Assembly, Integration, and Verification (AIV) Concept

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1.1	2019-01-19	AIV-WG		Reorganized document and incorporated comments and additions from v1.0; draft provided to project office per scheduled deliverable
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A.1	2019-07-26	R. Selina, L. Leyba-Newton	3, 8, 10.	Updating for Concepts & Stakeholder Requirements Review. Added summary, infrastructure and milestone sections.
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A.4	2019-08-09	C. Langley	Several	Incorporated comments submitted by AIV working group.
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A.6	2019-08-26	R. Selina, M. McKinnon	6.4, 10.	Addressing comments from MM. Added spectral line milestone.
B	2019-08-27	A. Lear	All	Prepared PDF for approvals & release of v.B.

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1 Introduction

1.1 Purpose

This document provides a concept for the ngVLA System Assembly, Integration, and Verification (AIV). This is one of the identified lifecycle stages of the ngVLA, and this concept will be used to identify requirements relevant to this stage of the project lifecycle that must be supported by the design. The description, approach, and functions associated with key organizational interfaces during AIV will also be explored.

1.2 Scope

This document provides a qualitative view both of the overall AIV process and the activity and interactions between the System AIV IPT and other ngVLA construction teams. The assembly, verification, and handoff of the civil, hardware, and software deliverables will be described, along with the integration and system-level testing that will be subsequently performed.

As a concept, neither specific technical requirements, detailed product assurance requirements, permitting requirements, nor budgetary information are considered within this document's scope. These concerns will be addressed in a future AIV plan, developed to support this AIV concept.

2 Related Documents and Drawings

2.1 Applicable Documents

The following documents may not be directly referenced herein, but provide necessary context and are incorporated by reference.

Reference No.	Document Title	Rev/Doc. No.
AD01	ngVLA System Engineering Management Plan	020.10.00.00.00-0001-PLA
AD02	ngVLA Operations Concept	020.10.01.00.00-0002-PLA
AD03	ngVLA System Reference Design	020.10.20.00.00-0001-REP
AD04	ngVLA Quality Assurance Plan	TBD (In prep.)

2.2 Reference Documents

The following documents are referenced within this text or provide supporting information:

Reference No.	Document Title	Rev/Doc. No.
RD01	ALMA Product Assurance Requirements	ALMA-80.11.00.00-001-D-GEN
RD02	B. Lopez, R. Jager, N.D. Whyborn, L.B.G. Knee, J.P. McMullin. Assembly, Integration, and Verification (AIV) in ALMA: Series Processing of Array Elements.	
RD03	R.E. Hills, A.B. Peck. ALMA Commissioning and Science Verification.	Proc. SPIE 8444, Paper 90 (2012)
RD04	D. Rabanus, M. Keating. Observatory Facility Staff Requirements and Local Labor Markets.	Proc. SPIE 8449, Paper 18 (2012)
RD05	S. Durand, ngVLA Electronics IPT Schedule.	TBD

3 Assembly, Integration, and Verification Concept Summary

Assembly, Integration, and Verification (AIV) is part of the construction stage of the lifecycle, and starts after the design phase is completed. In this lifecycle concept document, we outline the proposed approach and guiding principles for organizing and completing the AIV of the ngVLA system. The key conclusions from this exercise are summarized below.

- There is a general *AIV process*, whereby a progressively more complex deliverable is assembled from its constituent parts into an integrated assembly with verified performance. This general process is performed by many groups at all levels of the project—from work package, to IPT, to system-level.
- The AIV process will be performed at the earliest level possible. Each work package group will integrate and verify their respective deliverables before delivering them to their IPT for acceptance. Each IPT will then integrate these deliverables into sub-assemblies or subsystems, verify their performance to specification, and deliver them to a *System AIV group* responsible for system-level AIV.
- The AIV process will aim for most assembly and integration taking place off-site, in controlled environments, with appropriate QA processes. Site-based assembly and integration activities will be limited to only those required. For example, the Antenna Electronics IPT will integrate the front-end and back-end assemblies prior to site installation, and the computing and software IPT will integrate the various software modules into software release packages that are delivered to AIV.
- The provider of a deliverable will be responsible for the integration and verification testing of that deliverable. The group who receives the deliverable for integration into a higher-level element is responsible for deliverable acceptance. This is true for any level of the product path.
- The integration approach proposed will require a comprehensive test framework to enable validation of stand-alone systems as well as partially integrated systems, such as unit tests, hardware simulators, and test racks. These will be deliverables of the respective IPTs.
- The System AIV group integrates the IPT deliverables into a functional system, and provides verified *functional capabilities* to a Commissioning and Science Validation (CSV) group. CSV accepts these deliverables as providing these capabilities, and then develops *observing processes*. These observing processes demonstrate how to use the functional capabilities, delivered by AIV, to achieve a scientifically useful result.
- Operations will be concurrent with the construction activities of AIV and CSV, and the associated groups will need to share array resources. Early delivery of sub-array capabilities, as well as a configuration management system and issue tracking system, will be key to managing and sharing the array resources.
- The System AIV and CSV groups will work jointly on system integration and verification early in the AIV phase, bringing more resources and expertise to bear on system integration efforts. AIV and CSV will split into distinct groups once sub-array capabilities have been verified.

4 Assumptions

The items listed in this section are relevant assumptions or concepts that are not discussed elsewhere in this document.

