



<b>Title:</b> Commissioning and Science Validation (CSV) Concept	<b>Owner:</b> Hunter	<b>Date:</b> 2019-08-30
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## Commissioning and Science Validation Concept

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Status: **RELEASED**

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## Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2019-02-08	T. Hunter	All	Initial version
02	2019-03-15	T. Hunter	All	Implemented suggestions received during and since the second telecon; moved holography details to Appendix A
03	2019-03-24	T. Hunter	All	Implemented suggestions received during the third telecon; removed dates in Sec. 2.3; added two assumptions
04	2019-03-29	T. Hunter	All	Additional corrections implemented; submitted to project office
05	2019-05-20	R. Carver, A. Lear	All	Converted to Word document for project office review
06	2019-07-08	M. McKinnon	All	Minor edits throughout
A	2019-07-30	A. Lear	All	Prepared PDF for approval signatures and release
A.1	2019-08-14	T. Hunter	7	Clarify the working definition of an observing mode from the Observatory's perspective, and mention the new ObsMode WG.
A.2	2019-08-16	R. Selina	1.2, 2.1, 6.2, 7	Minor typographical corrections for StRR release.
A.3	2019-08-26	M. McKinnon, R. Selina	2.2	Addressing comments from MM and ensuring consistency with AIV concept.
B	2019-08-27	A. Lear	All	Prepared PDF for approval signatures and release as v.B

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## I 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 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 list of validated science observing modes as demonstrated by accompanying science-ready data.

This document also outlines the staffing, resources and support that will be required from other ngVLA work groups. In particular, it identifies 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 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 a specific list of validated science modes by the start of Full Operations in 2034.

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### 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 Transition Concept	020.10.05.00.00-0003-PLA
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	Central Signal Processor Preliminary Technical Specifications	020.40.00.00.00-0001-SPE
AD13	Computing and Software Architecture: Reference Design	020.50.00.00.01-002-REP
AD14	Computing and Software: Preliminary Requirements	020.50.00.00.01-0001-REQ
AD15	Calibration Requirements	022.20.00.00.00-0001-REQ
AD16	Subsystem Reference Design Description: Digital Back End/Data Transmission System	020.30.25.00.00-0002-DSN
AD17	ngVLA Assembly, Integration, and Verification Concept	020.15.00.00.00-0005-PLA
AD18	ngVLA Legacy Science Program	020.10.05.00.00-0004-PLA
AD19	ngVLA LO Reference and Timing: Preliminary Technical Specifications	020.35.00.00.00-001-SPE
AD20	ngVLA Preliminary System Requirements	020.10.15.10.00-0003-REQ

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## 1.4 Reference Documents

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

Ref. No.	Document Title	Origin
RD01	The Expanded Very Large Array	<i>Proc. IEEE</i> , Vol. 97, Issue 8, pp. 1448–1462
RD02	The Expanded Very Large Array: A New Telescope for New Science	<i>A&amp;J</i> , 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)	<i>PASP</i> , 123, 1087
RD06	Improvement of the Effelsberg 100 meter telescope based on holographic reflector surface measurement	<i>A&amp;A</i> , vol. 167, Oct. 1986, p. 390-394.
RD07	Out-of-focus holography at the Green Bank Telescope (Nikolic et al. 2007)	<i>A&amp;A</i> , vol. 465, p. 685
RD08	GBT Holography Simulation and Analysis of Lunar Scans (Schwab & Hunter 2007)	PTCS Project Note 59
RD09	EVLA Real-Time Science Software Requirements	EVLA-SW-005
RD10	ALMA Control Software Subsystem Science Requirements	Butler 2005
RD11	Removal of daytime thermal deformations in the GBT active surface via out-of-focus holography (Hunter et al. 2009)	2009 USNC/URSI annual meeting
RD12	Mapping the Large Millimeter Telescope primary reflector using photogrammetry: A first comparison with 12 GHz holography (Gale et al. 2016)	<i>SPIE</i> Volume 9912, id. 4F
RD13	The Paraboloidal Reflector Antenna in Radio Astronomy and Communication, J.W.M. Baars	Berlin: Springer, 2007

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## 2 Overview

The work required to bring the ngVLA Observatory from the period of construction through commissioning and into operations is divided among several groups. In brief, the Assembly, Integration, and Verification (AIV) group delivers functional capabilities, which includes verified hardware and accompanying software, while the CSV group develops the processes needed to demonstrate performance and validate science observing modes. The Operations group and Maintenance group operate concurrently with CSV and are responsible for managing and maintaining the array, respectively.

