ngVLA Memo #113
ngVLA Dynamic Range Requirements

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Abstract

This memo describes the basis for the ngVLA dynamic range science requirement, which is to enable the detection of a Milky Way like galaxy forming stars at $\approx 5\,M_\odot\,\mathrm{yr}^{-1}$ at the peak of cosmic star formation activity (i.e., $z \sim 2$) at 8 GHz in the observer reference frame. The rms at 8 GHz needed to detect such a galaxy at the 5σ level is $\sigma \approx 34.5$ nJy. Based on 1.4 GHz source counts, the brightest source within the full width at half maximum of the primary beam (assuming an 18 m diameter antenna) has an 8 GHz flux density of $S_\nu \approx 531.5\,\mu$Jy, requiring a brightness dynamic range of $\gtrsim$41.9 dB. However, given the Poisson uncertainty in choosing such a field that would only have a single bright source of that flux density along with a negligible amount of flux density being contributed by the remaining sources in the field, the dynamic range requirement for this science goal is conservatively set to $\sim$45 dB based on known radio source counts. It is expected that such a dynamic range could likely be achieved with existing self-calibration techniques. Given the current ngVLA design and corresponding performance estimates (October, 2022), the integration time to detect such a source is $\approx$37 hr.

1 Introduction

In this memo, the dynamic range requirement for the ngVLA is investigated. Specifically, the dynamic range required to detect a Milky Way like galaxy forming stars at a rate of $\approx 5\,M_\odot\,\mathrm{yr}^{-1}$ (e.g., Chomiuk & Povich 2011; Kennicutt & Evans 2012; Siegart et al. 2023) located at the peak of cosmic star formation activity (i.e., $z \sim 2$) at a frequency of 8 GHz in the observer reference frame. This use case is captured in the ngVLA Science Requirements as one of the ngVLA Key Science Goals (i.e., KSG3-011; Murphy et al. 2020).

One reason that this specific use case has been chosen to set the brightness dynamic range requirement is due to the fact that the concept of instrumental dynamic range becomes highly complex for images that are not dominated by point sources. This is because different arrays will have different responses depending on their (u,v) distributions, making a quantitive definition difficult to use in practice (e.g., see the Appendix where a brightness dynamic range is estimated at 27 GHz for KSG3-008). While challenging cases, such as that of imaging Cygnus A, have historically defined the dynamic range demands of radio interferometers, other metrics such as imaging fidelity may be equally or more appropriate to characterize the performance of the interferometer when imaging extremely bright and complex sources.

2 Assumptions and Calculation

For this calculation, the following assumptions are made:

- $d_{\rm Ant} = 18\,{\rm m}$: The ngVLA dishes have a diameter of 18 m.
- $\nu_{\rm obs} = 8\,{\rm GHz}$: The observed frequency is at 8 GHz.
- $z_{\rm src} = 2$: The source is located at $z = 2$
- ${\rm SFR} = 5\,M_\odot\,{\rm yr}^{-1}$: The galaxy is forming stars at a rate of 5 solar masses per year.
- $\alpha = -0.7$: The galaxy's radio spectral index is -0.7, where $S_\nu \propto \nu^\alpha$.
- $B = 30\,\mu{\rm G}$: The galaxy has an internal magnetic field strength of $30\,\mu$G.

Derived Parameters:

- The half power diameter of the primary beam at 8 GHz:

$$\theta_{1/2} = 1.02\left(\frac{c}{\nu_{\rm obs}\,d_{\rm Ant}}\right) * \left(\frac{206265}{60}\right) \quad (1)$$

$$= 7\overset{\prime}{.}3 \quad (2)$$

where c is the speed of light.

