spatial frequencies out to at least that high in order to provide continuous uv-coverage. Per the preceding discussion, the very shortest spatial frequencies are often not very well measured, and similarly the very highest spatial frequencies of the lower-resolution (*e.g.* single dish) capability may not be very well measured either. Best practices (see Stanimorivic 2002 and references therein) therefore dictate that the complementary instruments obey the relation:

$$X > (1.5 - 2) \times B_{min} \tag{2}$$

where B_{min} is the shortest baseline of the higher-resolution instrument in question, and X is the diameter of the single dish— or the *longest* baseline of the more compact interferometer— that is being used to provide larger-scale information. This ensures that the overlap of high-quality Fourier information is achieved, with the added benefit of facilitating verification of the consistency of the datasets, for instance, their calibration.

The primary beam of an antenna (of diameter D) determines the resolution of that antenna when it is operated as a single dish, and the field of view (FOV) when it is interferometrically cross-correlated with like antennas. If the aperture is uniformly illuminated, the primary beam is an Airy disk with FWHM $\theta_{FWHM} = 1.02\lambda/D$. The VLA and ngVLA have primary beams which approximately obey this relation (modulo subreflector blockage for the VLA). Antennas designed to operate as single dishes typically taper the illumination more gently, resulting in slightly fatter beams $\theta_{FWHM} = (1.15 - 1.2)\lambda/D$. We assume $\theta_{FWHM} = 1.15\lambda/D$ for single dish antennas unless otherwise specified.

3 Design Criteria & Process

We set out to define a reference architecture that provides short spacing information for the ngVLA 18-m reference array. Key considerations are:

1) The SBA should provide baselines out to at least $1.5 \times B_{min}$ of the ngVLA itself ($45m$), preferably closer to $2 \times B_{min}$ ($60m$); and should provide baselines down to $B_{min}/3$ or less in order to have intrinsically useful spatial dynamic range, and to overlap in uv-coverage with a modestly-sized single dish (*e.g.*, an 18m ngVLA antenna).
2) The SBA should have comparable surface brightness sensitivity as the ngVLA itself, when the ngVLA beam is tapered to a relevant angular scale. As discussed in the text, we take this to be either the ngVLA LAS, or the beam size of the complementary short-spacing capability in question.
3) The SBA should be maximally compact in order to sample the largest spatial scales possible, and provide good surface brightness sensitivity.
4) To minimize up-front and operational costs:
   a) The SBA should have a number of antennas $\sim 10\%$ (or fewer) that of the main array.
   b) The SBA antennas and their electronics should share components to the extent feasible.
5) The SBA must respect anntenna-clearance requirements.

An idea of what is required can be obtained by the following simple calculation. Assuming hexagonally close packed SBA antennas of diameter d, with a minimum baseline $B_{min} = 1.75d$ set by clearance requirements[1] an array covering out to $B_{max} = 45m$ will require a number of antennas

$$N_{ant} = 0.9069 \left(\frac{B_{max}}{1.75d}\right)^2.$$

Keeping $N_{ant} < 0.1 \times 214 \sim 21$ then requires $d > 5.3m$. Here 0.9069 is the area filling factor of hexagonally closed packed circles. The requirement that the SBA cover down to $B_{min,ngVLA}/3 = 10.1m$ implies that $d < B_{min}/(3 \times 1.75) = 5.77m$. Taken together this suggests an array of approximately 20 antennas with diameters between $5m$ and $6m$. More, smaller antennas would be scientifically desirable in order to sample shorter spacings and provide more uv coverage; the fundamental constraint is cost.

4 Short Spacing Array Reference Design

Based on these requirements, Dean Chalmers and collaborators at the National Research Council of Canada are designing a representative 6m antenna for the ngVLA short baseline array (ngVLA Doc: 020.05.40.05.01-0003-SOW). This antenna uses the ngVLA main-array receivers, an attractive feature for operations and cost containment. The physical clearance requirement is $11m$. Smaller antennas would likely require changes to the receiver optics, and could entail

[1] assuming a scaled ngVLA main array antenna design.

significant changes to the antenna response characteristics (e.g. polarization). Assuming a beam width $1.02\lambda/D$ this antenna has a primary beam of $105''$ (at $\lambda = 3\,\mathrm{mm}$).

A convenient, roughly circular coverage is provided by a hexagonal close packed configuration of 19 antennas. Using the NRC 6m antenna design, we propose the SBA reference configuration shown in Fig. 2 and listed explicitly in Appendix A. It is approximately hexagonally close packed, subject to the 11m clearance requirement and with the positions slightly randomized to improve uv-coverage. It has a filling factor of $f = 27\%$, with shortest and longest baselines of $11.0m$ and $55.7m$, respectively. At $\lambda = 3mm$ the natural-weight synthesized beam FWHM is $\sim 10''$; using the previously stated guideline ($\theta_{LAS} = 0.5\lambda/B_{min}$) guideline gives $\theta_{LAS} = 28''$, but since the SBA is a close packed array with many short baselines we expect that better performance on large scales will be achieved. For purposes of matching sensitivity with a total power antenna (§ 5) we make the more conservative assumption— in terms of the requirement imposed on the single dish— that the SBA can recover scales down much closer to λ/B_{min}.

The instantaneous uv coverage of the SBA and ngVLA SWcore is shown in Fig. 3. The SBA uv coverage and PSF obtained in a short (1000 second = 16 minute 40 second) track is shown in Fig. 4. The relatively high sidelobes result from the multiplicity of the very shortest baselines and are characteristic of close-packed arrays. They can be mitigated somewhat by longer observations, which increases the uv-coverage. These results were obtained using a simulation in CASA. For information on how to run CASA simulations of the SBA see Appendix B.

