Systems Engineering Management Plan

020.10.00.00.00-0001-PLA

Status: **Released**

PREPARED BY	ORGANIZATION	DATE
T. Kusel, Systems Engineer	Program Mgmt. Dept., NRAO	2022-01-18

APPROVALS	ORGANIZATION	SIGNATURE
T. Kusel Systems Engineer	ngVLA, NRAO	Thomas Kusel Thomas Kusel (Jan 18, 2022 14:35 EST)
R. Selina Project Engineer	ngVLA, NRAO	R. Selina R. Selina (Jan 18, 2022 12:37 MST)
W. Esterhuyse Project Manager	ngVLA, NRAO	
J. Meyers Project Manager	ngVLA, NRAO	Jill R. Meyers Jill R. Meyers (Jan 18, 2022 13:11 MST)
T. Beasley Project Director	Director, NRAO	Tony Beasley

RELEASED BY	ORGANIZATION	SIGNATURE
T. Beasley Project Director	Director, NRAO	Tony Beasley

Change Record

Version	Date	Reason
1	2017-08-22	Initial Draft
2	2017-09-08	Elaborated on Tech Process descriptions, Configuration Management
3	2017-10-17	Elaborated on Tech Process descriptions, Architecture, V&V, Quality
4	2017-12-27	Added entrance/exit criteria for reviews, other minor edits, prepared as Release Candidate A
5	2018-02-09	Downgraded from Release Candidate A to Draft Ver 4 Updated sec 2.3-2.5
6	2018-03-13	Minor edits and cleanup comments
7	2018-10-01	Add ngVLA Stakeholder Requirements as RD 06, changed Ref Design Review to IPDSR/EPDSR
8	2018-12-11	Implemented RIDs for IPDSR; made minor grammatical and formatting edits; updated Table of Contents
9	2019-11-05	Comprehensive update to incorporate guidance from ISO/IEC/IEEE 24748-4 and various other changes
A	2019-11-06	Format and copy-edit to prepare PDF for approvals and release
A.1	2020-05-13	Clarified AIV stage overlap with Design and Construction lifecycle phases
A.2	2020-11-18	Comprehensive update on most sections. Inclusion of a Life Cycle Plan. Released for formal review.
B	2021-01-27	Update following formal review of RevA.2
C	2022-01-18	Update terminology of major reviews to align with the NSF Research Infrastructure Guide [RD01]

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1 Introduction

1.1 Identification

This document defines the Systems Engineering Management Plan (SEMP) for the Next-Generation Very Large Array (ngVLA) Project. The ngVLA is an interferometric array with scope as defined in the ngVLA Reference Design [RD07].

1.2 Purpose and Scope of this document

The Systems Engineering Management Plan (SEMP) is a high-level technical planning document that defines the technical management processes that are necessary to coordinate the engineering effort in a coherent and efficient manner, across the life cycle of the project. The SEMP includes a definition of the following aspects of engineering management:

a) How the generic Systems Engineering (SE) process is tailored for the Radio Astronomy environment and specifically to the ngVLA project. The SEMP identifies which aspects of the generic SE processes are important for the project and defines how these processes are adapted for the project.
b) The ngVLA project life cycle from concept definition to operations. The SEMP defines how the process is applied for different types of subsystems and how the processes at the different levels are harmonized at the system level. The life cycle is defined in terms of life cycle stages, stage gates and major project reviews that occur at the stage gates.
c) The SEMP defines the Systems Engineering activities that should occur and the deliverables that should be produced for the review at the end of each life cycle stage.
d) Application of Systems Engineering tools and models.
e) Project processes that are related and complementary to Systems Engineering, the SE relationship to such processes and reference to documents that define these processes.

The scope of the document is limited to the development part of the life cycle up to steady state operations. The document does not define the operational or divestment stages of the life cycle.

2 References

Applicable Documents are Systems Engineering plans and procedures that are subordinate to the SEMP. *Reference Documents* either are referenced within this document or provide supporting context to the preparation of the SEMP.