### 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 elements, for example, a group of antennas and a portion of a correlator along with their corresponding control software that supports a specific observing 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, which includes the processes of observing and data reduction, along with the associated technical documentation and procedures 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 procedures will include checklists for activities such as re-integrating an antenna into the array after a receiver package replacement.

Although CSV will formally end once the initial set of science observing modes that define Full Operations has been validated, the Observatory envisions an ongoing program to commission new observing modes that are motivated by future science developments (§ 8) [AD03,18]. These activities will follow the example established by CSV during construction.

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, including subarray capability. Good communication between the teams in this Early Delivery Phase of AIV [AD17] 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.

Considering the large scale of this Observatory, it will be essential for CSV to attack and retire the high technical risk items early. Two primary issues of concern arise from the technical challenges of operations beyond the traditional baseline lengths of the VLA:

- the fidelity and stability of the LO/IF system on long baselines of the Main Array and the Long Baseline Array (LBA), and
- the effectiveness and reliability of WVR correction in a variety of weather conditions across the array.

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For example, the preliminary designs for the data transmission system do not treat the long baseline stations in detail [AD16]. 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 Assumptions

The concept for CSV outlined in this document draws in broad terms from the ngVLA system reference design [AD02]. To the extent that fundamental aspects of the design may change, for example the polarization basis of the receiver feeds or the allocation of paired array elements on the mid baseline stations, the details of this concept may need to be modified.

### 2.2.1 Uniformity of Receiver Packages

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] rather than a partial set like ALMA initially fielded. Of course, in order for all receiver bands to be useful for general-purpose CSV, they must be delivered with verified focus and collimation offsets, if necessary.

The initial delivery of antenna capabilities from AIV will focus on verification of Band 3, with all other bands verified later as separate capabilities. Although much CSV can be pursued with a few antennas and only a single operational band, having multiple 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. Delivery of additional band capabilities is therefore desirable relatively early in the commissioning sequence.

### 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 AIV Concept [AD17] 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 (with all supporting electronics) into each category of distance of the Long Arms (50 km and 500 km) in a relatively early stage of the AIV process (i.e. soon after milestone AIV30.0). These stations will be critical for fundamental tests of the LO/IF system, delay server, etc., during AIV. The CSV team should be prepared to use these antennas to test the efficacy of WVR correction and other calibration schemes on long baselines [AD15].

### 2.2.3 Verification of Antenna Surface Performance

Another important 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 and CSV must be expressed and captured during the ongoing detailed design process. For example, we will need to practice (first at the Central Cluster 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. While beam cuts across the Moon can provide initial information on the level of surface error on different length scales of the aperture [RD08], the determination of surface corrections requires more detailed methods. But the method chosen depends heavily on the antenna design. We describe the primary options in Section 9.2 of the Appendix.

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## 2.2.4 Multiple Sub-Array Capability

Given the scale and complexity of the ngVLA project, scientific validation will require multiple activities to proceed simultaneously on the array. Subsets of antennas and other hardware must be able to be used independently of each other with minimal crosstalk to support parallel operations. Sub-arraying capability is a key early capability to be developed by the AIV process, and its delivery will mark the end of the Early Delivery Phase [AD17].

## 2.2.5 Verification of Offline Software by AIV

Because the AIV group delivers functional capabilities to the CSV group, AIV will be responsible for accepting both the online control software and the accompanying offline data processing pipeline before delivering a new capability to CSV. This step will help to shield the CSV group from experiencing glaring bugs. The CSV group will exercise and validate specific releases of the pipeline, finding the more subtle bugs and inadequacies. Feedback from CSV will inform the next release. Occasional patch requests from CSV to the pipeline team may be necessary to avoid overall project delay.

