Operations Concept

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Change Record

Version	Date	Author	Affected Section(s)	Reason
01	2016-11-18	Selina, Carilli	All	First draft incorporating text from Prospectus.
02	2016-11-23	Selina et al.	All	Expanded after discussions with Claire Chandler, Steven Durand, Alan Erickson, Wes Grammer, Jeff Kern, Wayne Koski, Dave Parker, Peggy Perley, Nathan Towne, and Denis Urbain.
03	2016-11-30	Selina, Grammer	6	Added maintenance model by Grammer.
04	2016-12-01	Selina, McKinnon	All	Format updates & adding DMS context Pulled From MM SPIE paper.
05	2016-12-07	Selina	5,6	Minor corrections for clarity before review.
06	2016-12-07	McKinnon	All	Corrections throughout; identified areas for additional development.
07	2017-10-02	Kepley	4	Complete rewrite of Section 4 to better incorporate Sci. Ops.
08	2017-10-12	Selina	2, 8	Added change log, appendix, reference documents section, etc.
09	2017-10-30	Selina	1, 8, 9, 10, 11	Started to update outline with ngVLA TAC input.
10	2017-10-30	Selina		Fixed ToC & minor typos.
11	2017-11-09	Ford, Murphy	1, 6, 8	Corrections and expansion on areas.
12	2017-11-13	Kern, Treacy	4–9	Input and expansions of various sections.
13	2017-11-15	Langley, Cole	9, 11	Operations and Site input.
14	2017-11-22	Selina	Appendix	Minor edit to commensal correlator modes.
15	2017-12-20	Treacy	Appendix	Moved operations planning material to Ops Plan, clean up comments, update science use table, overall coherence.
16	2018-02-05	Ford	2, 4, 13	Moved driving requirements and abbreviations to beginning of document.
17	2018-03-26	Ford	8–12	Elaboration of ideas from OWG input.
18	2018-04-09	Ford	All	Reorganization of documentation. Expanded on array & maintenance concepts, aligning the former with science operations. Add ngVLA Development section.
19	2018-04-25	Ford	Various	Incorporating feedback.
20	2018-05-25	Ball	All	Updated Science Operations based on subgroup work, tidied language and consistency throughout.

Version	Date	Author	Affected Section(s)	Reason
21	2018-05-29	Ball	All	Incorporating SciOps WG feedback.
22	2018-05-30	Ford	All	Additional incorporation of feedback.
23	2018-05-31	Kern	6.6, 8, 12	Clarifications.
24	2018-06-06	Wrobel	6	Added annual meeting at SOC, clarifications.
25	2018-06-08	Ball, Ford, Kepley, Kern, Koski, Perley, Treacy	All, 6.2	Final submission of clarifications by authors, author list revised. Clarified allocation of observing time to pre-defined subarrays.
A	2018-06-11	Ford	Title block, All	Revision change for release review, revision of capitalization.
A.1	2018-10-08	Treacy	many	Edits following StRR, RIDs tracked by JIRA Tickets under bugs.nrao.edu, JIRA Project ngVLA Stakeholder Requirements Review, JIRA ticket numbers of the form StRR-xx.
A.2	2018-10-18	Ford	Many	Revisions due to accepted SRR and Internal Pre-Decadal Submission Review RIDs.
A.3	2018-11-05	Ford	8, 12	Clarified maintenance tiers, described development program (which includes LSP funding).
B	2019-05-20	Lear	All	Incorporated PD's revisions and prepared document for final release.

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1 Executive Summary

The Next Generation Very Large Array (ngVLA) will be an astronomical observatory operating from 1.2 GHz to 116 GHz. The observatory will be a synthesis radio telescope constituted of approximately 263 reflector antennas; 214 each of 18 meters diameter in the main array, 19 antennas each of 6 meters diameter in a short baseline array (SBA) located near the core, and 30 antennas each of 18 meters diameter in a long baseline array (LBA) to provide continental-scale baselines. The instrument is capable of operating in a phased or interferometric mode. See [RD01].

The facility will be operated as a proposal-driven instrument with the science program determined by Principal Investigator (PI)-led proposals. Regular calls will solicit observing proposals, which will be peer reviewed and assigned a rank based on scientific merit and technical feasibility. Trained staff will incorporate the approved observations into dynamically scheduled blocks based on environmental conditions and array status, and in accordance with the user's scientific requirements.

Three primary centers will support the operation and maintenance of the array. A Maintenance Center will be located with expedient access to the array core. Field Technicians from the Maintenance Center will provide day-to-day maintenance support for the antennas and associated array systems. An Array Operations Center and Repair Center will be located in Socorro, NM, and staff based there will repair failed system elements and provide system diagnostics and engineering support along with array operation and supervision. A Science Operations 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 between the Array Operations and Science Operations Centers as appropriate. Technicians responsible for maintaining remote long-baseline antennas may be based at additional small service depots (Remote Support Stations).

The central signal processor will be highly configurable and, in addition to a variety of interferometric modes, will include commensal observing capabilities to permit the division of the array into subarrays and the processing of single-dish and single-baseline data in multiple ways, such as concurrent cross-correlation and transient searches. Phased array modes will support VLBI recording, pulsar timing, pulsar searches, and transient searches with multiple beams within the antenna primary beam.

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.

Through the delivery of quality assured Science Ready Data Products and the provision of standard observing strategies, the Observatory will aim to both support a broad community of scientific users that extends considerably wider than experts in radio interferometry, and to facilitate multi-wavelength and multi-messenger astronomy. Innovative, non-standard observations not accessible through the standard modes will also be supported where the scientific goals are of sufficient quality.

This Operations Concept informs the identification of ngVLA operational requirements through a subsequent Operations Plan, a Transition Plan, and a Development Plan. The Operations Plan will fully describe the operational model to be employed following ngVLA construction, while the Transition Plan will cover the transition from VLA operations to ngVLA operations. The Development Plan will describe the research and development activities necessary to advance the ngVLA's technical and user support capabilities after construction has ended and operations has begun.

2 Project Description

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 ngVLA will open a new window on the Universe through ultra-sensitive imaging of thermal line and continuum emission down to milliarcsecond (mas) resolution, as well as unprecedented broadband continuum polarimetric imaging of non-thermal processes.

The ngVLA will have approximately ten times the sensitivity of the JVLA and ALMA, with main array baselines of over 1,000 kilometers and long baselines of nearly 9,000 kilometers providing mas-resolution, plus a dense core on km-scales for high surface brightness sensitivity. Such an array bridges the gap between ALMA, a superb sub-mm array, and the future SKA1, which is optimized for longer wavelengths.

The majority of the antennas and the signal processing center of the array will be located at the VLA site, on the plains of San Agustin, NM. The main array will include stations in other locations throughout New Mexico, west Texas, southeastern Arizona, and northern Mexico. The high desert plains of the US Southwest at over 2000 m elevation provide excellent observing conditions for the frequencies under consideration. Long baseline stations will be located in Hawaii, Washington, California, Iowa, Massachusetts, New Hampshire, Puerto Rico, the US Virgin Islands, and Canada.

Maintenance and operations will be conducted from a Maintenance Center located with expedient access to the core of the array (~30 km, likely in Magdalena, NM) and an Array Operations and Repair Center (AOC) in Socorro, NM, respectively. Additional technicians responsible for maintaining remote LBA and some mid-length baseline antennas will be based at remote sites to optimize operation expenses. Data processing and analysis will occur at a combined Science Operations and Data Center.

