ngVLA Memo # 58

μas Astrometry with the ngVLA

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Abstract

Accurate and precise astrometry is required to address many impactful science cases. Astrometry in the US that is competitive with current EU projects is often done with the VLBA; for the US to continue being relevant we must keep pace with improvements to VLBI. As it will be the next big radio interferometer project in the US, we explore the potential for an ngVLA to routinely deliver order-of-magnitude better astrometric accuracy and precision ($\sim$1 μas) compared what is currently done with the VLBA ($\gtrsim$10 μas). Simulations explore what is the best astrometric accuracy and precision that can be delivered by currently proposed ngVLA array configuration concepts and a hypothetical concept with southern hemisphere extensions. We identify a frequency of $\approx$27 GHz to be the sweet spot for pursuing μas astrometry due to angular resolution and calibration concerns. Calibration strategies play a critical role in obtaining μas astrometry, most important of which is the availability of a close-separation ($\lesssim$0.5°) primary phase-reference source. ngVLA VLBI stations populated with 5-6 antennas each would greatly improve the likelihood of finding such a calibrator and move us toward having full-sky coverage for conducting μas-level astrometric experiments. Our conclusion is that an ngVLA having VLBA-like and two southern hemisphere stations populated with 5-6 antennas each would be capable of routinely achieving μas astrometry.

Astrometry with the ngVLA

Very Long Baseline Interferometric (VLBI) astrometry on global scales has produced impressive results in the recent past (e.g., Loinard et al. 2007, Deller et al. 2013, Reid & Honma 2014, Melis et al. 2014). VLBI astrometry with existing arrays provides on the order of tens of μas astrometric accuracy and precision for $\sim$10 GHz experiments. The exciting science cases described for an ngVLA with long baselines in Reid et al. (2018) would benefit from improved astrometric capabilities relative to currently existing long-baseline arrays (like the VLBA). Specifically, order-of-magnitude improvement in astrometric accuracy and precision (μas-level) would open up a wealth of new discovery space and enshrine radio interferometric astrometry as the gold standard against which other methods and results are measured (e.g., like with the Pleiades – Melis et al. 2014; Gaia collaboration 2016). The ngVLA can achieve the above improvements in astrometric capabilities if care is taken to ensure the array has sufficiently long baselines combined with enhanced sensitivity especially on long-baselines (for calibrators and science targets) to produce accurate and precise relative positional measurements in phase referencing experiments.

Within this study we seek to provide quantitative assessments of the astrometric potential for the proposed ngVLA array configurations currently under consideration. This will help the community to have a reference when exploring astrometry science cases in general and will also demonstrate which arrays are capable of delivering μas astrometry. Then, with past experience, we provide guidance on calibration strategies for astrometric experiments and what is necessary to routinely deliver astrometric data sets that are accurate at the μas level.

Table 1: Synthesized Beam Sizes for 1 hr Tracks Centered at HA=0 hours

Array Configuration	Freq. (GHz)	DEC (°)	Synthesized Beam
ngvla-revC	27.1	+70	0.87 mas × 0.21 mas @ +1.7°
ngvla-revC	27.1	+20	0.79 mas × 0.24 mas @ −1.5°
ngvla-revC	27.1	−25	0.73 mas × 0.23 mas @ −2.6°
ngvla-revC-pujalm	27.1	+70	0.80 mas × 0.21 mas @ +4.6°
ngvla-revC-pujalm	27.1	+20	0.44 mas × 0.22 mas @ +15°
ngvla-revC-pujalm	27.1	−25	0.41 mas × 0.21 mas @ +15°

Note − Synthesized beams are quoted as beam size along the major axis, then along the minor axis, and the position angle of the ellipse on the plane of the sky in degrees East of North. Generally the larger beam size component is along the DEC direction.

ngVLA Astrometric Simulations

In general the limiting precision in measuring the centroid of a point-like object (i.e., modeled by a 2D gaussian) well-sampled on a regular grid is typically taken to be the size of the resolution element divided by the signal-to-noise ratio (SNR) of the detected source. So, for an array with synthesized beam size of $\approx$100 μas FWHM and a source detected with SNR$\approx$100 one would obtain a centering precision of $\sim$1 μas. In practice, various errors typically of atmospheric origin limit the accuracy of such astrometric errors to a factor of a few times the expected precision level. For VLBI these systematic error sources are well-cataloged and various methods are used to try and correct for them (e.g., Loinard et al. 2007, Reid & Honma 2014; Reid et al. 2017; Rioja et al. 2017). While significant improvements can be made, there still remain some residual inflation of the uncertainty due to these effects.

