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Title: Commissioning and Science Validation Concept (First Draft)		Version: 01



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020.10.05.00.00-0006-CON

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1 Introduction

[Note: the initial four paragraphs were copied from the System Reference Design]

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 the state of 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 collocated 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 amongst these centers as appropriate.

1.1 Purpose of this Document

This document describes the concept of the Commissioning and Science Validation (CSV) process envisioned for the ngVLA. It provides a qualitative expression of the approach that will be taken including the roles, duties and organization of the team and a preliminary list of the expected tests and milestones to be conducted on the way to delivering a functional observatory and a validated list of science observing modes. We also outline the staffing, resources and support that will be required from the Operations and AIV groups, as well as identifying the need for early participation by students and external experts from diverse backgrounds. A separate document (the ngVLA CSV Plan [AD07]) will develop the quantitative



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details of the proposed milestones and the level of staffing required at each point in the process.

1.2 Scope of Document

This document pertains to all activities associated with CSV, including participation in the Assembly, Integration and Verification (AIV) process, the formal start of CSV, through the start of Early Science in 2028 Q4, and on to the delivery of validated science modes by the start of full operations in 2034.

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.

Reference 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 Transition Concept	C. Chandler
AD05	Front End Technical Requirements	020.30.03.01.00-0001-REQ
AD06	The Next Generation Very Large Array: A Technical Overview	SPIE Volume 10700, id. 107001O
AD07	Commissioning and Science Validation Plan	TBD
AD08	ngVLA Reference Observing Program	020.10.15.05.10-0001-REP
AD09	ngVLA Antenna: Preliminary Technical Specifications	020.25.00.00.00-0001-SPE
AD10	Proposed lifecycle for new ngVLA observing modes	J. Hibbard
AD11	Monitor & Control System: Preliminary Requirements	020.50.25.00.00-0001-REQ
AD12	ngVLA Central Signal Processor Preliminary Technical Specifications	020.40.,00.00.00-0001-SPE
AD13	ngVLA Computing and Software Architecture: Reference Design	020.50.00.00.01-002-REP
AD14	ngVLA Computing and Software Requirements	020.50.00.00.01-0001-REQ
AD15	ngVLA Calibration Plan	C. Hales



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Reference No.	Document Title	Rev. / Doc. No.
AD16	ngVLA Data Transmission	

1.4 Reference Documents

The following non-project documents are referenced in this report

Reference No.	Document Title	Origin
RD01	The Expanded Very Large Array	Proc. of the IEEE, Vol. 97, Issue 8, p. 1448-1462
RD02	The Expanded Very Large Array: A New Telescope for New Science	ApJ, 739, L1
RD03	ALMA Commissioning and Science Verification Plan (Laing, 2007)	ALMA-90.00.00.00-007-D-PLA
RD04	ALMA CSV Implementation Plan (Hills & Peck, 2009)	ALMA-90.00.00.00-017-A-PLA
RD05	Holographic Measurement and Improvement of the Green Bank Telescope Surface (Hunter et al. 2011)	PASP, 123, 1087
RD06	Improvement of the Effelsberg 100 meter telescope based on holographic reflector surface measurement	A&A, vol. 167, Oct. 1986, p. 390-394.

1.5 Acronym list

Acronym	Description
AIV	Assembly, Integration and Verification
ALMA	Atacama Large Millimeter/submillimeter Array
API	Application Programming Interface
APM	Atmospheric Phase Monitor
CASA	Common Astronomy Software Applications package
CRE	Change Request
CS	Computing and Software
CSP	Central Signal Processor
CSV	Commissioning and Science Validation
ES	Early Science



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Acronym	Description
GBT	Green Bank Telescope
JAO	Joint ALMA Observatory
IF	Intermediate Frequency
LBA	(ngVLA) Long Baseline Array
LO	Local Oscillator
PI	Principal Investigator
QA	Quality Assessment
SB	Scheduling Block
SBA	(ngVLA) Short Baseline Array
SMA	SubMillimeter Array
SRDP	Science Ready Data Products
WVR	Water Vapor Radiometer

2 Overview

2.1 Definition, Goals, Challenges and Philosophy of CSV

The purpose of the CSV activity is to test and optimize the various elements of the ngVLA observing system to ensure that it meets the scientific requirements. The inputs to CSV from AIV will be verified capabilities, rather than individual components. These capabilities will typically include a set of hardware, for example, a group of antennas and a portion of a correlator along with their corresponding control software that supports a specific mode. By starting from verified capabilities, CSV will be able to focus primarily on measuring system performance on the sky and developing observing modes, rather than debugging basic operations. The principal outputs of CSV are validated science observing modes and the associated technical documentation essential for operation of ngVLA as a user facility. The documentation will include reports and memos quantifying the as-built performance, exceptions, recommendations for improvement and a verification matrix showing the performance as measured against the science requirements [AD01].