3 Related Documents

3.1 Applicable Documents

The following documents are applicable to this Operations Concept to the extent specified:

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA Legacy Science Program	020.10.05.00.00-0004-PLA, Murphy, V01, 2017-10-23

3.2 Reference Documents

The following references provide supporting context:

Reference No.	Document Title	Rev/Doc. No.
RD01	ngVLA System Reference Design	020.10.20.00.00-0001-REP
RD02	Summary of the Science Use Case Analysis	ngVLA Memo #18. Selina et al., 2017
RD03	Key Science Goals for the Next Generation Very Large Array (ngVLA): Report from the ngVLA Science Advisory Council	ngVLA Memo #19. Bolatto et al., 2017
RD04	Gender-Based Systematics in HST Proposal Selection	arXiv:1409.3528. Reid, 2014
RD05	Gender Systematics in Telescope Time Allocation at ESO	arXiv:1610.00920. Patat, 2016
RD06	Gender-Related Systematics in the NRAO and ALMA Proposal Review Processes	arXiv:1611.04795. Lonsdale et al., 2016
RD07	ngVLA Computing Architecture	https://osf.io/pfw4c/ Kern, 2017
RD08	A Preliminary Operations Concept for the ngVLA	SPIE. McKinnon, 2016
RD09	Reference Study: ngVLA Buildings & Infrastructure	020.60.00.00.01-0002-REP
RD10	SRDP System Concept	530-SRDP-014-MGMT
RD11	ngVLA Transition Concept	020.10.05.00.00-0003-PLA
RD12	Principles for ALMA Development Program	AEDM 2011-023-O v2

4 Operations Concept and Scope

The ngVLA Operations Concept is described here using three perspectives: scientific and array operations, array maintenance and engineering, and array development. The combination of these three areas of effort forms the ngVLA operations definition and, therefore, the scope of this document. This specifically means that operations does not include efforts or planning associated with ngVLA construction. Other key assumptions and constraints are captured in the Appendix (Section 12.2).

This document generally uses the VLA array operation and maintenance model as a starting point. The ALMA operations model and experience has been equally informative, especially for science operations and the delivery of Science Ready Data Products (SRDP).

This Operations Concept assumes that ngVLA is a US-funded observatory operated on behalf of the scientific community by NRAO. The concept is subject to change if international partners join the ngVLA.

4.1 Scientific and Array Operations

Science operations are the user-facing services provided by the Observatory, including observation preparation, scheduling, archive access, scientific performance of the array, and the delivered data products. Array operations involves the day-to-day operations of the working array, including the management of and administration of all operations. It encompasses the execution of observations and initiation of corrective maintenance actions and delivers observational data to Science Operations.

Given there will be formal data delivery from Array Operations to Science Operations, an interface to define that delivery will need to be developed.

4.2 Array Maintenance and Engineering

The maintenance and engineering effort covers the performance monitoring of the array and includes responsibility for preventive and corrective maintenance by engineers and technicians.

4.3 Array Development

Development activities determine and provide community-supported upgrades of the array. Managed by scientific and array operations, this includes research and development of hardware, software, infrastructure, and operations methods and techniques.

5 Scientific Operations

The primary objective of ngVLA science operations will be the delivery of the program of executable observations of the highest scientific ranking to collect data for the research community that produces the greatest possible scientific impact.

The ngVLA science program will be driven by proposals from the scientific community in response to regular calls for submissions. Proposals will be assessed for scientific merit through a peer review process. It is anticipated that astronomers will be eligible to apply for and be awarded ngVLA time regardless of their institutional affiliation (Open Skies) as is the case for other NRAO facilities.

It is expected that 80–90% of the scientific program will use a diverse, but well-defined, set of standard observing capabilities or modes delivered during construction for which the calibration and data processing will be undertaken through an automated pipeline developed and run by the Observatory. Proposals will include the information necessary for scheduling the telescope, configuring the instrument, collecting the data appropriate to address the scientific goals, and in most cases for automatically generating the appropriate Science Ready Data Products (SRDPs). Data will be delivered to the Principle Investigators as quality-assured SRDPs through an Observatory Science Data Archive.

In full operations, the Observatory will provide a set of standard supported observing modes, which are a construction project deliverable, necessary to achieve the key ngVLA science goals. At the start of ngVLA early science, only a small number of these modes that have been verified to work end-to-end (including delivery of SRDPs) 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. For standard observing modes, observing instructions (scheduling blocks) will be generated based on the scientific requirements specified by the PI in their submitted proposal.

In addition to the standard capabilities and modes, the Observatory will support innovative programs of sufficient scientific merit that require other instrument configurations and/or non-standard and non-automated data processing. It is anticipated that 10–20% of the science program may comprise such non-standard or Expert modes, and access to such time will require evidence of sufficient expertise and capability on the part of the proposers to deliver scientifically useful results. Non-standard observing modes will be severely restricted in early science operations, and may not be offered until full operations begins.

5.1 Proposal Submission and Assessment

As a proposal-driven instrument, the ngVLA will operate via a competitive peer review process similar to that of other large proposal-driven observatories such as ALMA, VLA, HST and JWST. Users will specify the scientific and technical requirements for their projects via an Observatory-supplied proposal tool. The proposal process will aim to minimize the need for PIs to have expert knowledge of the hardware, calibration and data processing issues specific to the ngVLA. The proposals will be evaluated for scientific merit by science review panels made up of experts from the broad astronomy research community, and a Time Allocation Committee will advise the Observatory of the scientific rankings of proposals.

Recent studies indicate differences between the outcomes from peer review processes for PIs of different gender [RD04], [RD05], [RD06]. The ngVLA proposal review process will adopt the best practices aimed at minimizing such differences.

Proposal attributes such as regular, large, triggered, monitoring, legacy [AD01], and joint (with other observatories) are expected to be supported once the Observatory reaches full operations, as will a diverse set of capabilities and observing modes. Different capabilities and observing modes will be made available in stages during the transition from construction through the start of science operations and the commencement of full operations. That transition is likely to take around ten years.

Observatory staff will schedule observations based on the scientific rankings of proposals, taking into consideration issues such as technical feasibility, data processing requirements, array status, and observing conditions. The Observatory Director will have the final responsibility for the scientific program that is executed.

5.2 Scheduling and Observing

A significant fraction of the array is expected to be available for scientific use at almost all times (once in full operation). Maintenance, testing, characterization, and capability development (including software) will primarily be done on a subset of the array, using subarrays where appropriate. A limited number of predefined science subarrays will be used by the Observatory to simplify scheduling of the scientific program, and allocation of observing time to subarrays may be recommended by the NRAO Time Allocation Committee based on the science goals of PI-defined projects. PIs will not be expected to request specific subarrays except for special circumstances. Subarray assignment will likely be used to balance observing pressure while maximizing the delivery of the data required to meet PIs' science goals.

The array will be dynamically scheduled in a fashion similar to the VLA and other modern instruments. Considerations will include the science ranking of projects, the most demanding projects that can be accommodated given the visible radio sky, the array status, and environmental conditions across the array or available subarrays.

A capability to interrupt the execution of the observing program in order to respond to a triggered observation with a higher scientific rank will be provided.

Submitted proposals will specify requirements based on scientific objectives (such as sensitivity, dynamic range and so on), but successful PIs will be awarded array time rather than guaranteed satisfaction of a scientific objective such as sensitivity. The Observatory will generally provide a defined observing strategy (including array characterization and calibration) for all standard modes and capabilities. Allocated time for standard observing modes will therefore generally be time on science target. Flexibility for PIs to make changes to the standard strategy—within limits and only when required to meet the scientific objectives—will be available.

5.3 Data Processing and Products

The standard method of delivery of scientific data from ngVLA to PIs will be automatically generated and quality-assured Science Ready Data Products. ngVLA data rates will be high enough to make data reduction at a PI's home institution challenging, but low enough that real-time processing of the visibilities (a la SKA) is not required [RD07]. Commercially available fiber will be used to transport the raw visibilities from the correlator (at the array core) to the Science Operations Center for data processing.