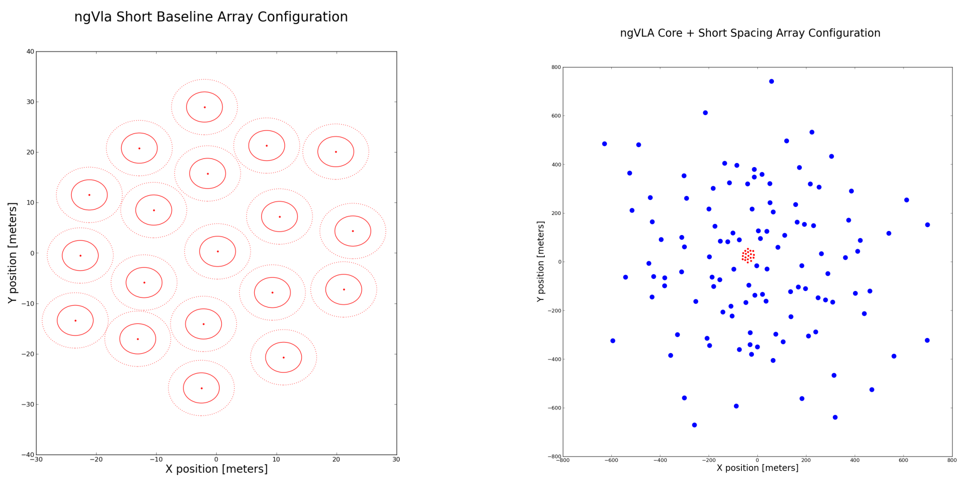


Figure 2: SBA reference design (left) and notional placement within ngVLA SWcore (right). SBA antennas are shown by red solid lines, with their clearance zones shown by red dotted lines. ngVLA 18m antennas are shown by blue solid lines, with their clearance zones depicted as blue dashed lines. A central placement of the SBA relative to other ngVLA antennas is desirable in order to provide reasonable uv-coverage for observations with the entire suite of antennas as a single interferometer.

Several of the science drivers require coverage to shorter baselines than is practical with the SBA interferometer (see again Fig. 1). For these, and other yet to be identified science cases, the SBA includes four 18m ngVLA antennas operated as single dishes, *i.e.* in total power mode. While it will be essential to carefully review and (likely) upgrade these antenna specifications with total power observations in mind, using a design closely based on the ngVLA 18m antenna design can enable some economies of scale while still meeting the requirement $D > 1.5B_{min} = 16.5m$ with respect the the SBA interferometer's minimum baseline $B_{min} = 11m$. As previously noted single dish telescopes are usually illuminated with a more gradually declining taper than the current ngVLA optics calls for in order to minimize sidelobes, particularly the nearest sidelobe. For this reason completely interchangable receivers may not be optimal for these single dishes.

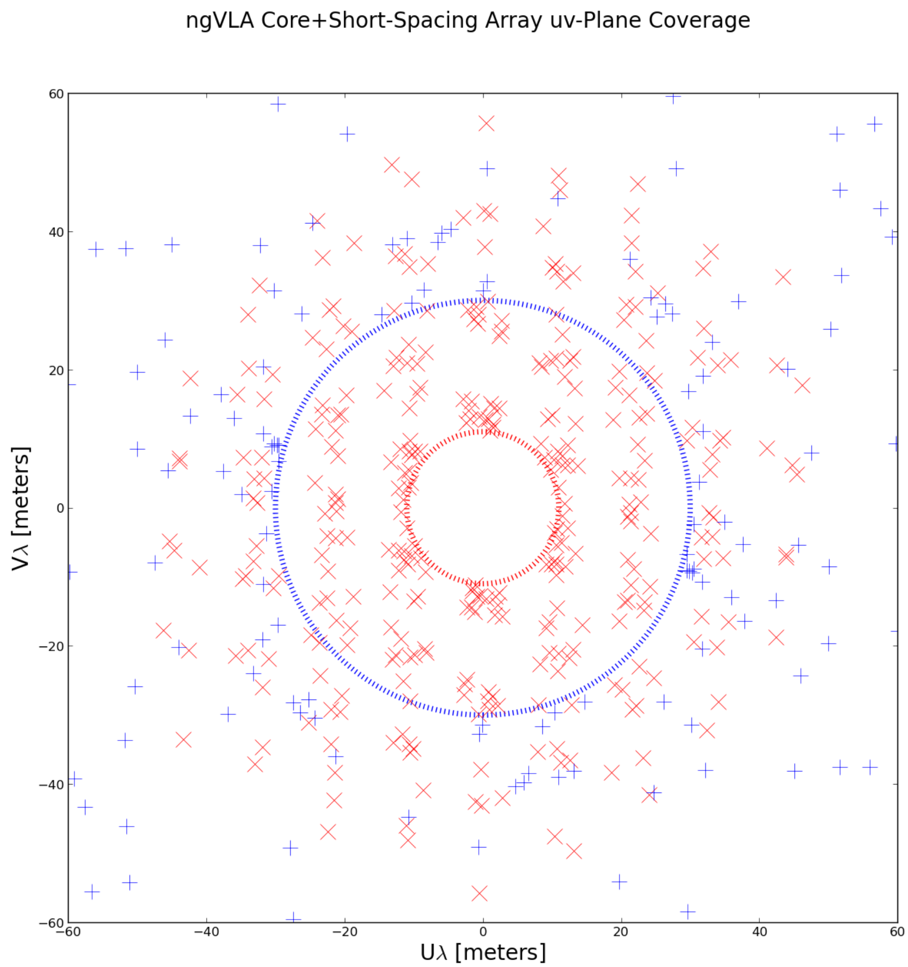


Figure 3: Instantaneous *uv* coverage of the SBA and the ngVLA SWcore, shown here near the origin. The ngVLA-core physical avoidance zone is shown as a dashed blue line, while the SBA avoidance zone is shown as a dashed red line.