1. As a basis for concept development, we describe the AIV of the Reference Design [AD03], with 263 antennas in the array, comprised of civil infrastructure, electronics, mechanical, and software system packages.
2. Thorough design reviews will be conducted at major project milestones. These may include a Requirements Review, Conceptual Design Review (CoDR), Preliminary Design Review (PDR), Final Design Review (FDR), Manufacturing Readiness Review (MRR), and an Operational Readiness Review (ORR). Delivery (Verification) and possibly Re-Verification reviews are also anticipated. Safety and safe product design will be a consideration at these reviews.
3. There will be an independent Configuration Control Board (CCB) and configuration management process to control changes to the construction deliverables. Configuration management processes and tools that are needed for version control will be in place prior to any AIV site deployment.
4. There will be a Product and Quality Assurance group (under Project Management) and associated quality assurance processes that will be in place prior to AIV activities.
5. Establishing project acceptance policy does not fall within the responsibility of AIV. Any acceptance procedures suggested or referred to in this document are superseded by procedures established by the Project Manager's office.
6. IPT construction staff are to be readily available for support during early AIV activities. This typically involves an on-site presence during the first installation of the IPT's deliverable. Some AIV expertise is intended to be drawn from the IPTs, and thus IPTs are to plan for this provision by including sufficient staff within their budget and arranging for succession planning, if needed.
7. IPTs will deliver the hardware, software, and civil/infrastructure deliverables necessary for verification and integration of capabilities on a schedule commensurate with the AIV plan. This may require partial or phased deliveries of key subsystems such as the central signal processor and signal generation and distribution system. Multiple software releases may be required with progressive functionality.
8. Land use/property purchases and land use agreements will be completed prior to AIV deployments to a particular site.
9. All site civil construction activities that are needed for site system integration and verification will be in place and accepted prior to a site's AIV deployment.
10. Logistics tools and resources (physical and human) will be in place to support efficient product flow from suppliers to antenna sites. The project will provide needed resources (physical and human) to support the planned cadence site integrations.
11. The project will provide adequate space needed for pre-deployment activities, equipment maintenance and storage, and AIV staff office space.
12. A well-established integrated project master schedule that captures all AIV dependencies will be in place prior to AIV site activities.
13. There will be an issue tracking tool that tracks open action items/punch list for site activities in place prior to the start of system-level AIV and site deployments.
14. System interface testing will be executed prior to AIV site deployments. Early site integrations will be used to work out any gaps in system interface testing.

5 Assembly, Integration, and Verification Process

AIV processes occur at multiple levels throughout the construction process, regardless of whether a construction activity takes place entirely internally to the project or partially at an external vendor. It is important to note that AIV does not dictate acceptance criteria but carries out the process that will result in a successful handover.

For example, construction of a power supply may be formulated as the acceptance of components from external vendors, assembly and integration into a power supply module, and verification that the assembled system meets specifications. In this document, we use AIV to refer to the process through which IPT Products (defined in Section 11.2) are accepted from the construction IPTs, assembled, and integrated first into Elements and then to the Telescope System; and finally the system being verified to meet system-level technical requirements.

5.1 Process Definition

Verification is the process of evaluating deliverables to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase. These conditions may include regulations, requirements, interfaces, and/or specifications that have flowed down from the project requirements. This may include satisfying imposed documentation requirements, the successful completion of design or specification reviews, and analysis or other inspections. Verification of the individual delivered products is subject to the AIV process, regardless of whether the delivery is to the System AIV group. This process is to be carried out internally at the Work Package and IPT levels before the handover of a product to the System AIV group. This is an objective process that will help determine the overall quality of a deliverable. Throughout the construction process, best practice dictates that an over-riding principle is that no group should be responsible for both the verification and acceptance of a product.

In this context, Acceptance is the declaration by the receiving party that a deliverable has been verified as defined above, and that the System AIV group may proceed to integration with reasonable expectation that the deliverable will meet the technical requirements. Prior to delivery, the IPTs shall submit a draft Verification and Validation (V&V) plan. Requirements will flow down from stakeholders and from the key science goals for the science requirements in accordance with the ngVLA Requirements Management Plan [AD01]. These requirements will be incorporated into the subsystem Requirements Verification Traceability Matrix (RVTM), which reflects all criteria necessary for acceptance. Verification of products will occur at the IPT level, prior to delivery. Once acceptance has been achieved, the IPT's warranty period commences.[1]

Integration is the assembly of accepted products to form higher-level products (e.g., *articles* to *elements* or *elements* to the *telescope system*). These higher-level products provide capabilities that were not demonstrable with the lower level products.

Finally, the integrated product must be *verified* to meet the system technical requirements, prior to delivery. The verification of system requirements will be performed on technical capabilities including interface compliance to ICDs and integrated functionality demonstrating that one or more technical requirement has been satisfied.

1. To prevent deliverables from dwelling excessively long in the acceptance phase, some IPTs may stipulate that the warranty period automatically commences a fixed period of time after delivery.

Systems with verified technical capabilities are delivered from the system-level AIV process to the CSV process. As with the acceptance from the IPTs, an agreed Capability Verification Plan will be produced prior to delivery of capabilities to CSV.

5.2 Work Package and IPT Deliverables

All IPTs (or other bodies) delivering products to the project will follow the same process. Most IPTs will have multiple types of deliverables. Deliverables include the hardware, software, firmware, test stands/equipment, test reports, civil construction, and supporting documentation.

5.2.1 Hardware

The IPTs are responsible for the design, verification, and delivery of their respective hardware to AIV. Upon design maturation, LRUs, Articles, and Sub-assemblies may be delivered directly to the antenna assembly location, to the project warehouse for storage until such time as it is scheduled to be integrated, or to another mutually agreed upon location. Packaging for delivered hardware shall ensure the safe storage of equipment in nominal warehouse conditions.

The warehouse, which may include buildings in more than one location, is under the purview of Operations, or an operations-like entity. The warehouse building or buildings will be built early during ngVLA project construction, and may serve an alternate purpose to support construction activities prior to being transitioned to operations. A primary AIV function of the warehouse is to store electronics and other assemblies delivered by the IPTs that require safe keeping prior to antenna integration, as well as to keep an accurate inventory of these items.

IPTs generally use the following documents to specify hardware:

1. Specifications, which detail requirements of the hardware;
2. ICDs, which provide interfacing details between the IPT's Hardware and other subsystems; and
3. SOWs, which provide details about how the hardware will be produced, delivered, and warranted.

5.2.2 Software

All software and firmware delivered to the project must be version controlled and be delivered with suitable automated unit, integration, and regression testing suites. Maintenance of delivered software remains the responsibility of the delivering IPT, until the acceptance of the final product from the IPT.