The Observatory will provide sufficient computing resources for the data processing associated with normal operations using standard modes and capabilities (including delivery of Science Ready Data Products to PIs) as well as reasonable reprocessing by PIs and a broader community of users of archival (public) data.

Delivery of a fully commissioned standard observing mode or capability will include an operational SRDP pipeline before it is offered for regular use through PI proposals.

The definition and delivery of ngVLA data products will be informed by NRAO's development of SRDPs via the ALMA data pipeline and the efforts already underway to extend this approach to the VLA [RD10].

Standard and optimized data products are anticipated to meet both the needs of the original PI for ngVLA observations, and the scientific goals of subsequent users of publicly available data from the Data Archive. Raw visibilities, calibration tables, and SRDPs will all be stored and made available through the Data Archive, as will some classes of user-generated data products where they can be suitably quality-assured.

Large and Legacy [AD01] scale projects will need to identify data processing requirements and resources, and may require additional computing resources to be made available from non-Observatory sources in order to be scheduled. Large and Legacy projects will likely not be offered until well after the start of science operations.

The Observatory will provide separate software packages to the user community for processing ngVLA visibilities and for data analysis. Both packages will be executable on Observatory computer resources and on non-Observatory computers, though the visibility processing software is likely to be aimed primarily at domain experts.

5.4 Data Archive

The Data Archive will be the point of interaction between Principal Investigators (and archival data researchers) and ngVLA data and data products. The raw visibilities, calibration tables, Science Ready Data Products, and Enhanced Data Products from Legacy projects will be archived. Archive functionality will allow users to inspect and select image data for download. Download of visibilities is expected to be rare. An interface to the Data Archive will allow scientists to initiate reprocessing of ngVLA data using Observatory-provided techniques and tools, and will include automated quality assurance processes.

PI access to data is expected to be protected by a proprietary period (nominally a year), after which the data and data products are fully and publicly accessible.

The Data Archive will have provisions for accepting user-produced data products where those products can be quality assured by the Observatory (such as products from Large or Legacy projects). In such circumstances, the Observatory will approve the user QA process, not the individual products.

Large and Legacy projects and some other special cases may have a different proprietary period. For Legacy projects, pipeline-processed data will likely enter the public domain immediately upon NRAO processing and validation, thereby enabling timely and effective opportunities for follow-on observations and archival research, for both the ngVLA and other observatories [AD01].

The Data Archive will provide a rich set of data and data products to support multi-wavelength astronomy and data reuse. Complementary data sets from surveys like WFIRST, LSST, and VLASS will also be available by the time ngVLA begins science operations. The Data Archive will be designed to interface easily with these and other similar archival systems to maximize the data discovery space. Where possible, interfaces to ngVLA data should favor processing the data in place, rather than transferring the data across the internet to the user.

5.5 Delivered Observer Capabilities

A defined set of standard capabilities will be developed, tested, and delivered during the construction project. Each delivered capability will include the observing sequence, calibration plan, and production of SRDPs. These sets of capabilities will include everything required to meet the most important science goals of the telescope.

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.

Early PI access—or Early Science—is expected to commence when roughly a VLA's worth of collecting area is available, and will include the first set of delivered capabilities offered for PI use. Additional PI access will be offered at other significant milestones prior to the end of construction (for example when baselines expand beyond the Plains of San Augustin). The handover of the defined delivered capabilities to science operations is expected to be completed by the time the construction project ends.

5.6 User Support

Direct scientific support is required for any aspect of ngVLA use related to proposing, observing, data quality, processing, and analysis through to the publication of scientific results. This support will be provided at three principal levels. First, adequate online documentation will be provided remotely through help-desk queries, which will be responded to primarily by data analysts or observatory scientists. Second, face-to-face interactions will be available at the Science Operations Center. Third, indirect scientific support to enable the best science possible by array users and/or archival data will be provided through service observations, maintaining auxiliary data bases (such as calibrator lists), calibration planning, and the development of observing strategies and techniques.

The ngVLA user community will be updated and expanded by Observatory-initiated and supported education programs such as workshops and community days, both at the Science Operations Center and elsewhere, and through self-training documentation, internships, and visiting or resident scientist programs. The ngVLA will contribute to NRAO's core mission of training the next generation of scientists and engineers through support of the NRAO postdoctoral fellowship program and graduate fellowship program. The Legacy Science Program will also serve to train the next generation of radio astronomers in university programs through its cohesive approach to developing unique and appealing projects. Finally, to ensure the visibility of the Science Operations Center, the ngVLA will host an annual science meeting or user workshop.

5.7 Ongoing Capability Development

After the completion of construction, the Observatory will have a mechanism to develop new observing and data processing modes beyond the set of capabilities delivered by the construction project, but which do not rely on new ngVLA instrumentation. In addition to these "observatory developed capabilities" and Legacy Science Program deliverables, there will be a mechanism to allow the user community to propose and participate in defining, testing, and verification of new capabilities to further enhance the ngVLA.

5.8 Array Health and Status

Regular health and status checks on array elements, including antenna physical and electronics, central electronics, and correlator, will be largely automated (as described under Maintenance). Similar checks and, where appropriate, re-measurement of calibration and related scientific performance characteristics of the array, will be performed as an Observatory function using small subarrays of antennas, contemporaneously with larger subarrays conducting scientific observing. The results of these checks will be used to update parameters such as delays that need to be set prior to observing science targets and to identify misbehaving elements. These processes and associated parametrization of the array performance will be automated and the relevant parameters stored for later retrieval as needed. This will be an integral part of the data processing pipeline and quality assurance process.

It is anticipated that the need to use the full array for such Observatory support functions will be very limited, thereby maximizing the array time available for science observations.

6 Array Operations Concept

Array operations personnel are responsible for the proper function of the ngVLA telescope, delivering science data as requested through science operations while interfacing with array maintenance and engineering staff to keep the array operational. The ability to control and monitor the telescope remotely and to automate aspects of maintenance planning and problem diagnosis will allow operations to be conducted remotely from the AOC with a reduction in overall operations cost. Depending on the degree of human intervention required in array supervision, multiple Operators may divide the workload.

6.1 Concurrent Maintenance and Observations

To meet the desired goal of observing at all times, the ngVLA will use a concurrent maintenance and observation model. This means that a substantial fraction of the entire array will generally be available for science, while at the same time some portion of the array will be undergoing or supporting maintenance, or being used in one or more subarrays for testing, characterization, or other operations activity. There will still be a need for maintenance and testing across the entire array, wherein no observing can be done, as determined by the electrical and networking infrastructure for example, but such times will be minimized. The majority of maintenance will be scheduled dynamically based on need and priority.

Existing array operation models typically allocate full array time for testing, commissioning, and maintenance. For ngVLA, such activities will generally be scheduled only on smaller subarrays, allowing a more continuous concurrent implementation of science observations, maintenance, and testing. For example, when an antenna that is part of a science array develops a problem, it could be removed from the science array and placed together with a neighboring antenna in a two-element array for problem diagnosis and repair. Similarly, testing may employ any available antennas configured as a subarray, concurrently with a science observation on a different subarray.

The subarray design implications, especially for software systems, will be carefully considered and be fundamental to the operation of the ngVLA. For example, it must be possible to run different software system versions concurrently on different subarrays for software testing and commissioning purposes.

Some of the identified science cases driving the VLA design require only portions of the array, or want the array subdivided into multiple subarrays for concurrent multi-frequency or multi-field observations. Calibration concepts under consideration may also require that antennas leave and enter subarrays in a fluid rotation. The possibility of differing environmental conditions across the array is also proportional to the array's extent. Maintenance time will be dynamically scheduled based in part on adverse local observing conditions or on scheduled preventive maintenance needs that align with science observing priorities.