5 Sensitivity Analysis

We use an extension of the formalism presented in Mason & Brogan (2013, hereafter MB13) to evaluate the sensitivities of the various capabilities under consideration— ngVLA 18m array, SBA interferometer, total power antennas— and to calculate relative integration time requirements. The original calculations of MB13 stipulated that the *flux density sensitivity* of (mosaic) maps made with two telescopes to be compared should be equal, when each map was made with data *only* from the common, overlapping *uv* range. This results in maps with comparable surface brightness sensitivities on the common spatial scales. The approach has the advantage that it is very straightforward to calculate the time ratios by counting baselines. Here (also as in Mason 2016) we adopt a more precise formulation that matches *surface brightness sensitivity* directly when the maps in question are *uv*-tapered to comparable or equal spatial resolutions. We discuss the choice of matching scale below, but in general we take it to be the resolution of the lower-resolution instrument, if that resolution is comparable to or less than the largest angular scale (LAS) that can be faithfully imaged by the higher resolution instrument. If the lower-resolution instrument's angular resolution is considerably lower than the high-resolution instruments LAS, we match at that LAS.

As discussed in MB13, Mason (2016), and Appendix C, the single-dish integration time t_{SD} (primary beam FWHM θ_{SD}) required to match an interferometer map's surface brightness

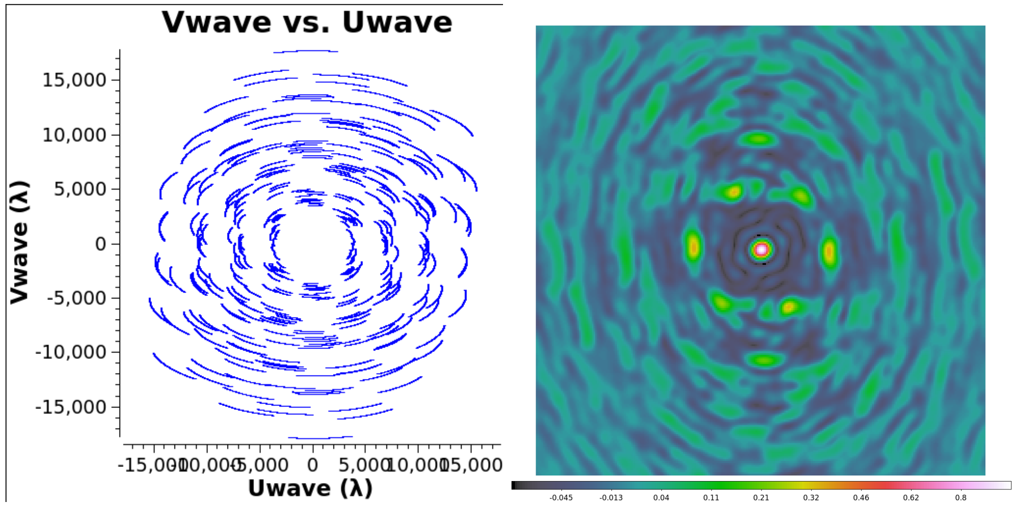


Figure 4: SBA uv-coverage (left) and point spread function (PSF − right) obtained in a short (16m40s = 1000s), simulated observation of a single field at $\delta = -17°$, at a nominal frequency of 100 GHz ($\lambda = 3.0\,mm$). The natural-weight synthesized beam PSF in this simulation is $11''.1 \times 10''.1$ (FWHM). (*note:* TCLEAN gridder='standard' was used to calculate this PSF).

sensitivity (synthesized beam FWHM θ_{int}, achieved by uv-taper in general) is:

$$\frac{t_{SD}}{t_{int}} = \left(\frac{D_{int}}{D_{SD}}\right)^2 \times \left(\frac{\theta_{int}}{\theta_{SD}}\right)^4 \times 2N_{b,eff}(\theta_{int}) \tag{3}$$

where D represents the diameter of the interferometer or single dish antennas, and $N_{b,eff}(\theta_{int})$ represents the effective number of interferometer baselines as a function of uv-taper, given by Eqs. 9 and 15 in Appendix C. Here we are assuming that instrumental parameters such as T_{sys} and aperture efficiencies are equal. This is probably a reasonable approximation for the SBA reference design, which shares a site and many design elements. Frayer (2017, ngVLA Memo 14) presents a detailed comparison of these instrumental parameters for GBT and ngVLA.

