**Total Power Integration Time Requirements for Two Representative NGVLA Configurations**

*Brian S. Mason et al.*

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*Apr 2017 - add references, correct factor of root(2) in synthesis map sensitivity*

The goal of this memo is to estimate the integration times that would be required to match the surface brightness sensitivity of two representative NGVLA configurations with single dish (total power) measurements that use a representative variety of antenna diameters. The NGVLA configurations under consideration are `config.150km.300.cc` and `config.150km.core`. These are two current reference configurations for the NGVLA design comprising 300 18m antennas with longest baselines of $\sim 300\,\mathrm{km}$; the "150km.core" configuration has an enhanced fraction of short baselines for better surface brightness sensitivity. The strategy will be to match the sensitivities of the single dish and interferometer maps, when the interferometer data is suitably tapered to match the beam size of the single dish in question. This is similar to the approach used in ALMA Memo 598 (Mason & Brogan 2013) to compute integration time requirements for different configurations and arrays of ALMA.

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)

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

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

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

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

$$\Delta I_{m,1} = \frac{2k_B}{\eta_Q A \eta_a}\frac{T_{sys}}{\sqrt{2\Delta\nu\tau}}\frac{\sqrt{\sum \mathscr{T}_k^2}}{\sum \mathscr{T}_k} \tag{3}$$

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

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

$N_{b_eff}$ 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 3 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).

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

$$\Delta I_{SD,1} = \frac{2k_B}{\eta_{Q,SD}A_{SD}\eta_{a,SD}}\frac{T_{sys,SD}}{\sqrt{\Delta\nu\tau}} \tag{4}$$

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

$$\frac{\tau_{SD}}{\tau_{int}} = \left(\frac{A_{e,int}}{A_{e,SD}}\right)^2 \frac{(\sum \mathscr{T}_k)^2}{\sum \mathscr{T}_k^2} = \left(\frac{A_{e,int}}{A_{e,SD}}\right)^2 \times N_{b,eff} \times 2 \tag{5}$$

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

$$\frac{t_{SD}}{t_{int}} = \left(\frac{\eta_{a,int}}{\eta_{a,SD}}\right)^2 \left(\frac{D_{int}}{D_{SD}}\right)^2 \frac{(\sum \mathscr{T}_k)^2}{\sum \mathscr{T}_k^2} \times 2 = \left(\frac{\eta_{a,int}}{\eta_{a,SD}}\right)^2 \left(\frac{D_{int}}{D_{SD}}\right)^2 \times N_{b,eff} \times 2 \qquad (6)$$

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.

Assume 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

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

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

The range of suitable single dish diameters to consider is constrained by the minimum baselines $b_{min}$ in the interferometeric array, which are 18.8m and 19.5m respectively for the "core" and "300.cc" configurations—quite close to the minimum physical baseline of 18m. Fundamentally the choice is driven by the imaging requirements (Stanimirovic et al. 2002), the standard rule of thumb being that the single dish should have a diameter of at least $1.5 \times b_{min}$, and preferably $2 \times b_{min}$ or larger. We consquently consider total power antennas of diameters 27m, 36m, as well as 50m and 100m. Results are in the following table -

| $D_{SD}$ | $(D_{int}/D_{SD})^2$ | Core | | 300.cc | |
|---|---|---|---|---|---|
| | | $N_{b,eff}$ | $t_{SD}/t_{int}$ | $N_{b,eff}$ | $t_{SD}/t_{int}$ |
| 27m | 0.44 | 19 | 16.9 | 9 | 8.0 |
| 36m | 0.25 | 39 | 19.5 | 14 | 7.0 |
| 50m | 0.13 | 76 | 19.7 | 20 | 5.2 |
| 100m | 0.032 | 286 | 18.5 | 58 | 3.8 |
| 300m | $3.6 \times 10^{-3}$ | 1970 | 14.2 | 396 | 2.8 |
| 500m | $1.3 \times 10^{-3}$ | 3695 | 9.6 | 817 | 2.1 |

Table 1: Ratio of integration time for single dish antennas of varying diameter to NGVLA integration time. SD time required assumes a single feed and will be directly inversely proportional to the number of feeds if a FPA is used. Note also that a SD map sensitivity can be improved by smoothing; the same is not simply true of an interferometer due to correlated image plane noise and incomplete *uv* plane sampling (hence the need for the calculations here).

These results suggest that the "300.cc" configuration would represent a modest improvement over existing single dishes in terms of surface brightness for many imaging use cases; and that the "enhanced core" configuration would be a considerably larger improvement. Conversely, the "enhanced core" configuration would suggest that modest-scale focal plane arrays would be desirable to provide total power data that usefully complements NGVLA data in a reasonable integration time.

*References:*

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)

A.R. Thompson, J.M. Moran, & G.W. Swenson, "Interferometry and Synthesis in Radio Astronomy", 2nd edition (2001, Wiley & Sons)