The challenging path toward reaching these goals will be eased by having the AIV and CSV teams work together closely through the delivery of the first few antennas and the first working interferometer. Good communication between the teams in these early stages will build a level of trust and expectation that will benefit the subsequent rate of progress toward their respective goals. After this initial period, the CSV team will need to balance the competing desires of achieving a minimum performance level for Early Science (ES) versus fully understanding and eliminating oddities in the system. It will often be necessary to choose the “simple but reliable” approach over exploring a more optimal or novel approach.



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Considering the large scale of this observatory, it will be essential for CSV to attack and retire the high technical risk items early. Two of the primary issues of concern arise from the technical challenges of operations beyond the traditional baseline lengths of the VLA: (1) the stability of the IF/LO system on long baselines of the Main Array and the Long Baseline Array (LBA) and (2) the effectiveness and reliability of WVR correction in a variety of weather conditions across the array. For example, the existing designs for the data transmission system do not include the long baselines, which will have special problems [AD10]. Demonstrating these capabilities early in the CSV process will help to ensure continued support from the scientific and public community for this Observatory.

2.2 Important Assumptions

2.2.1 Uniformity of antenna stations

The details of a commissioning concept and plan depend on how capabilities will be delivered from AIV to CSV. A fundamental assumption for this observatory is that when a receiver package is installed into an antenna by AIV, it will contain all receiver bands [AD05] not a partial set. Although there is a lot of CSV that could be pursued with a few antennas and only a single operational band, having all bands available will allow different commissioning tasks to use different receivers on different sets of antennas that are appropriate to the task. For example, in any given week, it may be most efficient to do holography and pointing in Band 3 (at 16 GHz), efficiency measurements in Bands 4 and 5 (at 27 and 40 GHz), or interferometry tests in Bands 1 and 2 (at 2.4 and 8 GHz), depending on the prevailing weather conditions.

Another assumption is that all stations must meet the same performance specifications, including rms surface accuracy [AD09]. The degree to which this requirement impacts the feasibility and cost of verifying the performance of antennas at remote stations by AIV must be expressed and captured during the ongoing detailed design process. For example, we will need to practice (first at the central array site) how accurately we can assemble and align an antenna surface by passive means. We will (almost certainly) need to confirm the final surface setting after assembly at each remote station. Options are photogrammetry (1 part in 10^5 may be achievable $\sim 180\mu\text{m}$) or holography. Since we cannot feasibly have holography towers at every remote station, it would need to be either celestial or satellite holography which will require expertise of the CSV team. In either case, obtaining a stable reference signal will be difficult if the nearest antenna is many tens or hundreds of kilometers away. So we may need to temporarily mount a separate reference receiver and feed on the antenna (like GBT [RD05]), or be able to transport and set up a small fixed antenna for geostationary satellite holography (like Effelsberg [RD06]).



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2.2.2 Order of antenna deployment

The bulk of the initial deployment of antennas will occur on the inner pads ($R < 1.3$ km) as has been envisioned by the Construction plan [AD??] and assumed by the Transition Concept [AD04]. However, in order to retire the technical risk of long baseline performance, and to validate the process of outfitting remote stations of the Main Array and LBA, it will be essential to deploy at least one antenna in each category of larger distances (≈ 30 km and ≈ 300 km) in a relatively early stage of the AIV process. These stations will be critical for fundamental tests of the IF/LO system, delay server, etc. during AIV. It will also allow CSV to test the efficacy of WVR correction schemes on long baselines [AD15].

2.3 Timescales and historical basis

The approximate timeline of events with impact on CSV are provided for reference.

