The Sensitivity of the next generation Very Large Array (ngVLA)

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Introduction

The design for the next generation Very Large Array (ngVLA) is now mature enough to make a much more detailed calculation of sensitivity than has been possible before. Previous estimates (e.g., Carilli et al.2015; Selina & Murphy 2017) have suffered from uncertainties in design specifics, some of which have been reduced through further development. Furthermore, it is of interest to compare these sensitivity numbers directly with existing and near-future instruments in the frequency range of ngVLA (1.2 to 116 GHz), namely the current Karl G. Jansky Very Large Array (VLA), the Atacama Large Millimeter/submillimeter Array (ALMA) and the Square Kilometer Array phase 1 (SKA1-mid). We base our sensitivity calculation on the one for ALMA presented in Butler &Wootten (1999), with modifications, along with current best estimates of receiver and antenna performance, combined with atmospheric models based on measured VLA site characteristics.

Sensitivity of the ngVLA

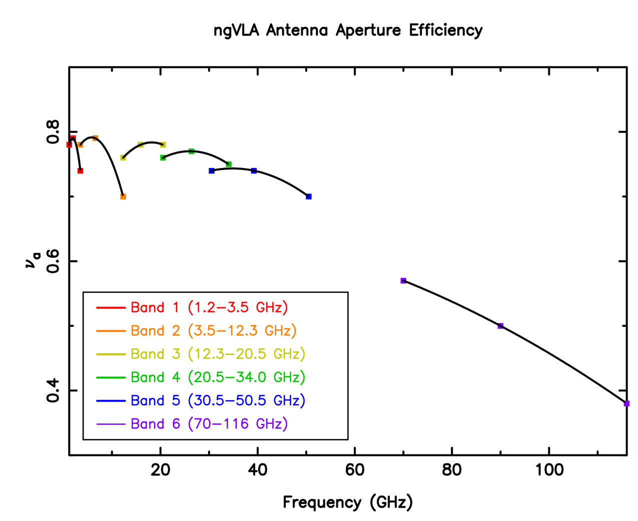
We define the ngVLA sensitivity as:

$$\Delta S(\nu) = \frac{35.9}{\sqrt{\Delta\nu\Delta t}} \frac{1}{\Delta\nu} \int_{\nu_1}^{\nu_2} \frac{T_{sys}(\nu)}{\eta_a(\nu)} d\nu \quad [\mathrm{mJy}]$$

For bandwidth $\Delta\nu$, integration time Δt, system temperature T_{sys}, and antenna efficiency η_a. This assumes the ngVLA has 214 antennas of 18-m diameter. We assume 6 receiver bands denoted as bands 1 through 6, with frequency ranges shown in the table to the right and in figure legends where appropriate.

Antenna Efficiency of the ngVLA

We take the antenna efficiency as a combination of feed illumination efficiency and surface efficiency (Ruze losses). The current design specification for the ngVLA antenna surface is 160 um, (under precision operating conditions), and we use that value, but we also include a calculation below where we use the value for non-precision conditions (300 um) for bands 1-5. For bands 1 and 2 we take the feed illumination efficiency from Weinreb & Mani (2017). For bands 3 through 6 we take this efficiency from an NRC DVA-1 internal report (Baker & Veidt 2014), scaled to the appropriate frequencies. The figure below shows the antenna efficiency over the entire frequency range of interest, along with fits used in evaluating the integral above.