The deliverables from the IPTs will consist of subsystem software package releases, with incremental delivery of functionality. Compatibility with interfacing systems will be tested and documented for each release.

Development tools, compilers, source code, and the build system shall be delivered (as required for long term maintenance). All delivered software and firmware products should be appropriately and uniquely identified using the native tagging process of the version control system.

AIV may perform isolated integration testing of delivered software and hardware prior to integration to Elements or the full system. All Application Program Interfaces (API) or other software interfaces must be defined in an ICD. Automated testing for conformance to the ICD shall be delivered with the product.

5.2.3 Infrastructure and Buildings

Civil site construction, utility systems, and buildings will undergo equivalent inspection and verification to other system-level deliverables.

Civil deliverables will, by definition, be accepted in-place at the respective site. Inspection to interface requirements will be key, and critical performance requirements (e.g., thermal stability of HVAC systems or effectiveness of RFI shielding) should be demonstrated and documented by the delivering IPT prior to being accepted by the System AIV group. Document deliverables for civil construction may include, but are not limited to, as-built drawings, site maps, schematics, pneumatics, equipment specifications, and maintenance procedures.

5.2.4 Documentation

In addition to hardware and software products, IPTs (or other delivering groups) are responsible for authoring all procedures associated with their delivered article and sub-assemblies. AIV will use these documents to assure an acceptable level of product support, and to confirm prior performance tests. The complete delivery package will be defined in a separate product assurance document. Required released documentation for hardware deliveries will include, but is not limited to, the following broad categories:

- Theory of Operation, including a Design Documentation Package
- Product Specifications
- Interface Control Documents
- Article Test Procedures, Plans, and Results
- Maintenance Plans and Procedures
- Standard Operating Procedures
- Site Protocols (Environmental regulations, landowner concerns, and so forth)

5.2.5 Product Test Stands and Equipment

Articles and other assemblies frequently require specialized test equipment and tools to independently verify and validate their performance outside of their subsystem environment. The design and construction of the individual product test stands, including any necessary test software (LabView executables and other test routines or scripts), along with the procurement of specialized tooling is the sole responsibility of the delivering IPT. These will be delivered at the time of the first article so as to verify functionality during the (re-)verification process (see Figure 1).

These deliverables will be governed by the project acceptance standards, and appropriate documentation shall accompany their delivery. That is, product test stands are expected to conform to the same documentation and acceptance requirements as other hardware delivered by the IPT. Maintenance and calibration of the test stands is the responsibility of the delivering IPT during the array construction phase until acceptance of the final product delivery from the IPT. AIV is subsequently responsible for maintenance until delivery to Operations. Identical test stands shall be provided by the IPTs to any production or destination facilities they use for the purposes of verification testing. In cases where a subcontractor is used, an additional test rack may be required at their location.

Any test stand delivered to AIV must conform to the global project requirements that address safety, EMC/RFI, electrical, mechanical, etc. as applicable for the test stand. Test stand delivery is a special case for acceptance and shall be addressed by collaboration of the Project Engineer, AIV, and IPT Lead. AIV is responsible for procuring any other test equipment that crosses IPT boundaries and is required during antenna integration.

5.3 General Verification and Acceptance Process

Working group and IPT-level construction and integration processes will follow best practices. This will be achieved in part with the help of a quality assurance (QA) team. The QA group will be a separate entity from the IPTs, although individual inspectors from the group will be embedded within each IPT to inspect workmanship, to assure all required documentation has been completed satisfactorily and all applicable standards have been addressed, and to verify that required testing prior to shipping has been successfully administered.

Each product that is provided from a vendor, a working group, or an IPT to another group will undergo functional testing and document verification milestones prior to the handoff and acceptance. Figure 1 provides a generic view of this process. It should be noted that the process will extend between AIV and CSV, though this is not specifically shown in the simplified figure.

A successful verification, defined as when all responsible parties sign off on the verification document, must be achieved prior to handoff of a product to the receiving group. To assure no damage has occurred during transit, all deliverables must undergo an inspection. In cases where an item is shipped from one working group to another, the assembly may be required to undergo a re-verification. Verification and re-verification, or acceptance procedures and documents may be similar, but not necessarily identical.