6.2 Array Supervision and Automation

Similar to the VLA, a human operator will oversee the array. The operator will supervise the scheduling tools and executor, ensuring that the intent of each observation is met and that the array is kept in a safe operating condition. There will not generally be an astronomer on duty. The operator will be provided with an alert screen to indicate array health. In the case of malfunction, the operator will be the "human in the loop" and will be informed regarding maintenance work order tickets.

However, due to the large number of antennas and subsystems compared to other arrays, and the correspondingly large set of performance data, continual analysis of array status and health will be largely automated and an automated maintenance scheduler will be the key source of maintenance tickets. The ngVLA operations staff will include a maintenance coordinator to oversee the initiation, triage, tracking, and closure of operations-based tickets. The maintenance coordinator will work closely with the engineering support staff and Array Operator to resolve tickets.

Effective coordination and scheduling of maintenance must include a maintenance system that provides a high degree of automation, monitoring, and integration of maintenance data with data from other observatory tracking systems. Data from other systems would include, but is not limited to, availability of staff, vehicles, specialized tools and equipment, configuration control, environmental and weather reports, and status and location of inventoried spares.

In addition to the automated array-monitoring, individual ngVLA antennas need to be more autonomous than is currently state of the art. The software architecture should accommodate an antenna supervisory system or equivalent, which would be responsible for controlling the antenna, evaluating its performance, calibrating, and solving routine problems. Examples of actions taken by the antenna supervisor include:

- identifying and restarting malfunctioning digital transmission and timing systems;
- performance monitoring, control, and optimization of the cryogenic system;
- monitoring point performance and failure trend analysis for use in predictive and preventive maintenance scheduling; and
- returning to an observational ready state after unplanned shutdowns, such as power outages.

6.3 Array Operations Performance Monitoring

Array operations personnel will be responsible for development and calculation of its operations performance metrics. These metrics are a measurement of various operations process characteristics that provide a quantitative understanding of a process and way to assess its performance against a baseline or other requirements. The Operations Plan will detail the specific metrics to be used such as array uptime, resource utilization, and operation costs per antenna.

7 Array Maintenance Concept

A primary constraint for both the design and the maintenance concept is increasing the collecting area and geographical extent of the array by factors of ten, compared to the VLA+VLBA, while minimizing the operations cost. This has resulted in cost goals for construction, operations, and maintenance budgets. The high-level driver for operations and maintenance is to keep these costs within a factor of three when compared to similar costs incurred for the VLA+VLBA.

Since operations costs are primarily determined by the staffing level, the maintenance efficiency must be improved over current observatory standards. For the ngVLA, the array maintenance efficiency will be improved (at a *minimum)* by a factor of three compared to the VLA through a reduction in the frequency and expense of maintenance visits in terms of resources required. Achieving these efficiency improvements requires careful operations planning and forward-looking design decisions long before the array is constructed and operational. The decision process includes a thorough understanding of expected equipment performance, system design to improve maintainability and repair, and an agile organization of maintenance personnel. Some types of maintenance efforts, which require specialized skills but only at part-time utilization, may be efficiently addressed through the retention of contracted vendors.

Preventive maintenance (PM) schedules and system Mean Time Between Failure (MTBF) estimates must be consistent with the expected staffing level for antenna systems expected to operate a year or more between PM visits. This requires an accurate calculation of Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) for major array components and systems, with a tradeoff in regards to resource costs. In other words, the limited number of maintenance staff will be checked against the expected failure rates during system design, and is likely to drive the overall system quality requirements. At the antenna, limited labor and equipment should be required for all but the most significant of overhaul procedures, with most tasks performed by two technicians in a standardized maintenance vehicle (truck or van).

Items not replaceable as LRUs must be identified in the unit's maintenance plan. These items will require periodic maintenance at predictable intervals and corrective maintenance due to unexpected failure. The maintenance plan shall incorporate both these aspects of maintenance in a way that will optimize use of maintenance resources. Monitoring within antenna cabins and other remote sites may include audio and video monitoring as well as monitor points on a data bus.

Consistent with the goal of efficient maintenance interaction, electronics will continue to be packaged as Line Replaceable Units (LRU), where LRU modules are interchanged at the antenna. Individual LRUs, and all other configurable items, will be electronically self-identifying to readily determine status, configuration, version, time-in-service, maintenance and history, and location tracking across the Observatory. Non-electronic items that require tracking will be uniquely identified through a system like a bar code, visible serial number, RFID tag, or other permanent marking impervious to its operational environment with a comparable level of detailed parameters readily available from the database under which they are managed.

LRUs will be centrally managed, tested, and repaired from the repair center (AOC). Maintenance work will be classified in tiers to assign the level of skill or equipment to fully resolve issues requiring corrective maintenance. This is similar to ALMA's three-tier approach that aligns with progressively more complex and distant diagnosis, repair, and testing. LRU design will be optimized to accommodate the tier-defined maintenance structure, ranging from swapping of LRUs or other *in situ* repair work at an antenna (Tier I), changing LRU sub-assemblies or replaceable components in a workshop (Tier II), and repair or replacement of individual components in a lab environment (Tier III). Diagnosis, repair, and calibration or acceptance testing is required at all tiers. Hardware and software will be designed to accommodate, recover, and initiate necessary firmware updates after hot swapping, with minimal interactions by the maintenance personnel.

The organization of the maintenance and repair teams will also be split to maximize efficiency of time spent on antenna visits and repair of equipment. Functional teams assigned to maintain and repair specific subsystems such as Front Ends or Cryogenic hardware will be employed for centralized repair, overhauls, and detailed troubleshooting of complex problems. This work will be done away from the array at the Repair Center. Separate cross-trained field services teams will perform most routine maintenance activities and any remaining troubleshooting at the antenna. Maintenance teams will be organized and scheduled based on the need for routine, constant preventive maintenance work and for critical corrective maintenance work, prioritized by their impact on science operations. The minimization of specialization by field service staff is desired to avoid disruption from personnel departures and to reduce delays due to resource unavailability. Maintenance work that does not align with core competencies of NRAO will be contracted to external parties, partners, or vendors if it is deemed more cost-effective. Examples of such consideration for the Operations Plan are automotive, carpentry, and HVAC compressor maintenance.

The ngVLA will employ a scheduled maintenance program for the antennas with a goal of minimizing repeat and unscheduled visits to each antenna. The program will be structured to incorporate both reliability data on critical components and actual performance of equipment. For example, cryogenic refrigerators and other components with a known service life will be replaced at a regularly scheduled maintenance intervals, regardless of their current operating condition. The components may also be replaced if analysis of their performance predicts an imminent failure. Both the maintenance scheduling and monitoring of array health are key parts of the maintenance concept and are elaborated upon below.

7.1 Maintenance Scheduling

The productivity of maintenance staff time must be adequate to meet the staffing and up-time requirements for an array on the ngVLA scale. As array time is dynamically scheduled, similar consideration should be given to optimizing maintenance staff time. Maintenance will be scheduled based on a combination of the severity of existing issues, required preventive maintenance, and predictions of pending problems within clusters of the array in order to reduce travel time and maintain system up-time. Data to support this planning hinges upon the integrity of MTBF, MTTR, and FMECA analysis during the design and construction phase. This data is assumed to be collected by ngVLA Systems Engineering personnel.

The large number of geographically distributed antennas lends itself to a continuous and ongoing program of periodic maintenance windows, scheduled by subarray rotation to allow maintenance days to interleave with continuous observing. Failure analysis is also a critical input to the operational budgeting for spares needed to support the array's 20-year lifetime. Failure analysis must include projected availability for spares, the time required to repair the failure, and viability of critical vendors with the threat of obsolescence taken into account for planning upgrades. Lifetime buys on critical items identified as not feasible or practical to redesign will be considered as part of spares planning.

