Observing Modes Calibration Strategy

020.10.05.05.00-0006-PLA

Status: **RELEASED**

PREPARED BY	**ORGANIZATION**	**DATE**
T. Hunter, B. Butler, P. Demorest, V. Dhawan, J. Hibbard, R. Hiriart, J. Kern, E. Murphy, V. Rosero, R. Selina, T.K. Sridharan, J. Wrobel	North American ALMA Operations, New Mexico Operations, NRAO	2022-08-31
Observing Modes Work Group	NRAO	

APPROVALS	**ORGANIZATION**	**SIGNATURES**
E. Murphy, Project Scientist	ngVLA, NRAO	E. J. Murphy E. J. Murphy (Sep 1, 2022 13:12 EDT)
T. Küsel, System Engineer	ngVLA, NRAO	Thomas Kusel (Sep 5, 2022 21:16 GMT+2)
R. Selina, Project Engineer	ngVLA, NRAO	R. Selina R. Selina (Sep 6, 2022 17:51 MDT)
W. Esterhuyse, Project Manager	ngVLA, NRAO	

RELEASED BY	**ORGANIZATION**	**SIGNATURE**
W. Esterhuyse, Project Manager	ngVLA, NRAO	

Change Record

Version	Date	Author	Affected Section(s)	Reason
A	2021-12-02	A. Lear	All	Initial Release
B	2022-08-31	T. Hunter	1.1, 2.1, 2.2, 4.1, 4.3, 4.5, 5.1, 7.2, 7.3, 10.2	Minor changes arising from CoDR comments and suggestions

Table of Contents

1 Introduction

The Next Generation Very Large Array (ngVLA) is a project of the National Radio Astronomy Observatory (NRAO) to design and build an astronomical observatory that will operate at centimeter wavelengths (25 to 0.26 centimeters, corresponding to a frequency range extending from 1.2 GHz to 116 GHz). The observatory will be a synthesis radio telescope constituted of approximately 244 reflector antennas each of 18 meters diameter and 19 reflector antennas each of 6 meters diameter, operating in a phased or interferometric mode.

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Data will generally be delivered to PIs and the broader scientific community as Science Ready Data Products: automated pipelines will calibrate raw data and create higher level data products (typically image cubes). Data and quality assured data products will be made available through an observatory science archive. Data exploration tools will allow users to analyze the data directly from the archive, reducing the need for data transmission and reprocessing at the user's institution.

The signal processing center of the array will be located at the Very Large Array site, on the Plains of San Agustin, New Mexico. The array will include stations in other locations throughout New Mexico, west Texas, eastern Arizona, and northern Mexico. Long baseline stations are located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Array Operations will be conducted from both the VLA Site and the Array Operations and Repair Centers in Socorro, NM. A Science Operations Center and Data Center will likely be located in a large metropolitan area and will be the base for science operations and support staff, software operations, and related administration. Research and development activities will be split among these centers as appropriate.

1.1 Purpose of this Document

This document describes the strategy for calibration for the observing modes envisioned for the ngVLA to support the numerous science use cases [RD07]. The goals are:

1. to illustrate the key hardware components that are essential for calibration
2. to capture the broad scope of pipeline recipes that will be needed to support calibration
3. to note the heavy reliance on software tools, including any third party software or services

The observing modes for the ngVLA will employ various configurations of the 8 functional operating modes defined in the System Requirements [AD03]. These are: Interferometric, Phased Array, Pulsar Timing, Pulsar and Transient Search, VLBI, Total Power, On-The-Fly Mapping, and Concurrent Interferometric with Phased Array. For defining the Observing modes, we adopt the observing mode matrix approach developed in the Observing Modes Framework [AD04] (see Figure 1 in Section 11.2, Appendix B). In this approach, there are three Observing Mode Components (data product, antenna subarray, and correlator mode), and a larger number of Observing Mode Attributes (each categorized as "major" or "minor" to reflect the perturbation they represent).

In this document, we gather the list of attributes in Section 2 needed to support the science requirements [AD01]. In Section 3, we briefly describe the philosophy of calibration in light of the desire to migrate from the initial approach of performing traditional on-sky calibration to developing and using a calibration database to the extent possible in full operations. In Section 4, we begin by describing the calibration strategy to support the most basic observing mode of **"Interferometric imaging to produce continuum and Stokes I cubes of a single sidereal target observed with a single pointing of a compact configuration of the large diameter antennas, using coarse, uniform spectral resolution."** The strategy shall capture the philosophy of calibration, but not all of the quantitative details of observing cadences. We then describe the kinds of modifications needed to support the major and minor attributes of this mode as identified in [AD04]. The process is then repeated for each of the other data products in the subsequent Sections 5–9. Section 10 describes some considerations for the Observatory-facing observing modes required to support the PI observing modes.

1.2 Scope of Document

This document describes the calibration strategy that is designed to cover a broad range of observing modes and observing mode attributes. It is important to recognize that only a subset of these modes will be commissioned by the CSV team and delivered to Science Operations in time for the first Early Science observing cycles. Furthermore, some of the observing modes included here will require capabilities for which the ngVLA system should be suited, but which may not be scheduled to be verified before the end of the construction project. As a result, this document may be updated for later cycles as those plans develop. Defining the process for handover of individual observing modes to Science Operations is out of scope.

1.3 Applicable Documents

The following project documents are applicable to this report and are incorporated by reference. In the event of conflict, the applicable document supersedes the content of this report.

Ref. No.	Document Title	Rev./Doc. No.
AD01	ngVLA Science Requirements	020.10.15.00.00-0001-REQ
AD02	ngVLA System Reference Design	020.10.20.00.00-0001-REP
AD03	ngVLA Operations Concept	020.10.05.00.00-0002-PLA
AD04	ngVLA Observing Modes Framework	020.10.05.05.00-0005-PLA
AD05	A Notional Envelope Observing Program	020.10.15.05.10-0002-REP
AD06	System Requirements	020.10.15.10.00-0003-REQ-C
AD07	Commissioning and Science Validation Concept	020.10.05.00.00-0006-PLA
AD08	Computing and Software Architecture: Reference Design	020.50.00.00.01-0002-REP
AD09	Software Requirements for RFI Management	ngVLA Computing Memo 3
AD10	Proposed Categories for New ngVLA Principle Investigator Observing Modes	020.10.05.05.00-0004-PLA
AD11	A SCREAM-Compatible ngVLA Pulsar Engine: Key Requirements Review and Option Trade-Off Study	ngVLA Electronics Memo 11

AD12	A SCREAM-Compatible ngVLA Cross-Correlation Engine: Key Requirements Review and Option Trade-Off Study	ngVLA Electronics Memo 10
AD13	Local Oscillator Reference and Timing: Design Description	020.35.00.00.00-0002-DSN
AD14	Central Signal Processor: Preliminary Technical Requirements	020.40.00.00.00-0001-REQ
AD15	Calibration Requirements	020.20.00.00.00-0001-REQ

1.4 Reference Documents

The following non-project documents are referenced in this report:

Ref. No.	Document Title	Origin
RD01	Preliminary ngVLA Observing Band Availability Estimate	ngVLA Memo #73: Butler, B.
RD02	Analysis of antenna position measurements and weather station network data during the ALMA long baseline campaign of 2015	Proceedings of the SPIE, Volume 9914, id. 99142L 19 pp. (2016), arXiv: 1610.04140
RD03	Telescope Time Allocation (TTA): Concept	688-TTAT-002-MGMT
RD04	Interferometry and Synthesis in Radio Astronomy	Thompson, Moran and Swenson, Springer Publishing, 2017
RD05	Advanced Gain Calibration Techniques in Radio Interferometry	Brogan, Hunter, and Fomalont, 2014 Synthesis Imaging Workshop, arXiv:1805.05266
RD06	Self-Calibration	Cornwell, Proc. of NRAO-VLA Workshop June 1982, p. 13
RD07	Science with a Next Generation Very Large Array	Murphy, E., ASP Conference Series Volume 517, December 2008
RD08	Planetary Bistatic Radar	Brozovic et al. 2018, ASP Conf. Series Volume 517, 113
RD09	TELCAL: The On-line Calibration Software for ALMA	Broguière, D. ; Lucas, R. ; Pardo, J. ; Roche, J. -C., 2011, ASP Conf. Series Volume 442, 277
RD10	ALMA Pipeline User's Guide for Release 2021, CASA 6.2.1	ALMA Pipeline working group, October 2021
RD11	ngVLA Science Use Case CoL: SS # 2	Brozovic et al., March 2017
RD12	Phase Cal Basics and RF System	Brian Corey, Haystack Observatory, presentation

RD13	Multi-Tone per Band Pulse Cal	R.C Walker, NRAO VLBA scientific memo #8, 1995.
RD14	The ALMA Phasing System: A Beamforming Capability for Ultra-high-resolution Science at (Sub)Millimeter Wavelengths	L. Matthews et al., 2018, PASP, 130, 015002
RD15	Size-of-Computing Estimates for ngVLA Synthesis Imaging	ngVLA Computing Memo 4

2 ngVLA Observing Modes

2.1 Observing Mode Components

As described in [AD04], the definition of an observing mode begins by specifying three fundamental components: data product, subarray, and correlator mode. The major sub-types within each component are listed below.