The equivalent expression for the case of two interferometric arrays, following Mason & Brogan 2013, is:

$$\frac{t_2}{t_1} = \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{\theta_1}{\theta_2}\right)^4 \frac{N_{b,eff,1}}{N_{b,eff,2}} \tag{4}$$

Another case of interest is that where one wishes to make a map with a sufficiently large single dish that its beam is considerably *smaller* than the largest angular scale that is well-measured by the interferometer. In this case, the most stringent use case would require matching surface brightness sensitivities not on the single dish beam scale θ_{SD}, but on the interferometer's LAS. If we allow that the single dish map in this case can be smoothed to a lower resolution $\theta > \theta_{SD}$, it can be shown that the required time ratio is

$$\left.\frac{t_{SD}}{t_{int}}\right|_{\theta} = \left(\frac{\theta}{\theta_{SD}}\right)^2 \frac{N_{b,eff}(\theta)}{N_{b,eff}(\theta_{SD})} \left.\frac{t_{SD}}{t_{int}}\right|_{\theta_{SD}} \tag{5}$$

Table 1 presents the time ratios needed to match four specific telescope pairings of interest:

1) the SBA interferometer and the ngVLA SWcore
2) an 18m single dish to the SBA interferometer
3) a 100m single dish (smoothed) to the ngVLA SWcore
4) and a 50m single dish to the ngVLA SWcore.

For cases 1-3 we assume a matching scale of the single dish beam, *i.e.* the interferometer is uv-tapered to θ_{SD}. Case 3— the 100m single dish— further assumes that the 100m map or cube is smoothed to the ngVLA Largest Angular Scale. For case 4, since $\theta_{SD} < \theta_{LAS}$, we taper the interferomter only to θ_{LAS}. These calculations show that within a factor of 2-3 in integration time (allowing for the 4 planned 18m dishes to support the SBA), these instruments are well suited to provide complementary data to each other.

Further discussion of these results and their implications is in the § 7.

Low-Res. Instrument	High-Res. Instrument	Match Scale	$N_{b,eff}$ (hi-res)	t_{low}/t_{high}
SBA	ngVLA SWcore	SBA beam	40.3	2.78
18m TP	SBA	18m PB	31.8	7.08
100m TP(smo.)	ngVLA SWcore	ngVLA $B_{min}/2$	41.9	4.89
50m TP	ngVLA SWcore	ngVLA $B_{min}/2$	41.9	2.21

Table 1: Ratio of integration times for Low-Resolution complements to different higher-resolution capabilities.

6 Other ngVLA Configurations

As we were completing this memo the Spiral-214 Rev. B configuration (Carilli 2018) emerged and may figure prominently in future work. Previous work (Frayer 2017, Mason 2016) used yet other configurations. Therefore we have repeated the SBA-ngVLA sensitivity calculations of § 5 for these other configurations, with results in Table 2. A histogram of baseline length for these configurations is shown in Figure 6.

ngVLA configuration	Match Scale	t_{SBA}/t_{ngVLA}
SWcore	SBA beam	2.8
Memo 12 “original” (300.*cc*)	SBA beam	2.0
Memo 12 “core”	SBA beam	9.2
Spiral-214 Rev.B	SBA beam	1.3

Table 2: Time ratios for SBA to match the surface brightness sensitivity to different ngVLA configurations. See also Figure 6.

7 Discussion & Conclusions

We have presented a design for a short baseline array that complements the ngVLA 18m array and fulfills the spatial frequency coverage requirements of the identified ngVLA science use cases. A major advantage of the SBA is that it covers the large spatial scales which are of interest to many scientists without unduly compromising the high resolution capabilities of the ngVLA main array. Under the most stringent requirements the SBA interferometer matches the sensitivity of the ngVLA SWcore configuration in 2.78× the integration time; the four SBA total power dishes match the SBA interferometer in 7.08/4 = 1.77× the SBA integration time, or $1.77 \times 2.78 = 4.92\times$ the ngVLA SWcore integration time. Our calculations (§ 6) indicate that the SBA will need approximately 1/2 the integration time when used with the Spiral-214 configuration as it does when used with the SWcore configuration.

We also considered the case where a single 50m or 100m telescope provides short spacing information instead of the SBA. Assuming equal instrument and site parameters we find these instruments can effectively complement ngVLA SWcore data in 2.2× (50m matched at ngVLA-SWcore LAS) to 4.8× (100m smoothed to and matched at ngVLA-SWcore LAS). If the 100m were to be smoothed to the resolution of a 50m total power map— about the lowest resolution consistent with $1.5 \times \lambda/B_{min}$— it would also require 2.2× the ngVLA-SWcore integration time. These are comparable to the results of Frayer (2017, ngVLA memo 14), who find $t_{GBT}/t_{ngVLA} = 3.6$ for the ngVLA Memo 12 “Original” configuration. The short baseline sensitivity of the “Original” (`config.150km.300.cc.cfg`) configuration is comparable to, but somewhat greater than, that of the configuration we have used (see § 6).

As previously noted the assumptions made in this analysis are maximally stringent with respect to the short-spacing capability. The choice of matching scale is of particular significance. Several points are worth noting. First, if a factor of $\sqrt{2.78} = 1.7$ higher surface brightness noise can be tolerated from the SBA at the ngVLA largest useful angular scale, then the SBA observations can be done in equal integration time as the ngVLA SWcore observations while still matching or exceeding the ngVLA surface brightness sensitivity on scales larger

