Observing Modes Framework

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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 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 (SRDPs): 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 process of defining the observing modes envisioned for the ngVLA. It provides a qualitative list of the technical capabilities that are required to achieve the Reference Observing Program (ROP), and how the complex combination of these capabilities can in principle be mapped to a finite number of observing modes that must be commissioned by the Commissioning and Science Validation (CSV) group. It provides a clear method for determining the number of scheduling blocks that are required to be executed and analyzed in order to validate each set of observing modes that are offered for the incremental proposal calls during Early Science and beyond.

1.2 Scope of Document

This document covers the initial observing modes that must be commissioned by the CSV and delivered to Science Operations for the first Early Science observing cycles. This document will be updated for later cycles as those plans develop. There may be other observing modes or capabilities that the ngVLA is capable of, but which are not scheduled to be verified before the end of the construction project; these are out of scope for this document. Defining the process for handover of modes to Science Operations is also 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	020.10.15.05.00-0001-REQ
AD02	System Reference Design	020.10.20.00.00-0001-REP
AD03	Operations Concept	020.10.05.00.00-0002-PLA
AD06	System Requirements	020.10.15.10.00-0003-REQ
AD07	Commissioning and Science Validation Concept	020.10.05.00.00-0006-PLA
AD08	Reference Observing Program	020.10.15.05.10-0001-REP
AD10	Proposed Categories for New ngVLA Principal Investigator Observing Modes	020.10.05.05.00-0004-PLA
AD15	Calibration Requirements	022.20.00.00.00-0001-REQ
AD18	Legacy Science Program	020.10.05.00.00-0004-PLA

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	*Proc. SPIE*, Volume 9914, id. 99142L 19 pp. (2016)
RD03	Telescope Time Allocation (TTA): Concept	688-TTAT-002-MGMT
RD04	Size-of-Computing Estimates for ngVLA Synthesis Imaging	ngVLA Computing Memo 4

2 ngVLA Observing Modes

2.1 Overview

The overarching functional configurations of the ngVLA system are described as *Functional Operating Modes* [AD06]. These eight functional operating modes (along with their corresponding system requirement codes) are

1. Interferometric Mode (SYS0002)
2. Phased Array Mode (SYS0003)
3. Pulsar Timing Mode (SYS0004)
4. Pulsar and Transient Search Mode (SYS0005)
5. VLBI Mode (SYS0006)
6. Total Power Mode (SYS0007)
7. On-the-Fly Mapping Mode (SYS0008)
8. Concurrent Interferometric and Phased Array Mode (SYS0202)

Each mode has unique online system setup requirements and different basic data products. Given the large number of modes, it is essential for the ngVLA project to define a specific list of Observing Modes within each Functional Operating Mode that are to be validated by CSV during the Construction project. Due to resource constraints, it is inevitable that only specific combinations of capabilities and paths through the observatory system will be validated during CSV, hence implying a limited number of observing modes, and a further limited number of *standard* observing modes (defined in Section 2.3).

The Observing Modes Workgroup was created in late 2019 to develop these lists of modes. From a high-level perspective, it is expected that at least 80% of the scientific observing time will be undertaken in a standard observing mode [AD03], so that is the goal for CSV. This goal does not necessarily imply that every Functional Operating Mode will be represented by a standard observing mode that has been fully validated by the end of the Construction project. In fact, modes that correspond to a small fraction of the total demand and also present unique requirements in data collection and/or pipeline processing, such as Solar Mode, will likely not be represented in the set of standard operating modes delivered by CSV.

2.2 Defining the Term "Observing Mode"

The definition of what constitutes an observing mode is the first issue to address. Starting from the science user's perspective, an observing mode provides a unique science capability, requires a scheduling block of a specific format, and produces a specific set of data products. This sort of definition is what is often presented in the summary document of a Call for Proposals, which typically contains broad science categories such as "Stokes I Continuum" or "Single Pointings and Pointed Mosaics" or "VLBI." However, such definitions hide all of the internal complexities of rules and decision trees that are needed to

1. determine which hardware and control software resources are required,
2. define a rigid sequence of observations of calibrators and science targets, and
3. specify which heuristics and methods should be used to process the data in the pipeline.