- The corresponding primary beam solid angle:

$$\Omega_{1/2} = \left[\frac{\pi\,\theta_{1/2}^2}{4\,\ln(2)}\right]\left(\frac{60}{206265}\right)^2 \quad (3)$$

$$= 5.11\times10^{-6}\,{\rm sr} \quad (4)$$

- The observed 8 GHz flux density of the source, assuming it is unresolved and that it obeys the FIR-radio correlation (Murphy et al. 2012)[1]:

$$S_\nu^{\rm obs} = 172.7\,{\rm nJy} \quad (5)$$

In Figure 1 the expected brightness of such a galaxy is shown as a function of redshift assuming its star-forming disk has a diameter of 2 kpc.

- The 8 GHz flux density of the brightest source in the field, extrapolated from 1.4 GHz number counts (Condon et al. 2012; Murphy & Chary 2018):

$$S_\nu^{\rm max} = 531.5\,\mu{\rm Jy} \quad (6)$$

[1] Conservatively includes estimate for possible synchrotron dimming by the CMB (Murphy 2009). If one neglects these effects, the corresponding 8 GHz flux density of the source is 211.4 nJy.

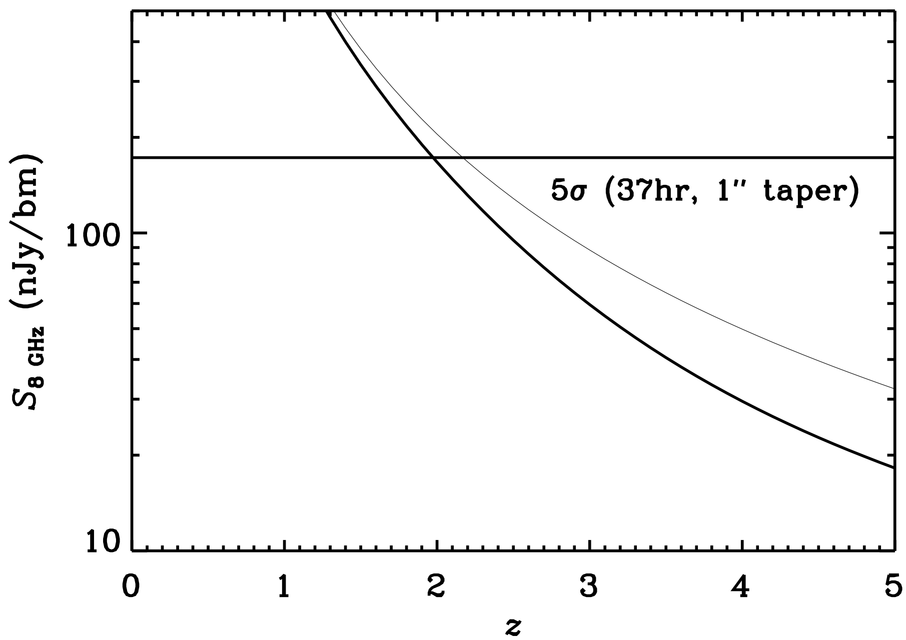

Figure 1: Telescope sensitivity in nJy bm^{-1} at 8 GHz plotted against redshift indicating the expected brightness of a 2 kpc disk galaxy forming stars at a rate 5 $M_\odot$ yr^{-1} with a magnetic field strength of 30μG. The heavy-weighted lines include estimates for synchrotron dimming due to IC scattering of CR electrons/positrons in galaxies due to the increasing Cosmic Microwave Background (CMB) energy density with redshift, while the corresponding lighter-weighted lines indicate the expected brightnesses in the absence of any synchrotron dimming due to CMB effects. The horizontal line shows the sensitivity of the ngVLA after a ≈37 hr integration and 1″ beam taper.