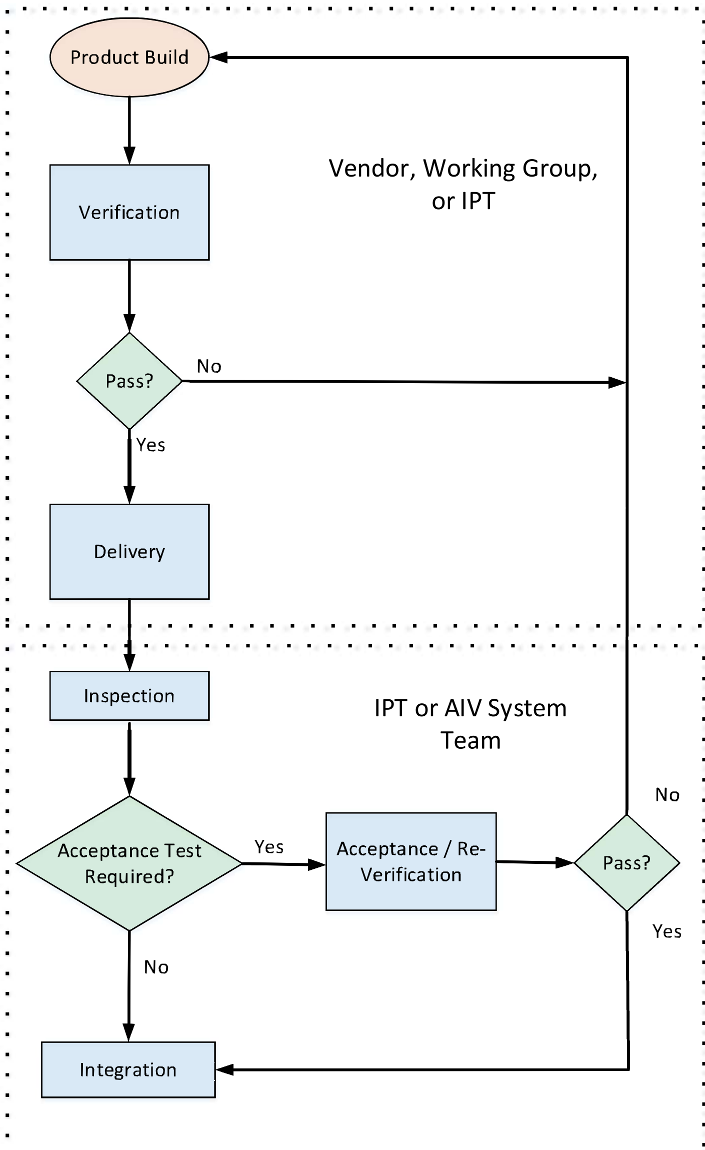

Figure 1 - Overview of ngVLA testing, verification, and acceptance processes.

Products are delivered to the AIV System group by the individual IPTs. The general product flow is depicted in Figure 2. IPTs will collaborate and work on system integration testing in a laboratory/testbed setting, prior to delivering their products to the AIV System team for deployment. Though a collaborative effort with the greater project, it is the responsibility of the delivering IPT to perform delivery verification. Within an IPT, verification testing may occur more than one time along the product assembly path prior to product handoff from the IPT to the AIV System team (or to another other receiving IPT), depending on the nature of the products and the location at which they are constructed.

Possible acceptance, or re-verification, on site may be required based on the Quality and Product Assurance plans. This preliminary acceptance is a milestone where AIV agrees that the product has been verified and is ready to take responsibility for it. Once the Telescope system is verified by the System AIV group to support a previously defined set of Capabilities, the system is delivered to CSV. Final acceptance may take place after integration, when the product has been demonstrated to meet all technical requirements.

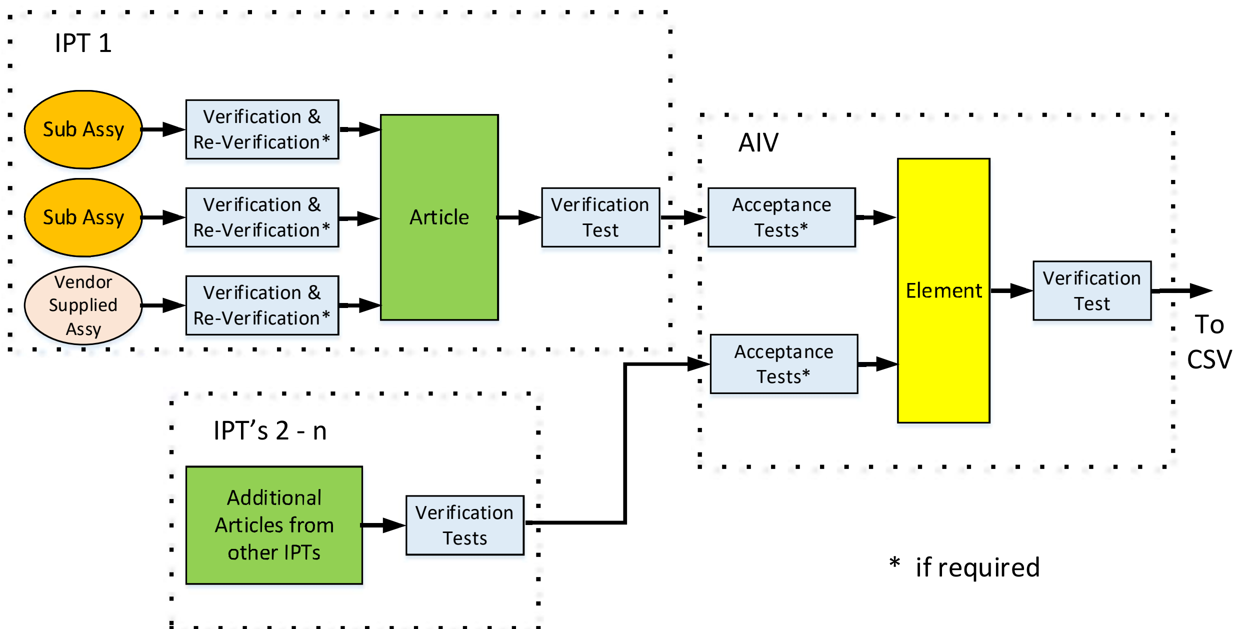

Figure 2 - Overview of ngVLA product flow.

6 System AIV Group Activities

The AIV Process described above is fundamentally a project level activity with direction and contributions from the project office (e.g. Quality Assurance and System Engineering activities). The System AIV group is also required to execute many of the tasks associated with the AIV process at the system level.

The System AIV group is responsible for:

- Producing procedures for their activities during assembly, integration, and verification.
- Participating in the Product Acceptance process (this process is led from a different group, likely Systems Engineering).
- Integration of these products into a Telescope System with defined technical capabilities.
- Performing the verification process to demonstrate that the Telescope System meets the system-level technical requirements.

The System AIV group has completed their charge when all technical capabilities and elements are delivered to the CSV group. This is expected to be near the end of the project construction phase. Delivery of the Telescope System to Operations is the responsibility of the CSV group after completion of commissioning and scientific validation.

6.1 Design and Development Phase

To assure performance and schedule success, AIV will fill key staffing roles prior to the integration and testing of the first antenna, as described later in this document.

Prior to element integration, the IPTs, AIV, and CSV will work concurrently to produce formal ICDs and to assure that all testing plans adhere to the project requirements and specifications.

Also during this period, AIV engineering and technical staff will specify, develop, and/or procure any test equipment that does not fall within the responsibility of the individual IPTs, but which will be necessary during integration and verification. Testing software will be developed in conjunction with this equipment.