Applicable Documents		
AD01	ngVLA Lifecycle Stages and Concepts	020.10.05.00.00-0001-PLA
AD02	ngVLA Documentation Management Plan	020.10.10.10.00-0001-PLA
AD03	ngVLA Configuration Management Plan	020.10.10.15.00-0001-PLA
AD04	ngVLA Requirements Management Plan	020.10.15.00.00-0001-PLA
AD05	ngVLA Verification and Validation Plan	020.15.00.00.00-0001-PLA
AD06	ngVLA Architecture and Interface Management Plan	020.10.00.00.00-0002-PLA
AD07	ngVLA Quality Management Plan	TBD
AD08	ngVLA Product Breakdown Structure	020.10.20.00.00-0004-DSN
AD09	ngVLA Logistics Engineering Management Plan	TBD

Reference Documents		
RD01	NSF Research Infrastructure Guide	NSF 21-107 (Dec 2021)
RD02	INCOSE Systems Engineering Handbook, Version 4	4th Edition
RD03	Project Execution Plan	020.05.00.00.00-0003-PLA
RD04	ngVLA Project Management Plan	020.05.00.00.00-0002-PLA
RD05	ngVLA Project Resource Management Plan	020.05.25.00.00-0001-PLA
RD06	ngVLA RACI Matrix	020.05.25.00.00-0002-PLA
RD07	ngVLA System Reference Design	020.10.20.00.00-0001-REP
RD08	ngVLA Work Breakdown Structure	020.05.05.00.00-0001-LIS
RD09	ngVLA Integrated Master Schedule	020.05.10.00.00-0003-SCD
RD10	ngVLA Preliminary System Architecture	020.10.20.00.00-0002-DWG
RD11	ngVLA Requirements Verification and Traceability Matrix	020.10.05.00.00-0002-REQ
RD12	ngVLA Risk Management Plan	020.05.35.00.00-0001-PLA
RD13	AUI Environment, Safety, and Security Program Manual	Oct 2016
RD14	ngVLA Procurement Management Plan	020.05.40.00.00-0001-PLA
RD15	ngVLA Technical Budgets	020.10.25.00.00-0002-DSN
RD16	MIL-STD-882D Standard Practice for System Safety	Feb 2000
RD17	ISO/IEC/IEEE 15288:2015 Systems and software engineering -- System life cycle processes	2015
RD18	ngVLA Commissioning and Science Verification Plan	020.10.05.00.00-0006-PLA

3 SE Process standards and tailoring

The ngVLA SEMP is based on the ISO/IEC/IEEE 15288 standard on life cycle processes [RD17] and the Systems Engineering Handbook [RD02] as a best practices guideline.

These standard processes are tailored in this SEMP to suit the specific needs of radio astronomy facility development and specifically for the ngVLA project. The tailoring is informed by lessons learnt from previous application of Systems Engineering on radio astronomy projects (VLA, ALMA, MeerKAT and SKA).

3.1 System Life Cycle Tailoring

Tailoring of the system life cycle is particularly important. Life cycle tailoring is not only applied at the system level, but must be adapted for subsystems individually to make provision for the unique characteristics and constraints of the underlying technologies. In particular:

a) For complex subsystems that will be produced in large numbers (e.g. Antenna & Antenna electronics) the V-model development approach (Figure 1) is appropriate for the design phase. This approach enables a systematic top-down design with roll-down of firm requirements and architectural design. When the design is completed down to leaf level, the approach enables a systematic verification and integration of qualified prototypes to build up the system and establish a qualified system design. Following the V-model the product is industrialized and then produced in quantity.
b) Infrastructure: The Architecture, Engineering & Construction (AEC) industry has a well-established process of construction management, which broadly follows a waterfall approach of requirements definition, design, design verification, construction and verification of the as-built configuration.
c) Software systems: software development can benefit from the low cost of incremental implementation and verification by adopting an iterative development approach. A number of lean agile management frameworks have evolved to facilitate this approach and ensure that it is managed efficiently and meets the overall project goals and milestones. The iterative software development should be subservient to the overall System Life Cycle and thus the Project Manager and Systems Engineer should act as clients to this process. The iterative approach should be complemented by an initial top-down design stage to establish a base architecture and requirements set to align with the system design.
d) Complex one-off systems (e.g. CSP and Reference Signals subsystems) should use a combination of top-down design, combined with hardware qualification and iterative software development.