Maintenance analysis must be automated, defining maintenance lists and scheduling maintenance crews. Maintenance task lists can be distilled from the diagnostics software output, combined with the operations schedule, road/weather conditions, technician location, spares availability, and other data. Such a system will reduce scheduling conflicts, wasted trips, and improve overall maintenance efficiency. Relationships to the maintenance scheduler are shown diagrammatically in Figure 1.

Automated diagnostics will be critical to making such a maintenance scheduler effective and are discussed in the context of the Monitor and Control (M&C) system.

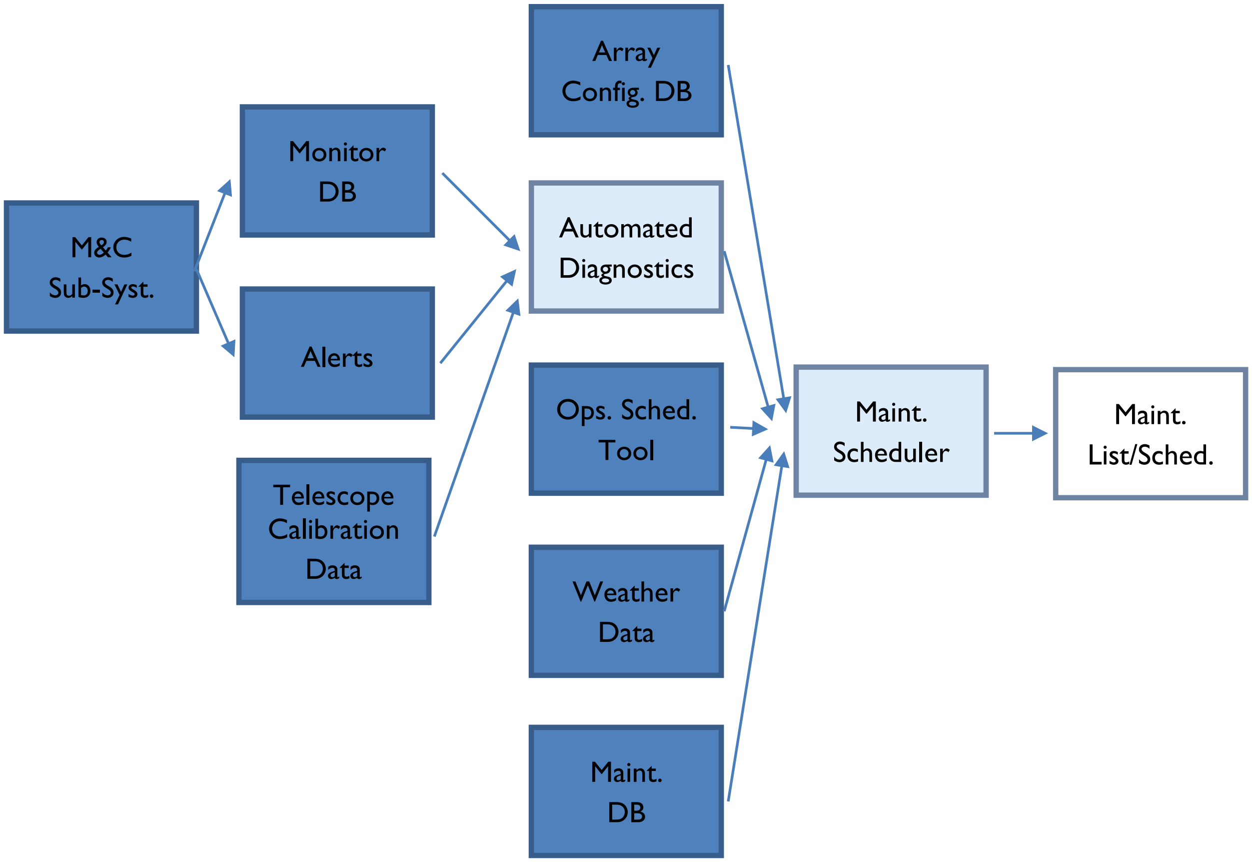

Figure 1 - Block diagram of the inputs and outputs of the maintenance scheduler.

7.2 *Maintenance Diagnostics*

The M&C system must be appreciably more sophisticated and have higher reliability than for existing arrays. The system must include more refined tools for remote automated monitoring and configuration management than presently exist in NRAO instruments. The automated diagnostic capabilities at the LRU and subsystem level are the primary means of troubleshooting and reporting system faults. LRUs and other subsystems must be smart devices with on-board diagnostics that can be accessed for troubleshooting via the M&C bus. The burden of remote fault monitoring and diagnostics must fall as much as possible upon intelligence within the LRU or item to ensure these goals are met within the constraints of the M&C Bus. The goal of remote diagnostic tools is to ensure that data is easily captured and analyzed so that the correct items are identified for replacement. This avoids interacting with functioning modules and reduces multiple repair trips to the same antenna.

Remote monitoring and diagnostic tools apart from the automated diagnostic capabilities shall include fast read out modes, providing a module-level oscilloscope function with buffers and triggers to monitor the time-varying nature of monitor points. This stream of data produced within the LRU will be delivered to the array M&C system through a standardized hardware and software interface layer. Consistent delivery of performance and operating diagnostics from each module or subsystem will allow the automated

Maintenance Scheduler to identify and prioritize maintenance issues and then create work orders. Work orders can be for both corrective and preventive maintenance since LRU and system performance data will be analyzed, such as through control charts, to identify pending failures and develop a knowledge base of system behavior. Automated diagnostics will also improve staff productivity by allowing engineers and scientists to focus solely on the most difficult problems that require human intervention and analysis.

The system configuration must also be remotely ascertainable from each major element of the system, so that the facility configuration can be tracked dynamically with minimal effort. Every LRU or large replaceable subsystem must be traceable in such a system, within reason, even those that do not typically have integrated diagnostic monitoring (e.g., cryogenic refrigerators). Otherwise, effort will be wasted in determining the makeup of systems when dealing with maintenance and development activities.

7.3 Failure/Anomaly Reporting Processing

In addition to errors detected by automated means, failures and anomalies will be reported by operators, data analysists, post-processing pipelines, and users. These reports, along with those generated by automated means, will be tracked in an issue tracking system with a corresponding database. Workflows will process new tickets to assign them to responsible maintenance personnel for problem identification and triage. Once a likely cause is identified and a severity assigned, these reports become inputs to an automated maintenance scheduler for eventual resolution and to be used to improve automated detections in the future.

7.4 Array Maintenance Performance Monitoring

Array maintenance groups will be responsible for development and calculation of their performance metrics as part of quality monitoring. These metrics provide a quantitative understanding of the maintenance process and way to assess its performance against a baseline or other requirements. The Operations Plan will detail the specific metrics to be used such as mean time to repair, resource utilization, and maintenances costs per antenna. Once a knowledge base is established through collection of metrics, trends will be identified which can be used to forecast budgetary and resource needs, also useful for forward quality monitoring and improvement.

8 Operations Infrastructure

The overall goal regarding operations infrastructure is to minimize the number of staff and the extent of operating equipment located on-site in lieu of working out of a nearby Maintenance Center (possibly in Magdalena, NM). A majority of, if not all, spare LRUs and equipment is expected to be located at the Maintenance Center and its warehouse. This means the array site will have only a small number of depots, garages, and storage buildings.

Items will be repaired offsite at a separate Repair Center, with "green-tagged" assets shuttled to and stored at the Maintenance Center. Shuttling of personnel from Repair Center and/or the Maintenance Center to the array will be minimized, as discussed in the Logistics section. Science, scientific and user support, and data analysis will be done remotely. Software support and research and development of hardware and software will likewise be done remotely.