## 2.2.6 Commissioning of the Data Center Is Out of Scope

CSV is responsible for demonstrating that science observing modes can be processed from beginning to end through the same pipeline data path that PI data will follow, ultimately producing a set of predefined SRDPs. Further commissioning of data center capabilities such as producing additional products, managing CPU and storage load, servicing special user requests, and providing remote data access will be performed by a different group in the Science Support IPT (to be identified in the CSV plan).

## 2.2.7 Telescope Operators to Be Supplied by Operations Group

Because CSV tasks will require late-night (and in some cases 24-hour) operation, a skilled staff of telescope operators will be needed to perform routine duties and launching of Scheduling Blocks (SBs), and to ensure the safety of the array elements. The operators will formally report to the Operations group but with the goal of supporting the CSV work plan.

## 2.3 Timescales and Historical Basis

The expected sequence of major events that will provide the framework for CSV activities is listed below.

1. First prototype antenna delivered by vendor.
2. First production antenna delivered by AIV.
3. First fringes (AIV+CSV).
4. Initial CSP, RSD, and six antennas delivered by AIV.
5. Science Validation of first Early Science mode.
6. Early Science First Call for Proposals.
7. Early Science First Observations.
8. All Main array antennas delivered.
9. Completion of Main array (214-element, <1000 km).
10. Completion of entire array (including LBA).

The projected period between the first antenna delivery and completion of the 214-element Main Array is expected to be only ten years. This rate of commissioning may be considered daunting when one considers that this number of antennas is comparable to the sum contained in 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. The commissioning of both SMA (with

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eight antennas) and ALMA (with 66 antennas) required eight years from first prototype antenna (1996 and 2003, respectively) to start of Early Science.

Similarly, MeerKAT (64 antennas) required nine years from first fringes to dedication. Furthermore, for ALMA, it took four additional years (for a total of 12) to acquire the first PI observations at the longest baselines. By comparison, ngVLA is targeting 11 years to LBA completion. In any case, the ongoing validation of new modes envisioned in Section 8 means that CSV-like activities will continue beyond the initial decade of commissioning, and will likely persist throughout the life of the Observatory.

## 2.4 Key Statements from Other Concept Documents that Impact CSV

The CSV concept has been developed to match the operational goals of the Observatory. Here we list the major goals from two other ngVLA concept and design documents that are most relevant, and briefly note their impact on CSV (in italics).

### 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.” *–In order to facilitate Early Science, the Early Science observing modes need to be defined at an early stage (§ 7.2).*

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 (§ 8).*

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.” *–The Science Validation (SV) milestones include a demonstration of SRDP generation (§ 7.2).*

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.” *–These will be the Science Validation targets (§ 7.2).*

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 sub-array operation must have high priority. Up to ten 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]. Indeed, the demonstration of sub-array operation marks the end of the Early Delivery Phase of AIV (§ 7.1).*

### 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.” *–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. While dedicated, controlled fiber connections are envisioned on the Central Cluster, Spiral Arms, and the nearer stations of the Long Arms (up to 300 km) [AD19], the more distant stations will be connected with commercial fiber. Because commercial fiber cannot provide sufficiently fine control required for LO transmission, the nominal plan is to outfit the LBA stations and the 17 other most distant stations on the Long Arms with hydrogen masers [AD02].*

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### 2.4.3 ngVLA System Reference Design [AD02]

Section 7.9: “Calibration tables that compensate for large-scale instrumental and atmospheric effects in phase, gain, and bandpass shapes will be provided.” –*The calibration database (see also [AD15]) will need to store additional antenna-based calibration parameters such as gain curves and polarization D-terms, while the calibrator database will need to store calibrator flux density histories and image models in order to support the online software selection of calibrators and their cycle times [RD09, RD10] and to support offline calibration. Both databases will need to be populated initially by CSV (Section 7.1) and accessible to SRDP (Section 7.2). Ideally, the calibrator database will also be accessible to proposal preparation and SB generation tools.*

## 3 Composition and Duties of the 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 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 pass/fail criteria.
5. Work with Computing 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. Populate the Observatory calibration database, such as primary beam models, flux calibrator image models, and polarization calibration information.
11. Write ngVLA memos and reports that summarize performance test procedures, results, and directions for future work.
12. Work with colleagues at ALMA and other facilities to better understand cutting-edge problems that each face.
13. Be familiar with the Reference Observing Program and the capabilities that these projects require.
14. Maintain familiarity with the calibration plan and provide feedback regarding feasibility.
15. Maintain familiarity with pipeline processing and development, and provide new requirements when necessary.
16. Deliver tested observing modes and work with the Operations group to achieve successful SV results.
17. Organization of CSV Team.