System Temperature of the ngVLA

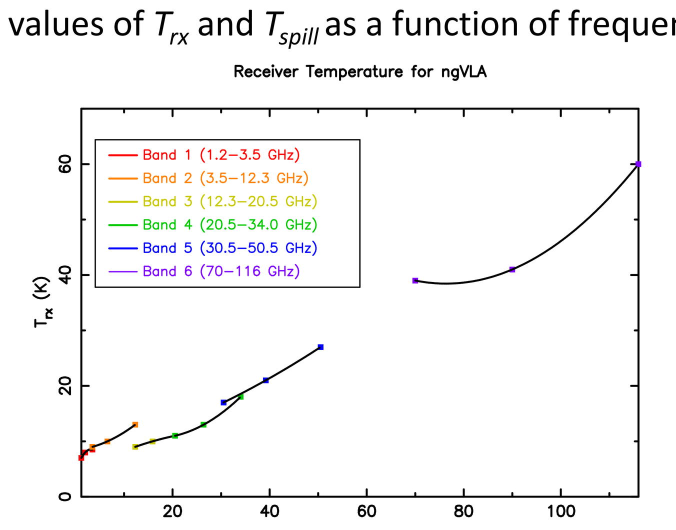
We refer the system temperature to a point above the atmosphere and calculate it as:

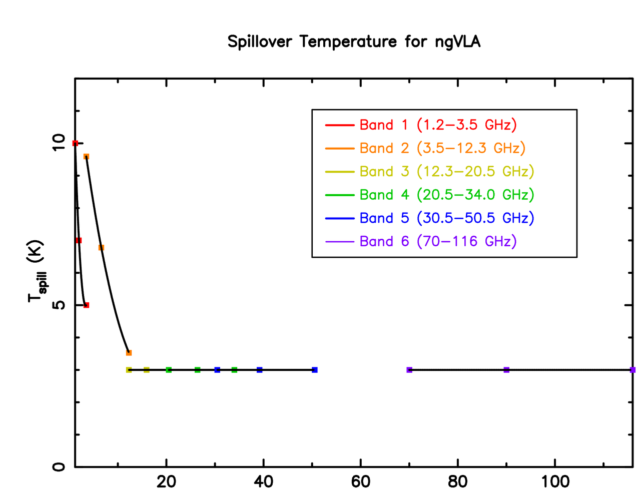
$$T_{sys}(\nu) = \alpha T_{rx} + \alpha \eta_l T_{atm} + \alpha T_{spill} + T_{bg} \quad [\mathrm{K}]$$

Where $\alpha = e^{\tau}$ is an opacity correction for opacity τ, T_{rx} is the receiver temperature, η_l is the fraction of the antenna power that is received in the forward direction (we assume η_l = 0.97), T_{atm} is the effective atmospheric temperature, T_{spill} is the spillover temperature and T_{bg} is the background temperature.

Receiver and Spillover Temperature of the ngVLA

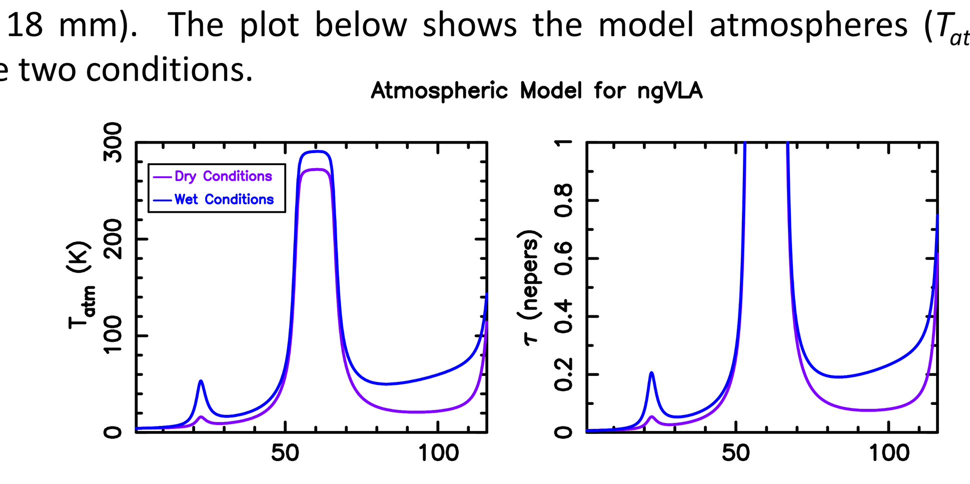
We calculate T_{rx} by taking contributions from the LNA, receiver, cal coupler, feed, window, IR filter, post-amplifier, and coaxial losses, given our current baseline design for the receiver package. We model T_{spill} including diffraction, multiple reflections, and other effects, using simulations based on the current antenna optics and feed designs Srikanth & Weinreb (personal communication). The figures to the left and right below shows values of T_{rx} and T_{spill} as a function of frequency.