- The 8 GHz rms noise level needed to detect the galaxy at 5σ:

$$\sigma = S_\nu^{\mathrm{obs}}/5 \quad (7)$$
$$= 34.5\,\mathrm{nJy} \quad (8)$$

With an rms sensitivity of 0.21 μJy bm^{-1} in 1 hr at 8 GHz for a 1″ tapered beam (October, 2022)[2], the integration time to detect such a source at a 5σ significance level is ≈37 hr. This sensitivity estimate assumes the full bandwidth (i.e., 8.8 GHz) of ngVLA Band 2 and takes into account the heavy beam sculpting necessary to achieve a well-behaved response function (see Rosero & Carilli 2022). This in turn results in an rms noise value that is a factor of ∼1.5 larger than what is achieved by the natural weighted sensitivity of the array.

[2] https://ngvla.nrao.edu/page/performance

3 Discussion & Conclusions

Given the above calculation, the corresponding dynamic range necessary for the detection of such a source at 8 GHz is 41.9 dB. However, the brightness dynamic range is defined by the quadrature sum of the peak brightnesses of all sources in the field (Murphy et al. 2020). When randomly selecting a field, or choosing an existing, well-established deep field to conduct such an observation, it is unlikely for it to contain a single bright source of that flux density along with a negligible amount of flux density being contributed by the remaining sources in the field. Consequently, to achieve this science goal, I conservatively set the **dynamic range requirement for an 8 GHz deep field to 45 dB**, which is a factor of two larger than what is measured using the brightest source in the field alone based on expectations from known radio source counts.

The factor of 2 used to set the final dynamic range requirement is chosen assuming a radio source count distribution of $n(S) \propto S^{-2}\,dS \propto S^{-1}d(\log S)$ (Condon 1974; Condon et al. 2012) along with the fact that it is the quadrature sum of peak brightnesses that contribute to the dynamic range. For logarithmic bins of width log(2), the contribution from the N brightest sources will typically be around $1 + 2 * (1/4) + 4 * (1/16) + ... = 1 + 1/2 + 1/4 + ...$ For large N, this results in the summation $\sum_{n=0}^{\infty} 2^{-n} = 2$. It is additionally worth noting that this calculation has assumed that the brightest source in the field is located at the phase center. Consequently, the value of 45 dB could be considered an upper limit given that the primary beam response will attenuate source brightness with increasing distance from the phase center.

The ngVLA should be able to achieve this brightness dynamic range. Using three different examples of possible antenna configurations, Cotton and Codon (2017) show that dynamic ranges of 50 dB or better are possible for deep field imaging at 3 GHz even after including effects of strong sources, pixelization, and calibration/pointing errors. For such an observation it is also worth noting that self-calibration techniques can likely be used to achieve this dynamic range requirement.

References

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Appendix: Resolved Sources at 27 GHz

As stated above, defining the instrumental dynamic range of an interferometer is complex for images that are not dominated by point sources. However, here I make an attempt to define the dynamic range requirement for the ngVLA at 27 GHz based on the science use case of creating free-free emission images of nearby galaxies at an angular resolution of $\approx 1''$, similar to what is currently done via imaging the Hα recombination line of Hydrogen (i.e., KSG3-008; Murphy et al. 2020). To achieve this science goal requires a sensitivity, in terms of SFR surface density, of $\approx 0.005\,M_{\odot}\,\mathrm{yr}^{-1}\mathrm{kpc}^{-2}$, to match the sensitivity of extremely deep Hα images such as those included in the Local Volume Legacy survey (Kennicutt et al. 2008). For galaxies at the distance of Virgo (i.e., $d_{\mathrm{L}} = 16.6\,\mathrm{Mpc}$), an rms noise at 27 GHz of $\approx 0.18\,\mu\mathrm{Jy\,bm}^{-1} \approx 35\,\mathrm{mK}$ is required.

Using Hα images from 50 galaxies included in the Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et la. 2003), all of the flux in summed quadrature above 3σ and divided that number by the σ in each map to estimate the dynamic range, where σ is the measured rms in the Hα image. The maximum dynamic range value among all 50 galaxies is ~**35 dB, which is assigned as the ngVLA 27 GHz dynamic range requirement**.