2.1.1 Data Products

The 7 fundamental sets of data products are:

1. Interferometric continuum imaging (IQUV) with Stokes I spectral cubes
2. Interferometric spectral polarization imaging (Stokes IQUV)
3. Pulsar search mode data (power vs time/frequency/polarization)
4. Pulsar timing mode data (folded pulse profiles)
5. Phased beam baseband channels (VLBI or radar recording)
6. Single-dish autocorrelation imaging (analogous to single-dish “mapping”)
7. Single-dish / interferometry combined imaging (continuum and cubes)

2.1.2 Subarrays

The 8 fundamental types of subarrays, from which science subarrays are built, are:

1. Main array (Core dominated)
2. Main array (Spiral dominated)
3. Main array (Mid-baseline)
4. LBA (with or without some antennas from the Main Array)
5. SBA (with or without total power antennas)
6. Concurrent science arrays within Main Array (e.g., simultaneous observing in 2 bands)
7. Single antenna VLBI (one or more unphased antennas writing baseband data)

8. Single dish total power (one or more antennas)

2.1.3 Correlator Configurations

The 7 fundamental types of correlator configurations are:

1. Uniform resolution
2. Mixed resolution
3. Advanced configuration modes (such as zoom windows)
4. Phased array (single beam)
5. Phased array (N beams)
6. Pulsar Binning
7. On-the-fly interferometry

2.2 Observing Mode Attributes

Attributes are the various ways in which the observational setup, execution, or offline processing need to differ from the default method in order to achieve the science goals of the project. Attributes shall be classified as major or minor depending on how significant of a perturbation they require on the parent observing mode. Major attributes will typically require independent validation datasets when used in combination with different observing mode components. As a result, the most often-used major attributes should be represented in the public Science Validation datasets, so their commissioning will require careful prioritization order during the CSV period. Attributes can arise from each of the observing mode components as well as from many other aspects of the telescope hardware and software configuration and usage. As emphasized by the ALMA and VLA experience, any property of the observation that changes the fundamental content of the raw data or impacts how that data shall be processed by the pipeline should be captured as an attribute. These items can include information gathered from the PI proposal [RD03], and we begin with that category in the following subsections.

Examples of Major Attributes: Sidereal target (default), Ephemeris target, higher precision calibration, widefield gridding.

Examples of Minor Attributes: One science target per SB (default), Multiple science targets per SB, Multiple phase calibrators per SB, Online channel averaging, Pointed mosaic observations and imaging, Time-critical processing, Target of Opportunity.

Below we provide a more complete list of attributes classified by origin, as gathered from [AD04] and slightly updated and augmented.

2.2.1 Attributes as Additional Data Product Requirements Gathered from the PI

1. Spectral index images (including multiple Taylor terms when necessary)
2. Per-execution or per-epoch images
3. Calibrated visibility spectra
4. Time-critical processing (e.g., need position for another observatory)
5. Higher-order data products (e.g., source finder, spectral line finder)
6. Rotation measure cubes (Faraday dispersion cube)

7. Processing of multiple phase centers (see Section 2.5.8, Attribute 4 of [AD04])
8. Include autocorrelation spectra for diagnostics and calibration purposes (time resolution TBD)

2.2.2 Attributes Related to Specifying the Target Information Prior to Observations

1. Target of opportunity
2. User-provided ephemeris
3. Required time windows (e.g. multi-wavelength coordinated monitoring)

2.2.3 Attributes for Antenna Motion

1. Reference pointing measured and applied online
2. Application of rapid time sampled encoder corrections from the pointing table in offline imaging
3. Ephemeris position tracking (including solar)
4. Two-Line Element (TLE) position tracking (Earth satellites) with local pointing corrections measured on the target
5. Non-zero proper motion (i.e. specifying a rate rather than a table; e.g., nearby stars or fast pulsars)

2.2.4 Attributes for Receiver Band Usage

1. Single receiver band with single subband setup
2. Doppler setting of one or more subband windows (i.e., line observations in the TOPO frame)
3. Multiple subband setups per SB (note that LOs are fixed in all bands)
4. Multiple receiver bands for science per SB (e.g., insure close-in-time SED measurement of a point source for which the frequency-based change in angular resolution is not problematic)
5. Bandwidth switching (i.e., use wider bandwidth on phase calibrator scans vs. science target scans)
6. Band-to-band transfer (e.g., gather ionospheric delay corrections from band 1[1] when observing science target in Band 2)
7. Solar mode (alternative attenuator setups, etc.)

2.2.5 Attributes for Calibration Accuracy

1. Phase transfer assessment: Observe extra complex gain calibrators in SB, add pipeline stage
2. Higher astrometric accuracy: Observe extra complex gain calibrators in SB, add pipeline stage
3. Finer resolution bandpass calibration: Observe bandpass calibrator in SB
4. Finer polarization calibration: Observe polarization calibrator(s) in SB
5. Higher photometric accuracy: Observe flux calibrator(s) in SB

2.2.6 Attributes for SB Setup

1. Multiple fields per SB

[1] Frequency ranges of bands are given in [AD02], with smaller numbers indicating lower frequencies.

2. Multiple groups of fields per SB
3. Use of different calibrators for different subband setups
4. Use of different calibrators for different receiver bands
5. Solar observations (to request non-standard hardware setup)

2.2.7 Attributes for Correlator/Beamformer Setup

1. Online channel averaging or decimation
2. Advanced window functions (if necessary)
3. Doppler setting in frames other than LSRK or ephemeris body
4. Multiple phase centers for pulsar modes or LBA (dividing correlator resources), of order 4 expected (10 allowed, subject to bandwidth limitations)
5. Capture normal visibilities (at lower spectral resolution) at same time as phased array output
6. Possible special issues for solar observations (arising from data with higher correlation and non-linearity)
7. Conversion from linear basis to circular basis for summed array observations (this capability might be descoped)

2.2.8 Attributes for Dump Times and Archive Storage Rate

1. Shorter dump time than standard is needed (such as solar observations)
2. Exceeds standard data rate limit
3. Exceeds standard data volume limit
4. Baseline length dependent averaging in the Correlator Back End computer cluster (CBE) after the correlator (to drop data rate by factor of ~5)[2]
5. Extra-high data rate into CBE (to support real-time RFI excision or Fast Radio Burst (FRB) detection)

2.2.9 Attributes for Calibration Heuristics and Pipeline

1. Dual polarization calibration
2. Full polarization calibration (including special reference antenna heuristics across executions)[3]
3. If modes specified in Section 2.5.6 of [AD04] are triggered, then will need special calibration rules or recipes

---

[2] There is still much to be determined about the feasibility of baseline-dependent averaging, and the project needs to weigh the benefit of having much less data against the downsides (for example, it would compromise the sensitivity and granularity of auto-flagging heuristics for antenna-based issues). For now, we will keep the option open, at least.

[3] Wide-field polarization correction is envisaged via the A-projection method (see ngVLA computing memo 4 [RD15]). Polarization calibration strategies as a whole have not been finalized and are under revision, but it will include storage of beam patterns/D-terms in the calibration database.

4. RFI excision in correlator informed from a database of RFI (in addition to more advanced offline RFI flagging heuristics)

2.2.10 Attributes for Imaging and Non-Imaging Data Product Heuristics and Pipeline

1. mtmfs continuum imaging
2. Self-calibration of science targets
3. W projection (gridder='widefield'), including faceting in the uv domain
4. AW projection (gridder='awproject')
5. Exceeds standard image area or cube volume
6. Ephemeris velocity tracking
7. Near field imaging correction (solar system bodies)
8. Joint deconvolution of 6m-6m and 18m-18m visibilities (i.e., not 6m-18m)
9. Radar aperture synthesis
10. Any other non-standard imaging algorithm (including 6m-18m baselines, e.g,. “Kitchen sink” array or Main+SBA)

3 Philosophy for the Calibration Strategies

Traditional interferometer observatories rely heavily on on-sky calibrator observations and post-processing to measure and produce a variety of calibration tables to apply to science data. In addition, a real-time software module (e.g., TelCal on VLA and ALMA [RD09]) is also used to produce calibration solutions that are essential to apply during observations, and for first order assessment of system health or atmospheric stability. While ngVLA will use both of these techniques [AD08], it also aims to build and utilize a calibration database to increase the efficiency of observations wherever possible.