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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 simultaneously not allowing some items to receive no attention, which could raise the risk of significant rework at later stages of the project. Establishing a number of teams with a specific focus will help to expedite the CSV process. 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 process than might otherwise happen in the inevitable push to make the Central Cluster 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. It will also be useful for members of the CSV team to 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. These leaders should be System Astronomers with previous experience in commissioning and an ability to interact efficiently with System Engineers in the AIV group. 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, and 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. On the other hand, we want to avoid single-point failures within the CSV staff, so defining cognizant deputies for the larger items will be necessary. 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.



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## 4 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 progress details will be presented by team members both informally at weekly group meetings and to a wider audience through lunch talks at the science center. To enable and encourage remote participation, the weekly meeting will need to be held at a time and day convenient to all NRAO sites, likely 11AM or 2PM MT on a day that does not conflict with colloquia schedules. Once multiple antennas are available for CSV, a higher cadence coordination meeting (either Mon-Wed-Fri or daily) among the team leaders and the current and upcoming observers will likely be needed to assess the top priorities and plan the upcoming 24–48 hours of observing tests, but should be limited to 30 minutes as much as possible. A representative from the Computing group and Operations group should also be present.

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 prevent repeating mistakes of the past as well as increasing awareness of 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.

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## 5 Resource Requirements

The CSV Plan document [AD07] will specify resource 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 IPTs.

### 5.1 Software

The software needs of the CSV group to efficiently perform its work will include both in-house data analysis software and commercially available products. A preliminary list is provided below.

1. A system to report and track problems (such as JIRA).
2. A monitor data archive [AD11], with automatic filling and the capability to list and plot contents. Configurable monitoring and the ability to trigger high-frequency sampling for short periods (the “oscilloscope function”) will be desirable (to be provided by Computing & Software (CS) [AD13]).
3. A centralized database to store system configuration data (including calibration models) under version control (will be provided by the 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 calling high-level array functions, prior to the widespread use of Scheduling Blocks (SBs) (to be provided by CS group [AD13]).
6. Simulators to enable the development of observing scripts without the real system (to be provided by CS group [AD13]).
7. Interactive shell access to the calibration and imaging software (assumed to be CASA), and the python scientific stack running on an Observatory-supported Linux OS (see Section 6.2.4).
8. Access to commercially licensed analysis tools if needed (MATLAB, etc.).
9. The value of having VLA and ALMA providing contemporaneous flux densities, spectra, and polarization of calibrators in the various ngVLA bands should not be overlooked.

### 5.2 Hardware

#### 5.2.1 Weather Stations and APM

The scheduling and interpretation of commissioning observations will rely on accurate knowledge of the weather at the Central Cluster, each station of the Main Array, and LBA sites. For the remote stations, webcams showing sky conditions would be helpful. An interferometric atmospheric phase monitor (APM) at the Central Cluster will also be essential to make efficient use of test observing time. An all-sky, mid-infrared cloud monitor located at the Central Cluster would be useful for detecting the presence of hydrosols during observations, which would help to commission the continuum fitting and removal function in the WVR phase correction software.

#### 5.2.2 Staged Delivery of 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 initial correlator for AIV and CSV purposes might well include all stations but a limited bandwidth (few hundred MHz) and only a couple of modes.

#### 5.2.3 On-Site Control Room Workspace

During the Early Delivery Phase when AIV and CSV are working closely together on the first antennas, there will need to be a dedicated workspace provided in the local control room at the array site. Once

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the control system is established reliably, telepresence using a remote control room at the local science center should work well (as it did for the EVLA WIDAR project).

### 5.2.4 Computing

The remote control room used by CSV must 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 forcing people to carry their laptops back and forth to the control room in order to be able to do anything.