1. First prototype antenna: 2024
2. First antenna delivered by AIV: early 2026
3. First fringes: late 2026
4. Early Science first Call for Proposals: April 1, 2028
5. Early Science first observations: Oct 1, 2028
6. Target completion main (214-element, <1000 km) array: Jan 1, 2034
7. Target completion entire array (including LBA): Jan 1, 2035

The projected 10-year period between the first antenna delivery and completion of the 214-element array may be considered daunting when one considers that this number of antennas is comparable to the sum of all similar interferometers to date. However, there is some historical basis for this value based on the commissioning of prior interferometers with a large range in total number of antennas. Both SMA (with 8 antennas) and ALMA (with 66 antennas) took 8 years from first prototype antenna (1996 and 2003, respectively) to start of Early Science. For MeerKAT (64 antennas), it took 9 years from first fringes to dedication. Furthermore, for ALMA, it was 12 years to the first PI observations at the longest baselines, while ngVLA is targeting 11 years to LBA completion. In any case, the ongoing validation of new modes envisioned in section 9, means that CSV-like activities will continue throughout the life of the observatory.



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2.4 Key statements from other Concept documents that impact CSV

2.4.1 Operations Concept [AD03]

Section 6.0: “At the start of ngVLA Early Science, only a small number of these modes that have been verified to work end-to-end will be available to PIs. The number of modes available to users will increase as early science progresses, with all modes deliverable from the construction projects available in full operations.” – Clearly, the ES modes need to be defined at an early stage.

Section 6.1: “Different capabilities and observing modes will be made available in stages during the transition from construction through ... commencement of full operations.” – The Science Validation (SV) milestones shall be staged with specific observing modes in mind.

Section 6.3: “Delivery of a fully-commissioned standard observing mode will include an operational SRDP pipeline before it is offered for regular use through PI proposals.”

Section 6.5: “The Observatory will release a set of first look science products - defined with input from the user community - ahead of PI access to the array.”

Section 13.1: “All elements of array design and operations ... must support operation of multiple sub-arrays for different purposes right from initial commissioning.” – Clearly, the commissioning of subarray operation must have high priority. Up to 10 subarrays are envisioned [AD12]. It should be possible to run different versions of software running in different arrays, with deployment and configuration management handled remotely in order to support efficient operations [AD13].

2.4.2 Technical overview [AD06]

“...the long baseline antennas, would fall into a VLBI station model with a number of local oscillator (LO) and data transmission stations located beyond the central core. These stations will be linked to the central timing system, correlator, and monitor and control system via long haul fiber optics. Several options will be explored for precision timing and references at these stations, including local GPS-disciplined masers, fiber optic connections to the central site, and satellite-based timing.” – Clearly this is an important problem to be solved and will require placing one or more antennas on remote pads as early as possible during CSV to avoid delays in achieving long baseline science.



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3 Composition and Duties of CSV Team

Because the telescope will present a broad range of capabilities and frequency coverage, and many aspects of the design and technology will differ significantly from other NRAO facilities, the experience of the CSV Team will need to be diverse, drawing from all areas of radio astronomy research including scientists of all ages with experience in RF, digital, and software engineering as well as single-dish and interferometric calibration and imaging. The members of the CSV team will be distributed among the following work activities, with group leaders appointed where necessary. This list of activities is meant to indicate the sorts of skills that we will need to seek when hiring new staff or assigning current staff.

1. Assess the implications of major design choices on CSV during the future detailed design phase
2. Assess impact of CREs submitted by other subsystems during the construction phase, including obtaining and analyzing any necessary data
3. Assist AIV teams with on-sky testing of hardware prior to delivery to CSV, including the prototype antenna, receiver and correlator performance
4. Devise and execute integrated performance tests of AIV-delivered items with specific criteria for pass/fail
5. Work with Computing team to write observing scripts to achieve successful on-sky performance tests ("manual mode")
6. Develop utilities for performance data analysis (and temporary metadata fixes) as needed and manage them as a coherent package (similar to ALMA's analysisUtils)
7. Report system deficiencies encountered back to AIV and Maintenance for resolution via JIRA tickets
8. Interact with hardware and software engineers to be aware of the latest status of problem investigations and fixes
9. Devise and execute performance tests of the array as a whole (items of stability and fidelity that typically require long integrations or observing sequences)
10. Write ngVLA memos and reports that summarize performance test procedures, results, and directions for future work
11. Work with colleagues at ALMA and other facilities to better understand cutting-edge problems that each face
12. Be familiar with the Reference Observing Program, and the capabilities that these projects require
13. Maintain familiarity with the calibration plan; provide feedback regarding feasibility
14. Maintain familiarity with pipeline processing and development; provide new requirements when necessary
15. Deliver tested observing modes and work with the Operations group to achieve successful SV results