All of these considerations must lead to a predefined set of data products that can be numerically validated against future pipeline releases. It is exactly this latter combination of items that must set the observatory's internal definition of an observing mode. Some observing modes will rely on similar subsets of capabilities as other observing modes, some modes will require unique capabilities, and some modes can be achieved by using different combinations of capabilities, some less optimal than others. But all modes require individual commissioning.

In this sense, each observing mode comprises a list of rules that every subsystem must follow in order for the data product to be successful. This definition will help to avoid costly problems at the validation stage that can result when different subsystems make different assumptions about each observing mode.

2.3 Standard versus Non-Standard Observing Modes

As the capabilities of the array expand during CSV, each observing mode will pass through a sequence of commissioning milestones as outlined in the CSV Concept document [AD07]. This path includes modes that will become Standard during the Construction project, as well as additional modes with lower user demand that are expected to still be non-standard at the end of the Construction projects. **A Standard Observing Mode is one for which all stages of the process, from generating scheduling blocks to producing quality-assured science ready data products, is automated, and has been extensively tested and validated for use by PIs.**

While the main goal of CSV is to produce and validate Standard modes, these may not be the only modes offered to users. The project may choose to offer additional modes prior to their reaching the Standard Mode readiness level, on a "Shared Risk" basis. However, the vague label of "Shared Risk" is insufficient to categorize the various ways in which an observing mode is not yet standard. Therefore, an additional nomenclature of Observing Mode Status level has been developed [AD10]. The five status levels are New Mode Test Observations (NMTO), Shared Risk Observing (SRO), Non-Standard Data Reduction (NSDR), Principal Investigator Data Reduction (PIDR), and Standard Mode Data Reduction (SMDR).

The different status levels involve a very different amount of work to validate them. The CSV and Science Operations teams will together decide which status level to assign to all observing modes offered for a given cycle of Early Science, considering the available commissioning resources and user impact. The ultimate goal is to move most modes to the SMDR level, but this could take several commissioning seasons for some modes.

2.4 System Considerations for Defining Observing Modes

Based on experience from the ALMA ObsMode process, we first developed a list of 12 categories of requirements and information to be considered in aggregate when defining a unique observing mode. This list is given in Table 1, and provided an initial framework for the discussions within the Observing Modes Workgroup. For each category, we then developed a list of detailed items that we expected to encounter when considering any specific science use case. This more detailed list is the topic of Section 2.5.

1. List of information that must be captured from the PI via an observing tool (including target positions, lines, velocities, peak intensity, total flux density, spatial resolution, LAS, FOV, and requested data products).
2. Subarray(s) of antennas required, including how many, and whether they need to be

	simultaneous; is the Short Baseline Array (SBA) required and does that data need to be imaged in combination with the Main array data?
3.	Antenna motion (e.g., pointed vs. OTF, or ephemeris tracking).
4.	Receiver bands(s) and list of tunings (including whether WVR correction is required, whether VTEC corrections will be needed, whether different bandwidths are needed on complex gain calibrator vs. science targets, or if solar settings are required).
5.	Heuristics for splitting the PI-selected targets and tunings into separate scheduling blocks (SBs).
6.	Calibrator observation sequence (including which database values are needed, e.g., D-terms, antenna positions, bandpass, flux).
7.	Prescribed mapping of calibrator scan intents and specific calibrator scans (or calibrator database entries) to science targets.
8.	Correlator setup(s) (including Doppler setting to center lines in individual windows, antenna phasing, and/or time gating).
9.	Minimum dump times and archive storage rate required.
10.	Calibration heuristics and pipeline (including categories of QA scoring).
11.	Imaging and non-imaging data product heuristics and pipeline (including categories of QA scoring).
12.	Pointer to suitable software tools to enable PIs to interrogate their data (e.g., source finder, generic spectral line fitting programs, polarimetric analysis tools).

Table 1 – List of 12 categories of information needed to define an observing mode.