In the latter stages of IPT design and development, a prototype antenna will be assembled on site well before the commencement of formal array construction. The prototype antenna subsystem will be installed on a close-in pad or dedicated test pad near the center of the future array. The IPTs, working closely with AIV, will install their prototype hardware on the antenna. This will allow the IPTs the opportunity to refine interfaces, better understand the environment, and perform initial performance testing, while giving the System AIV group hands on training. The IPTs will use this information to finalize the test requirements to be transferred to AIV for formal construction. The IPTs will have an opportunity to remove and replace hardware as needed on the test antenna.

Should project funding and schedule constraints not allow for one or more prototype antennas to be outfitted and tested prior to formal construction, the planned activities will necessarily take place during the beginning of the production, or pre-production, phase.

6.2 Early Delivery Phase

The Early Delivery phase begins with the acceptance of the first products from the IPTs and continues through at minimum the delivery to CSV of the first Telescope System with sub-array capabilities. Throughout the Early Delivery Phase, the AIV and CSV groups will work together to refine the processes, verification tests, and procedures that will be used to verify future product deliveries.

Products delivered to the AIV Team will have already been verified by the IPT. AIV may complete spot checks or re-verification as required by the project Quality Assurance Plan (AD04).

The primary AIV tasks during this phase are to assemble and integrate the products into a functional and safe telescope or small set of telescopes (although not yet capable of meeting all specifications), establish the initial technical performance, and ensure the stated technical requirements and capabilities are met.

The System AIV and CSV teams are responsible for developing and maintaining the software necessary to perform and automate verification tests for products that span IPT boundaries. These programming environments may include LabView code, scripts, or similar diagnostic tools. These tools shall use the APIs delivered by the CSW IPT.

6.3 Delivery Phase

Once the first Telescope System with sub-arraying capabilities has been delivered, the System AIV and CSV teams will begin to work more independently. At that time, the ngVLA will be a functional telescope, although with limited capabilities. As production increases and multiple antennas are undergoing assembly and integration, AIV will necessarily expand to several construction teams. When an antenna's integration approaches completion of the AIV process, CSV resources may be diverted to those systems that are close to the time of handoff. The AIV team will continue to integrate products to the system, integrating and delivering to CSV a system with increased capabilities. Some capabilities will continue to require refinement or development of the verification procedures (increasing baseline length, new correlator modes or capabilities) while others (such as the verification of integrated antenna elements) should become a routine and efficient process. Routine processes may be streamlined to improve efficiency at the discretion of the Project Engineer.

During the construction process, should IPT hardware suffer a failure after having been delivered to CSV, AIV will intervene to solve these problems by engaging the originating IPT.

6.4 Late Construction and Project Closeout

Only after all products have been delivered from the IPTs can the final assembly and verification be completed. During this period, where AIV is verifying the performance of the full ngVLA system, it may be efficient to have AIV and CSV again work closely together.

Once all technical capabilities of the full array have been verified, the AIV team will have completed its primary mission and complete a project closeout. AIV will continue to exist for some time (approximately one year) after all deliveries to CSV are complete. This will assure the group has adequate time to complete any remaining documentation requirements, and that they are present to support commissioning of the final elements. All procedures, test equipment, and test software shall be delivered to the Operations and Maintenance staff. It is expected that many key individuals from the AIV team will transition to the Operations and Maintenance staff to preserve the expertise and institutional knowledge developed during the construction project. An acceptance review of the AIV materials to Operations may be held independently or as part of the project-wide closeout review process.

7 AIV Group Organization

During the Design and Development phase, AIV will not be fully staffed and may only consist of the AIV manager and a few support staff. The AIV Lead should be in place two years prior to the first antenna article delivery in order to participate in AIV planning, with the second-tier managers in place the following year. A detailed ramp up (and down) staffing plan will be described in the AIV plan, and the overall timing of this ramp is tied to the delivery of sufficient products to begin assembly and integration of the first antenna element.

7.1 Staff Duties and Responsibilities

Multiple teams of engineers and technicians will be required to outfit and verify the various system elements. While the number of teams is not yet determined and will be set by other timetables in the project, the following roles are expected to be required within the AIV team. Additional specialists may be called upon to support AIV activities.

Position	Minimum Requirements	Responsibilities
AIV Lead	Advanced Engineer or Scientist	Process-centered individual responsible for managing AIV, including hiring, budget, and reporting status. Has signature authority over the AIV budget.
AIV Commissioning Scientist	Scientist/Research Engineer	Responsible for ensuring AIV is testing to specification. Interfaces with CSV and the AIV test staff.
AIV Software Lead	Software Engineer IV	Responsible for managing the team that integrates software and hardware deliverables. Oversees the development of AIV test software.
AIV Software Engineer	Software Engineer II	Responsible for development, maintenance and updates of V&V tools through production and installation. Performs tests of software and hardware integration.
AIV Electronics Lead	Electronics Engineer IV	Responsible for managing the team that integrates LRU/Sub-assemblies and articles. Performs tests, ensures testing reliability, calibration and documentation.
AIV Site Engineer	Civil or Mechanical Engineer IV	Responsible for ensuring all ngVLA elements interface successfully with the site buildings and infrastructure. Interfaces with Buildings & Infrastructure IPT staff.
AIV Electronics Engineer	Electronics Engineer II	Responsible for the installation of the LRU/Sub-assemblies and articles. Performs tests.
AIV Electronics Technician	Electrical Technical Specialists II & III	Responsible for the installation of the LRU/Sub-assemblies and articles.
AIV Mechanical Lead	Mechanical Engineer IV	Responsible for the installation of the LRU/Sub-assemblies and articles. Performs tests.
AIV Mechanical Technicians	Mechanical Technical Specialist III & IV	Responsible for the installation of the LRU/Sub-assemblies and articles.

8 AIV Infrastructure

The AIV approach described here implies the need for significant supporting infrastructure (including related safety equipment) within the construction project scope. The following list is not intended to be comprehensive, but is provided for context.