With the caveat of systematic uncertainties in mind (the likes of which we assume can be mostly circumvented by well-chosen observing frequency and calibrators; see below), it is desirable to try and determine whether the proposed ngVLA array is capable of probing desired science cases and what observational strategies would be necessary. We have performed a suite of simulations to explore the range of statistical astrometric precisions obtainable with a given array configuration for various source flux densities, *uv*-plane coverages, and declinations.

At the time of the writing of this memo, the December 2018 configurations were current and hence ngvla-revC was explored here. This array includes 244 antennas of 18 m diameter and extends over a maximum baseline of $\approx$8860 km. The main interferometric array (the Spiral214) includes 214 antennas of 18 m diameter and has baselines up to $\approx$1000 km mostly contained within the Southwest United States. The long-baseline component of the array has 30 antennas located in 10 different continental-scale stations including Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada. Additionally, we explore an experimental array configuration that adds to nglva-revC two sets of 3 antennas: one near the ALMA site and another to the SE of Pujili, Ecuador; we refer to this configuration as ngvla-revC-pujalm.

Inherent in the conducted simulations are a variety of assumptions to focus on the desired parameter space. In all simulations, a central observing frequency of 27.1 GHz is chosen (see details below) and a bandwidth of 14 GHz (ngVLA band 4 or a proxy of the Ka-band; see e.g., ngVLA Memo #17). A record time of 10 seconds is used during simulated observations which leads to a 1σ sensitivity per record for each baseline of 1 mJy (consistent with the ngVLA band 4 SEFD of