In addition to considering the items in Table 1, we note that all observing modes shall include the recording of real-time diagnostics to be used by various parties, even if they are not ultimately used by the data processing pipeline. For example, online solutions for gain, phase, delay, and bandpass, averaged over various intervals, can inform operations and maintenance staff of problems more quickly than offline processing may discover them. On a related note, the need for observatory-facing (non-PI) observing modes to support the calibration infrastructure is discussed in Section 5.

2.5 Observing Mode Requirements for the Reference Observing Program

To explore each of the categories in Table 1, we considered the ROP [AD08] science use cases as well as additional science use cases not covered in that document but likely to have general scientific demand. For each use case, we identified the specific requirements to enable those observations. As an initial assessment, requirements that involve major distinctions in hardware or software capabilities were given the preliminary label of "modes," while the other items were labeled as "attributes."

The term "attributes" is meant to describe properties of an observing mode that represent a limited perturbation on the required capabilities and/or data products compared to more standard uses of that mode. For each category, we then combined the results from all use cases to define a default mode (and a list of assumptions when necessary), along with a set of optional modes and attributes for that category. The details are presented in the following subsections.

2.5.1 Information Captured from PI, and list of expected data products

Assume all science use cases will require capturing the following information from the PI:

1. Angular resolution (including "I don't care" as an option)
2. Largest Angular Scale (LAS)
3. Field of View (FOV)
4. List of targets/fields
5. Time on target (combination of sub-requirements: sensitivity, *uv* coverage, orbit coverage, constraints from time evolution of source; see Telescope Time Allocation (TTA) tools document [RD03])
6. "Basic" calibration performance (otherwise: go to Section 2.5.7 below)
7. Estimated image dynamic range and/or spectral dynamic range (will affect threshold for warnings regarding interpretation of image cubes; see end of Section 6.2.1 in the Calibration Requirements document [AD15])
8. Special data products requested

Regarding item 8, because observing modes will have a predefined set of data products, we should only need to capture special requests from the PI, which will then be classified as attributes. Nevertheless, we have categorized all the different data products we envisioned in this exercise into the general terms of modes and attributes for subsequent reference.

Modes:

1. Interferometric continuum images and Stokes I spectral cubes (per spectral window and aggregate)
2. Interferometric full polarization cubes (Stokes IQUV)
3. Pulsar search-mode data (power vs time/frequency/polarization)
4. Pulsar timing-mode data (folded pulse profiles)
5. Summed-array (phased beam) baseband data (VLBI or radar recording)[1]
6. Single-dish autocorrelation imaging (continuum and cubes) analogous to "single-dish mapping"
7. Single-dish / interferometry combined imaging (continuum and cubes)

Attributes:

1. Spectral index images (including multiple Taylor terms when necessary)

[1] As a point of clarification, the "summed-array baseband data (VLBI)" mode refers to the mode where baseband data from a set of phased ngVLA antennas are recorded and subsequently shipped to a separate location for non-real-time correlation with data from other antennas operated by other observatories.

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)
8. Include autocorrelation spectra for diagnostics and calibration purposes (time resolution TBD)

Additional 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)

2.5.2 Subarrays Required

Default mode: One subarray that is an observatory-defined and observatory-selected "science subarray" on the Main Array that provides an adequate resolution and spatial dynamic range that matches the requirement. This subarray may be a superset of individual observatory-defined science subarrays, in order to achieve the desired angular resolution and LAS in a single observation. The complete list of subarray modes is provided below.

Modes:

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)

2.5.3 Antenna Motion

Default mode: Pointed mode, i.e. sidereal tracking (including traditional "point and shoot" mosaics)

Modes:

1. Pointed mode
2. OTFI (on-the-fly interferometry)
3. Lissajous pattern (i.e., single-dish)

Attributes:

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
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)

2.5.4 Receiver Bands

Assume that all modes will utilize the WVR data stream for path length corrections, although the usefulness of these corrections in the lowest frequency bands is an open question.