3.1 Calibration Database Concept and On-Sky Calibration

The calibration database is designed to store those system calibration parameters that are stable over significant time periods so that they can be retrieved and applied during offline processing [AD15], and thereby reduce the time overhead of calibration scans. Once this mechanism is in place and commissioned, the ultimate goal is to minimize the need to observe calibrators in standard observing modes, other than the complex gain calibrator(s) and, at high frequency, pointing calibrators and (possibly) flux calibrators.

Regarding on-sky calibration, we may wish to determine if dynamic integration times on the gain calibrator (i.e. determined at the outset of an observation or immediately prior) are worth the effort in terms of increased efficiency vs. complexity, or whether we should simply use a conservative (longer) fixed integration time based on a minimum signal to noise ratio and the most recent database flux density value adjusted for a nominal decay rate. For now, we will assume that standard observing modes will use the fixed time approach.

3.2 Validation of the Calibration Database Performance Prior to Usage

It is important to recognize that in the early years of CSV, prior to the population of the calibration database (Sections 10.4–10.6), each observation will need to observe calibrators for all calibration quantities. Once the database begins to be populated, each observation will still need to observe calibrators for any quantity that sufficient calibration cannot be obtained from the database and shown to be reliable. The process of proving that the database entries are reliable will require a period where database entries are available, but the on-sky calibration scans are still obtained. We envision that during the trial validation period of the database, the science pipeline recipes will pre-apply the database calibration, but still solve for the calibration tables of those quantities and present and assess the residual solutions, which in principle should be zero phase and unity gain. Only after reliable calibration from the database has been demonstrated for a specific calibration type (via this quantitative comparison of pipeline reduction of datasets that did observe all necessary calibrator types) will those associated calibrator scans be removed from the default generation of standard science SBs. However, even after this milestone is passed, it will be prudent for long duration SBs (e.g., several hours) to continue to include at least one bright (bandpass/polarization) calibrator in order to help diagnose any unexpected problems in the dataset and perhaps recover the science data, which might otherwise be lost. For non-standard modes still under commissioning [AD10], the use of the calibration database for a specific calibration intent will be decided on a case-by-case basis.

4 Calibration Strategy for Interferometric Imaging Capability

4.1 Default Calibration Methods

Below are the default methods of calibration, based on Section 2.5.6 of [AD04]:

1. Pointing and focus calibration: reference pointing scans in high frequency bands (likely bands 4–6), reduced rapidly online and applied in real time (by TelCal). For optimum performance, the focus setting in the highest frequency band(s) may need to rely on focus curves. If so, these curves shall produce monotonic changes vs. time (including any thermal/solar-related terms) to insure that no sudden phase jumps occur.
2. Complex gain calibration: observe calibrator nearby the target source(s) in all SBs in the same spectral windows. (Bandwidth switching to maximum bandwidth on the calibrator can be used once return-to-phase between spectral setups is confirmed and the pipeline can process it.) If a project requires separate observations in more than one band, e.g. due to different weather constraints, then it should be possible to request that the same calibrator (obtained via a query) used in the first observation also be used in subsequent observations (to promote astrometric consistency), if its characteristics are still appropriate.
3. Bandpass calibration: access from calibration database (at least for low-resolution "continuum mode"); setups with higher resolution, or those with very broad lines will likely require observation of a bandpass calibrator in the SB (see Section 10.3 for observatory mode to populate the database); instrumental baseband delays to be measured periodically by TelCal.
4. Spw-to-spw phase offsets: use bandpass calibrator if observed, otherwise use the time average of gain calibrators, with a heuristic to check for any drifts with time.
5. Polarization calibration: full stokes calibration (including true V):
    a. For standard low-resolution “continuum mode” setups, access the leakages from the calibration database (if they are stable), and access crosshand phases from the instrument (either from a observing a calibrator which will give the antenna terms or using the time-multiplexed noise diode calibrated against a source on the sky); for

polarization angle, observe a brief scan on a position angle calibrator (see Section 10.4 for observatory mode to populate the database).

b. For high spectral resolution setups (or to populate the calibration database for low-resolution setups, Section 10.4) measure leakages by observing a polarization calibrator over a wide range of parallactic angles; for polarization angle, observe a brief scan on a position angle calibrator.

6. Opacity tracking within an individual SB: switched power system.
7. Opacity at time of SB start: TBD (possibly from: a model based on meteorological data; by starting every relevant SB with a tipping scan; or estimated from the WVR data combined with the atmospheric model).
8. Atmospheric delay calibration: wet tropospheric (WVR, 1 second timescales), dry tropospheric (traditional gaincal, 5 minute timescales), plus ionospheric calibration at low frequencies (band 1). <u>All critical information about the delay model (not merely the version of Calc/Solve, etc.) shall be recorded in the science data model</u>. This includes tables containing both the static values and the time-dependent terms (such as precession, nutation, ocean and atmospheric loading, etc.), along with the total value.
9. Ionospheric Faraday rotation correction (lower bands only, up to band 2): ingest GPS-derived Vertical Total Electron Content (VTEC).
10. Absolute amplitude: the switched power system will be used to remove electronics gain variations during an observation. For setting the absolute flux scale, a table of lab-measured Tcal values can be used along with measured gain values (Jy/K) for each antenna/band. These Tcal values will be tied regularly to the celestial flux scale by the observatory calibrator monitoring program to produce a column of correction factors to apply to the Tcal values that is updated regularly (monthly, or whenever a front-end is changed), and accessed and applied by the pipeline during offline calibration.
11. Cycle times: will be used for all observed calibrators with intervals based on calibration intent and observational setup (as a tabulated function of frequency and array size). The complex gain calibration might eventually be made adjustable based on current atmospheric phase stability across the active subarray (as measured by TelCal phase solutions on the prior track and/or the WVR datastream).
12. Astrometric calibration: populate the calibrator database (Section 10.1) with ICRF grid sources with accurate positions determined (at least initially) by NASA Goddard or other VLBI community efforts. The coordinate equinox will be J2000 for now [CAL 0302 in AD15], but could be changed in the future to a new IAU adopted frame [Chapter 12 of RD04].
13. Station position accuracy: use ITRF positions, also imported from the VLBI community initially. Frame tying requires a dedicated observation with external, well-located antennas, e.g. VLBA. Will need to be measured periodically to account for possible pad settling or atmospheric model improvements [RD02].
14. For all observed calibrators, the target fields to which the corresponding calibration solution should be applied shall be recorded in the data model in order to prevent confusion downstream in the pipeline heuristics, especially when there are multiple groups of targets each assigned a separate complex gain calibrator and check source. For cases of multiple calibrators per intent, the field combination heuristics should be specified in the data model. For cases of multiple scans

per field for a given calibration intent (such as flux or bandpass), the solution interval and interpolation method to be used should be specified in the data model. The pipeline can of course choose to apply different heuristics via advanced (experimental) recipes, but the data model should contain the choices that were originally envisioned.

4.2 Attributes for Higher Calibration Accuracy

These items originated from Section 2.5.5 of [AD04].

1. Phase transfer assessment: Observe extra complex gain calibrator(s) in SB as "check source(s)", and insert a pipeline stage to perform analysis.
2. Higher astrometric accuracy: Observe extra complex gain calibrator(s) in SB, and insert a pipeline stage to perform analysis.
3. Finer resolution bandpass calibration: Observe a bandpass calibrator in SB for each frequency setup.
4. Finer polarization calibration of leakages: Observe polarization calibrator(s) in SB over wide range of parallactic angles.
5. Higher photometric accuracy: Observe flux calibrator(s) in SB.

4.3 Interferometric Observing Modes with Additional Distinctions

4.3.1 Solar Mode

Absolute amplitude calibration will be performed with the switched power system, accounting for the extra level of attenuation used on the target vs. the gain calibrator(s). For the active Sun, an additional adjustment of requantizer gains may be necessary on a scan-to-scan basis, along with a different strength of noise power injected from the noise diodes. The use of gain calibrators at a larger than typical angular separation is likely to be needed to avoid solar signal in antenna sidelobes. For active region observations (flares), it may be required to perform special system adjustments to prevent the signal from saturating the electronics. It is unlikely to be feasible to offset the pointing on the Sun scans to put the region of interest in the first sidelobe of the antenna primary beam. The ngVLA beam size is ~2*lambda arcmin, where lambda is in cm. Putting the active region in the first sidelobe would mean that the main beam is still on the disk of the Sun, in most cases, implying that not only is there the signal from the active region, but from the Sun itself. Also, at issue is whether the active region would be the size of the sidelobe or not, and whether the sidelobes will be sufficiently well-characterized to map a time- and space-variable source (the active region). Defocusing will also not work, since the Sun fills the beam and inner sidelobes for all wavelengths <~ 10 cm. The ALMA approach of de-tuning/de-biasing the Front End (SIS mixers) to reduce signal level may be feasible (via the bias of the cold LNAs); that remains to be investigated. In any case, quiet or mildly active sun is the highest priority to support, strong flares are lower priority. Methods to handle strong flares will be discussed with the engineering team going forward.