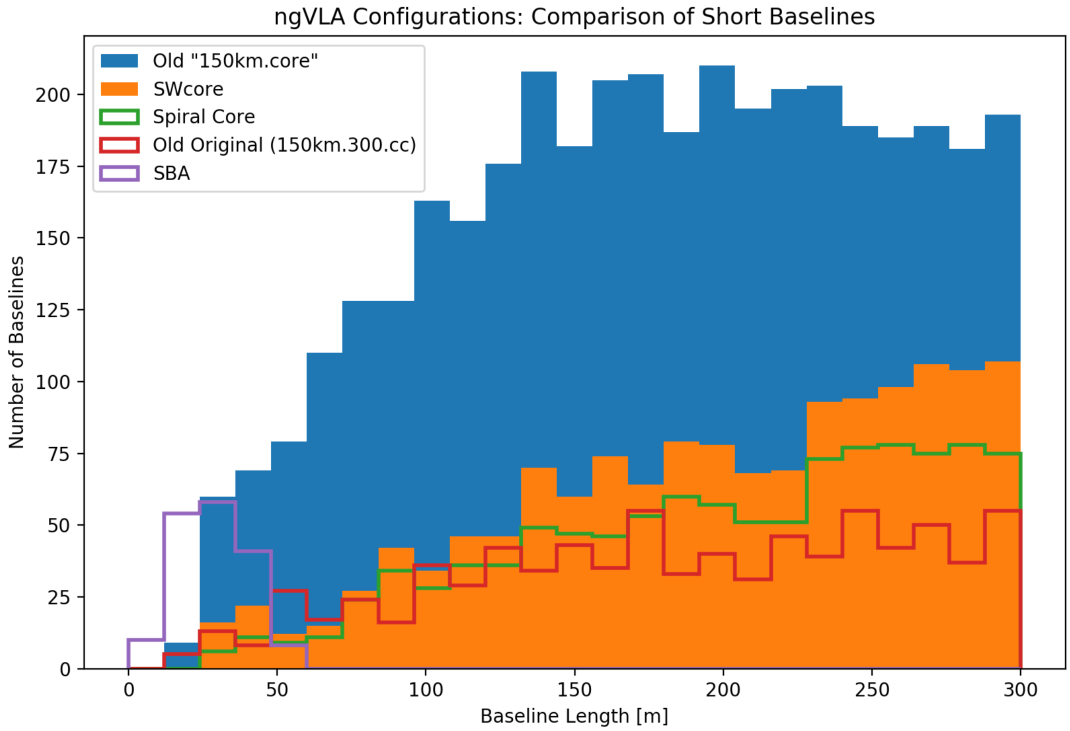


Figure 5: Histogram of baseline lengths out to 300m for the configurations considered in Table 2. The width of each bin is 12m. Note the known issue that early configurations do not respect antenna clearance requirements.

than $0.75 \times \theta_{las}$. This could enable concurrent SBA-ngVLA observations with all baselines including 18m-6m baselines. Similarly, the amount of time required for a single TP antenna to complement SBA observations can be substantially reduced by tolerating some excess noise on overlapping scales: if we instead match the TP and SBA using at $0.5\lambda/B_{min}$, the integration time ratio is 2 instead of 7. The optimal choice is likely use-case dependent in ways that can only be addressed by detailed simulations. The choice of imaging algorithm may also be important in order to optimally weight data on overlapping spatial scales according to their intrinsic noise properties. In this analysis we have generally made the most stringent assumptions, and we find that the relatively modest short-spacing capability described herein is sufficient.

Finally, we emphasize that the hardware and software requirements of single dish observing and interferometric observing are different. While our reference SBA design includes four repurposed ngVLA antennas to provide total power information, the necessary differences between single dish and interferometric telescopes will reduce somewhat the cost efficiency gains of this choice. It is essential that any telescope subsystems be reviewed with total power specific issues in mind. This includes optics, antenna drive and servo requirements, stability of IF and electronics systems, and the suitability of backend electronics.

References:

B. Mason & C. Brogan "Relative Integration times for the ALMA 12-m, 7-m, and Total Power Arrays" 2013, NAASC Memo 113/ ALMA Memo 598.

B. Mason "Total Power Integration Time Requirements for Two Representative NGVLA Configurations" 2016, `http://http://www.gb.nrao.edu/~bmason/ngvlatp.pdf`

ngVLA Memo 12: "The Strength of the Core" C. Carilli (10/2016)

ngVLA Memo 14: "Short Spacing Considerations for the NGVLA" D. Frayer (6/8/17)

ngVLA Memo 17: "ngVLA Reference Design Development & Performance Estimates" R. Selina & E. Murphy (7/18/17)

ngVLA Memo 18: "Summary of the Science Use Case Analysis", R. Selina, E. Murphy, & A.

Erickson (7/26/17)
ngVLA Memo 19: "Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council", ngVLA Science Advisory Council (8/2/17)
ngVLA Memo 41: "Initial Imaging Tests of the Spiral Configuration", C. Carilli & A. Erickson (3/21/18).
S. Stanimirovic, D. Altschuler, P. Goldsmith, & C. Salter, in "Single-Dish Radio Astronomy: Techniques and Applications" (2002, Astronomical Society of the Pacific)
G.B. Taylor, C.L. Carilli & R.A. Perley, "Synthesis Imaging in Radio Astronomy II" (1999, Astronomical Society of the Pacific)
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D.J. Wilner & W.J. Welch, 1994 ApJ 427, 898