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4 Organization of CSV Team

The extensive number of performance items that CSV needs to validate will be a daunting task. It will be a challenge to maintain focus on a few major issues at a time while also not letting some items receive no attention, which could raise the risk of significant rework at later stages of the project. For example, it will be prudent to define a team that focuses on long-baseline issues and commissioning in order to expedite finding problems earlier in the CSV process than might otherwise happen in the inevitable push to make the central array available for Early Science. Another example is a team responsible for flushing out all the issues associated with Autocorrelation data, rather than leaving it for a later time. Similarly, additional groups will be needed for RFI and for short baselines. In addition, it will also be useful for members of the CSV team to also serve as members of other closely related groups such as the Array Calibration Group and the Control Software Group.

The leadership of the CSV group will include a division head and the leaders of the various teams, each with a scientific background. In order to promote an efficient organization of CSV effort, responsibility will be divided between the team members so that each person is encouraged to take ownership of one or a small number of specific commissioning items. That person will follow the natural workflow of proposing the tests to be run, executing the tests, analyzing the data and writing the report, consulting with other members of the team and the wider scientific staff as needed at each stage. Handing off items from one person to another in a turno style should be discouraged in order to avoid misunderstandings of what the next steps should be. Presence on site should not be a requirement for contributing to the CSV team, especially because skilled and conscientious staff working at remote locations can efficiently examine test data during the mornings immediately following test observations.

5 Communication Plan

Communication of progress on commissioning items will be recorded in a weekly log (compiled from the daily shift log [AD13]) that is distributed to the team and made available to other subsystems. Further details of progress will be presented by team members both informally at weekly group meetings and to a wider audience through lunch talks at the science center. Once multiple antennas are available for CSV, a daily coordination meeting among the team leaders and current observers will likely be needed to assess the top priorities and plan the upcoming 24 hours of observing tests. To encourage remote participation, this meeting will need to be held at a time convenient to all NRAO sites, likely 2PM MT, and should be kept to 30 minutes as much as possible. As each major commissioning item is completed, reports or ngVLA memos will be written that summarize the performance test procedure, current results, and directions for future work. Team members should also give presentations of recent successes and ongoing vexing problems at outside institutions, particularly those with radio astronomers on the faculty. The latter venue may help to prevent the repeating of mistakes of the past as well as become aware of



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more efficient methods to make progress. Members of the CSV team should likewise be encouraged and enabled to maintain visibility in the science communities of their choice during their years of service.

6 Resource Requirements

The Plan document will specify requirements in more detail, such as the personnel effort and time required for various commissioning tasks and milestones. The following is a general list of items that will be needed, many of which will be supplied by other subsystems.

6.1 Software

The software needs of CSV group to efficiently perform its work will include both in-house data analysis software and commercially available products.

1. A ticket reporting and tracking system (such as JIRA)
2. A monitor data archive [AD11], with automatic filling and the capability of listing and plotting contents. Configurable monitoring and the ability to trigger high frequency sampling for short periods (a.k.a. the “oscilloscope function”) will be desirable (will be provided by the CS Group [AD13]).
3. A centralized database to store system configuration data (including calibration models), under version control (will be provided by CS group [AD13]).
4. A hardware revision control system, with history of LRU installations and repairs. It should be possible to find version and serial number for any hardware module installed on an antenna
5. A science-oriented API (scripting interface) for high level array functions prior to SBs (will be provided by CS group [AD13])
6. Simulators would be useful so that work on scripts can proceed without the real system (will be provided by CS group [AD13])
7. CASA, and python scientific stack on an observatory-supported Linux OS (free)
8. Access to commercially licensed analysis tools if needed (MATLAB, etc.)
9. The importance of having VLA and ALMA providing contemporaneous fluxes, spectra, and maybe polarization of calibrators and targets at the ngVLA bands should not be overlooked.