To process commissioning data promptly, CSV staff will require guaranteed access to high-performance computing cluster nodes and disk space. Provisions must also be made in the data center for CSV staff to access the visibility data outside of the automatic, non-interactive processing model that is envisioned for the steady-state operational mode in the Operations Concept document [AD03]. In this interactive access mode, having the ability to filter portions of the data easily will be important, especially because some problems may only begin to arise once large numbers of antennas are operating in one subarray.

## 5.3 Personnel

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

### 5.3.1 Internal Staff

We will expect contributions from the scientific staff of all NRAO sites (SO, CV, JAO) and many of the partner organizations. These scientists will both participate in CSV and mentor ngVLA research associates hired specifically for CSV. The research associates will provide the bulk of the daily testing, reporting, and CSV software effort. There should be a path for associates to join the ngVLA Operations team.

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.

### 5.3.2 External Staff

The CSV leadership may wish to invite visiting scientists, with demonstrated interest and experience on specific commissioning campaigns, to participate in commissioning campaigns. These invitations will be one way to augment the experience of the CSV staff, which may be too limited in some particularly specific areas. Such invitations will need to offer at least partial financial support for travel and other expenses.

In addition, it will be important to the Observatory during the CSV phase to attract and engage graduate students and additional (non-ngVLA) research associates to help test the capabilities that serve their research interests. We recognize there will be competition for their attention with other facilities like SKA, and that this will require financial support, including travel and accommodations.

### 5.3.3 Operators

The Operations group will provide skilled telescope operators to assist with the execution of CSV observations and to ensure the safety of the array elements. The operator training process might involve some assistance by CSV staff, for example to explain the concepts and goals of current tests and how they can be most efficiently accomplished.

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## 6 Milestones

The milestones are organized into three sections. First listed are the milestones for commissioning the general capabilities and measuring performance level of the Observatory (enumerated by the “C” prefix), both of which are required for science validation to proceed. These milestones are based loosely on the ngVLA System Reference Design [AD02], so any significant changes to that design may necessitate a revision in the milestones.

Second are the milestones required to validate each observing mode (enumerated by the “SV” prefix). The order in which science modes are commissioned is described in Section 8. Finally, we list the milestones to prepare validated observing modes for Early Science (“ES” prefix).

### 6.1 Milestones for Commissioning

The list of commissioning milestones follows 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 four 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 the pointing and focus model coefficients and the nominal antenna surface setting, it is not expected that a complete characterization of elevation dependence of antenna performance will be provided, so this work will fall to CSV. As a result, the first four milestones correspond to the Early Delivery Phase of AIV [AD17], during which the AIV and CSV teams will work closely together up until the point that multiple subarray operation is successfully demonstrated.

The list of milestones below will be presented in more detail in the ngVLA CSV Plan [AD07], with direct reference to the system technical requirements [AD20]. In general terms, 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 (21 61 on the 18m antennas), while avoiding the RFI at low bands and frequent tropospheric limitations in Bands 5 and 6.

#### 6.1.1 Joint AIV+CSV Commissioning Milestones During the Early Delivery Phase

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

C2. Begin single-dish operations.

- Most items in this category (alignment, pointing, focus, beam profiles, gain curves, surface performance) should eventually be done through interferometry, because it is easier and often more accurate. But we may be able to start some of the measurements before interferometry is possible.
- Also, we must remember that single-dish mapping using autocorrelation data is a required capability of the Observatory.

C3. Begin Interferometry Operations I: Correlation of several Central Cluster antennas leading to a stable interferometer.

C4. Validate simultaneous multiple subarray operation.

- Acceptance of subarrays marks the split of CSV from AIV.

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### 6.1.2 Subsequent Commissioning Milestones for CSV Group