4.3.2 Mosaic Imaging

Application of encoder errors during the imaging stage becomes more important to achieving high image fidelity when there is emission across the primary beam, especially near the half-power point. Accurate primary beam models are also essential for mosaic imaging. Parametrization of these models will be needed in order to promote efficient imaging (in terms of CPU time). Measurements need to be made to support these models (Section 10.3).

4.3.3 Extra Wide Field Imaging with OTFI

Calibration heuristics for OTFI mosaic imaging will be informed from the ongoing optimization of the VLASS S-band data product. Maintaining consistent delays on all antennas at the high rate of phase center update (~20 Hz) will be challenging given the issues seen on the VLA with only 27 antennas at 0.9-second scan update rate (2 integrations per scan) with a brief look-ahead in calculations. For equatorial targets, we will need to account for the effect of the geosynchronous belt compressing the samplers, and the off-axis full polarization beam patterns (also measured with OTFI). Computation requirements are substantial. Performing a continuous update of the delay model to follow the antenna pointing center (rather than quantized steps) is a possibility under consideration.

Science use cases for OTFI only require the 214-antenna array, so making that a restriction to limit the baseline length offered is needed to avoid complications of differing (i.e., asynchronous) zenith passes at different LBA sites.

4.3.4 LBA (and Mid Antennas)

The main difference in observing modes utilizing long baseline antennas is in the calibrator targets that can be used. Because the standard flux calibrator targets that have tabulated and stable flux density vs. frequency are typically too resolved on these angular scales, single-dish SEFD measurements are used for absolute amplitude calibration. We will use known bright objects like planets, planetary nebulae, and quasars to get the K/Jy value for each antenna, and their measured Tsys from the noise diode. Short baseline data can be (and should be) used to verify the consistency of calibration of the two methods. Quasars and non-variable maser lines with simple structure can be monitored during short-baseline observations to establish their total flux for the few golden objects that are strong enough to see in single dish mode. (See also Section 7.2). Large differences in parallactic angles between stations may require additional techniques. Application of WVR corrections and opacity corrections may also need different strategies compared to the Core and Spiral antennas. If LBA stations are not on a common clock (i.e., packet delays approaching 1 sec), then additional calibration will be needed. If the nearest maser is close enough to distribute the clock to its neighboring antennas, then you do not need a maser for each antenna in a group. The current plan has each group sharing one maser [AD13]. We note that a pulse cal system (inserting a ~1 MHz timing signal locked to the local clock signal injected at or near the front end potentially with the same coupler as the switched power signal, see Section 9.5.7 of [RD04]), is not currently in the ngVLA design. Further details on such a system and the various benefits it can offer are described in Section 11.3 (Appendix C).

4.3.5 SBA

The increased level of shadowing due to the short baselines of the SBA may require different heuristics for the maximum amount of shadowing allowed in offline processing of the data. These heuristics will be developed in future revisions to the Calibration document [AD15].

4.3.6 Concurrent Science Arrays within Main Array

Concurrent subarrays can fulfill the use case that requires simultaneous observations of the same target or sequence of targets in 2 (or more) bands. In general, the calibration strategy will follow Section 4.1 for each subarray. However, the usage of the same complex gain calibrator should be able to be requested by the user in order to maintain consistent astrometry of the resulting images in the different bands, provided that its characteristics are appropriate to both bands. The same ability should be true for the flux calibrator (if observed).

4.3.7 Radar Aperture Synthesis Imaging

One use case of radar observations is to make direct images of objects through standard interferometry [RD08, RD11]. In general, the calibration of such observations is no different from normal spectral line interferometry. We assume that calibrated visibilities will be on a flux density scale (Janskys), not on a received power (Watts) or reflectivity (%) scale, so that information related to the transmitted power, effective transmit area, etc., are not needed for calibration. Such quantities may be needed in imaging, but are not needed for calibration. Similarly, a correction for the attenuation of the transmitted wave (if significant) need not be made at this stage. One significant note, however, is that the received power (flux density) can be very high, and there should be enough headroom to accommodate for its effects; for example, if there is a saturation curve for such high-strength signals, then it will need to be accounted for in the calibration.

4.4 Flagging Strategy for Interferometric Observing Modes

Successful calibration will require flagging of bad data caused by deterministic and non-deterministic causes. While a complete treatment of flagging heuristics is beyond the scope of this document, we describe the major features that will be needed for interferometric data.

4.4.1 Flagging for Deterministic Issues

Some types of flags can be applied automatically at the outset of offline data processing. In the ALMA pipeline, these categories include: flags generated by the online control system (such as "antenna off source", or "LO out of lock"), flags generated by the QA0 process, antenna shadowing (with a choice of distance overlap threshold), spw edges (if necessary to remove non-calibratable channels), autocorrelations (if they are not used), and extending partial polarization product flags (i.e., when only a subset of polarization products are flagged bad by the online system for whatever reason it is likely that the others are bad too).

4.4.2 Flagging for Instrumental Issues

Bad data will inevitably be produced by malfunctioning or mal-adjusted hardware. For cases of obviously and consistently bad data from specific antennas or specific antenna/spw combinations, it is possible to generate flags at the QA0 stage based on comparison of the antenna gain solutions compared to the median of all antennas. However, for lesser outliers, merely assessing the gain solutions is no longer effective, because some apparent outliers will calibrate out, and flagging them is unnecessary as well as costly in terms of observing efficiency. The true outliers must therefore be identified during processing.

Regardless of the origin of the flags (QA0 or during processing), the flags must be captured into an observatory database along with their origin. This database needs to be used by array operations to identify systematic errors that persist between different observations in order to stimulate further investigation and maintenance.

Over the past few years, the ALMA pipeline working group expended substantial effort to devise a powerful flagging strategy for both point source calibrators and extended science targets which should be useful for ngVLA pipelines. In the ALMA pipeline, which is based upon CASA, the first flagging step identifies antenna/spw combinations that show low gains on the bandpass calibrator (those with amplitude solutions less than half the median of all antennas). This step (hif_lowgainflag) eliminates obviously bad data from compromising the performance of the subsequent stages.

The subsequent flagging stages in the ALMA pipeline are based on a fundamental procedure (correctedampflag), which first determines a preliminary calibration (pre-applying the Tsys and WVR corrections and solving for initial bandpass, and temporal gains), applies this calibration, computes statistics on the scalar difference of the corrected visibility amplitudes minus the model visibility amplitudes, and then flags the outliers [RD10]. The philosophy is that only outlier data points that have remained as outliers after calibration will be flagged. There are several thresholds defined in terms of sigma, where sigma is based on the ratio to the median absolute deviation: (amplitude-median)/MAD, and there are heuristics for aggregating or extending the fundamental baseline/time flags into antenna-based or baseline-based flags. The phases of the data are not assessed, so some rare conditions where the corrected phase is an outlier from the model will not be caught if the corrected amplitude is not also an outlier. Assessment of the phases for outliers could be a future improvement. It is essential to use a slightly lower minsnr value in these preliminary gaincal solves than will be used in the subsequent final calibration stage (in order to avoid outlliers just below the applycal flagging threshold from slightly exceeding the threshold in the subsequent solves and reappearing as “zombie” outliers).

When this algorithm is applied to science targets, only the highest-level outlier threshold is used because there is no *a priori* uv model (i.e., a point source is used). In order to automatically adapt to the uv structure of the extended emission of the target, a set of uv bins is defined and the statistical calculations and comparisons are performed sequentially within each bin. To avoid flagging good data at short baselines where the amplitude can vary quite strongly with baseline orientation, the uv bins are shifted by half their width and the calculation is repeated. A visibility must be an outlier in both rounds in order to be declared an outlier. While this method works pretty well, further improvements can be imagined, particularly in the context of automated self-calibration and the development of a source model for each science target that can then be used instead of a point source.