8.1 Antenna Assembly

The Antenna IPT will be responsible (either directly or via contract) for erecting the antenna at each site, after acceptance of the site foundations and infrastructure. Assembly will require a crane and other heavy equipment for a nearly eight-year period, suggesting that procuring this hardware may be the most economical solution.

In addition to the site assembly equipment, additional integration areas may be required at the VLA site depending on the chosen antenna concept. For example, construction of single piece composites would require a thermally controlled building with large bay doors and a gantry crane. A paint shop would also be required.

These heavy equipment and building costs could be direct expenses to the Antenna IPT or contractor expenses, depending on the antenna contract structure. These details should be addressed in a future IPT-level AIV plan.

8.2 Antenna Electronics Integration

The electronics deliverables from each antenna electronics work package would be integrated by the Antenna Electronics IPT prior to antenna installation. It is preferable to integrate the front-end electronics at the secondary focus and the back-end electronics in the pedestal rack in a controlled environment off site to improve quality control and reduce the risk of site errors. This approach will require an integration facility near the site. The requirements are similar to the repair center envisioned for the operations phase, so early construction of this facility could meet both needs.

8.3 Warehouse

This concept generally calls for delivery of tested subsystems by IPTs to the central warehouse. It is possible that this warehouse could be the same as the one envisioned for the operations phase, so early construction of this facility could meet both needs.

8.4 Office Space, Test Stands, and Test Area

The schedule for AIV requires multiple AIV teams as described in Section 7.1. These individuals will require office space, adjacent to a test area with access to test stands and associated test equipment. Proximity to the warehouse would seem to be desirable, so the maintenance center described in the operations concept may be a suitable location if constructed on an appropriate timeline. Thought should be given to the concurrent AIV and operations phase as early science starts, and the building should be sized accordingly.

8.5 Vehicle Fleet

As described in Section 7.1, the schedule for AIV requires multiple AIV teams working on site installation. These teams will require an appropriate number of fleet trucks to transport system hardware and test equipment to the respective installation sites.

8.6 Software Integration and Test

The quantization of the software deliverables generally requires that a full software package be delivered concurrently from the respective IPT. This delivery mode places the integrated testing responsibility upon the delivering IPT, suggesting that the project must provide a software integration suite, unit test and regression test suite, and hardware simulators.

8.7 Communications Infrastructure

The nature of remote site work can complicate communications with remote teams. Establishing data and voice service at each antenna site should be a priority in the AIV of each site. The feasibility of providing 3G/4G data at the construction sites, or even using the Iridium network should be considered.

8.8 Equipment and Configuration Tracking

A number of computerized tracking systems will be required to track inventory in the warehouse, equipment configuration and test data, the status of maintenance teams and the system configuration. The needs of AIV seem similar to the needs for long-term maintenance, so early delivery and deployment of these systems may satisfy both needs.

9 AIV Interactions with CSV

The primary deliverables from AIV to CSV are integrated telescope systems with verified system capabilities. Of course, to accomplish this, integrated and characterized antennas elements with supporting signal generation and transport must be verified and integrated. As discussed above, during the Early Delivery Phase of the project AIV and CSV will work closely together to develop procedures and tests to clearly define expectations for future handoffs. During this time, the two groups will co-develop the test plans and other handoff requirements and will achieve several common milestones (AIV0.1 through AIV6.1) as described in Section 10.

Finally, by working essentially as a single group during these early deliveries, a path for efficient knowledge transfer between AIV and CSV will be established.

Once subarray capabilities have been verified, CSV and AIV will begin independent operations.

10 AIV Milestones

The following milestones describe the incremental integration of IPT deliverables into a functioning system, and the resultant verification of system-level functionality. Milestones AIV0.1 through AIV6.1 would be conducted in collaboration with CSV. After this milestone, each group would continue independently as described in Section 9. The overall flow of these milestones is as follows.

1. Integration of infrastructure systems necessary to support the AIV process.
2. Single dish integration and test.
3. Basic interferometer integration and test.
4. High-level M&C integration and test.
5. First functional interferometer delivered to CSV.
6. First functional interferometer for early science operations delivered to CSV.
7. Incremental delivery of the full system capabilities to CSV.

The ordering of milestones after the delivery of the first functional interferometer for early science operations (AIV30.0) is notional, and is not intended to suggest a priority of science capability. That is not the purview of this document, and the order will be determined through discussions with the community on early and legacy science, as well as the needs of the commissioning team. This document only aims to define technical antecedents, not milestone priority, beyond AIV30.0.

The milestones are described in qualitative terms in this AIV Concept, and will be defined in detail as part of the AIV Plan. Milestones may be refined, added, or combined as the plan and the system design mature.

10.1 AIV0.1: AIV Infrastructure

Predecessor: None.

Description: This milestone provides verification that infrastructure systems to support AIV are in place. In particular, the M&C system, configuration management, issue tracking system are implemented and tested.

Pass Criteria: The milestone would be passed with the M&C supervisory system deployed and recording data in the engineering database. The configuration management system is deployed, tested, and ready to ingest subsystem calibration coefficients by serial number. The Issue tracking system is deployed, tested, and pre-populated with the system product tree.

10.2 AIV1.1: Single Dish Integration

Predecessor: AIV0.1

Description: This milestone demonstrates the functional integration of a single antenna's analog signal path using Band 3. It also demonstrates antenna integration with the M&C system.

Band 3 is selected since it is presently the lowest frequency axially corrugated feed horn. The lower fractional bandwidth, reduced sidelobe level, and quieter RFI environment at Band 3 are expected to make this band easier to commission than the wide-band Band 1 or Band 2 receivers in the reference design.

Pass Criteria: Antenna points and tracks to RA/dec coordinates when commanded through a console/terminal M&C interface to the ACU. Signal read-out confirms on-source status using the Band 3 signal chain, using the IRD module as a (continuum) power detector for each sub-band.

10.3 AIV1.2: DSP Signal Path

Predecessor: AIV1.1

Description: This milestone demonstrates the functional integration of the single dish DSP signal chain to the central signal processor. This milestone may be achieved with a single sub-band (expected to be ~200 MHz, depending on final CSP design) to allow progressive AIV of the CSP.