Default mode: A single receiver band and single "tuning" (i.e. a single collection of sub-bands) per SB

Modes:

1. Single receiver band with single sub-band setup
2. Doppler setting of one or more sub-band windows (i.e. line observations in the TOPO frame)
3. Bandwidth switching (i.e., wider bandwidth on phase calibrator vs. science target)
4. Band-to-band transfer (e.g., ionospheric delay corrections from Band 1 when observing Band 2)

Attributes:

1. Multiple sub-band setups per SB (note that local oscillators (LOs) are fixed in all bands)
2. Multiple receiver bands for science per SB (e.g., guarantee close-in-time SED measurement of a point source for which the frequency-based change in angular resolution is not problematic)

2.5.5 Splitting the PI Targets and Tunings into Separate SBs

Assume the observing tool will fully automate these selections, and the PI would need to override if desired. Basic requirements:

1. The tool needs to identify groups of targets that can share a complex gain (phase) calibrator. The same such calibrator should be used in all bands, as much as possible.
2. Once groups are defined, the tool needs to decide (based on total time required, spatial resolution request and range of bands requested and their weather requirements [RD01]) how many SBs are needed, and how often to cycle through each group within a SB.
3. As assumed in Section 2.5.9, the tool will need to enforce a maximum dump time to avoid time smearing for the longest baselines of the antenna subarray.
4. When generating executable SBs, there are bounds for the size of the SB (too large can't be effectively scheduled; too small cannot achieve required sensitivity). Between these bounds, the procedure would break them down on several axis (target, bands, antenna subarray, etc.) in order to optimize efficiency. This optimization also depends on the available observation time per band and configuration.

5. For target-of-opportunity projects, SBs are made containing dummy targets (and dummy spectral setups when relevant) which are filled in by the observatory when triggered.
6. Include functionality to alert the PI to proposed observing schedule and provide specific forms of feedback within some standardized timeline.
7. Include a procedure for identifying acceptable observing conditions for each SB (troposphere, ionosphere, RFI, wind, nighttime precision operating conditions, solar and interplanetary conditions).

Attributes:

1. Multiple science fields per SB (i.e. fields share the same complex gain calibrator and check source)
2. Multiple groups of science fields per SB (i.e. different groups use different complex gain calibrators and check sources)

2.5.6 Calibrator Observation Sequence

The calibration database is designed to store system calibration parameters that can be retrieved and applied during offline processing [AD15]. These parameters will need to be tagged with serial numbers, and will need to be re-measured and updated in the database whenever hardware changes are made due to maintenance work (replacement of receiver components, etc.) either before (or very shortly after) the antenna is returned to service for the affected observing bands. The ultimate goal is to avoid the need to observe calibrators routinely in standard observing modes, other than complex gain calibrators and, at high frequency, pointing calibrators. Non-routine insertion of bright sources, such as into long science tracks, will be helpful to diagnose unforeseen problems with individual antennas (or the whole array) and possibly salvage data that might otherwise be lost. We may wish to determine if dynamic integration times on the gain calibrator (i.e., determined by TelCal) are worth the effort in terms of efficiency vs. complexity, or just use a conservative (longer) fixed integration time based on a minimum signal to noise ratio and the most recent database flux density value. For now, we will assume that standard observing modes will use the fixed time approach.

1. Default complex gain calibration: observe nearby calibrator(s) in all SBs.
2. Default bandpass calibration: access from calibration database (at least for low-resolution "continuum mode"); high-resolution setups will likely require observation of bandpass calibrator in the SB.
3. Default polarization calibration: full stokes calibration (including true V), access leakages from calibration database, access crosshand phases from instrument (time-multiplexed noise diode).
4. Default opacity tracking within an individual SB: WVR-determined PWV combined with atmospheric model
5. Default opacity at time of SB start: TBD (either: measured by starting every relevant SB with a tipping scan; or estimated from prior SB's WVR-determined PWV measurement combined with atmospheric model).
6. Default atmospheric delay calibration: wet tropospheric (WVR, 1 sec), dry tropospheric (traditional gaincal, 5 min), ionosphere (Band 1).

7. Default ionospheric Faraday rotation correction (lower bands only, up to two?): ingest GPS-derived VTEC.
8. Default absolute amplitude: switched power system (tied regularly to celestial scale by observatory).
9. Default pointing calibration: reference pointing scans in high frequency bands (such as Band 4–6).
10. Default cycle times: will be used for all observed calibrators based on intent and observational setup (for example the frequency and array size).