A Appendix: ngVLA Short Baseline Array Reference Configuration

Following is a CASA-readable array configuration file documenting the ngVLA SBA reference design. This is the configuration file used in the simulations in this memo; its absolute location is near the center of the `SWcore` configuration. The center coordinates of the final SBA reference design will likely differ somewhat based on an analysis of topography and infrastructure. Note that the analysis in this memo uses a Universal Transverse Mercator projection since it gives a convenient two-dimensional Cartesian grid, and over the distances involved in this analysis, the flat-Earth approximation is valid. The ngVLA web site distributes fully 3-dimensional configuration files in a geocentric coordinate system (CASA designation `XYZ`), which is necessary for higher-resolution simulations involving more distant antennas.

```
# observatory=NGVLA
# coordsys=UTM
# datum=NAD27
# zone=13
# hemisphere=N
# Easting Northing el diam pad
258360.58 3774018.51 2112.57 6. ngvlaSA1
258379.39 3774031.30 2112.57 6. ngvlaSA4
258381.52 3774017.23 2112.57 6. ngvlaSA5
258380.34 3774002.15 2112.57 6. ngvlaSA6
258382.20 3773989.30 2112.57 6. ngvlaSA7
258369.55 3774025.77 2112.57 6. ngvlaSA2
258358.18 3774030.80 2112.57 6. ngvlaSA3
258368.51 3773983.22 2112.57 6. ngvlaSA8
258348.35 3774009.49 2112.57 6. ngvlaSA9
258347.51 3773996.62 2112.57 6. ngvlaSA18
258390.89 3774030.10 2112.57 6. ngvlaSA19
258371.21 3774010.31 2112.57 6. ngvlaSA16
258393.73 3774014.35 2112.57 6. ngvlaSA17
258368.87 3773995.92 2112.57 6. ngvlaSA14
258358.97 3774004.13 2112.57 6. ngvlaSA15
258349.86 3774021.52 2112.57 6. ngvlaSA12
258392.21 3774002.76 2112.57 6. ngvlaSA13
258369.03 3774038.95 2112.57 6. ngvlaSA10
258357.92 3773992.97 2112.57 6. ngvlaSA11
```

B Appendix: CASA Simulations

CASA $5.1.1-5$— the current CASA release as of the date these calculations were performed— was used for the simulations in this memo. Several points are worthy of note:

1) `simobserve()` in CASA 5.1 will infer the correct primary beam *for the 18m antennas* if the antenna configuration file sets the `observatory` keyword to `NGVLA`.
2) A special procedure is required to obtain the correct 6m (or other) interferometric beam in CASA 5.1. This procedure is documented below.
3) Simulations of heterogeneous arrays other than ALMA (`e.g.` NGVLA 6m and 18m antennas, including the cross baselines) are not possible with `simobserve()` in the current CASA release. We hope that heterogeneous array simulations will be supported in a near future CASA release (5.3 or 5.4). For more details the interested user can refer to `CAS-8592`.
4) Newly implemented internal infrastructure in CASA 5.1 gives rise to a serious bug in mosaic imaging which affects simulated data (only). The bug can be avoided by setting an environment variable called `VI1` prior to starting CASA, or by using a previous version of CASA. This issue is fixed in the upcoming CASA 5.3 release. For more details see ALMA Knowledge Base article 407 ("Why are the fluxes in my CASA 5.1 simulated mosaic image incorrect, and how can I fix it?") or `CAS-11271`.

The procedure to set an alternative (e.g. 6m) primary beam in CASA is as follows.

```
# to create the custom ‘‘voltage pattern’’ table:
vp.reset()
vp.setpbairy(telescope='NGVLA',dishdiam=6.0,blockagediam=0.0,maxrad='3.5deg',
   reffreq='1.0GHz',dopb=True)
vp.saveastable('sba.tab')

# subsequently this can be loaded as
vp.reset()
vp.loadfromtable('sba.tab')
# ^^^ do this immediately before simobserve() and do
# NOT do a vp.reset() between loading and simobserving.

# in calls to TCLEAN() you should pass the voltage pattern
#  table explicitly as:
vptable='sba.tab'
```

Finally, if thermal noise matters for a given simulation, the user should take care to ensure that the expected noise is achieved since `simobserve()` noise defaults are not generally appropriate for ngVLA. One procedure to do so has been described in a technical note by Carilli et al. (2017) which is linked at `http://ngvla.nrao.edu/page/tools`

C Appendix: Derviations & Formulae

Following the spirit of the calculations described in ALMA Memo 598 (Mason & Brogan 2013), we match sensitivities for different telescopes or arrays by equating mosaicked image sensitivities with the beams also matched by tapering; alternately, we consider matching *surface brightness* sensitivity with the beams not matched, but probably in practice comparable. Below are the basic formulas used in these calculations. Refer to Mason & Brogan 2013 or Mason 2017 for more detail (see also Frayer 2017). All of the following is for a single polarization; assuming both instruments measure the same number of polarizations nothing would change by including polarization explicitly.

As a starting point we calculate the sensitivity (in Jy/bm) at the center of a single interferometer pointing to be (Taylor, Carilli & Perley 1999; Thompson, Moran & Swenson 2001)

$$\Delta I_{m,1} = \frac{\sqrt{\sum \mathscr{T}_{1,k}^2 \Delta S_{1,k}^2}}{\sum \mathscr{T}_{1,k}} \tag{6}$$

The noise $\Delta S_{1,k}$ on a measurement on a single baseline k involving antennas i and j, is:

$$\Delta S_{1,k\rightarrow(i,j)} = \frac{2k_B}{A\eta_Q}\sqrt{\frac{T_{sys,1,i}T_{sys,1,j}}{\eta_{a,1,i}\eta_{a,1,j}\Delta\nu\tau}} \tag{7}$$

Assuming antennas and receiving systems are identical, the sensitivity equation then reduces to

$$\Delta I_{m,1} = \frac{2k_B}{\eta_Q A \eta_a}\frac{T_{sys}}{\sqrt{2\Delta\nu\tau}}\frac{\sqrt{\sum \mathscr{T}_k^2}}{\sum \mathscr{T}_k} \tag{8}$$