- C5. Begin array performance testing, typically requiring long integrations (stability of phase, bandpass, beam patterns).
- C6. Demonstrate operation from Scheduling Blocks.
- C7. Test fundamental calibration plan and report performance.
  - Begin populating the calibrator and calibration databases.
- C8. Begin Interferometry Operations II: Correlation of Spiral Arms with Central Cluster.
  - Provide surface performance validation of remotely assembled antennas.
- C9. Test polarization calibration of Central Cluster and Spiral Arm antennas and report performance.
  - Will we apportion some of the correction to Observatory-provided values and some that is experimentally measured?
- C10. Begin testing first observing modes.
  - Confirm the production of viable raw data in the Science Data Model (SDM).
- C11. Test automated processing of each observing mode.
  - Provide feedback to Pipeline and SRDP developers to facilitate subsequent SV milestones.
- C12. Declare observing modes using Central Cluster and Spiral Arms ready for Science Validation.
  - Present results for official acceptance by Operations, including calibrator and calibration databases.
- C13. Begin Interferometry Operations III: Core antennas with remote stations of Long Arms and LBA.
  - Provide a preliminary performance assessment.
- C14. Test polarization and amplitude calibration plan of Long Arms and LBA and report performance.
  - Demonstrating polarization angle and D-term calibration over this wide range of baseline lengths will be challenging.
- C15. Declare Long Arm and LBA observing modes ready for Science Validation.
  - Present results for official acceptance by Operations.

## 6.2 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 is First Look Science [AD18], which is applicable for the first few years of Early Science. In the final years of CSV and beyond, the name

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for such data from new modes will likely evolve to Public Science Verification or Demonstration Science [AD10]. In both cases, there needs to be agreement with Operations on what constitutes successful, robust processing of a mode, perhaps in terms of Key Performance Indicators. The commissioning status of each science mode will be tracked with an integer code indicating its current level of support (see the definitions in § 9).

SV1. Select Science Validation target fields and identify previous VLA and/or ALMA datasets.

- Gain scientific input from the user base, facilitated by the Project Scientist.

SV2. Select Science Validation calibration plan (in collaboration with the Calibration group).

SV3. Determine the list of inputs that will be required of the PI for this observing mode, or if any special data quality assurance (QA) considerations are needed.

SV4. Generate Science Validation SBs using the Observing Tool (with assistance from Operations).

SV5. Execute Science Validation SBs.

SV6. Perform initial quality assessment, adjusting, and repeating observations until successful (with assistance from the Operations group).

SV7. Demonstrate quality-assured Pipeline processing of successful SBs (with assistance from the Pipeline and SRDP groups).

SV8. Demonstrate quantitative agreement with previous VLA and/or ALMA datasets of same target fields.

- Subtle bugs are often discovered when two different observatories closely compare similar observations of the same target.

SV9. Demonstrate that the SV data can be successfully calibrated and imaged through the same processing path that the subsequent ES data will ultimately follow.

- The larger task of “commissioning the data center,” including the generation of additional data products or viewing capabilities, will not be performed by CSV (see § 2.2.6).

### **6.3 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 the Call for Proposals).

ES3. Assist Operations group with writing the Technical Handbook (prior to the 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].

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

## 7 Order of Science Observing Modes to Be Commissioned

It is essential for the ngVLA project to define a specific list of observing modes to be validated by CSV. The definition of what constitutes an observing mode is the first issue to address. From the science user's perspective, one definition is what is presented in the summary document of a Call for Proposals, which typically contains broad categories such as "Stokes I Continuum" or "Single Pointings and Pointed Mosaics". However, such definitions hide all of the internal complexities of rules and decision trees that require resources, define a sequence of observations of calibrators and science targets, and rely on specific heuristics and methods to process the data in the pipeline. It is exactly this latter combination of items that must set the Observatory's 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. In this sense, an observing mode becomes a list of rules that every subsystem must obey 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.

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. The definition of observing modes has become the charge for a new work group: the Observation Mode (ObsMode) work group, which will have significant overlap with the Science, CSV, Computing, and Pipeline/SRDП work groups. Pending the result of that effort, in this document we consider the expected observing modes as defined from the user perspective. The ngVLA Reference Observing Program (ROP) [AD08] provides examples of observations that support the Key Science Goals of the Observatory. Because these examples cover a number of different science observing capabilities, it raises the question of the order in which these capabilities should be commissioned and made available to Science Validation and First Look Science (FLS).

At this stage of the project, it is premature to present a recommended order of commissioning of science modes, particularly because community workshops establishing the science goals of ngVLA are ongoing during 2019. Nevertheless, as a start, this section distills the science projects identified in the ROP into a preliminary list of science observing modes based simply on two components: sky coverage and spectral coverage. A possible third axis of distinction would be baseline length within the Main Array. Most likely, the general guideline is that smaller arrays will be commissioned first, which will naturally impact the order in which science observing modes are validated, and thus the order of release of FLS data. This concept will be further developed in the CSV Plan [AD07].