For observations that require a higher degree of calibration than can be achieved by the defaults listed above, additional observations may be needed in the SB, along with the corresponding data processing steps. These modifications correspond to attributes that must be validated. An initial list is given below.

Attributes:

1. Higher astrometric accuracy: Observe extra complex gain calibrators in SB
2. Finer resolution bandpass calibration: Observe bandpass calibrator in SB
3. Finer polarization calibration: Observe polarization calibrator(s) in SB
4. Higher photometric accuracy: Observe flux calibrator(s) in SB

In addition, in the early years of CSV, prior to the population of the calibration database, each observation will need to observe calibrators for any quantity that sufficient calibration cannot be obtained from the database. Thus, the testing of some of these attributes will naturally begin early in CSV.

2.5.7 Prescribed Mapping of Calibrator Intents and Scans (or equivalent Calibrator Database Entries) to Each Science Target

The observing tool must make the association between each science target and the observed calibrator intents and specific scans (intent alone is insufficient) explicit in the data model. If a calibrator database entry is to be used, a static (long-lived) pointer to the entry must be written to the data model.

2.5.8 Correlator Setup

Default mode: Uniform resolution mode (all spectral windows have the same width on the same grid at standard tuning; allow reduced width up to modest factor of N, i.e. continuum mode or broad spectral lines). Doppler setting is available for at least one sub-band.

Modes:

1. Uniform resolution
2. Mixed resolution: spectral windows (spws) are fully tunable with Doppler setting and can have different widths, i.e., simultaneous high-resolution line + low-resolution continuum mode
3. Advanced mode (any aspect that requires additional commissioning, such zoom windows, or storing only subsets of spws)
4. Phased array (single beam)
5. Phased array (N beams)

6. Pulsar Binning
7. On-the-fly interferometry

Attributes:

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 four 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)

2.5.9 Minimum and Maximum Dump Times and Archive Storage Rate Required

Assume that a maximum dump time will be set automatically to avoid time smearing for the longest baselines of the antenna subarray. A standard dump time will be established that is smaller than the maximum, but does not overtax the data rate.

Attributes:

1. Shorter dump time than standard is needed
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)

2.5.10 Calibration Heuristics and Pipeline

Default mode: Assume that default calibration will include dual-polarization processing with state-of-the-art flagging heuristics and appropriate interpolation of solutions in time and frequency (with support for full-polarization calibration from the beginning as a goal).

[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.

Modes:

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 are triggered, they will need special calibration rules or recipes
4. RFI excision in correlator using a database of RFI (in addition to more advanced offline RFI flagging heuristics)
5. Paired antenna calibration (if needed, for example within LBA stations)

2.5.11 Imaging and Non-Imaging Data Product Heuristics and Pipeline

Assume that default image products will be cleaned using a broadly applicable autoboxing heuristic with primary beam correction performed in the image plane.

Modes:

1. Single field
2. Pointed mosaic
3. OTFI

Attributes:

1 Multi-Term Multi-Frequency Synthesis (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 non-standard imaging algorithm (such as joint deconvolution that includes 6m–18m baselines, e.g,. Kitchen sink array or Main + SBA)

3 Organizing the Observing Mode Requirements

While the preliminary list of modes and attributes compiled in the previous section is rather large, it is at least finite. Ideally, we would distill this information into a flat list of Observing Modes. However, the phase

[3] Wide-field polarization correction is envisaged via the A-projection method (see ngVLA computing memo 4 [RD04]). 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.

space of combinations is very multi-dimensional. Fortunately it is also somewhat sparse, suggesting that there is some hope to be able to visualize the information in a small number of two-dimensional matrices.