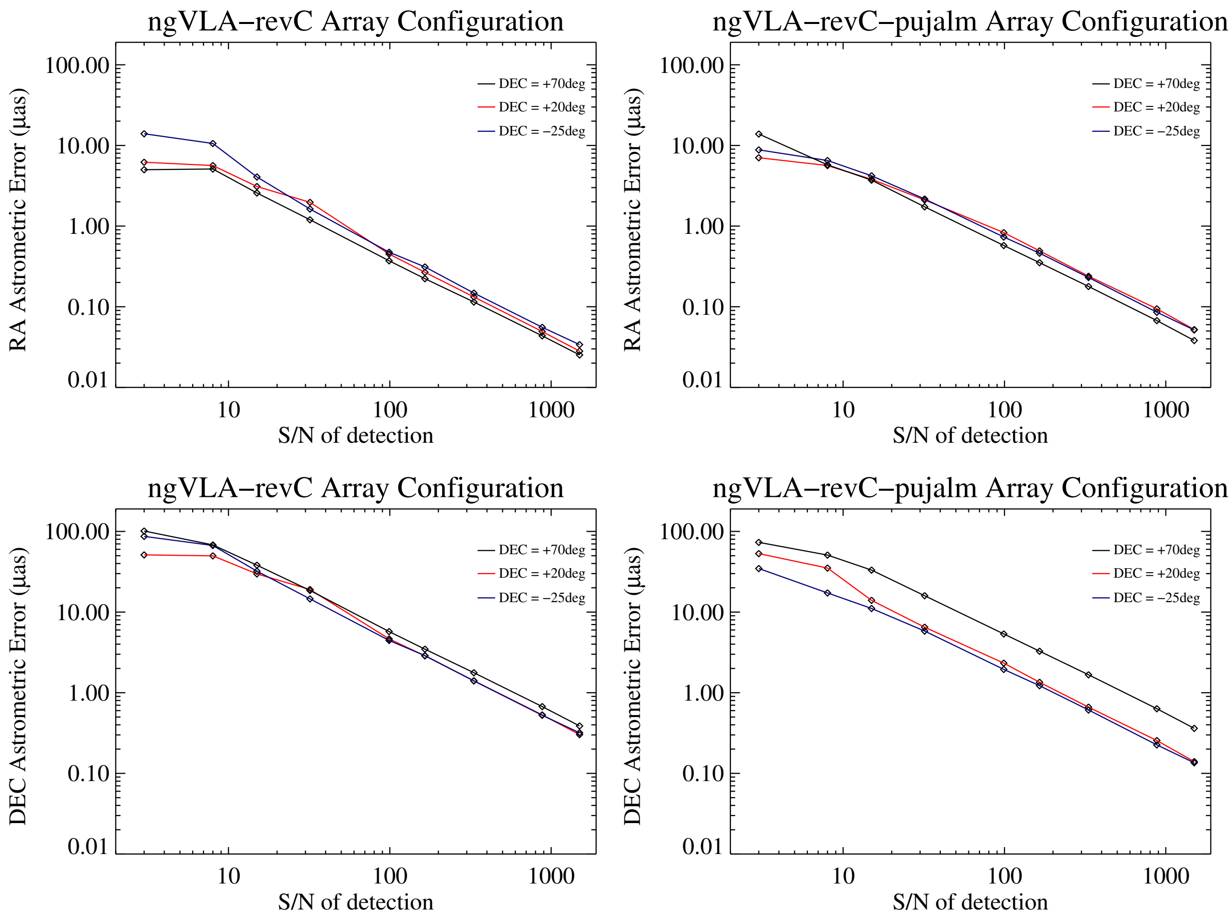

Figure 1: Results from simulations exploring the statistical error component of astrometric measurements as a function of signal-to-noise ratio of the source detection. Two different array configurations (as labelled) are used and sources with northern, middle, and southern declinations (black, red, and blue curves respectively) are plotted. The top row plot shows error in the measurement of the RA position while the bottom row plot shows error in the measurement of the DEC position. In these simulations, all tracks were 1 hour in total duration (i.e., observations within a given DEC case have the same *uv*-coverage and hence synthesized beam size; see Table 1).

457.7 Jy and antenna efficiency of 0.75; ngVLA Memo #17). To highlight the impact of a given array configuration on observing sources in different parts of the sky we explore targets having three declinations as shown in Table 1.

Simulated observations are done with the CASA 5.4.0 simobserve task with an input sky image containing a single point-source. This point source is located at phase center for the observation unless noted otherwise and contained within a grid of cell size 0.01 mas. The peak flux of the source is scaled to the desired flux density level for the simulation being run; that is to say, the source flux is set to obtain a desired S/N ratio for the expected map rms noise level. The observation date for all simulations is fixed and the source is assumed to transit mid-way through the simulated track regardless of the length of the track unless noted otherwise. Thermal noise is added to the measurement set output from simobserve with the sm.setnoise task with mode="simplenoise" and simplenoise="0.001Jy" (see above).

Imaging of the corrupted visibilities is performed with the clean task in CASA with Briggs weighting, robust of -2 (which obtains the most compact synthesized beam at the expense of increased noise), a cell size $\sim$1/8$\times$ the minor axis of the synthesized beam size, and a clean threshold set to 3$\times$ the expected map rms noise level (for a 3600 second total time-on-source track the rms noise level is $\sim$1 μJy beam^{-1}; there is a factor of a few variation in this value that comes from choice of array configuration and imaging parameters). A 2D gaussian fit is then performed on the resultant cleaned image within the CASA viewer without the "sky component" (this fitting algorithm was verified to provide comparable results to the AIPS JMFIT task).

Uncertainties from this 2D fit, the statistical component of the astrometric precision and the best one could hope to do with a given array for the given S/N level, are recorded and reported in Figures 1 and 2. For source detections with S/N>10 and at most target Declinations, the ngVLA-revC-pujalm array configuration concept can deliver <10 μas astrometry. For the ngVLA-revC array configuration concept, comparable astrometric results require S/N$\gtrsim$50. *uv*-coverage is not especially important except in the case of high-Declination sources where longer tracks produce more circular beams.

Calibrating and Phasing of Array Elements

Calibrations are critical in phase-referencing experiments that seek to obtain accurate and precise astrometry. VLBI phase-referencing tracks typically require frequent calibrations, mainly the interleaving of target and phase-reference source scans to track phase variations and to tie the science target position to that of the calibrator. Phase delays contribute to systematic errors in relative astrometry in phase-referencing experiments, thus minimizing these as much as possible is necessary to obtain μas astrometry. Atmospheric contributions to these delays come from the ionosphere and troposphere. Modeling the effects from these parts of the atmosphere during the reduction process can mitigate the impact of their contribution to the final astrometric uncertainty to some degree (see references above), but it is of value to try as much as possible to minimize them during the experiment through choice of observation frequency and calibration source.

Ionospheric contributions to astrometric uncertainty are more pronounced at lower frequencies (e.g., Fomalont 1995). While modeling of the ionospheric free electron content with the use of GPS data has significantly reduced the impact of this source of uncertainty, it is worse at frequencies <10 GHz and yet essentially negligible above frequencies of $\approx$30 GHz (especially for the goal of μas astrometry; see e.g., Table 1 of Guirado et al. 2000). As one goes to higher frequencies, tropospheric turbulence becomes the dominant source of astrometric uncertainty (e.g., Fomalont 1995). Additionally, rapid phase variation and the ability to tie phases from all baselines together becomes dependent on the ability to switch between calibrator and target fast enough (Beasley & Conway 1995). Along these lines, it is worth noting that water vapor radiometers on all ngVLA antennas (especially those doing VLBI) would greatly improve the ability to monitor in realtime and model out tropospheric effects. Considering all of these effects and the ability to routinely obtain high-sensitivity images leads to the conclusion that a frequency near 30 GHz is the best compromise. A frequency of $\approx$30 GHz also provides the desired synthesized beam size to allow one to obtain $\sim\mu$as astrometry for detections with S/N$\gtrsim$10 (lower frequencies would require higher S/N detections).