At present, the ROP does not convey which projects require SBA or Total Power observations, but these have been integrated into the list below where they seem most appropriate. Any special performance concerns are listed in italics alongside the associated science mode. Finally, we have assumed that the option of full polarimetry is delivered with each mode rather than being commissioned separately.

### 1. Single pointing interferometry

- Continuum only: basic calibration needs to be established.
- Spectral lines with continuum: spectral purity and correct labelling need to be established.
- Imaging that includes SBA datasets: multi-aperture data combination needs to be established.

### 2. Pointed mosaic interferometry: accurate primary beam patterns will be essential

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- Continuum only
- Spectral lines with continuum
- Imaging that includes SBA datasets

### 3. Phased array

- VLBI mode
- Pulsar modes including timing and multiple phase centers

### 4. On-the-fly mosaic interferometry: accurate primary beam patterns will be essential

### 5. Rapid response to transient source alerts: *reduced time overhead in command and control*

### 6. Total Power (i.e. single dish continuum and spectral line imaging): antenna performance for rapid scanning is needed

- Continuum only
- Spectral lines with continuum

### 7. Single pointing LBA interferometry: stable LO reference and timing system at LBA sites

- Continuum only
- Spectral lines with continuum

## 8 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 lifecycle of new modes will be clearly defined including the product delivered to the PI. The Lifecycle document [AD10] proposes the following categories, to which we have attached integer levels for easier reference:

- Level 3: Standard Mode Data Reduction (SMDR): SBs are automatically generated; data are fully pipeline-ready and have well defined SRDPs.
- Level 2: Non-Standard Data Reduction (NSDR): SBs are automatically generated; data are not pipeline-ready but can be processed by automatically-generated scripts and have defined SRDPs but are likely to be refined.
- Level 1: Shared Risk Observing (SRO): SBs require manual editing; data are not pipeline-ready but can be calibrated.
- Level 0: New Mode Test Observation (NMTO): an experimental stage that precedes SRO.

In addition, there is an option to have a mode called Principle Investigator Data Reduction (PIDR) for cases where specific complicated data reduction is required. In this mode, the SBs are automatically generated, but the Observatory does not perform quality assurance.

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## 9 Appendix

### 9.1 Abbreviations and Acronyms

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
EDP	Early Delivery Phase (of AIV)
ES	Early Science
FLS	First Look Science
GBT	Green Bank Telescope
JAO	Joint ALMA Observatory
IF	Intermediate Frequency
KSG	Key Science Goal
LBA	(ngVLA) Long Baseline Array
LO	Local Oscillator
PI	Principal Investigator
QA0	Quality Assurance Level 0 (Data can be calibrated)
ROP	Reference Observing Program
RSD	Reference Signal and Distribution
SB	Scheduling Block
SBA	(ngVLA) Short Baseline Array
SDM	Science Data Model
SMA	SubMillimeter Array
SRDP	Science Ready Data Products
SV	Science Validation
WVR	Water Vapor Radiometer

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## 9.2 Validating Antenna Surface Shape and Determining Panel Corrections

To illustrate the impact that antenna surface validation will have on the CSV concept, we briefly review the primary options for deriving surface corrections: photogrammetry and holography. Photogrammetry requires placing reflective tape at hundreds of positions across the surface (ALMA antennas have 1080 [RD13]), taking pictures at various angles and solving for the 3D surface [RD12], for which one part in 105 is readily achievable (180 $\mu$ m for an 18m primary). Holography requires measuring the complex beam pattern of the antenna using a strong signal source. Since we cannot feasibly build 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. In ngVLA configuration main-revC, there are seven antennas for which the nearest antennas is >100 km away (up to 284 km, in fact, for pad m083 = Kitt Peak) as shown in Figure 1. Rapid scans in an asterisk pattern through the target (as used by ALMA celestial holography) might mitigate the stability problems, but will need wide bandwidth to detect the source far enough off-axis to acquire the necessary complex beam pattern.