Atmospheric Temperature of the ngVLA

We calculate T_{atm} and τ by creating model atmospheres and integrating to find the quantities, using an atmospheric radiative transfer model. We use model atmospheres based on the past 7 years of VLA weather measurements, and we create two such models: one for "dry" conditions (PWV = 4 mm); and one for "wet" conditions (PWV = 18 mm). The plot below shows the model atmospheres (T_{atm} and τ as a function of frequency) for these two conditions.



Results for the ngVLA

We calculate the sensitivity for each of the bands for the ngVLA using the above information for a 1 hour observation, shown in the table below.

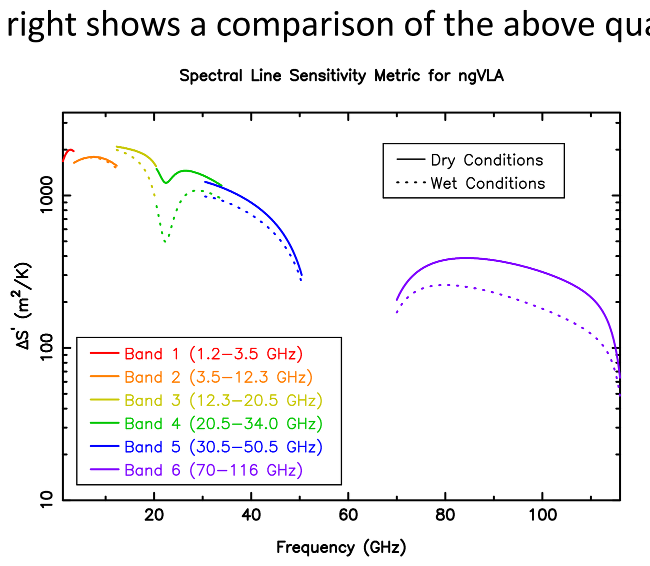
band	frequency range (GHz)	precision dry sensitivity (μJy)	precision wet sensitivity (μJy)	non-precision dry sensitivity (μJy)	non-precision wet sensitivity (μJy)
1	1.2-3.5	0.356	0.355	0.356	0.355
2	3.5-12.3	0.202	0.205	0.203	0.206
3	12.3-20.5	0.190	0.234	0.196	0.242
4	20.5-34.0	0.210	0.334	0.229	0.362
5	30.5-50.5	0.315	0.372	0.389	0.459
6	70.0-90.0	0.675	0.964	–	–
6	95.0-115.0	0.965	1.641	–	–

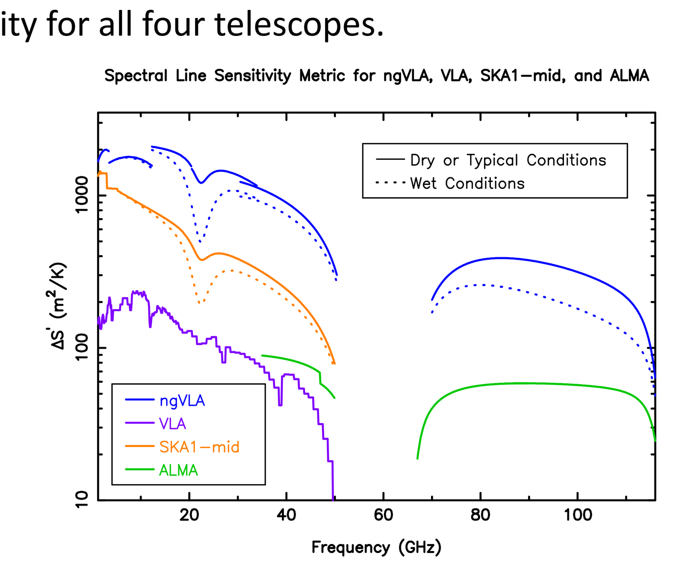
Spectral Line Sensitivity Metric for the ngVLA, VLA, SKA1-mid, and ALMA