Table 1 gives a breakdown of the type of work done and buildings and equipment needed at the various Operations locations. It starts with the work to be done at the array core and progressively moves further away.

At Array Core	Near Array	Within State	Anywhere
Personnel • On-shift security • Working O&M staff: techs, safety, EMT/firefighter • Visitor's Center staff	Personnel • Safety • Security • Field Techs/Engs • Infrastructure Techs/Engs	Personnel • Operations • Administration • Repair Techs/Engs • Correlator Support • Computing Support • Safety	Personnel • Scientists • Administration • Data Analysis • User Support • Data Management • Software
Buildings • Central Electronics • Garage • Depot • Security • Small medical clinic • Visitor's Center (nearby)	Buildings • Maintenance Center (parts depot, work space, garages) • Remote Support Stations	Buildings • Array Operations Center • Repair Center	Buildings • Science Center • Research & Development • Data Center
Equipment & Assets • Antennas • Correlator • Other Array Assets • Heavy equipment required at site at all time • Fire engine	Equipment & Assets • Spare LRU/Hardware • Small cryogenics lab • Vehicles • Equipment for testing, working on antenna, infrastructure, transferring parts	Equipment & Assets • Items under repair • Repair/test equipment • Repair components • Vehicles for shuttling assets and staff	Equipment & Assets • R&D equipment • Data storage • Data Processing Resources

Table 1 - Operations infrastructure overview.

8.1 Central Electronics Building

The ngVLA's Central Electronics Building would house the central signal processor (correlator), centralized IT infrastructure, and time and frequency distribution equipment. The footprint of the ngVLA equipment is expected to be appreciably smaller than VLA equipment on a per-antenna basis, and can be likely accommodated within comparable areas to the VLA equivalent systems.

The VLA Control Building is similar to the envisioned ngVLA Central Electronics Building and it may be feasible to reuse it. The current footprint is of order 2000 m^2 and is expected to remain unchanged. Priority should be given to housing the electronics systems onsite rather than personnel, who would be better located at the offsite Maintenance Center.

8.2 Central Support Buildings

Additional buildings located near the core of the array will include garages and depots for storing heavy equipment that cannot be easily delivered or driven from the nearby Maintenance Center. The buildings will also support the maintenance and repair staff temporarily on-site while performing their duties. To maintain site security, a guard booth will allow security staff to provide a constant security presence.

Buildings that are no longer required will be demolished and removed. For example, this would include the transporter shop and antenna barn, due to anticipated design of the ngVLA antennas.

8.3 Central Infrastructure

Supporting infrastructure will be required for the central site buildings. The existing electrical switchgear, sewer system, and landfill will be assessed for suitability to ngVLA operation and upgraded or replaced as necessary. Extensive additions for the electrical and networking operations of the array core are expected.

8.4 Visitor Center

The ngVLA's core will create an impressive display of radio astronomy technology, inspiring visitors to travel to the site. In order to accommodate this desire, while minimizing the impact of detrimental radio-frequency emissions, the ngVLA Visitor Center will be located very near the array, but at some distance from the center of the core. A candidate location would be near the current intersection of the VLA's north arm with US Highway 60. It is also desired that an ngVLA antenna be located close to the visitor center in order to encourage closer interaction with such a key element of the array. This arrangement would remove the building, NRAO staff, and the visitors from the immediate proximity of the bulk of the telescope while still allowing for an encompassing view of array and a close-by antenna to approach. Another possibility is the current effort to repurpose the existing cafeteria building at the VLA site into a VLA/ngVLA visitor center.

8.5 Maintenance Operations Center and Warehouse

Much of the current maintenance activity and related infrastructure found at the VLA will move to a Maintenance Center located at or near Magdalena, NM. This center will provide the duty station for safety, security, and maintenance personnel. The maintenance personnel include technicians and engineers responsible for antenna, central signal processing, and infrastructure maintenance. This center will serve as the node for maintenance activities and the storage of ready spares, but not for module repairs.

Garages for heavy equipment and vehicles will be part of the center. Where cost-effective, work packages will be contracted to other parties rather than conducted by array operations staff, or partnership arrangements may be used. Remaining service functionalities will also need to be justified as cost-effective. The equivalents of current VLA facilities that still will be located at the Maintenance Center include

- Machine Shop,
- Electrical Shop,
- Warehouse, and
- Antenna Mechanics.

The warehouse will house all available spare assemblies and LRUs used in array maintenance visits. It shall therefore include a loading dock to facilitate receipt of repaired LRUs and shipping of LRUs for repair. The warehouse specifications should consider requirements during the assembly and construction phase; it is likely that some elements of antenna integration may take place within this space if space at the array site does not become available in time for ngVLA construction. This will be determined as part of the Antenna Assembly and Integration Plan.

8.6 Array Operations Center

The AOC and perhaps other facilities located in Socorro, NM, will house approximately 250 staff and will incorporate the Repair Center with sufficient space to host offsite array operations and to transfer, diagnose, repair, and test electronic LRUs and other equipment. LRUs and other equipment that fail or are pulled from the array would be sent to the AOC/repair center for repair before returning to the Maintenance Center warehouse. The AOC would include a typical complement of office space, laboratory space, storage and transfer capabilities, and computing infrastructure.

The VLA DSOC has an approximate area of 6200 m^2. It presently houses of order 140 staff and has a footprint of order 45 m^2 per person. This building should be reused as part of the ngVLA Array Operations Center/Repair Center, but a substantial addition will be required to accommodate the new occupants and additional repair laboratory areas, such as servo and cryogenics.

8.7 Science Operations Center

The Science Operations Center (SOC) is likely to be co-located with the Data Center, and will house approximately 175 staff, largely scientists, data analysts, computing, software, and IT positions, and some administrative and management staff. The facility will primarily consist of office space and computing infrastructure.

The location of the SOC is not determined, but Boulder, Austin, Albuquerque, Tucson, Dallas, Houston, or another metropolitan area are examples of possible candidates.

8.8 Remote Support Stations

Finally, Remote Support Stations (RSS) will likely be located in southern New Mexico, west Texas, Arizona, and Mexico to service mid-baseline stations of the main array. RSSs will also be used to service each of the LBA stations. The number and location will depend on the array configuration and expected reliability of equipment. It may turn out that it is more effective, from a cost and operational standpoint, to send maintenance and repair personnel from a central site to remote antennas.

An RSS will be similar in many ways to a VLBA station in that each RSS will act as a central depot and duty station for remote site technicians. Each RSS will likely have a footprint of order 186 m^2, supporting workbenches, organized tools, supplies, and inventory including spare LRUs required for routine maintenance of a group of antennas. Other central infrastructure may also be co-located at the RSS, such as time and frequency distribution systems. The RSS should include a loading dock to facilitate shipping.

An alternative to explore and cost could include using uninhabited buildings that serve as depots and work areas for a cluster of remote antennas. Each cluster would have a small compound with temporary living quarters and indoor/outdoor work areas, for the use of visiting preventive maintenance teams. Normally, these stations would be unmanned, other than periodic inspections by security and safety personnel, to ensure they were in good condition. The required LRU spares, tools and heavy equipment would travel with the preventive maintenance team. Personnel might be out for several weeks, like VLBA Tiger Teams, working on several antennas in a given area before returning.

9 Operations Logistics

9.1 *Staff Logistics*

As described above, support staff will be located in groups depending on the nature of their interaction with the instrument in order to minimize unique instances of travel (and therefore operations costs) balanced against the fact that having a duty station close to a population center generally makes it easier to recruit and retain staff.

Technicians who need regular access to the antennas, central electronics, and infrastructure systems will be located close to their work responsibilities. For most such personnel, this will be at the Maintenance Center, although a small number may be based at Remote Support Stations.