4.4.3 Flagging for RFI Issues

Flagging of data affected by RFI is a System Requirement (SYS 4100-4102 [AD06]) and is discussed in ngVLA Computing Memo 3 [AD09]. To summarize, It is envisioned that some flagging can be implemented in real time at various places in the signal path, including the digital backend, the central signal processor (including the spectral channelizer, the frequency slice processors “X-engine” [AD12], and pulsar engine [AD11]), the correlator backend, and finally in post-processing in the pipeline. Heuristics development and tuning to the current RFI environment will be needed for all of these stages where automatic flagging will be attempted. A version of RFI flagging is implemented in the VLA pipeline using the flag task, but the current heuristics also flag narrow spectral astronomical spectral signals in the data (including, but not limited to, masers). The concept of an RFI manager and database will be used to provide a coordinated approach to solving the RFI problem through observation scheduling and improvements in flagging heuristics.

4.5 Self-Calibration of Science Targets

4.5.1 Definition

The term self-calibration (hereafter "self-cal") is used to describe the procedure for obtaining a time series of antenna-based complex gains (phase and amplitude) that minimize the deviation of the observed visibilities from a model of the source visibilities [RD05]. The Calibration requirements [AD15] were derived without allowing for the potential benefits of self-cal, primarily because not all science targets will have sufficient signal on the angular scales of interest. Nevertheless, iterative self-cal can be used to overcome a wide range of standard calibration inadequacies, regardless of whether the source structure is known a priori. It is a common misconception that self-cal is only important when atmospheric gain variations happen on shorter timescales than the switching time between phase-calibrator and science target. In fact, the transfer of gain solutions between a calibrator in a particular direction to another direction in the sky at another time (i.e., your science target) is never perfect. Following normal calibration, the residual (uncorrected) phase and amplitude errors often limit the sensitivity of the resulting science target image. In particular for bright sources, the noise in the image will be set by a dynamic range limit rather than a thermal noise limit. Another common misconception about self-cal is that absolute astrometry is always lost. In fact, it is not lost as long as you begin the process with the traditionally-calibrated phase-referenced image that has some reasonable level of coherence, which is the primary scenario that we are referring to in this section and which we envision for the pipeline. Astrometric changes between the initial and final image will typically be at the scale of a fraction of the pixel size used to sample the synthesized beam.

4.5.2 Prerequisites

In contrast to ALMA, the ngVLA will award observing time [AD03] instead of guaranteeing a requested sensitivity level. Formally, this distinction means that performing automated self-cal may not be strictly required to deliver ngVLA data products, but it would increase the fraction of those products that are delivered as "science ready", and therefore is essential to maximize the science impact of ngVLA. We also expect that self-cal will be key in (regularly) reaching the imaging dynamic range requirements of 45 dB at 8 GHz and 35 dB at 27 GHz (SYS 6103 in [AD06]). The main prerequisites for effective self-cal are to perform a high-quality initial calibration and to avoid doing too much time averaging of the visibility data of bright sources prior to storage and thereby limiting the shortest self-cal solution interval.

4.5.3 Sensitivity Benefits of ngVLA

The larger number of antennas offered by the ngVLA means that fainter targets will benefit from self-cal compared to the current VLA. It also means that more of the initial science target images based on traditional calibration will be dynamic range limited than currently is the case, although the amount will be mitigated somewhat by the application of WVR corrections. While the current ALMA and VLA general purpose pipelines do not yet attempt self-cal of science targets, planning has already begun to add continuum self-cal to the ALMA pipeline because it is routinely performed manually by a substantial number of users to generate more sensitive images of their science targets, beyond what is achievable with standard calibration including WVR corrections. At high frequency (~40 GHz), where the effective area of an 18m ngVLA antenna is comparable to a 25m VLA antenna, the reduction factor of the critical flux density necessary for continuum self-cal scales as sqrt(N–3) [RD06]. The number of antennas (N) for the various antenna subsets [AD05] and the corresponding factor are given in Table 1. For the 214-antenna Main array, the factor is sqrt(211/24) = 2.97. Assuming that traditional calibration successfully removes the spw to spw offsets, the source structure is constant over the observing band, and that multiple Taylor terms are used in imaging (to account for source spectral index), then spws can be combined in the solution. Thus, the wider bandwidths offered by the ngVLA in the higher frequency bands will potentially lead to further reduction in the critical flux density for self-cal. Alternatively, the higher SNR will allow more parameters to be solved for than merely the traditional phase and amplitude gains.

Subset of antennas	Number of antennas	VLA:ngVLA ratio for minimum flux density required for self-cal (using same bandwidth; assuming equal Tsys and effective collecting area per antenna)
Core	114	2.15

Core + Spiral	168	2.62
Spiral	54	1.46
Spiral + Mid	100	2.01
Mid	46	1.34
Main	214	2.97
Main + LBA	244	3.17
Mid + LBA	76	1.74 (or 3.23 relative to 10-station VLBA)

4.5.4 Algorithms

Table 3 of the ngVLA Computing Memo 4 [RD15] shows the computing algorithms needed for the different KSGs, which include using externally-derived antenna-dependent and time-varying aperture models along with the A-Projection algorithm in the imaging/self-calibration loop. Self-calibration of antenna pointing offsets vs. time exists in experimental form already, and higher-order solvers are in the theory stage within the NRAO Algorithm R&D group. For the ionospheric effects, the use of models derived from TEC maps has been demonstrated by some groups. However, achieving high dynamic range images in the lowest bands of ngVLA will be quite challenging, and the best approaches to handle direction dependent effects is a topic worth further research from the user community.

5 Calibration Strategy for Pulsar Timing Mode

5.1 Real-Time Array Phasing

Phasing the array requires interferometric observations of a sufficiently strong complex gain calibrator nearby the target source. Phase and delay solutions must be computed in (near) real time, as a sum of three components: geometrical, atmospheric, and electronic. These solutions are then applied to the per-antenna signals before summation to create the single-pixel voltage time series on the target. The required cycle time for re-phasing depends on observing band and baseline length, and in general will be comparable to the cycle times in Section 4, possibly slightly relaxed. The calibrator may require either a traditional slew (SYS 0204) or be an in-beam calibrator (SYS 0205). Some of the remaining questions are as follows.

5.1.1 Latency of Solution

What is the latency on the computation and application of the real-time phase/delay solutions? Clearly, it must be a small fraction of the cycle time. While the exact specification is TBD, three seconds seems plausible (e.g., 1 second integration, 1 second to produce the solution, and 1 second to apply it). Currently on the VLA, the processing is scan-based and so the latency is tens of seconds when a few 10-second scans are used to compute the solution. There is also a fundamental latency of a few seconds for any data emerging from CBE even for very short scans. On the VLA, the cycle time typically ranges from a few minutes to tens of minutes, but this will need to be shorter at the higher frequency and longer baselines of ngVLA. The value may depend on whether WVR data is being used to perform phasing corrections, a capability which is a system-level requirement ("Closed-loop calibration" on 1-30 sec time scales) [SYS0205 in AD06].

5.1.2 Scope of Solutions

Will we have TelCal compute solutions per-spw versus per-baseband? Because different spws can have different bandwidths, their SNRs will be different. Using wider-band solutions allows fainter calibrators but also requires a more stable, well-behaved system. In any case, we need to be able to choose which spws to combine in the solution.

5.1.3 Maximum Baseline Length

What is the maximum baseline length we will try to phase? SYS 0201 [AD06] states the maximum aperture diameter of 700 km corresponding to the Main Array. However, since the performance will be limited by atmosphere/weather [RD01], the default will likely be the Core, or Core plus Spiral if more sensitivity is needed and/or at low frequency. Regardless of the antenna combinations used, SNR-based weighting of antennas shall be possible (see Section 7.2.4 of [AD06]). If conditions support it, then the use of the Mid baselines may also be attractive to utilize any antennas left idle by concurrent science subarrays. However, for real-time array phase-up to work with these longer baseline antennas, an accurate model of the phasing calibrator's source structure will be necessary. It may also be necessary to study tradeoffs in the inclusion of these longer baselines; for example, if phasing efficiency is generally lower on the longer baselines, then the effective sensitivity gained by inclusion of those antennas is reduced. And based on experience with phased ALMA, there is evidence that in some cases inclusion of the (noisier) longer baselines can reduce the overall quality of the phasing on shorter baselines as well [L. Matthews, private communication].

5.1.4 Reference Antenna

Selection of a reference antenna for generic offline calibration is a solved problem in the ALMA and VLA pipeline heuristics, which sets a score based on array geometry and percentage of online flagging. This section is specifically about how the reference antenna used for online phasing will be chosen, which could have a different (simpler) heuristic. In any case, it will be desirable to be able to assign a fixed antenna to use as the phasing reference throughout an observation, and across day-to-day observations.