Empirically it is known that close primary calibrator sources are essential for VLBI phase referencing experiments and especially accurate and precise astrometry (e.g., Pradel et al. 2006). Experience tells us that calibrators with separation <2° should be sought out and that closer is better. However, there is no real guidance on what really constitutes the "optimal" closeness or if

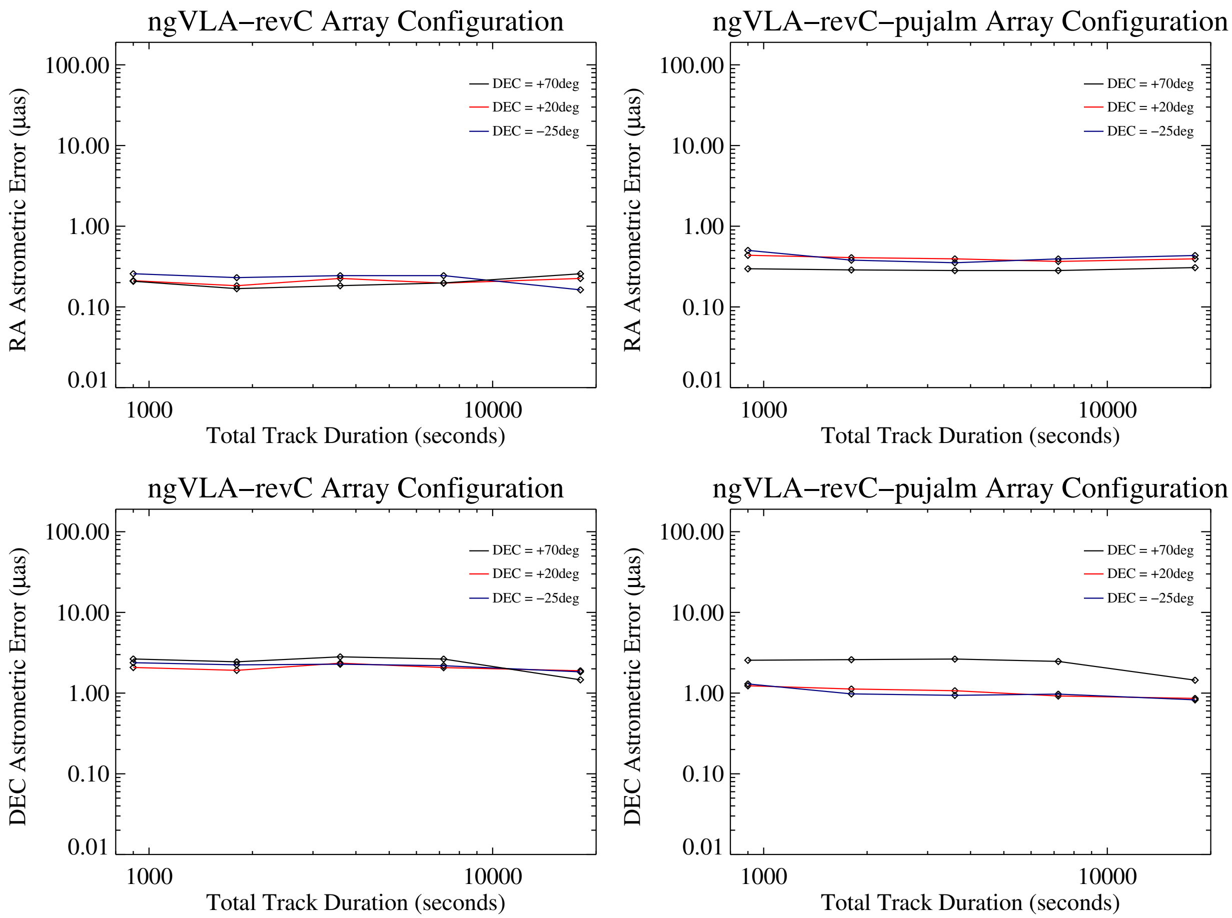

Figure 2: Results from simulations exploring the statistical error component of astrometric measurements as a function of total track duration (a proxy for *uv*-coverage). Two different array configurations (as labelled) are used and sources with northern, middle, and southern declinations (black, red, and blue curves respectively) are plotted. Top row plots show error in the measurement of the RA position while bottom row plots show error in the measurement of the DEC position. In these simulations, all tracks resulted in a S/N=200 detection of the target source.