Another alternative is phaseless “Out-of-focus” holography (i.e. imaging a point source at multiple focus settings), which can recover large-scale dish surface deformations without the use of a reference receiver [RD07]. This technique is used to correct thermal deformations in the GBT surface prior to high-frequency observations [RD11]. But this method will likely not provide sufficient resolution for validating antenna surface assembly, which will inherently involve measuring the sharp alignment discontinuities at panel boundaries.

If neither photogrammetry nor celestial holography can provide sufficient results, then we may need to perform geostationary satellite holography on a Ku band beacon. This technique would require temporarily mounting a separate reference receiver and feed on the antenna (like the GBT uses [RD05]), or transporting and setting up a small fixed antenna near the antenna (like the Effelsberg 100m has used in the past [RD06]). This simplest solution for a backend would likely be a portable system containing a two-channel IF processor (with a single sideband downconverter and narrow band anti-aliasing filter), a 90-degree phase shifter, three-channel ADC, and a digital complex correlator. The autocorrelations and cross products would be stored on a local control computer and retrieved over the Internet for remote processing and archiving.

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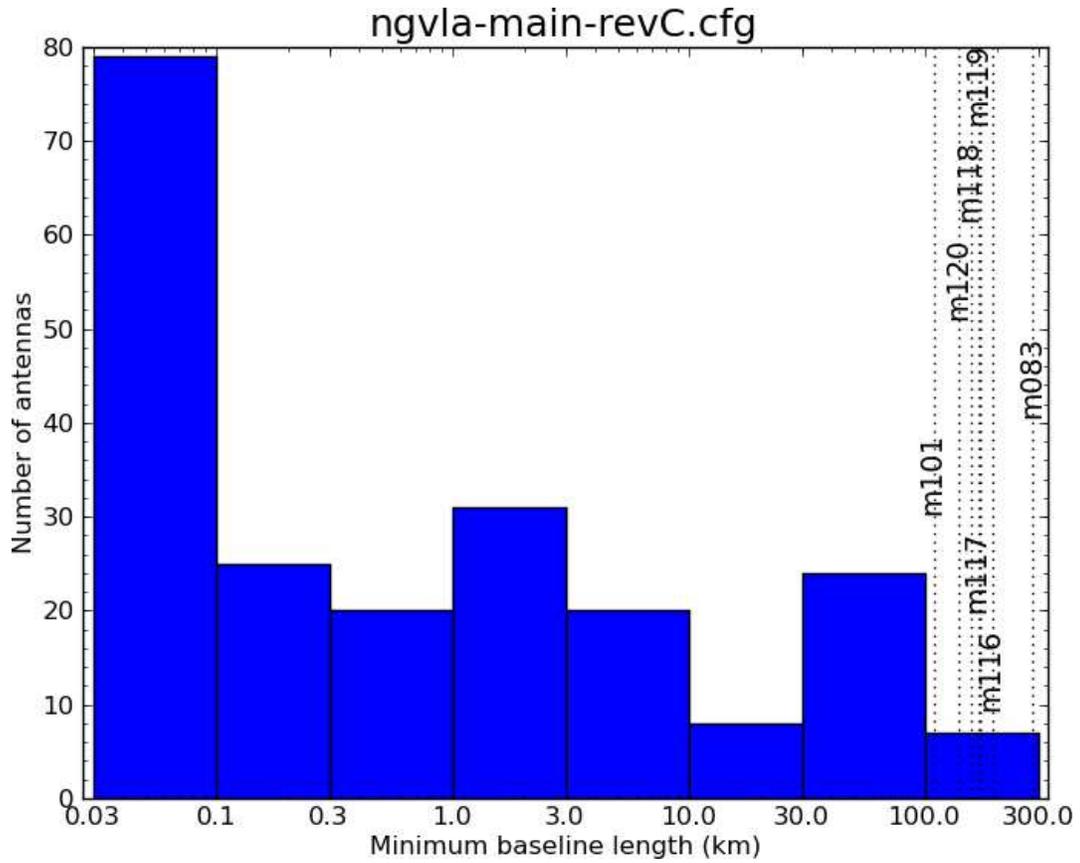


Figure 1 - Histogram of the shortest baseline of each ngVLA antenna in the Main Array of 214 antennas, using the main-revC.cfg file. The names of the seven pads where this length is >100 km are labeled.