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6.2 Hardware

6.2.1 Weather stations and APM

The scheduling and interpretation of commissioning observations will rely on accurate knowledge of the weather at the central array, and each station of the Main Array, and LBA sites. For the remote stations, webcams showing sky conditions will be helpful. An interferometric atmospheric phase monitor (APM) at the central array will also be essential to make efficient use of test observing time.

6.2.2 Prototype correlator

Prototype correlators were important in the past for commissioning new interferometers (ALMA, WIDAR and also the original VLA). But new correlator designs come in big chunks, and the prototype concept becomes rather different. For instance, a reasonable prototype correlator for ngVLA might well be all stations but a limited bandwidth (few hundred MHz) and only a couple of modes.

6.2.3 Computing

The control room used by CSV will need to contain a sufficient number of IT-supported workstations, in addition to the main multi-monitor control console where the operator sits. These machines will ensure that scientific staff have a place to work, either on the cluster nodes, or interacting with real time systems, while preparing for pending observational tests. We should avoid the situation where people are forced to carry their laptops back and forth to the control room in order to be able to do anything.

6.3 Personnel

The list of personnel described in section 4 will need to draw from scientists both inside and outside the observatory.

6.3.1 Internal staff

We will expect contributions from the scientific staff of all NRAO sites (SO, CV, JAO) as well as the National Research Council Canada (NRCC). These scientists will both participate in CSV and mentor a group of ngVLA postdoctoral fellows hired specifically for CSV. The postdocs will provide the bulk of the daily testing, reporting and CSV software effort. There should be a path for these fellows toward



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joining the Operations team of the ngVLA. The staff scientists assigned (in part) to ngVLA will be relied upon to provide skeptical review of results, engage in problem solving efforts on fundamental interferometry issues, and provide experience in recognizing data anomalies. It will be important to recruit the top performing AIV staff into CSV roles, either scientist or engineer, in order to have a transition of expertise that will retain knowledge of the system. Outside the CSV team, we will require operational support from computing, maintenance, and other subsystems as needed .

6.3.2 External staff

Visiting scientists with interest and experience on specific commissioning campaigns (will we offer financial support?)

Graduate students and postdocs: attract and engage their support on testing capabilities that serve their scientific interests. We recognize there will be competition for their attention with SKA etc., and that this will require modest financial support (travel? accomodation? RSRO-like program offering some advantage in Early Science?)

6.4 Facilities

In the early days when AIV and CSV are working closely together on the first antennas, there will likely be a need to have space in the local control room at the array site. Once control system is established, telepresence using a control room at the local science center will work well (as it did for the EVLA WIDAR project).

In order to process commissioning data promptly, the CSV staff will require guaranteed access to high performance computing cluster nodes and disk space.

7 Order of capabilities to be commissioned

This section will distill the projects identified in the Reference Observing Program [AD08] into a list of science capabilities and a recommended order of commissioning them.



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8 Milestones

The milestones are organized into three sections. First, we list the milestones for commissioning the general capabilities and measuring performance level of the observatory, both of which are required for science validation to proceed. Second, we list the milestones required to validate each observing mode. Finally, we list the milestones to prepare validated observing modes for Early Science.

8.1 Milestones for Commissioning

The list of commissioning milestones follow the expected flow of capabilities as systems are delivered from AIV. The Plan document will provide more detail including mapping the activities to specific items in the Science and Technical Specification documents and their respective pass/fail criteria. The order may not be sequential depending on the actual schedule of deliveries achieved. Also, the point of interface between AIV and CSV through the first three steps is likely to be somewhat fluid as the teams gain experience with the antennas and other systems. For example, while AIV is responsible for delivering pointing and focus models and nominal antenna surface setting, it is not expected that a complete characterization of elevation dependence of antenna performance will be provided, so this will work fall to CSV. The list below will be augmented from the more extensive list in the ALMA CSV Plan. We expect that the mid-frequency receiver bands (2-4) will be exercised the most in the early days as they supply a reasonably small primary beam for pointing and interferometry (2' – 6' on the 18m antennas), while avoiding the RFI at low bands and frequent tropospheric limitations in Bands 5 and 6.

C1. Initial tests of delivered components (prior to antenna availability)

- Demonstration of standalone WVR operation: control and data analysis

C2. Begin Single dish operations

Most of the items in this category should eventually be done through interferometry, just because it is easier. But we may need to start some of them before interferometry is possible. However, single-dish mapping using autocorrelation is a required capability of the observatory.