5.2 Flux Calibration of the Summed Array Data

If all digital gain factors (rescaling, bit selection, etc.) applied throughout the system are recorded rigorously, then the flux scale of the summed array data can be computed from the interferometric observations of the calibrator used for phasing (assuming its flux density is known); this is the ideal approach. A supplementary approach: if unknown gains are applied to the phased-array signal, then the switched power signal present in the summed data can be used to estimate the flux scale.

5.3 Polarization Calibration

Cross-hand phases can be determined either from observations of a strong calibrator, or from the switched power signal (or equivalent calibration signal as in Section 4.1). Relative polarization gains can be determined from the phasing calibrator (if unpolarized or of known polarization) or from the switched power signal. Note that this requires the absolute leakage for each antenna be known, not just the differences between antennas. If antenna leakages are known and stable, then they can be applied from tabulated values determined from interferometric observations (Section 4). This strategy is convenient as there are no polarization performance requirements specific to pulsar modes beyond those required for Interferometric imaging performance. If there are large differences in polarization response between antennas, this may require per-antenna polarization corrections be applied in real time before summing (as mentioned in [AD11]), to avoid depolarization (this probably needs some more study). In any case, the largest perturbation of changes in response will likely be hardware swaps, so re-measuring these responses on an antenna with recently-updated hardware will be critical before an antenna can be re-enabled for phased array usage.

To summarize, for optimal performance in the sum, the different antennas are to be:

1. weighted by SNR^2;
2. corrected for leakage of each antenna, if they vary in leakage or parallactic angle (via stored predetermined parameters). Assuming these values are stable, the accuracy of the calibration will improve by the sqrt of the number of antennas.

5.4 Clock Corrections

While not always considered a "calibration," all variable signal path delays must be accounted for so that the data can be referred to a standard absolute time scale, with an error of at worst 10 ns (ideal 1 ns) for high-precision timing (SCI 0112 = SYS 2002). Tying to the GPS (or UTC) time scale is assumed (SYS 2002). For pulsar timing purposes, these precise time corrections can be applied post-observation; they do not need to be known in real time. Note that VLBI has different, and in some respects stricter, requirements on timekeeping (see Section 7.4 for details).

6 Calibration Strategy for Pulsar Search Mode

Calibration for pulsar search mode is in general the same as for timing mode described in Section 5. For example, the phasing procedures are identical to those in Section 5.1. As search mode observations are often detection experiments, precise flux and polarization calibration can sometimes be neglected.

7 Calibration Strategy for VLBI Phased Array

7.1 Real-Time Array Phasing

The phasing procedures for VLBI are the same as given in Section 5.1. For the case of multiple concurrent phase centers within the primary beam, the basic phase/delay/amplitude factors are applied (which center the narrow summed-array beam on the central position used) and then offsets are added for each additional position in the primary beam based only on sky geometry. A separate data stream is then produced for each position (i.e., multiple correlation outputs if real-time) or multiple recorded streams. The total data volume (Nchannels and short time integrations) that emerges post-correlation, in either case, can then be less compared to what would have been needed to image the entire primary field of view to avoid time smearing. The multiple phase center implementation is currently planned to use the subarray mechanism, where the same set of antennas is used by multiple subarrays. This scenario will limit the number of phase centers. The current requirement is 10 for the pulsar modes (CSP0321, CSP0421) and 3 for VLBI (CSP0521) [AD14].

7.2 Amplitude and Flux Calibration of the Summed Array Data

7.2.1 Tsys and Efficiency (or SEFD)

Current VLBI data are generally automatically gain corrected to record 2-bit voltages. This method requires measurement of single-dish Tsys and efficiency (or combined into SEFD) from single dish antenna measurements (from switched power or autocorrelations) on planets, quasars, etc. For the ngVLA, these values can be determined in comparison with connected antennas on short baselines, including local LBA station arrays. The alternative described in Section 5.2, in which all gain factors are recorded, can also be considered here. The determination and use of opacity and antenna gain curve vs elevation is the same as Section 4. These techniques will enable single standalone ngVLA antennas to operate as VLBI stations.

7.2.2 Flux Scale Verification

One can perform a short-baseline test with single dish(es) to verify the interferometric and phased-array flux scales and confirm that the loss-factors from various processing steps are accounted for or understood. An example is the TYAPL task in AIPS (see its help file) which uses predetermined gains (Jy/Kelvin, gain curves, and loss factors) and the measured Tsys, to get absolute flux.

7.2.3 Post-Processing

Use a program to gather the individual antenna SEFDs and produce the effective SEFD of the phased array (does not account for real-time phasing errors, but can include various known losses, e.g. 2-bit quantization loss etc.). The assembly is currently done in the AIPS task VLAMP, which reads the interferometer visibilities (see its help file). The calibration assembly should account for the following steps. The individual spw must be gain-adjusted at the 2-bit re-quantizers (or 4-bit etc.) to optimally drive the last sampler before VDIF output is produced. If this is done, then the TelCal output amplitude is proportional to the SNR of each antenna in that spw. Optimal weighting of antennas in the summed-array is then to weight them by SNR^2, i.e., the amplitude in addition to delay and phase are used and applied in real time (as described in section 5.3). We do not yet do this on the VLA, we just sum with equal weight, which is sufficient for most initial tests, since antennas are nominally identical. But, if an antenna goes dead or weak, it just adds noise, so using the optimal weight would protect against that. Thus, the weight should be recorded, in addition to the upstream Requantizer gains, as already covered in Section 5.2.

7.3 Polarization Calibration

The general interferometer use case is to make all 4 polarization products during correlation prior to recording visibilities. The VLBI use case is different since the relevant cross-hand products cannot be generated prior to recording the data. We will likely write (i.e., send to correlation) only 2 streams, either summed-antenna linear (to be converted to circular after correlation) or summed-antenna circular (to match the recordings of other VLBI stations). We note that there is no current provision for the beamformer to convert from linear to circular, nor any strong desire from the community to do so, given the existence of alternative software tools [RD14].

As described in Section 5.3, we may ultimately need to apply per-antenna polarization calibration corrections to avoid depolarization in the sum. However, because only the central position of the Main array will be summed (at least initially), we may be able to ignore the differences between antennas if they are small, but we will have to allow for making a circular signal from the summed linear components (assuming we do it before VLBI correlation).

7.4 Clock Corrections

Regarding the specifications for clock error, for both pulsar and VLBI use, we mean the a-priori values, from e.g., GPS monitoring. To avoid fringe searching over wide windows in delay and rate, the clock-to-GPS uncertainty of the station clock (here, the clock of the phased array) should be within +/-500ns (for 1MHz channels), so the current spec of 10 ns is fine (SYS 2002). The rate error should be within 0.05 turn (18 deg phase) over a scan (long term drift specification). Assuming 100 sec for the latter, at 100 GHz, the predicted drift rate (clock prediction) should be accurate to 5x10^-15 sec/sec. At 10 GHz, the rate error can be 10x worse; in practice the rate error is set by atmospheric variation, not the telescope stability. Post-correlation (or post-pulsar-timing) results will be much more accurate depending on the SNR of the target. For example, for VLBI of a ~1 Jy source with modest SNR in 1 minute, the post-correlation accuracy rms is sub-ps, but limited to 10 ps by typical tropospheric variation.

8 Radar Observations for Non-Synthesis Imaging Modes

Besides aperture synthesis imaging (Section 4.3.7), other radar use cases include detecting unresolved objects, speckle analysis, and performing delay-Doppler imaging [RD08]. In almost all respects, these observing modes are analogous to pulsar (Section 5) and VLBI (Section 7) observing, in that either a number of single antennae or phased subarrays would be used to record the data. The primary data product would likely be the voltage time series, recorded in VDIF format, and would be processed through completely different software from other observing modes, provided by the observing community, not by ngVLA. We do not see calibration (or other) requirements for this kind of observing as significantly different than those for pulsar or VLBI observing.

9 Total Power Imaging (Single-Dish Autocorrelation)

The total power working group was only recently created, so the strategy for this observing mode is still under development. Some form of fast modulation will be needed during these observations, such as fast scanning of the primary mirror across the field, or use of a chopping subreflector combined with slower scanning across the field.

10 Calibration Strategy for Additional Observatory-Facing (Non-PI) Observing Modes

In order to support the commissioning efforts and calibration infrastructure envisioned for the ngVLA, a significant number of Observing modes will be needed for internal purposes. Here we list a few of the most important examples which, like science observing modes, will need detailed strategies defined.