To reach the array center, daily buses will run to the Maintenance Center in/near Magdalena from the Array Operations and Repair Center in Socorro. Staff will then use a fleet of maintenance and service vehicles to reach areas of the array requiring maintenance. The technicians located at the Maintenance Center will be cross-trained so that they service multiple systems on each required trip to an antenna.

Technicians and engineers who need regular access to components and LRUs—but only periodic access to the antennas, central electronics, and infrastructure systems—will be located at the Array Operations and Repair Center in Socorro. Unlike their counterparts assigned to the Maintenance Center, these staff are expected to be system specialists focused on the repair or overhaul of equipment that requires laboratory space with advanced test equipment. It is more efficient to move batches of components or equipment to the specialist personnel and labs than it is to move personnel closer to the distributed antennas and other equipment.

Scientists, hardware and software engineers, data specialists, and other support staff that do not need regular access to antenna-based hardware and infrastructure systems will be remotely located at the Science and Data Center. The chosen location should have a large pool of skilled workers to pull from, as well as schools and employment opportunities for their partners.

9.2 *Shipping and Inventory*

An inventory of commonly used supplies will be centrally maintained at the ngVLA warehouse. The inventory must be electronically tracked to determine usage rate and location of spares throughout the locations in the array.

Each logistics center will have central shipping and receiving and be integrated with an NRAO-run shipping system between sites. A regular shuttle will ship supplies and parts between the ngVLA site and the AOC daily. Logistical support to RSS stations will use a combination of commercial carriers and NRAO-run shuttles for larger freight. Spares should be managed in a Kanban-type method at each RSS, so that notice is sent to produce and deliver a new shipment of items as the RSS consumes them. Using NRAO-controlled shipping will ensure prioritization, possession, and safe handling of items during transit.

Standardized practices for shipping must be adopted where possible to reduce delays and damage. Pelican cases or equivalent packaging shall be considered for all LRUs. The shipping cases and packing practices shall provide ESD protection in addition to mechanical shock absorption.

9.3 *Spares Management and Maintenance Repair Process*

LRUs will be centrally managed, tested, and repaired from the Repair Center in Socorro, NM, but will be stored near the point of service at the ngVLA Maintenance Center and RSS locations. Maintenance tracking, which should be tied into the configuration management as discussed below, will indicate the status of each LRU (in the array, under repair, or available from spare inventory). This tracking will also indicate the nature and history of repair work done on the LRU or item.

Component-level spares will be stored in a warehouse near or at the AOC and provided on an as-needed basis to AOC-based repair staff. The warehouse will include the stock of spare components procured during the construction phase, and a lifetime supply of spare components should be included in the construction budget of each element, if possible. This lifetime supply should be based on predicted Mean Time Between Failures (MTBF), Failure Modes Effects and Criticality Analysis (FMECA), and Mean Time to Repair (MTTR) for the components and their operational environment. Storage shall be closely and automatically inventoried in order to minimize duplicate orders or loss of product.

During the repair process, testing and quality control procedures must be sufficient to mitigate process errors and address pending failures before components and systems are redeployed. Acceptance testing of software and hardware deliverables must occur before delivery to or installation on the array in order to minimize maintenance trips. Repair groups will provide acceptance test data to the groups responsible for either inventorying or using the repaired items. Maintenance leads for technical support groups responsible for particular subsystems and their components shall review the work done and accept the repaired article for restock at the warehouse. The associated repair log and test data shall be entered into a database prior to acceptance review and should be globally visible to all groups from any location, even out in the field at remote antennas. The equipment shall only be considered repaired and ready for use upon acceptance of this test data.

9.4 Configuration Management

Configuration management is critical to provide a history of versions deployed across the array, documentation associated with particular versions, forward and backward compatibility, physical facilities, and understanding sufficient to control the array's software and hardware performance and attributes. A configuration management system will be required to indicate which serial numbers of LRUs and other hardware items are in the array, under repair, or available from spare inventory as well as each configuration item's location, repair, and upgrade history. A configuration database of the software employed on the array will identify the software's functional attributes at various stages in the array's lifecycle while also providing control and traceability of any changes. The systems must be in place during the construction phase of the array. Specific information unique to each configuration item (for example, calibration data, lookup tables, etc.) shall be included in the configuration management strategy.

Configuration management will be a useful tool to plan upgrades, mitigate failures, and smoothly evolve the array to the configuration needed for commissioning.

9.5 Physical Security

Physical security for the ngVLA site and the remote sites will be provided through:

- Basic physical barriers (gates, locks, signs) and remote monitoring equipment;
- Regular threat assessments and training for local security personnel;
- Regular physical patrols where practical, especially in the array core, to cover gaps in remote monitoring;
- Procedures, plans, and training for fire hazards and fire-fighting;
- Design with resistance to the elements, consistent with a remote, unoccupied site; and
- Design strategies deterrent to infiltration and nesting by rodents, insects, birds, and other wildlife and vegetation that would interfere with site operation or deteriorate site integrity.

Remote monitoring equipment will include, at minimum:

- Door sensors and alerts for all antennas and remote sites
- Video surveillance using webcams or equivalent
- Microphones or other audio recording equipment
- Environmental monitors to inform need to stow antennas

An interface layer will identify data streams with interesting information (e.g., a change in the field of view). These streams will be recorded and also monitored either by an array operator or a security guard. In the event of an intrusion, local law enforcement will be contacted and relied upon for a response.

Each remote site should be fenced completely with a gated entrance. Trees and other vegetation should be cleared from the edges of the fences for protection of the site and to maintain clear sightlines.

9.6 Cybersecurity

ngVLA IT systems will be hardened against intrusion consistent with existing NRAO CIS policies. This security will protect ngVLA information and data transfer from disruption, malware, and exploitation of technical vulnerabilities. Given the dependency on computerized remote operations and maintenance, equipment is particularly vulnerable to cybersecurity attacks and breaches in ways not experienced on previous instruments. This presents a tremendous risk that must be given in-depth analysis by cybersecurity experts against monetary loss and instrument downtime, complete with a mitigation strategy and adequate cost to inform security design and operations planning.

9.7 Administrative and Other Shared Support

Operations will require various types of administrative and functional support from NRAO. These will be defined in the Operations Plan and will be allocated to the appropriate divisions and groups. Funding of the support will be done through overheads applied to the Operations effort. Examples of shared support include

- Program Management
- Computing and Information Services
- Human Resources
- Budgeting and Fiscal support
- Shipping and Receiving
- Contracts and Procurements
- Environmental, Safety, and Security
- Management Information Systems

10 Reuse of VLA and VLA-to-ngVLA Transition

To minimize the cost of the construction of the ngVLA, as well as reduce the cost of VLA decommissioning, ngVLA will endeavor to reuse existing VLA elements wherever suitable. All existing buildings and infrastructure systems will be assessed for suitability as part of a construction plan [RD09]. Assessments will be based on lifecycle cost analysis, assuming the need for an additional 20 years of operation. However, given the goal of minimizing the physical presence of staff and continuously operating equipment at the array core, extensive reuse is not expected.

The minimization of need for buildings or ngVLA operations support activities based at the array core will simplify the transition from VLA operations to ngVLA operations. It is expected that the VLA will shut down or enter a period of significantly simplified science operations as ngVLA construction activities ramp up. Obvious break points include when construction of the ngVLA reaches a point of unacceptable interference with VLA science operations, and the start of installation of the ngVLA correlator if it is to be in the existing VLA control building. The addition of extensive infrastructure will eventually require an interruption of existing service to the VLA. The Array Operations Center and operations staff will also have to transition in design and function as additional and different equipment is repaired and the remote operation of the ngVLA begins.