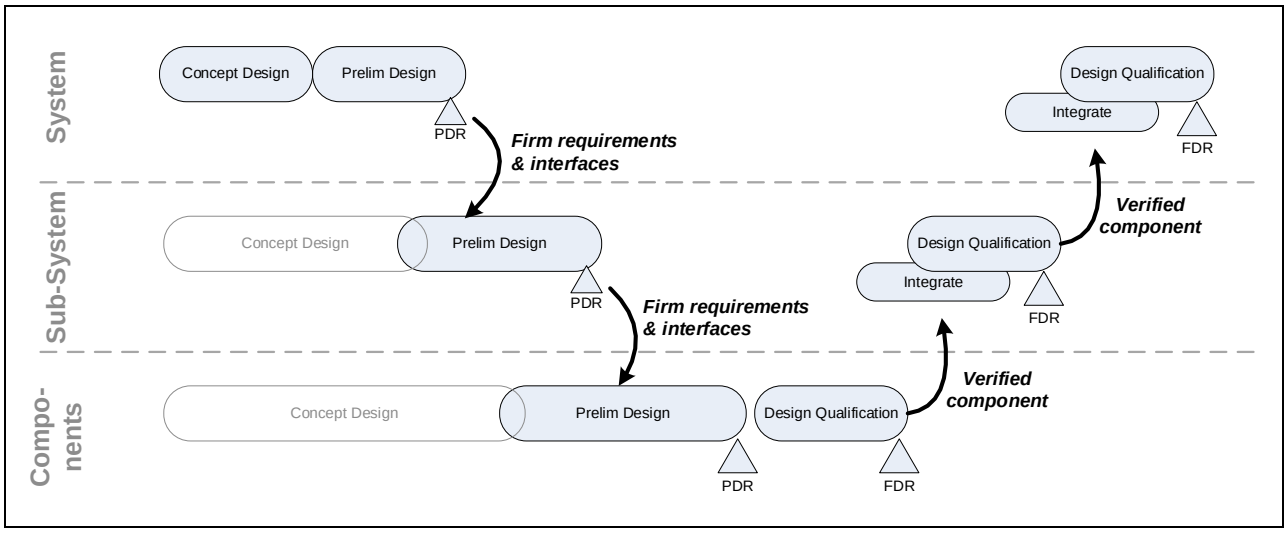

Figure 1: Product development V-model

4 ngVLA Life Cycle

The Life Cycle model plays a central role in the overall management of the project. It defines the project stages, stage gates and reviews for the system and for all major components. The project's work breakdown structure and schedule should be aligned with the life cycle model.

The purpose of this section is to give an overview of the ngVLA life cycle. The detailed definition of the stages and formal reviews is defined in more detail in Section 5.

Figure 3 and Figure 4 show an overview of the ngVLA life cycle, including the major activities and reviews at the system and subsystem levels, including their interdependencies. The life cycle is shown in relation to the NSF Major Facilities Life Cycle. The main focus of the SEMP is to define the Design and Construction stages of this Life Cycle.

4.1 System Life Cycle

4.1.1 Development Stage

The first stage of the NSF life cycle is the Development stage. The activities in this stage include the definition of key science goals, prioritized science requirements, a broad facility concept and the scope of the project in terms of work, schedule and budget. The purpose of this phase is to demonstrate facility concept alignment with the community research priorities and requirements, and to define the project in sufficient detail to execute the design phase. Key deliverables for this phase are the Science Book and Reference Design. Governance structures are established including a Technical Advisory Committee and Science Advisory Committee. This phase includes the review of stakeholder requirements and system requirements.

4.1.2 Design Stage

The Design stage is broadly divided into a conceptual design, preliminary design and final design phase.

4.1.2.1 Conceptual Design

The system conceptual design phase culminates in a formal conceptual design review. The purpose of this review is to down-select the implementation options as far as possible and to confirm the detailed scope of the project, including the cost driving and performance driving requirements and key design features (See Section 5.1 for more detail). The purpose is also to create a firm baseline with limited options to focus the detailed design activities of the preliminary design phase. The conceptual design review is a formal review with community involvement.

The CDR is primarily a system level review and the subsystem conceptual designs are developed in support of the system CDR. Subsystem CDRs will be staggered over time as the conceptual designs of the subsystems mature. The subsystem CDRs will be informal internal reviews and should preferably be conducted ahead of the system CDR, but may in some cases only be conducted afterwards.

4.1.2.2 Preliminary Design

The purpose of the system preliminary design phase is to define a detailed system architecture and to prepare a stable requirements and architectural baseline for the detailed design of the subsystems (See Section 5.2 for more detail). The system PDR should thus be conducted prior to the subsystem PDRs, in line with the V-model of system development (as described in Section 3.1). The system PDR will be a formal review with community involvement. The preliminary designs of the subsystems are developed concurrently to support the system architectural design activity.