10.1 Calibrator Surveys

This mode will perform continuum observations in one or more frequency bands of a large number of potential calibrator fields to determine accurate positions and up-to-date flux density measurements to populate the calibrator database. While the subarray requirement will need to be flexible, a uniform correlator mode should be sufficient, with a major attribute of sidereal fields and a minor attribute of multiple fields. The selection of fields to be observed should be automated based on a science target direction, frequency band, and expected uv range of the science observation. The observation should draw from either a large pool of potential calibrator sources which have (at least) approximate positions in the catalog, or a specified total area of sky if a search for new sources is needed. SB generation should be automatic, including standard flux calibrator(s) and (previously known) phase calibrator sources. We expect that standard continuum (full-polarization) imaging products will be produced by the pipeline recipe. Such images are needed to check the extent of the targets and establish valid uv ranges for use of the calibrator. Analysis of the images to provide positions and flux densities will need to be tailored to provide robust and automated results for the calibrator database. Using the calibrated amplitudes may be sufficient for subsequent monitoring once the first image in the target band has been established. The flux density database will also be populated by suitable PI observations that have met QA criteria in the science pipeline recipe.

10.2 Antenna Position Determinations and All-Sky Pointing Calibration

Because antennas will be added to the array throughout the CSV period, an observing mode designed to measure accurate antenna positions and axis offsets will be essential. The number and arrangement of antennas to be included will need to be flexible. Similarly, all-sky pointing observations will be needed to determine pointing models for each receiver band as antennas are added to the array, or receiver packages are replaced. Because the ngVLA antennas are expected to be non-mobile [AD02], one might imagine that the antenna positions can be measured once and for all time. However, the reality is that our ability to disentangle atmospheric effects from geometric position on long baselines is an ongoing research topic still faced by ALMA [RD02], and will likely mean that the antenna position model of the ngVLA will evolve at the submillimeter precision level for quite some time during Operations. Physical settling of the pads over time may produce detectable changes. Long-term changes due to plate tectonics will also play a role, at least for the LBA antennas. But the goal should be to not need to apply antenna position corrections in the science pipeline, or only on rare occasions, in contrast to the pipeline for an ever-moving array like ALMA.

A related observing mode will be needed to measure focus curves, for elevation dependence and thermal dependence, which will be needed to deliver optimal performance and will impact the measurement of antenna gain curves (section 10.6).

10.3 Holographic Measurements of Each Antenna

The complex beam pattern of each antenna will need to be measured in at least one receiver band and at least one polarization in order to determine surface deformation, and in all receiver bands and both polarizations to determine receiver feed illumination offsets. The specific scheme for this observing mode remains TBD (see the Appendix of [AD07]), but could include tower holography on the inner array, and geosynchronous satellite targets or strong celestial targets on the remote antennas. Measurements would need to be repeated upon relevant hardware changes (feed, etc.). Celestial holography will likely be used in the long-term to monitor the surfaces, so we will need an observing mode that captures the necessary scans and an automated procedure to generate surface maps by the holography software tool.

10.4 Bandpass, Delay, and Polarization Leakage

As described in Section 3.1, the calibration database is designed to contain per-antenna, per-receiver band quantities to be used during pipeline calibration and imaging. The primary quantities are: the complex bandpass response as a function of frequency for the most commonly-used spectral setup(s); the basic delay model for each baseband (fine adjustments will be made on-sky on a ~daily basis), and the polarization leakage terms as a function of frequency. We will need observing modes that measure these quantities on strong quasars. The bandpass and delay can be measured in the same observing mode, with delays solved in the first scan and applied online. The requirements for the observing mode to measure the polarization terms are given in Section 4.1. We will need pipeline recipes to process and quality assess these observing modes. Additional calibration quantities to be measured are listed in Section 10.6.

10.5 Full Polarization Beam Pattern Measurements of Each Antenna

To support full polarization calibration and imaging, the beam pattern of each antenna in all polarization co-products and cross-products will need to be measured in each receiver band on celestial targets at several antenna elevations and parallactic angles, for storage in the calibration database. The different elevations will enable an assessment of how the change in spillover affects the pattern. We will need an observing mode that acquires data at a few elevations, and a pipeline recipe to calibrate these observations and produce and quality assess these patterns. These measurements will need to be repeated when feeds are replaced due to maintenance.

10.6 Other Calibration Measurements for the Calibration Database

The calibration database will require per-antenna measurements of other quantities on bright calibrators. For example, gain curves as a function of antenna and elevation will be needed, particularly for the high frequency bands. We will need an observing mode that acquires data at a full range of elevations, and a pipeline recipe to calibrate these observations and produce and quality assess these gain curves. Another quantity is the feed offsets for each band that is not the reference band for all-sky pointing in Section 10.2. We will need an observing mode that cycles through the bands on a strong target and a software task (possibly within TelCal) that can solve for the offsets to be recorded into the calibration database.

10.7 Pulsar Period Determination (for Upcoming Pulsar Imaging Observations)

It is necessary to have an accurate period for a pulsar if online binning is being used to accumulate data prior to dumping integrations, as it is with the VLA. Online binning will likely be necessary also the ngVLA for short period pulsars (otherwise dump times of <~1-e4 sec would be needed). In offline processing, the phase range to use for imaging can be determined from the binned pulse profile. Even if the pulsar period is not used by the control system during the observation, such as for a long period pulsar that can be sampled by fast dump times, the period should still be known accurately at the time of observation in order to avoid delays in pipeline processing. Because ngVLA will be one of the most sensitive telescopes, particularly in the northern hemisphere, we will need an observing mode where the target pulsar is observed briefly in standard continuum mode within a few days prior to the upcoming observation, in order to measure its period using a special pipeline recipe.

10.8 System Health Test of Array Timing

To support pulsar timing projects, the absolute time of the array data product needs to be accurate. The validity of the array timing will need to be checked occasionally, which will require an observing mode that observes a well-known pulsar and processes the data with a corresponding pipeline recipe to determine the timing accuracy relative to prior observations at ngVLA or other observatories. VLBI observations with other facilities will also produce clock differences for subsequent analysis.

11 Appendices

11.1 Appendix A: Acronym List

Acronym	Description
AIPS	Astronomical Image Processing System
Calc/Solve	Goddard Space Flight Center VLBI Analysis Center's traditional software package
CASA	Common Astronomy Software Applications
CBE	Correlator Back End
CSV	Commissioning and Science Validation
DiFX	Distributed FX-style correlator
FFT	Fast Fourier Transform
FRB	Fast Radio Burst
GPS	Global Positioning System
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
ITRF	International Terrestrial Reference Frame
Jy	Jansky
LBA	Long Baseline Array
LSRK	Local Standard of Rest Kinematic
MAD	Median Absolute Deviation
mtmfs	Multi-Taylor-term multi-frequency synthesis (imaging algorithm)
OTFI	On-the-Fly Interferometry
PI	Principal Investigator
QA	Quality Assurance
RFI	Radio Frequency Interference
ROP	Reference Observing Program
RTP	Round Trip Phase

SB	Scheduling Block
SBA	Short Baseline Array
SED	Spectral Energy Distribution
SEFD	System Equivalent Flux Density
SIS	Superconductor Insulator Superconductor
SNR	Signal-to-Noise Ratio
spw	Spectral Window
TBD	To Be Determined
Tcal	Measurement value of the noise calibration diode
TelCal	Telescope Calibration software module
Tsys	System Temperature
UTC	Universal Time Coordinated
WVR	Water Vapor Radiometer
VDIF	VLBI Data Interface Format
VGOS	VLBI Global Observing System
VLA	Very Large Array
VLASS	Very Large Array Sky Survey
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VTEC	Vertical Total Electron Content

11.2 Appendix B: Observing Mode Matrix for Initial Observing Modes

Data products	Subarray					Correlator Mode							Major Attributes				Minor Attributes					Number of new validation SBs	ROPs enabled
Milestone 0 (close to VLA equivalent in many ways)	**Core**	**Plains**	**MidBL**	**LBA**	**SBA**	**Uniform**	**Mixed**	**Advanced**	**Phased array 1-beam**	**Phased array N-beams**	**Gated**	**OTFI**	**Sidereal single field**	**Ephemeris targets**	**Higher precision calibration**	**Widefield gridding**	**Multiple fields**	**Pointed mosaic**	**Time-critical processing**	**ToOs**	**Channel averaging**		
Continuum images (IQUV); spectral cubes (Stokes I)	1	1								X												8	3.1
Spectral polarization cubes (IQUV)										X	X												
Pulsar timing-mode data				X	X		X	X			X	X	X	X			X	X	X				
Pulsar search-mode data				X	X		X	X			X	X	X	X			X	X	X				
Phased visibilities (VLBI)											X	X			X	X	X	X	X				
Single-dish autocorrelation imaging	X	X	X	X					X	X	X	X			X	X	X	X	X				
Single-dish combined imaging with interferometry			X	X					X	X	X						X	X	X				
Milestone 1	**Core**	**Plains**	**MidBL**	**LBA**	**SBA**	**Uniform**	**Mixed**	**Advanced**	**Phased array 1-beam**	**Phased array N-beams**	**Gated**	**OTFI**	**Sidereal single field**	**Ephemeris targets**	**Higher precision calibration**	**Widefield gridding**	**Multiple fields**	**Pointed mosaic**	**Time-critical processing**	**ToOs**	**Channel averaging**		
Continuum images (IQUV); spectral cubes (Stokes I)	2	2	1	1						X												4	1, 3.1
Spectral polarization cubes (IQUV)	1	1								X	X											9	2, 3.4
Pulsar timing-mode data	1			X	X		X	X			X	X	X	X	X	X	X	X	X			1	5.5
Pulsar search-mode data				X	X		X	X			X	X	X	X	X	X	X	X	X				
Phased visibilities (VLBI)	1										X	X			X	X	X	X	X			1	VLBI
Single-dish imaging	X	X	X	X					X	X	X	X			X	X	X	X	X				
Single-dish combined imaging with interferometry			X	X					X	X	X						X	X	X				