For comparison to other observatories, we define a monochromatic metric which excludes most constant terms:

$$\Delta S'(\nu) = \frac{N \pi D^2 \eta_a(\nu)}{4 T_{sys}(\nu)} \quad [\mathrm{m}^2/\mathrm{K}]$$

This quantity is plotted in the figure below and to the left for the ngVLA. For comparison to the other telescopes, we must repeat the calculation of T_{sys}, and η_a as done for ngVLA. For the VLA, we use SEFD measurements on the current array for these quantities. For SKA1-mid, we use the baseline design, which has 130 15-m antennas in addition to 64 13.5-m MeerKAT antennas. We take model atmospheres using 5 mm for dry conditions and 20 mm for wet conditions, and other quantities from Braun et al. (2018). For ALMA we use at atmosphere with PWV of 5 mm, and other quantities from Mangum 2017. The plot in the figure below and to the right shows a comparison of the above quantity for all four telescopes.



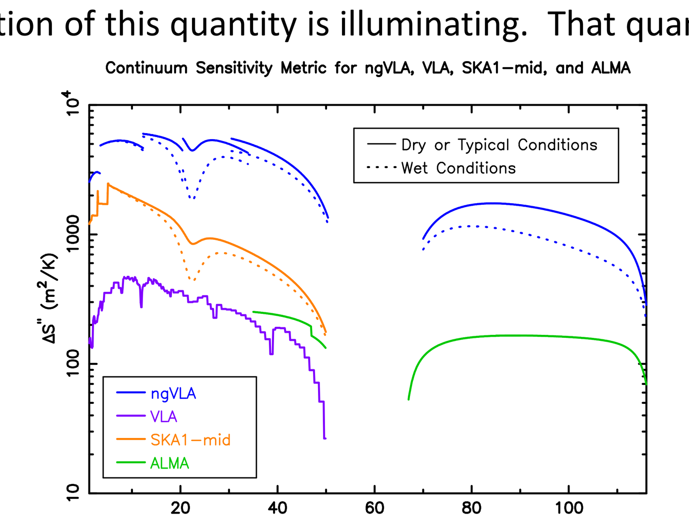


Continuum Sensitivity Metric for the ngVLA, VLA, SKA1-mid, and ALMA

The above metric is appropriate for doing spectral line observations, but for continuum observations we must also take into account the available bandwidth of the various telescopes. To account for that we define a new metric for continuum sensitivity:

$$\Delta S''(\nu) = \frac{\sqrt{\Delta\nu} N \pi D^2 \eta_a(\nu)}{4 T_{sys}(\nu)} \quad [\mathrm{m}^2/\sqrt{\mathrm{GHz}}/\mathrm{K}]$$

There are several caveats when considering such a quantity, of course, including the fact that the entire bandwidth is not available at every frequency (because of band edges and RFI). Also, for very large fractional bandwidths, the definition of sensitivity in terms of flux density at a given frequency becomes a function of the spectral shape of the source itself. The parameter defined in the equation above is appropriate for flat spectrum sources. Still, examination of this quantity is illuminating. That quantity is plotted below for all four telescopes.



Summary

We find sensitivities of a few tenths of a μJy for ngVLA in a 1 hour observation for bands 1-5, and less than 1 μJy for band 6. This is roughly a factor of ten more sensitive than the VLA and ALMA and a factor of 2-4 more sensitive than SKA1-mid for spectral line observations, and a factor of more than 10 more sensitive than the VLA and ALMA and a factor of 3-10 more sensitive than SKA1-mid for continuum observations.

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