- Continuum (total power detectors or autocorrelation)
 - Perform subreflector and receiver alignment: optimization of AIV settings
 - Measure radio pointing: first level confirmation of blind and offset pointing specification, including diurnal performance
 - Measure focus curves vs. elevation and diurnal variation
 - Measure beam profiles vs. elevation and diurnal variation
 - Measure gain curves: efficiency vs. elevation



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- Validate Trx and Tsys measurement techniques
 - * Tsys is somewhat lower priority than the other quantities because Telcal will provide the combination of $\text{efficiency} \times \text{SourceFlux} / \text{Tsys}$, which is what is needed for calibration and observation. With source flux from VLA or ALMA, measuring Tsys provides reassurance that the front end group calculations are correct, which is important in the long run
 - Surface and illumination
 - Perform surface optimization at one elevation: photogrammetry and/or tower or satellite holography
 - Measure surface performance vs. elevation: celestial holography on brightest quasar
 - Measure illumination pattern and alignment error of each receiver feed
 - Autocorrelation
 - Attempt continuum mapping
 - Attempt spectral line mapping
- C3. Begin Interferometry operations I: correlation of core antennas (within VLA site) leading to a stable interferometer
- Obtain first fringes on bright continuum sources
 - Demonstrate loading of data into CASA and verify accuracy of metadata
 - Demonstrate fringe tracking: assess gross stability, search for delay jumps, and phase discontinuities
 - Obtain visibility spectra with a variety of different channel spacings
 - Demonstrate interferometric focus and pointing: second level confirmation of blind and offset pointing specifications, including diurnal performance
 - Demonstrate phase closure and investigate the imperfections. With the FX design, it is likely to be very good, and what remains is likely to be band-dependent (and the long baselines of the Main Array and LBA may have special problems)
 - Demonstrate simultaneous subarray performance
 - Demonstrate LO modulation: Walsh functions and f-shifts, if applicable in the design
 - Assess spectral frequency labeling accuracy using narrow line observations
- C4. Begin array performance testing, typically requiring long integrations
- Perform phase stability measurements: short baselines, long baselines
 - Perform bandpass stability measurements
 - Plot the per-channel rms from image cubes to look for anomalies
 - Assess noise performance across each band and rms achieved vs. integration time (continuum)



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- Write reports for each band (like EVLA memo 137)
- Measure spectral purity of correlator on a strong line (including ghosts due to splatter) and dynamic range limit
- Measure stability of complex beam pattern (each band)
- Assess stability of antenna position measurements: fit for antenna axis offsets, analyze residual delay and assess atmospheric model
- Assess astrometric performance
- Assess flux density accuracy and repeatability

C5. Begin Interferometry operations II: correlation of remote stations

- Surface confirmation/adjustment after dish (re)assembly: photogrammetry (might be sufficient) or celestial holography (Ku satellite beacon with reference receiver?)
- For each remote station, repeat the items from step 3 as necessary
- Test and decide on pointing and focus methodology for remote stations

C6. Begin operations as a full array: core antennas with remote stations

- Assess performance(item 3)
- Assess sensitivity to variable weather conditions across the stations – may require more advanced processing of the WVR data than initially implemented

C7. Demonstrate operation from Scheduling Blocks

- Single subarray
- Multiple simultaneous (fully asynchronous) subarrays

C8. Test fundamental calibration plan and report performance

- Delay / bandpass phase
- Bandpass amplitude
- Temporal gain (phase and amplitude)
 - WVR
 - Phase referencing
- Flux

C9. Test polarization calibration plan and report performance

- Measure leakage between and relative phasing of the polarization channels, and the stability of these quantities



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- Compile primary beam models
- Test accuracy of full-beam imaging and full-polarization imaging
- Make quantitative comparison with previous VLA and ALMA full polarization datasets of same fields

C10. Test that observing modes produce viable raw data (SDM):

- Single pointing continuum (coarse spectral resolution)
- Single pointing continuum plus spectral lines (mixed spectral resolution)
- Ephemeris objects
- Pointed mosaics
- Special capabilities: pulsar, VLBI, solar

C11. Test automated processing of each observing mode (with feedback to developers aimed at subsequent SV)