Color Key denotes how the mode may be offered:	standard	shared risk	not commissioned	post Construction	X unallowed

Notes:

Number in each cell is the calibration technique level: 1=hardcoded calibrators (in SB), 2=dynamic calibrators, 3=database calibration (wherever possible)

Uniform = Uniform mode (contiguous channels of equal width)

Mixed = Mixed mode with Doppler setting multiple windows (including velocity scale commissioned to high precision)

Advanced = Advanced mode (greatest flexibility, such as recirculation)

Phased = Phased array (up to N beams)

Gated = Pulsar gated mode (for imaging)

OTFI = On-the-fly Interferometry (large area mapping)

Figure 1: Observing Mode matrix for CSV milestone 0 (top matrix) and CSV milestone 1 (bottom matrix).

11.3 Appendix C: Description and Operational Benefits of a Pulse Cal system

This appendix describes the concept of a Pulse Calibration system (hereafter, pulse cal): what it does (the science case) and what it is physically, along with some comments and opinions.

11.3.1 What it Does

A pulse cal enables the measurement, monitoring, and removal of phase and delay changes in the antenna signal path. The science case is Astrometric and Geodetic applications, especially with the long baselines of ngVLA, including:

- Parallaxes & Proper motions of Galactic objects.
- Definition & upkeep of the ICRF, Celestial Reference Frame.
- Earth Orientation & ITRF, the Terrestrial Reference Frame.
- Ephemeris Tie to Solar System; Precision Spacecraft Orbit determination.
- Geophysics - Solid/fluid angular momentum exchange, sea level change, plate tectonics.

These results rely on phase and delay measurements over long timespans, wide bandwidths, and all-sky coverage, with instrument contributions separated from the direction-dependent geometric and atmospheric path length changes. Astronomy use cases seldom need this separation, and the standard phase transfer from a nearby calibrator suffices to (nearly) remove the lump sum of phase errors.

11.3.2 What it Is

- Old version: essentially a diode with very short rise time, making high harmonics of a 1MHz (or other frequency) tone, which is locked to the (maser) timing reference.
- New version: uses digital gates as described by Corey [RD12, a detailed tutorial including modern versions of the hardware, see esp. pages 7,8.].

The pulses go up to 25 GHz (VLBA version) and are injected via the same coupler where the noise-cal diode signal enters the front-end amplifier (after the polarizer). The further upstream it is located, the better, to traverse more of the signal path. The pulses are extracted downstream e.g. the VLBA has one extractor before the data recorder (in the Xcube Research and Development unit, which gets VDIF packets from the digitizers) and again after disk playback, in the DiFX correlator.

Extraction is by pulse-folding at the known rate (1 or 5MHz) and FFT. The software overhead is small. The result is an amp & phase measurement every second, for each 1MHz tone (up to 512 over the IF bandwidth, for each polarization). The data go to the monitor archive, and are applied offline.

The pulse cal is also useful for single-antenna diagnostics, comparing the reference phase with that which emerges after all the electronics have imprinted on it.

11.3.3 Comments

There are items closely related to the pulse cal system, including Round-trip phase/delay (RTP). The RTP is some modules and software to measure delays in reference signals, e.g.:

- VLBA [RD13]: Pulse cal goes with a cable cal "round-trip phase" which measures the delay changes in the cable carrying the reference signal up to the pulse injection point. These variations are removed from the pulse cal to get the true variation of signal on the astronomical path.
- EVLA: The EVLA had (has, but turned off) an RTP scheme "L352 module" to account for the changes in delay of the LO reference signal as it travels by fiber from the Central timing rack to each antenna. To shorten a longish tale, we get along fine without it. Think of it as insurance we did not die for. In this case, it monitors only up to

the LO receiver; I think to be more useful it should include signals that travel down through the signal chain, not just the reference signal to the LO. ALMA has an RTP as well.

11.3.4 Summary

Pulse Cal is:

- Not a big overhead in either hardware or software. Already in use at VLBA, all new VGOS (geodetic) antennas, many others. Application software already exists (in AIPS).
- Not essential for astronomy; will not hurt.
- Can be used for both amplitude and phase calibration (the tone amplitudes have information on Tcal/Tsys).
- Can be useful for single-antenna diagnostics.
- Other techniques (e.g., pulse folding on the noise-diode switching waveform) can track relative phase between signal channels, but not the total electrical path length on the antenna.
- For geodesy, laser measurement of antenna deformations, optics path, and axis offsets might be better (but do not measure at the signal frequency).
- For the ngVLA, it might be sufficient to use laser metrology on a few antennas and apply the model to the rest, assuming they are similar. See also next point.
- Finally, if there is no pulse cal on any ngVLA antenna, we should proceed as follows:
  - Determine a full suite of parameters for the antenna locations xyz, axis offset, gravitational changes in focus and feed position, etc. based on the shortest baselines <1km, where the fit residuals can be <1ps (0.3mm) in good weather.
  - Apply the parameters so determined to all distant antennas, where the atmosphere prohibits the actual measurement.

Of course, having low fit residuals does not guarantee a clean separation of nearly degenerate terms. This procedure can be supplemented by other antenna metrology systems, as available.

020.10.05.05.00-0006-PLA-Obs_Modes_Calibration_Strategy

Final Audit Report 2022-09-07

Created:	2022-08-31
By:	Alicia Kuhn (akuhn@nrao.edu)
Status:	Signed
Transaction ID:	CBJCHBCAABAAyHI7gxRxUu9iqUqlAuojCmaq_tIR6Wxa

"020.10.05.05.00-0006-PLA-Obs_Modes_Calibration_Strategy" History

Document created by Alicia Kuhn (akuhn@nrao.edu)
2022-08-31 - 8:29:58 PM GMT

Document emailed to emurphy@nrao.edu for signature
2022-08-31 - 8:30:51 PM GMT

Email viewed by emurphy@nrao.edu
2022-09-01 - 0:54:27 AM GMT

Signer emurphy@nrao.edu entered name at signing as E. J. Murphy
2022-09-01 - 5:12:27 PM GMT

Document e-signed by E. J. Murphy (emurphy@nrao.edu)
Signature Date: 2022-09-01 - 5:12:29 PM GMT - Time Source: server

Document emailed to Thomas Kusel (tkusel@nrao.edu) for signature
2022-09-01 - 5:12:31 PM GMT

Email viewed by Thomas Kusel (tkusel@nrao.edu)
2022-09-05 - 7:16:41 PM GMT

Document e-signed by Thomas Kusel (tkusel@nrao.edu)
Signature Date: 2022-09-05 - 7:16:59 PM GMT - Time Source: server

Document emailed to rselina@nrao.edu for signature
2022-09-05 - 7:17:01 PM GMT

Email viewed by rselina@nrao.edu
2022-09-05 - 7:45:46 PM GMT

Signer rselina@nrao.edu entered name at signing as R. Selina
2022-09-06 - 11:51:56 PM GMT

Document e-signed by R. Selina (rselina@nrao.edu)
Signature Date: 2022-09-06 - 11:51:57 PM GMT - Time Source: server

Document emailed to westerhu@nrao.edu for signature
2022-09-06 - 11:52:00 PM GMT

Email viewed by westerhu@nrao.edu
2022-09-07 - 7:09:35 AM GMT

Signer westerhu@nrao.edu entered name at signing as Willem Esterhuyse
2022-09-07 - 7:10:13 AM GMT

Document e-signed by Willem Esterhuyse (westerhu@nrao.edu)
Signature Date: 2022-09-07 - 7:10:15 AM GMT - Time Source: server

Agreement completed.
2022-09-07 - 7:10:15 AM GMT