3.1 Observing Mode Matrix

After considering the various axes, we decided to organize the information into two groups: Observing Mode Components and Observing Mode Attributes. The three Observing Mode Components are

1. Data Product
2. Antenna Subarray
3. Correlator Mode.

For purposes of display as a matrix, we have chosen the Data Product to be the primary axis. We then define four additional secondary axes as

1. Antenna Subarray
2. Correlator Mode
3. Major Attributes
4. Minor Attributes.

Attributes will be classified as major or minor, depending on the degree of perturbation they impart on the parent observing mode. Major attributes will typically require independent validation datasets when used in combination with different observing mode components, and should be represented in the public Science Validation datasets. Because the additional validation effort needed for each major attribute will require significant CSV scientist effort, the major attributes described in this document will need to be carefully prioritized during the CSV period. To visualize the landscape of observing mode components and attributes, a four part matrix can be constructed with the different Data Products in rows and the individual options of each secondary axis as columns. By color-coding the cells, this matrix can be used to illustrate which combinations are targeted for operational commissioning by CSV, and which are out of scope, since some combinations have no conceivable science use case. The color definitions are

- Green = fully commissioned/Standard Mode
- Yellow = partially commissioned/Shared Risk
- Red = currently uncommissioned/not offered
- Grey = will not be commissioned during CSV (but is expected to be during ongoing operations)
- 'X' = will never be offered (no science use case)

The format of the proposed matrix is shown in Figure 1 (next page). An additional level of detail can be provided by placing numbers in each cell in the Subarray matrix to indicate the calibration technique level, where 1=hardcoded calibrators in each SB, 2=dynamic calibrators automatically chosen (upon first execution of the SB), and 3=database calibration (for quantities where this technique is proven possible). The terms "Standard Mode" and "Shared Risk" encompass several possible states of commissioning which are described in more detail in Section 2.3.

3.2 Roll-Out Framework

This matrix and the color/number scheme of Section 3.1 can also be used to illustrate the current status of overall commissioning, as well as a snapshot of what capabilities are intended to be offered for a specific cycle of observations during Early Science. Using such a snapshot, one can develop a flat list of Observing Modes to be commissioned for that cycle, as a delta from the prior cycle. To avoid confusion with official ngVLA Cycles, which are currently impossible to predict (years in advance) and will naturally be kept fluid up until each Call for Proposals, we recommend that CSV develop an enumerated list of CSV-named milestones, each of which is graphically represented by a snapshot of this matrix.

3.3 Minimum Number of Validation Scheduling Blocks Required

Another major benefit of this matrix arrangement is that it allows for easy calculation of the minimum number of scheduling blocks required to validate each observing mode. This number will help to quantify the level of effort required of the CSV staff, which will assist in setting limits on what is feasible for each commissioning period. The formula is indicated by the arithmetic sign (x, x, +) contained in the three white columns separating the four colored matrices in Figure 1. One takes the number of green cells in the Subarray matrix times the number of green cells in the Correlator Mode matrix times the number of green cells in the Major Attributes matrix plus the number of green cells in the Minor Attributes matrix.

As an example, for a hypothetical CSV Milestone 0, for which only continuum imaging using the Core or Plains subarray with uniform correlator mode (with optional online channel averaging) targeting sidereal fields or ephemeris objects observed with single pointings or mosaics (including ToO possibility) requires eight SBs (= 2 x 1 x 2 + 4). These eight SBs correspond to the eight Observing Modes that this Milestone contains. A list of these modes are written out explicitly in Section 4.1. To reduce the number of SBs required, especially in later milestones, some modes and major attributes can be combined creatively into the same SB. For example, we can make an Ephemeris observation that exercises two correlator setups: Uniform and Mixed.

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	x	Uniform	Mixed	Advanced	Phased array 1-beam	Phased array N-beams	Gated	OTFI	x	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).

4 Developing a List of PI Observing Modes

4.1 Modes to Be Commissioned During Construction

It is envisioned that CSV will progress through a series of semi-annual milestones. Specific capabilities and observing mode requirements will be the subject of each CSV milestone in order to deliver the Observing Modes promised for the next cycle of Early Science observing. Each milestone's combination of new capabilities will be indicated by a new instance of the observing mode matrix. The matrix for each milestone can then be used to construct a flat, verbose list of observing modes that need to be commissioned for it. Taking CSV Milestone 0 for Interferometric Mode (Figure 1) from Section 3.1 as an example, here is the corresponding list of Observing Modes to be validated:

1. Continuum imaging (IQUV) and spectral cubes with a Core sub-array with Uniform correlator mode on a single sidereal field
2. Continuum imaging (IQUV) and spectral cubes with a Plains sub-array with Uniform correlator mode on a single sidereal field
3. Continuum imaging (IQUV) and spectral cubes with a Core sub-array with Uniform correlator mode on a single ephemeris field
4. Continuum imaging (IQUV) and spectral cubes with a Plains sub-array with Uniform correlator mode on a single ephemeris field
5. Any of the above with one (or more) of the following:
   a. Multiple science target fields
   b. A pointed mosaic
   c. A target of opportunity
   d. Online channel averaging

Subsequent CSV milestones will each add an additional list of observing modes to be validated, until all of the Key Science Goals of the observatory are covered. Clearly, the final list of observing modes will be quite long in this format. However, it would not be presented to users in that format, but rather in a more compact statement of prose that summarizes the capabilities. An example for CSV Milestone 0 for Interferometric Mode would be:

"Continuum imaging using the Core or Plains subarray with uniform correlator mode (with optional online channel averaging) targeting sidereal fields or ephemeris objects observed with single pointings or pointed mosaics (including ToO possibility)."

4.2 Modes Not Commissioned During Construction

There will likely be a set of highly-specialized or challenging observing modes that are not prioritized for commissioning during construction, primarily because they are not required to achieve the Key Science Goals of the observatory [AD01] and have extra (unique) observing or data processing requirements. The primary examples are time-gated correlation, multi-beam VLBI observing, and Solar observing. Whether or not these modes are fully commissioned during the construction project will depend upon the availability of additional internal and external staff not already occupied by higher priority CSV work, and the availability of array resources. Fortunately, because subarray functionality is an important early goal for ngVLA, there may be ample opportunity to commission these observing modes using small subarrays, such as during daytime maintenance hours. However, the delivery of these modes will not be guaranteed by the Construction project. In any case, whenever these additional modes are ultimately commissioned and delivered, the decision for when they have reached the level of a Standard mode must ultimately be made by the Operations team.

5 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.

5.1 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. 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 and frequency band and either a large pool of potential calibrator sources which have 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 flux and phase calibrator sources. We expect that standard continuum (full-polarization) imaging products will be produced, but analysis of the images to provide positions and flux densities will need to be tailored to provide robust and automated results.

5.2 Baseline 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 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 (and focus) 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. Changes due to plate tectonics will also play a role, at least for the LBA antennas.

5.3 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.

5.4 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, in order to assess how the change in spillover affects the pattern.

5.5 Other Calibration Measurements for the Calibration Database

The calibration database will require large numbers of measurements of other quantities on bright calibrators, including the complex bandpass response as a function of frequency for all bands and (at least) all commonly-used spectral setups. Gain curves as a function of antenna and elevation will also be needed, particularly for the high frequency bands.

6 Appendix

6.1 Abbreviations and Acronyms

Abbreviation	Non-Abbreviated Reference
ALMA	Atacama Large Millimeter/submillimeter Array
CBE	Correlator Back End computer cluster
CSV	Commissioning and Science Validation
FOV	Field of View
FRB	Fast Radio Burst
GPS	Global Positioning System
LAS	Largest Angular Scale
LBA	Long Baseline Array
LO	Local Oscillator
LSRK	Local Standard of Rest – Kinematic
mtmfs	Multi-Term Multi-Frequency Synthesis
ngVLA	Next-Generation Very Large Array
NMTO	New Mode Test Observations
NRAO	National Radio Astronomy Observatory
NSDR	Non-Standard Data Reduction
OTFI	On-the-Fly Interferometry
PI	Principal Investigator
PIDR	Principal Investigator Data Reduction
QA	Quality Assurance
RFI	Radio Frequency Interference
ROP	Reference Observing Program
SB	Scheduling Block
SBA	Short Baseline Array
SED	Spectral Energy Distribution
SMDR	Standard Mode Data Reduction
spws	Spectral windows
SRDP	Science Ready Data Products
SRO	Shared Risk Observing
TBD	To Be Determined
TLE	Two-Line Element
ToO	Target of Opportunity
TOPO	Topocentric frame
TTA	Telescope Time Allocation
VLA	Jansky Very Large Array
VLBI	Very Long Baseline Interferometry
VTEC	Vertical Total Electron Content
WVR	Water Vapor Radiometer

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