These issues and others will be identified in a Transition Concept [RD11] and will be fully addressed in a subsequent VLA-to-ngVLA Transition Plan. This plan will define milestones, resources, and costs for operations ramp-up of ngVLA activities while coordinating with the shutdown of the VLA and any decommissioning requirements.

11 Development Program

An ngVLA Development Program is needed to ensure the array's scientific growth throughout its lifetime. Using scientific and technical community proposals and other initiatives, the program will fund the competitive studies and projects designed to encourage three areas of development typically outside the scope of operations:

- Scientific development projects, focusing on scientific advancement and enhancements of capabilities of the array;
- Technical development projects, focusing on development of new or improved hardware, software, or techniques; and
- Legacy science program [LSP] projects, which are observing or archival projects that require significant resources.

Encompassing the Legacy Science Program [AD01], the Development program will allow for a clean separation between operations efforts and research and development initiatives. The Development Program will ensure that these activities do not compete against operating costs. Determination of the program's structure, funding profile, frequency of call for proposals, and management will be captured in an ngVLA Development Program Plan.

Potential scientific and technical development projects could be

- Complete new additions to the array;
- Extension of existing capabilities with more sensitivity, improved image quality, better dynamic range, etc.;
- Improvements to existing hardware or software systems resulting in enhanced availability and capability of ngVLA data; and
- Improved infrastructure that reduces risks, increases availability, and makes operation easier/less expensive.

Legacy Science Projects are observing or archival projects that are distinguished from typical PI-led observing investigations by the following fundamental principles:

- They are large and coherent science projects, not reproducible by any reasonable number or combination of smaller general observing investigations.
- They have general and lasting importance to the broader astronomical community for which the ngVLA data will yield a substantial and coherent database.
- They generate raw and pipeline-processed data that enter the public domain immediately upon NRAO processing and validation, thereby enabling timely and effective opportunities for follow-on observations and for archival research, with both the ngVLA and other observatories.
- They provide the community with some combination of deliverables, such as Enhanced Data Product (EDPs), analysis software/tools, etc.

11.1 Development Funding

The ngVLA Operations budget funds the ngVLA Development Program. Per [AD01], the Legacy Science Program anticipates funding needs of approximately $3M per year to support multiple individual projects. Scientific and technical development projects will require an additional $5M per year, based on the funding required to manage the similar aspects of the ALMA Development Program.

11.2 Technical Development Proposal Requirements

Each proposed technical development project must address the impact it will have on the scientific capability and or operational performance of the array.

In general, proposed projects should not increase the operations cost. However, each project will be evaluated on its own scientific merit, and operations costs will be considered in the prioritization of potential development projects.

Each project proposal must have a plan that addresses the following items, in addition to its science objectives:

- Cost (including AIV, commissioning and science verification)
- Schedule
- Safety plan
- PA/QA plan
- Software development plan
- Integration plan addressing also AIV, commissioning and science verification.
- Draft operation manual
- Maintenance plan

12 Appendix

12.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
ALMA	Atacama Large Millimeter/sub-millimeter Array
AOC	Array Operation Center
CIS	Computing and Information Services
CSP	Central Signal Processing
DB	Database
EDP	Enhanced Data Products
FMECA	Failure Modes, Effects, and Criticality Analysis
LRU	Line Replaceable Unit
LSP	Legacy Science Program
LSST	Large Synoptic Survey Telescope
MTBF	Mean Time Between Failures
M&C	Monitor & Control
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
OWG	Operations Work Group
PI	Principal Investigator
QA	Quality Assurance
RAOC	Remote Array Operation Center
RD	Reference Document
RFI	Radio Frequency Interference
RFID	Radio Frequency Identification
RSS	Remote Support Station
SAC	Science Advisory Council
SKA	Square Kilometer Array
SRDP	Science Ready Data Products
TAC (ngVLA)	ngVLA Technical Advisory Council
TAC (NRAO)	NRAO Time Allocation Committee
TBD	To Be Determined
VLA	Jansky Very Large Array
VLASS	VLA Sky Survey
WFIRST	Wide Field Infrared Survey Telescope

12.2 Driving Requirements and Key Assumptions

A few high-level requirements and constraints for the ngVLA, as well as assumptions made by the authors, shape this operation concept. These are captured below. The requirements and constraints come from draft systems requirements or external guidance.

Requirement/Constraint
ngVLA shall be a proposal-driven, general purpose, pointed instrument.
ngVLA operations cost efficiency shall be improved with a goal of not exceeding $75M (FY17) per year, three times the VLA+VLBA operations cost.
The ngVLA shall replace the VLA, with VLA ceasing to operate.
The ngVLA core shall be located within the existing VLA site.
Operations lifetime shall be 20 years from completion of construction.
Antennas shall be non-relocatable.

Assumption
Governance and Management
The ngVLA is US-funded and operated by the NRAO on behalf of the astronomy research community. The concept is subject to change if international partners join.
Construction/Project/Transition
VLA will continue science operations (possibly with a reduced range of capabilities) until early science operations of ngVLA. Once ngVLA science operations starts, NRAO will cease operations of the VLA.
All stations will depend on commercially supplied power.
All stations will have high-speed network connectivity.
Integration of the existing observatory infrastructure and personnel is desirable.
The reuse of land leases/easements and the inner mile is expected, but not a requirement.
The reuse of VLA site infrastructure (roads, electrical, fiber, sewer, water, etc.) and buildings (CB, maintenance buildings, cafeteria, AOC, etc.) is desirable, but not required or expected. The design should be optimized for total lifecycle cost over the expected operational life defined above.
The construction budget will provide for the development of data pipelines for a defined set of capabilities through the construction and commissioning phase. Thereafter, further development must fit within the operations budget cap defined above.
Retention of construction staff for operations employment is highly desired where skills match the Observatory needs.
Antenna locations as presently approximated by the SW214 configuration.
Antenna manufacturing, whether off or on-site, will not impact VLA Operations.
Current VLA electrical infrastructure can supply 1/3rd of anticipated ngVLA power requirements at the core.
MTBF, MTTR, and FMECA analysis of construction items are done by ngVLA Systems Engineering staff.
Array Operations
There will be one major Maintenance Center near the array. If determined necessary, there may be multiple remote service depots.
Operations and repair centers will not be located near the array.

The number of staff and operating equipment located on the array will be minimized in lieu of working out of a nearby Maintenance Center.
Maintenance scheduling will be automated, based on array conditions and requirements.
Array assets will be repaired offsite where possible, with the exception of fixed items that are not easily removed and must be serviced in-situ.
Maintenance staff should consist of or be trained by construction staff.
Maintenance shall be both preventive and predictive based on monitored conditions of the array.
Science Operations
All elements of array design and operations, both hardware and software, must support operations of multiple subarrays for different purposes right from initial commissioning.
For the majority of projects (that use standard capabilities) ngVLA will deliver Science Ready Data Products through the use of automated processing pipelines.
Users will not be constrained to use standard modes. Where the science goals warrant it, non-standard observations that do not deliver SRDPs will be accommodated.
Standard calibration schemes will be provided for standard observing capabilities and modes.
PIs will be awarded time on science targets, not guaranteed sensitivities.
The Science Center and Data Center will likely be co-located, probably in a metropolitan center to maximize ability to recruit and retain highly specialized and mobile staff.
The Observatory will support scientific discovery through both PI-initiated observing projects and use of publically-available science data from the Observatory archive.
Operations Costs
The expected operating and maintenance requirements and costs of delivered products (HW, SW, Infrastructure) will be provided by the construction project participants or aggregated by the ngVLA Systems Engineering staff.
Service Level Agreements with NRAO groups will be required during operations and will be outlined in the plan.
Other
The array's subsystems may be heterogeneous in composition while still meeting system requirements. An example will be rolling upgrades of some electronics. Configuration of each system and subsystem is therefore critical and will be monitored by the M&C system.