The *effective* number of baselines, after downweighting by the taper weight, can be identified as

$$N_{b,eff} = \frac{(\sum \mathscr{T}_k)^2}{\sum \mathscr{T}_k^2} \tag{9}$$

$N_{b_{eff}}$ is the number of *un*-taper-reweighted baselines that would be needed to provide identical Jy/bm sensitivity. To see this consider the form of equation 8 in the case that all $T_k = 1$. This heuristic provides a useful check on the numerics since in the limit that the taper is broader than the longest baselines $N_{b,eff}$ should revert to the physical number of baselines (which is the case for the calculations we present). We are supposing that the synthesis map, for purposes of this sensitivity-matching comparison, is tapered down to some scale on the order of the single dish resolution. We make this assumption because otherwise one of the datasets would dominate the image noise on the common spatial scales, which is indefficient and therefore undesirable. $N_{b,eff}$ as a function of *uv*-taper is shown for ngVLA, the SBA, ALMA C43-1, and the ALMA 7m-array in Figure 6.

The sensitivity in the center of the equivalent single-dish pointing is

$$\Delta I_{SD,1} = \frac{2k_B}{\eta_{Q,SD}A_{SD}\eta_{a,SD}}\frac{T_{sys,SD}}{\sqrt{\Delta\nu\tau}} \tag{10}$$

Assume equal efficiencies, system temperatures etc. Then to achieve equal sensitivities at the centers of these individual pointings requires

$$\frac{\tau_{SD}}{\tau_{int}} = \left(\frac{A_{e,int}}{A_{e,SD}}\right)^2 \frac{(\sum \mathscr{T}_k)^2}{\sum \mathscr{T}_k^2} = \left(\frac{A_{e,int}}{A_{e,SD}}\right)^2 \times N_{b,eff} \times 2 \tag{11}$$

To mosaic a finite area with the interferometer will require some number of pointings N. Assume identical pointing strategies for the instruments, *e.g.* each fully samples the sky on a hexagonal mosaic suitable to its antenna diameter. As argued in ALMA memo 598, in this situation the single dish and interferometer mosaics will have equal sensitivity when the *single pointing sensitivities are equal.* The other information we need to know is the total number of interferometer and single dish pointings needed to cover the area of interest. The single dish will then require a number of sequential pointings $N_{SD} = N \times (D_{SD}/D_{int})^2$. Then the *total* time $t = N\tau$ required to cover some region of interest is

$$\frac{t_{SD}}{t_{int}} = \left(\frac{\eta_{a,int}}{\eta_{a,SD}}\right)^2 \left(\frac{D_{int}}{D_{SD}}\right)^2 \frac{(\sum \mathscr{T}_k)^2}{\sum \mathscr{T}_k^2} \times 2 = \left(\frac{\eta_{a,int}}{\eta_{a,SD}}\right)^2 \left(\frac{D_{int}}{D_{SD}}\right)^2 \times N_{b,eff} \times 2 \tag{12}$$

The single-dish map will often require a "guard band" of blank sky around the region of interest; we neglect this edge effect as a use-case dependent overhead, which is smaller for larger mosaics. We also neglect slewing and settling overheads which are use-case and implementation dependent. The full expression, putting back in the system temperatures and quantum efficiencies and allowing the interferometer synthesized beam FWHM θ_{int} to differ from the single dish primary beam FWHM θ_{SD}, is:

$$\frac{t_{SD}}{t_{int}} = \left(\frac{\eta_{Q,int}T_{SD}}{\eta_{Q,SD}T_{int}}\right)^2 \left(\frac{\eta_{a,int}}{\eta_{a,SD}}\right)^2 \left(\frac{D_{int}}{D_{SD}}\right)^2 \times \left(\frac{\theta_{int}}{\theta_{SD}}\right)^4 \times 2N_{b,eff} \tag{13}$$

The equivalent expression for the case of two interferometric arrays, following Mason & Brogan 2013, is:

$$\frac{t_2}{t_1} = \left(\frac{\eta_{Q,1}T_2}{\eta_{Q,2}T_1}\right)^2 \left(\frac{\eta_{a,1}}{\eta_{a,2}}\right)^2 \left(\frac{D_1}{D_2}\right)^2 \times \left(\frac{\theta_1}{\theta_2}\right)^4 \frac{N_{b,eff,1}}{N_{b,eff,2}} \tag{14}$$

A convenient analytical expression for the matching taper can be derived by first assuming the single-dish beam FWHM is given by

$$\theta_{SD} = 1.15\lambda/D_{SD}$$

The interferometer synthesized beam, for a *uv*-taper of FWHM (in meters) of D_{taper}, is

$$\theta_{int,taper} = 0.882\lambda/D_{taper}$$

This expression gives a synthesized beam of $0.9''$ for a $200k\lambda$ (FWHM) taper, consistent with standard rules of thumb. For these calculations derive the taper from setting $\theta_{int,taper} = \theta_{SD}$, giving $D_{taper} = (0.882/1.15)D_{SD} = 0.767D_{SD}$. The *uv* taper itself is given by

$$\mathscr{T}_k = Exp(-q_k^2/(2\sigma_{taper}^2)) \tag{15}$$

where q_k is the *uv* radius of baseline k and $\sigma_{taper} = D_{taper}/2.354/\lambda$.