Pass Criteria: Autocorrelation total power is read out over an M&C interface at correlator F-engine.

10.4 AIV2.0: First Fringes

Predecessor: AIV1.2

Description: This milestone demonstrates the functional integration of a two antenna interferometer by generating on-sky fringes using two antennas in Band 3 on a ~1-km baseline, with fringe tracking, in a continuum mode.

1 km baselines are selected based on perceived difficulty. Very long baselines are hard due to the decorrelation introduced by the troposphere, but very short baselines can also be difficult during these early stages due to common RFI, or coupled signals between antennas. 1 km is a notional value where these short baseline and long baseline effects are believed to be minimized.

Pass Criteria: Stable on-sky fringes (amplitude and phase) on a 1-km baseline while pointing at an astronomical calibrator (point source) using the continuum mode.

10.5 AIV3.0: Phase Closure

Predecessor: AIV2.0

Description: This milestone demonstrates fringe tracking for three antenna elements and determination of closure error(s) using Band 3.

Pass Criteria: All baseline-based complex residuals within 1% in amplitude and within 1 degree of phase for all (~1km) baselines on a high SNR (~1 Jy) point source.

10.6 AIV6.0: Six-Element Array w/ Commissioning Interfaces

Predecessor: AIV3.0

Description: This milestone demonstrates functional integration of a six-element array at Band 3. It also demonstrates functional integration of the high-level (GUI) interfaces for array operation. A six-element array is considered the practical limit for console/terminal based interfaces, so high-level interfaces are required early in the AIV process. However, operation is still expected to be scripted (rather than through scheduling blocks).

Pass Criteria: Determination of closure phase residuals, to same spec as AIV3.0, for all baselines. Functional demonstration of the operator control and monitoring through GUI interfaces for scripted operations. Fringe amplitude and phase plotted in near-real-time using graphical tools for each baseline.

10.7 AIV6.1: Sub-Arrays

Predecessor: AIV6.0

Description: This milestone demonstrates the functional division of the system into sub-arrays. Pointing, LO tuning, and other key parameters should be demonstrated for a minimum of two sub-arrays. It is desirable to also demonstrate separate instantiation of software systems within each sub-array. This milestone marks the split between AIV and CSV into separate teams.

Pass Criteria: Division of the system into two sub-arrays with independent configurations. Corrections for sampler and clock offsets in the correlator. GUI display of status for both sub-arrays.

10.8 AIV6.2: Spectral Line Mode

Predecessor: AIV6.1

Description: This milestone demonstrates the functional operation of the CSP in spectral line mode. This is a necessary precursor to detailed receiver band characterization. Correlator back-end ingest and recording at the associated higher data rates is also demonstrated.

Pass Criteria: High spectral resolution (~100kHz) visibilities recorded in the correlator back end. Bandpass plots are generated for each baseline.

10.9 AIV30.0: VLA C-Configuration Analog

Predecessor: AIV6.2

Description: This milestone aims to demonstrate comparable performance to the VLA in C-Configuration, in Band 3. The full bandwidth of Band 3 (~8GHz) should be processed for a 30-element array of approximately 5 km in extent. Correlator back-end interfaces should provide data in the correct format for calibration and imaging, and data should be ingested into the archive. Both continuum and spectral line modes must be demonstrated. This milestone, after subsequent actions by the commissioning team, will enable the beginning of science validation.

A 30 antenna array is chosen for this milestone as being roughly equivalent in both sensitivity and (u,v) coverage to the VLA at the same RF frequencies. The bandwidth processed by the CSP also matches VLA continuum capabilities.

Pass Criteria: Integration of 30 antennas into a functional array at Band 3, operating at full bandwidth and recording in the correct data format for calibration and imaging. Data ingested into the archive.

10.10 AIV30.1: Band Validation

Predecessor: AIV30.0

Description: This milestone aims to duplicate the functional testing of the VLA-C analog at all bands (1 through 6). The system would still be limited to 8 GHz of Bandwidth.

While this milestone is notionally listed as subsequent to AIV30.0, effort to achieve this milestone should be in parallel to the AIV30.0 effort, starting after the spectral line mode is demonstrated in AIV6.2. Early band validation will be functional in nature and can start immediately after AIV6.2. Final receiver band validation is expected to wait until sufficient correlator bandwidth is available to render this process efficient, but not so late as to create significant rework if many antennas have been deployed (30 antennas represent about 12% of the ngVLA design baseline).

Pass Criteria: Acceptable SEFD, bandpass structure and closure phase residuals at all bands for 30 antennas.

10.11 AIV31.0: Incremental Antenna Integration

Predecessor: AIV30.1

Description: After AIV30.1, the 30-element array has been verified to work at all frequencies and the antennas are considered fully deployed/verified. Each additional antenna added to the array will subsequently have its performance verified at all bands. This milestone will be repeated for each additional element added to the array after completion of the AIV30.1 milestone.

Pass Criteria: Acceptable SEFD, bandpass structure, and closure phase residuals at all bands for each new antenna.

10.12 AIV60.0: VLA C+D Configuration Analog

Predecessor: AIV30.1

Description: This milestone aims for comparable (u,v) coverage to the VLA in C+D Configuration. System now extended to full bandwidth (20 GHz/pol).

Pass Criteria: Integration of 60 antennas into a functional array at all bands. Demonstration of data recording for the full 20 GHz/pol bandwidth on all baselines.

10.13 AIV90.0: VLA B+C+D Configuration Analog

Predecessor: AIV60.0

Description: This milestone aims for comparable (u,v) coverage to the VLA in B+C+D Configuration.

Pass Criteria: Integration of 90 antennas into a functional array at any/all bands. Demonstration of data recording for the full 20 GHz/pol bandwidth on all baselines while mitigating time/bandwidth smearing.

10.14 AIV120.0: VLA A+B+C+D Configuration Analog

Predecessor: AIV90.0

Description: This milestone aims for comparable (u,v) coverage to the VLA in A+B+C+D Configuration.