there is some threshold separation at which there is no improvement if one utilizes a closer calibrator. Fomalont (1995) suggests that there can still be systematic errors even for in-beam calibrators due to the systematic offset in elevation between the target and calibrator. Investigations into how close a calibrator should be in general during an astrometry experiment should be conducted. Regardless of ambiguities around how close is close enough for a primary phase reference calibration source, to obtain the best astrometric accuracy and precision one would seek to use the closest, most compact, calibration source to the science target.

Experiments that have small science target-calibrator separations appear to mitigate some VLBI astrometry systematic error sources. For example, Pleiades stars benefited from a $<0.5^\circ$ separation phase-reference calibrator and thus were able to achieve close to the best-expected VLBA astrometric performance at 8 GHz without the use of geodetic block observations which address systematic errors from tropospheric delays (Melis et al. 2014). Based on this experience, it is our assertion that with observations at $\approx$27 GHz, regularly well-detected science target sources (S/N$\gtrsim$10), and a nearby phase referencing calibration source (e.g., like the $<0.5^\circ$ separation calibrator used in Melis et al. 2014), one can obtain astrometry accurate at the μas level.

In the remainder of this section we discuss specific approaches to calibrating an ngVLA operating at 27 GHz with the intent of obtaining μas astrometry. Rapid-style switching observations are necessary for high-frequency, long-baseline, phase-referencing experiments. VLBA Scientific Memo #20 (Ulvestad 1999) suggests that typical cycle times for observations at wavelengths of 10 mm are about 45-90 seconds depending on weather conditions. To obtain at least 10 seconds on the calibrator and target in one cycle for the shortest cycling time, it is essential that the ngVLA antennas take a maximum of 10 seconds to slew and settle for sources separated by $\lesssim 2^\circ$.

As discussed above, the expected per-baseline sensitivity for the ngVLA 18 m antennas in band 4 (27 GHz) is about 1 mJy for a 10 second record. Sources as faint as $\sim$10 mJy in the Ka-band can be used as phase-reference calibration sources provided that they are compact on long baselines. Phasing of local array elements can improve performance when sensitivity is necessary, e.g., if one wanted to utilize even fainter calibration sources. A grouping of 6 antennas could be phased up to allow calibrators as faint as $\sim$4 mJy to be used. According to source count derivations made by Murphy & Chary (2018), 27 GHz sources as faint as $\sim$4 mJy would be $\approx 9\times$ more abundant than those having flux density of $\sim$10 mJy thus making it much more likely to find one within $\lesssim 0.5^\circ$ for astrometry calibration needs. The exact number, position, and compactness of sources down to $\sim$4 mJy at high frequencies on long baselines is not well-established and surveys should be conducted to identify them.

Phasing up components of a VLBI array requires significant overheads which are strongly dependent on the spacing between elements in the phased array (phase-up scans with the Karl G. Jansky VLA in A-array need to be much more frequent than when the array is in the D-configuration). If antenna groupings at long, isolated, baselines are to be employed as phased arrays to improve calibrator availability, they should have maximum baselines $<$450 m to minimize phasing-calibration scans and to ensure a large synthesized beam size for the phased array within which the source or calibrator needs to fall when pointing (450 m baselines at 27.1 GHz yield a synthesized beam on the order of $5''$). Ideally, the spacing of such groupings would be no more than necessary to avoid shadowing.

Conclusions

In principle, an ngVLA could be capable of achieving μas astrometry. To do so, it must operate at higher frequencies than typical VLBI experiments, have improved sensitivity through vastly larger total array collecting area (as would be realized through $\approx$250 array elements), utilize continental-scale and cross-hemisphere baselines, and have long baseline sites equipped with multiple close-packed antennas to ensure an accessible close-separation phase calibration source. Slew and settling times of $\lesssim$10 seconds for ngVLA antennas are necessary and water vapor radiometers on all antennas (and especially those important for VLBI) would further improve the ability to mitigate systematic astrometric errors of atmospheric origin. Southern extensions to the ngvla-revC array configuration concept (e.g., a cluster of antennas near the ALMA site and another in a dry part of Ecuador) would enable more circular beams across a range of target declinations and hence routine $<10\,\mu$as-level astrometry in both RA and DEC for detections with $10 \lesssim \mathrm{S/N} \lesssim 100$.

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