Calibration Strategies for the ngVLA

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Next Generation Very Large Array

ngVLA Reference Design

The Next Generation Very Large Array (ngVLA) is being designed to address a broad range of high priority scientific questions in astrophysics. These motivations have been captured in the ngVLA Science Book (Dec 2018), including 5 identified Key Science areas spanning planet formation, astrochemistry, galaxy evolution, fundamental physics, and the dynamic multi-messenger sky.

A detailed, low technical risk, costed concept of the facility to address these scientific forefronts has been completed and released publicly as the ngVLA Reference Design (Aug 2019). Key features are:

- 263 feed-low offset Gregorian antennas at fixed locations centered at VLA site
- 214 x 18m antennas spanning baselines from 30m to 1000km
- 30 x 18m antennas extending up to continental-scale baselines of 8860km
- 19 x 6m antennas spanning baselines from 11m to 60m
- 4 of the 18m antennas may be equipped to operate in total power mode
- 1.2-116 GHz coverage using 6 receiver bands with linearly polarized feeds
- Operating modes: interferometric, phased, total power, solar, subarrays
- High observing efficiency (on target) and extensive automation

Over 80% of the scientific program will be accommodated through a diverse but well-defined set of standard observing modes. Data from these modes will be delivered to PIs and the community as Science Ready Data Products (SRDPs).

To ensure delivery of key scientific capabilities, the Reference Design incorporates derivations of corresponding technical requirements. These in turn shape the calibration strategies that will be needed to remove corrupting effects arising from the electronics, antenna structures, and the atmosphere.

Antenna

Pointing:

- Affected by factors such as gravitational, thermal, and wind loadings
- Remove slowly varying systematic terms using regular offset pointing
- Requirement: 4 arcsec (2D error) offset pointing capability

Primary beam:

- Requirement: Measure power pattern per polarization within -10 dB contour to within 0.1% - 1% of the boresight response in each of at least 10 independent 10 MHz wide channels sampled across each band

Amplitude

- Relative calibration within observation (gain, opacity): switched power system
- Absolute calibration: tie switched power system to regular observations of celestial standards, yielding <6% (best 1%) absolute flux density accuracy
- Requirement: Noise diodes stable within 0.1% over 5 min, 1% over 1 month
- Requirement: Antenna elevation gain dependency modeled within $1.5\times10^{-6}\ \nu_{\mathrm{GHz}}^{2}$

Bandpass

- Observatory to measure instrumental bandpasses and supply to science observations with compensation for time-variable atmospheric opacity
- Requirement: Store measurements in a calibration database, with accuracies 1% amplitude, 0.3° phase, in 0.1 km/s channels, with accountability of filters for averaging (baseband, subband)

Requirements Flow Down

The ngVLA will be a general-purpose instrument with a scientific program determined by peer-review of PI-led proposals. While the end goal is to build the most generally capable system, technical requirements in the Reference Design have been determined by identifying the most demanding aspects that drive design and are necessary to satisfy the Key Science Goals (KSGs). Traceability is built into the requirements flow down to enable iterative feedback in the design process.

Level 0: Science & Stakeholder Requirements (Use Cases)

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Level 1: System Requirements (Implementation Agnostic)

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Level 2: Sub-System Requirements (Architecture Presumed)

This poster summarizes the Level 2 calibration requirements. These are sensitive to quantitative parameters such as the assumed number of antennas in the array.

Key drivers include image dynamic range (L0), observing efficiency (L1), and the desire to satisfy KSGs without relying on self-calibration (not always practical).

Image dynamic range limitations arise from errors in measured visibility amplitudes or phases. Many of the technical requirements were derived by restricting residual errors sufficiently to support the L0 image dynamic range requirements, which are 45 dB at 8 GHz on-axis and 35 dB at 27 GHz over wide-field mosaics.

Polarization

- Full Stokes calibration, observatory measures and provides absolute leakages
- Requirement: Store measurements in a calibration database, within error modulus 10% in 10 km/s channels, accounting for circular polarization zero-point
- Requirement: Measure crosshand bandpass phases using noise diode system

Delay

Antenna Location:

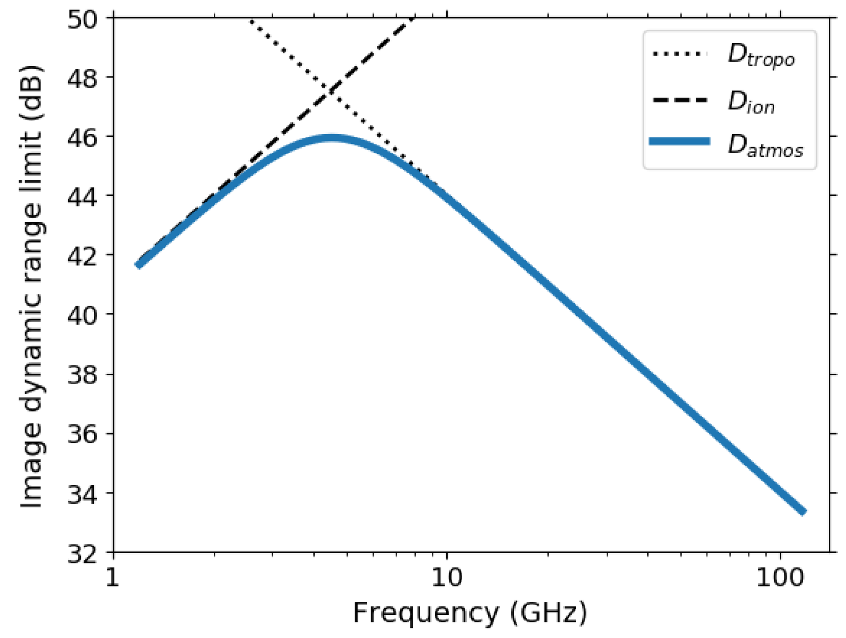
- 0.7 mm after removing systematic drifts

Timing Accuracy:

- 3 µsec over 1000 km baselines

Atmosphere:

- Troposphere: 0.3 psec noise in 2 sec
- Ionosphere: $7/\nu_{\mathrm{GHz}}^{2}$ psec noise in 2 sec
- Preferred Solution: 22 GHz water vapor radiometer per antenna with regular (>5 min) observations of a nearby gain calibrator to track dry and ionospheric delays



Above: Estimated worst-case image dynamic range limits arising from delay fluctuations in the troposphere (summer), ionosphere (solar maximum), and combined. All other error contributions (e.g. 4" pointing) are negligible by design.

Further Information

C. Hales, *Calibration Strategy and Requirements*, 020.22.00.00.00-0001-REQ (rev. B, 2020); see ngvla.nrao.edu/page/projdoc

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