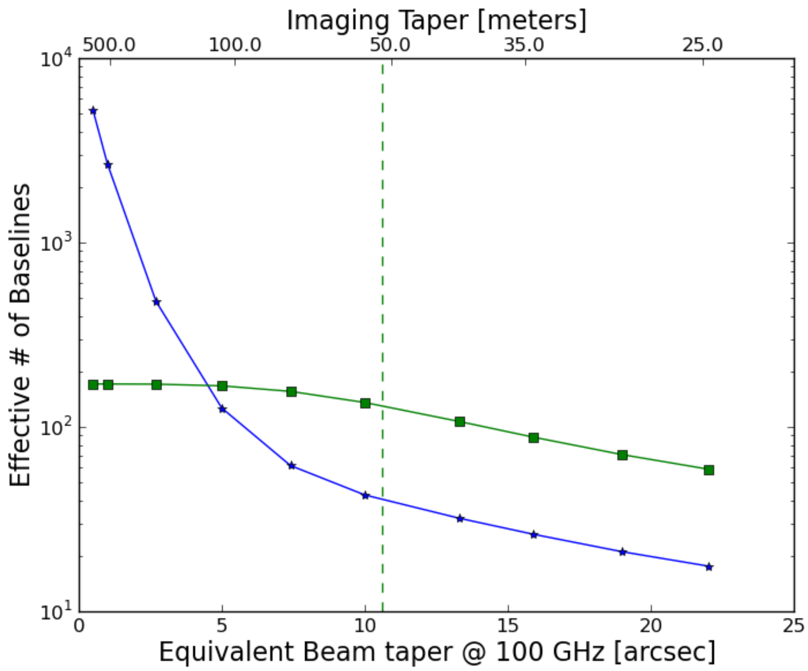
Finally, we state several facts that are useful to bear in mind regarding how surface brightness sensitivity varies as a function of resolution. First, the surface brightness noise ΔT in a map made by a large single dish is *the same* as the surface brightness noise made by a smaller-diameter single-dish in equal time, if the higher resolution map is smoothed to the resolution of the lower resolution map and the telescope are otherwise identical. This comes about because the large single dish must spend a factor of $N = (D_{large}/D_{small})^2$ less time per beam, resulting in a loss of $\sqrt{N}$ in sensitivity which is exactly compensated by smoothing. Second, for a *given* single dish map, the surface brightness noise of the map as it is smoothed by a smoothing kernel of size θ_{smo} goes like:

$$\Delta T(\theta_{smo}) \sim \frac{1}{\theta_{smo}}.$$

Lastly, the surface brightness noise of an interferometer map as it is "smoothed" by imaging at a range of *uv*-tapers scales with θ_{taper} like:

$$\Delta T(\theta_{taper}) \sim \frac{1}{\theta_{taper}^2} \frac{1}{\sqrt{N_{b,eff}(\theta_{taper})}}.$$

In general this has different behavior than the single-dish case. In particular, since real-world *uv*-distributions are often somewhat centrally concentrated, it can counter-intuitively result in *more rapid* reduction in ΔT as a function of increasing θ_{taper} than would be obtained by smoothing a single-dish map of the same resolution. One way of looking at this is that larger values of θ_{taper} throw out more sparsely-sampled long baselines, increasing the effective filling factor of the interferometer and thereby its surface brightness sensitivity.



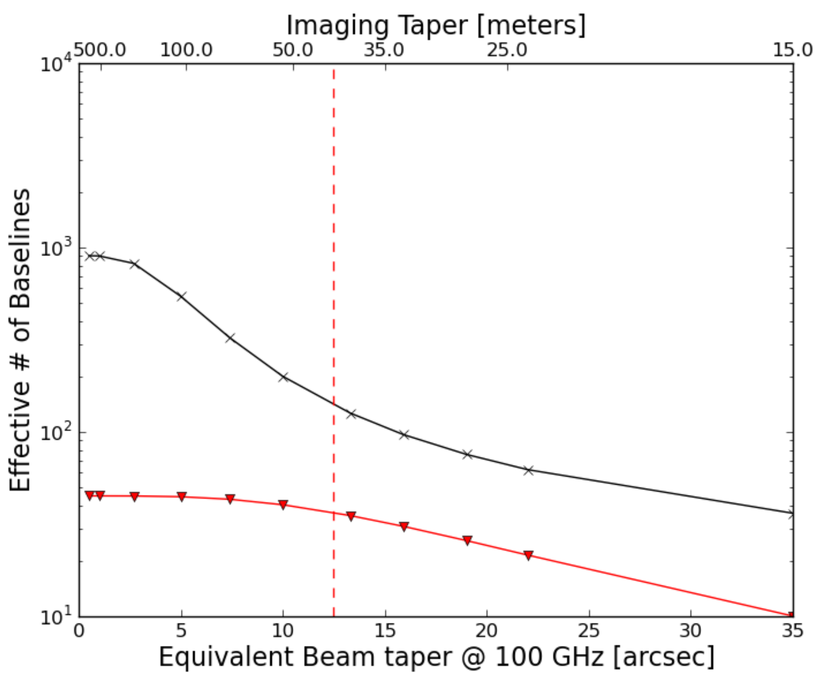


Figure 6: Top: Effective number of baselines *vs.* Gaussian beam taper for the ngVLA-SWcore (blue) and the SBA interferometer (green). The vertical dashed line is the natural-weight SBA beam width. Bottom: same, for the most compact ALMA configuration C43-1 (black) and the ALMA 7m-array (red). The vertical dashed line is the 7-m beam width.

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