- First: through QA0 (data quality and calibration integrity)
- Second: through automated calibration and calibrator imaging, including RFI flagging of calibrators and science targets
- Third: through automated imaging of science targets

C12. Declare observing modes ready for Science Validation

8.2 Milestones for Science Validation

Science Validation is the process of acquiring observations of well-known objects from Scheduling Blocks, and processing them through Calibration, Imaging and SRDP. It will follow the approach used successfully by ALMA. Unlike ALMA, for which no comparable facility existed, we will be able to quantitatively demonstrate agreement with prior observations from VLA and/or ALMA. For each observing mode approved for Early Science by the project as a whole, the following tasks must take place. Steps 1-4 can be done as preliminary work before the array is ready. Step 5 (onward) will require a functioning, reliable interferometer of at least 25 antennas. Steps 3-6 require close collaboration with the Operations group. Whether Step 7 is performed for every observing mode, or only a subset, will likely depend on the resources available in the run up to the Call for Proposals. The name suggested for those modes that include a public data release include: Public Science Verification or Demonstration Science (see the Life Cycle document). There needs to be agreement with Operations on what constitutes successful processing of a mode, perhaps in terms of Key Performance Indicators.

SV1. Select Science Validation target fields and identify previous VLA and/or ALMA datasets (with scientific public input organized by Project Scientist)



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- SV2. Select Science Validation calibration plan (in collaboration with Calibration group)
- SV3. Determine the list of inputs that will be required of the PI for this observing mode, or if any special QA0 considerations are needed
- SV4. Generate Science Validation SBs using the Observing Tool (with assistance from Operations group)
- SV5. Execute Science Validation SBs
- SV6. Perform QA0, adjusting and repeating observations until successful (with assistance from Operations group)
- SV7. Demonstrate QA2 Pipeline processing of successful SBs (with assistance from pipeline and SRDP groups)
- SV8. Demonstrate quantitative agreement with previous VLA and/or ALMA datasets of same target fields

8.3 Milestones to prepare validated modes for Early Science

As observing modes are validated, the CSV group will also need to participate in the following documentation and announcement activities, along with the Operations team.

- ES1. Document any exceptions in the characteristics of the data that would invalidate the suitability of this mode to the pipeline
- ES2. Release of raw and processed data products to public (prior to Call for Proposals)
- ES3. Assist Operations group with writing the Technical Handbook (prior to Call for Proposals)
- ES4. Declare observing modes ready for Early Science (prior to the Call for Proposals)
- ES5. Define Shared Risk Observing modes that do not meet the readiness criteria for Early Science (prior to the Call for Proposals)
- ES6. Participate with the Operations team in popularizing the ngVLA and its observing modes via talks at other institutes (after the Call but before the Deadline)
- ES7. Write IEEE and PASP/ApJ journal articles on the ngVLA as a whole (ALMA did not do this), modeled on the papers produced for the EVLA by Perley et al. 2009 [RD01], and Perley et al. 2011 [RD02].

For the observing modes not offered for Early Science, but required to be delivered before the end of Construction, the steps above will need to be repeated.



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9 Post-construction Activities

Not all observing modes will be commissioned at the end of construction. CSV-like activities to commission further modes will be merged into the Ongoing Capability Development (OCD) effort, as defined in the Operations concept document (section 6.7). Such new observing modes may include specific science areas such as advanced Pulsar modes. Since most of the CSV staff may have moved on to other projects, it will be important to transfer knowledge of the commissioning process to the Operations staff, and to solicit help from experts in the community.

The life cycle of new modes will be clearly defined including the product delivered to the PI. The Life Cycle document proposes the following categories:

- Standard Mode Data Reduction (SMDR): SBs automatically generated; data are fully pipeline-ready and have well defined SRDPs
- Non-standard Data Reduction (NSDR): SBs automatically generated; data are not pipeline-ready but can be processed by automatically-generated scripts and have defined SRDPs but likely to be refined
- Shared Risk Observing (SRO): SBs require manual editing; data not pipeline-ready but can calibration
- New Mode Test Observation (NMTO): an experimental stage that precedes SRO

In addition, there is an additional option for Principle Investigator Data Reduction (PIDR) for specific complicated data reduction is required. The SBs are automatically generated; but we do not perform QA2.