Pass Criteria: Integration of 120 antennas into a functional array at any/all bands. Demonstration of data recording for the full 20 GHz/pol bandwidth on all baselines while mitigating time/bandwidth smearing.

10.15 AIV130.0: 50km Baselines

Predecessor: AIV30.1

Description: This milestone demonstrates the performance of frequency transmission, data transmission and phase calibration on long baselines, with the maximum baseline in excess of 50 km.

Pass Criteria: Stable fringe tracking on a 50-km baseline. Transmission of 8 GHz of bandwidth per polarization to the correlator.

10.16 AIV140.0 500km Baselines

Predecessor: AIV130.0

Description: This milestone demonstrates the performance of frequency transmission, data transmission and phase calibration on long baselines, with the maximum baseline in excess of 500 km.

Pass Criteria: Stable fringe tracking on a 500-km baseline. Transmission of 8 GHz of bandwidth per polarization to the correlator.

10.17 AIV700.0: Phased Array Mode

Predecessor: AIV30.1

Description: This milestone demonstrates the functionality of the phased array mode over a 30-km aperture.

Pass Criteria: Phased array time series is recorded in Correlator Back End (CBE).

10.18 AIV701.0: Pulsar Timing Mode

Predecessor: AIV700.0

Description: This milestone demonstrates the functionality of the pulsar timing mode.

Pass Criteria: Singe phased array beam ingested by pulsar engine in Pulsar Timing (PT) mode, generating a PSRFITS output.

10.19 AIV702.0 Pulsar Search Mode

Predecessor: AIV701.0

Description: This milestone demonstrates the functionality of the pulsar search mode.

Pass Criteria: Singe phased array beam ingested by pulsar engine in Pulsar Search (PS) mode, generating a PSRFITS output.

10.20 AIV801.0: First SBA Antenna

Predecessor: AIV30.1

Description: This milestone functionally tests the first SBA antenna, with first fringes to three antennas in the main array.

Pass Criteria: Stable fringes in Band 3 on an astronomical calibrator.

10.21 AIV801.1: SBA Band Validation

Predecessor: AIV801.0

Description: This milestone aims to validate the performance of an SBA Antenna at all bands.

Pass Criteria: Acceptable bandpass structure and closure phase residuals at all bands.

10.22 AIV819.0: SBA Sub-Array

Predecessor: AIV801.1

Description: This milestone demonstrates deployment of the full SBA as a sub-array. 20 GHz of processed bandwidth.

Pass Criteria: Full SBA antenna complement tested at all bands and operated as an independent sub-array.

10.23 AIV903.0: First LBA Cluster

Predecessor: AIV140.0

Description: This milestone demonstrates the deployment of the 1st LBA Cluster (three antennas) and first fringes with the Main Array.

Pass Criteria: Short baseline cross-correlation within the cluster, and long baseline cross-correlation with core antennas. Short baseline and long baseline fringes on a calibrator source.

10.24 AIV930.0: LBA Sub-Array

Predecessor: AIV903.0

Description: This milestone demonstrates the deployment of full LBA and operation as a sub-array.

Pass Criteria: Full LBA antenna complement tested at all bands. Full bandwidth to correlator as a stand-alone sub-array.

10.25 AIV999.0: Full Array Deployed

Predecessor: (All)

Description: This final AIV milestone demonstrates concurrent operation of all 263 elements as a single array.

Pass Criteria: Full array demonstrated cross correlation at the highest specified time resolution (~500 msec) and 100k+ spectral channels (i.e. the maximum permitted data rate).

11 Appendix

11.1 Abbreviations and Acronyms

Acronym	Description
ACU	Antenna Control Unit
AIV	Assembly, Integration, and Verification
API	Application Program Interface
RFI	Radio Frequency Interference
AE	Antenna Element
FE	Front End
BE	Back End
CBE	Correlator Back End
CCB	Change Control Board
CDR	Critical Design Review
CoDR	Conceptual Design Review
CSP	Central Signal Processor
CSV	Commissioning and Science Validation
CSW	Computing Software
DSP	Digital Signal Processing
ES&S	Environment, Safety, and Security
GUI	Graphical User Interface
ICD	Interface Control Document
IPT	Integrated Product Team
IRD	Integrated Receiver/Downconverter and Digitizer
LBA	Long Baseline Array
LRU	Line Replaceable Unit
M&C	Monitor and Control
MRR	Manufacturing Readiness Review
ngVLA	Next Generation VLA
ORR	Operational Readiness Review
PA	Product Assurance
PDR	Preliminary Design Review
PS	Pulsar Search
PT	Pulsar Timing
QA	Quality Assurance
RA	Right Ascension
RSD	Reference Signal and Distribution
RVTM	Requirements Verification Traceability Matrix
SBA	Short Baseline Array
SE	Systems Engineering
TBD	To Be Determined
V&V	Verification and Validation
VLA	Jansky Very Large Array

Acronym	Description
WP	Work Package
WVR	Water Vapor Radiometer

11.2 Glossary

Element: A functioning collection of Articles. A fully functioning and verified antenna, comprised of various articles and subsystems, is an ngVLA Array Element, (AE).

Hardware Article: Delivered as a complete package to AIV, an integrated collection of LRUs and Sub-assemblies which are designed for a specific function.

Integrated Product Team (IPT): An organizational group responsible for the design and delivery of a product.

IPT Product: An integrated subsystem designed for a specific function. Products are the fundamental deliverables of the IPTs, either to the AIV process or less frequently to another construction IPT.

Line Replaceable Unit (LRU): A modular component which typically fits into a larger assembly, with an ability to be replaced quickly with no required software/firmware modifications.

Scientific Capability: Integrated functionality meeting one or more of the system level scientific requirements.

Sub-assembly: A separately assembled unit designed to be incorporated into a larger manufactured product or article.

Technical Capability: Integrated functionality meeting one or more of the system level technical requirements.

Telescope System: An integrated combination of software and hardware that is capable of performing one or more [Technical/Scientific] capabilities.