After the system PDR, the focus of the system team activities is to oversee the detailed design of the subsystems and to conclude their PDRs. This requires updating the system architecture to keep it aligned with the subsystem designs as they develop. If required, an internal detailed design review may be conducted on the system level after the subsystem PDRs have been concluded to verify that all the preliminary designs of the subsystems have been incorporated and integrated on the system level and that the system architecture is coherent and complete.

4.1.2.3 Final Design

Following subsystem PDRs, the project moves into the final design stage.

For serial production components, this requires the implementation of the design in the form of a prototype and testing (qualifying) the prototype to provide justification evidence that the implemented design can meet the requirements. The System team oversees the qualification of individual subsystems and the conclusion of subsystem qualification by means of subsystem Final Design Reviews (FDRs see Section 5.3). When the qualification models of the Antenna systems become available, the System team coordinates the integration of the antenna electronics on the antennas and conducts integrated system verification of the antenna, including on sky testing. The system AIV plan [AD05] indicates that the 18m antenna integration and verification will precede the 6m antenna. After subsystem FDRs are concluded and the integrated antenna testing has been completed, a formal system level FDR is conducted with community involvement. The sequence of stages and reviews at the system and subsystem levels up to FDR stage is shown in Figure 2 below.

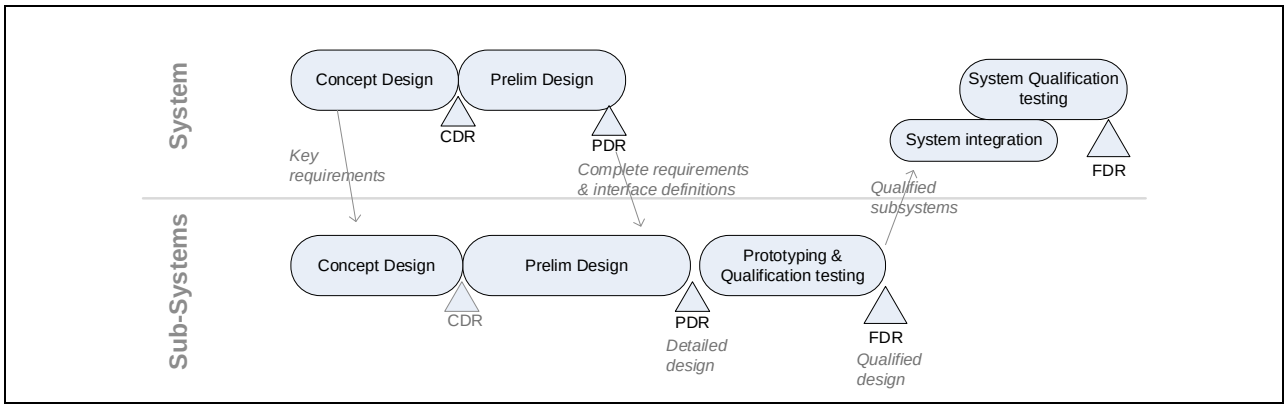

Figure 2: Sequence of phases and reviews on system and subsystem levels

4.1.3 Construction Stage

Following the FDR, the focus of the system team is to oversee the industrialization of production hardware, concluding in PRRs. The System team, together with the Quality Manager are important stakeholders in the industrialization process. Concurrently, the System team is also a stakeholder in the procurement of the infrastructure construction work package.

When the first few production antennas become available, the System team proceeds with the verification of the individual antennas, followed by array integration and verification as defined in the AIV Plan [AD05]. Interaction between the System team and the Software teams throughout the life cycle is important to ensure that the necessary Minimum Viable Products (MVPs) are delivered within scope and timelines to support the system AIV activities. The Commissioning and Science Verification (CSV) activities occur concurrently with the system AIV activities and are defined in the CSV Plan [RD18].

4.1.4 Transition to Operations

A System Acceptance Review (AR) is conducted near the end of the system AIV phase. The System AR follows the ARs of the Subsystems (See Sections 5.5 and 5.6). The System AR is a gate for formal acceptance of the project deliverables by the Observatory. The deliverables for the System AR should include all the documentation and information that is required to transition the product to the operational phase including:

a) System and Subsystem verification reports.
b) As-built documentation with Physical Configuration Audit (PCA) reports.
c) User documentation including operating and maintenance manuals.
d) Spares required for the operations phase.
e) Support equipment required for the operations phase.

Following the Acceptance Review, the Operational and Support Baseline (OSBL) is established for the system and the use and maintenance of the product is transferred to the operations team.

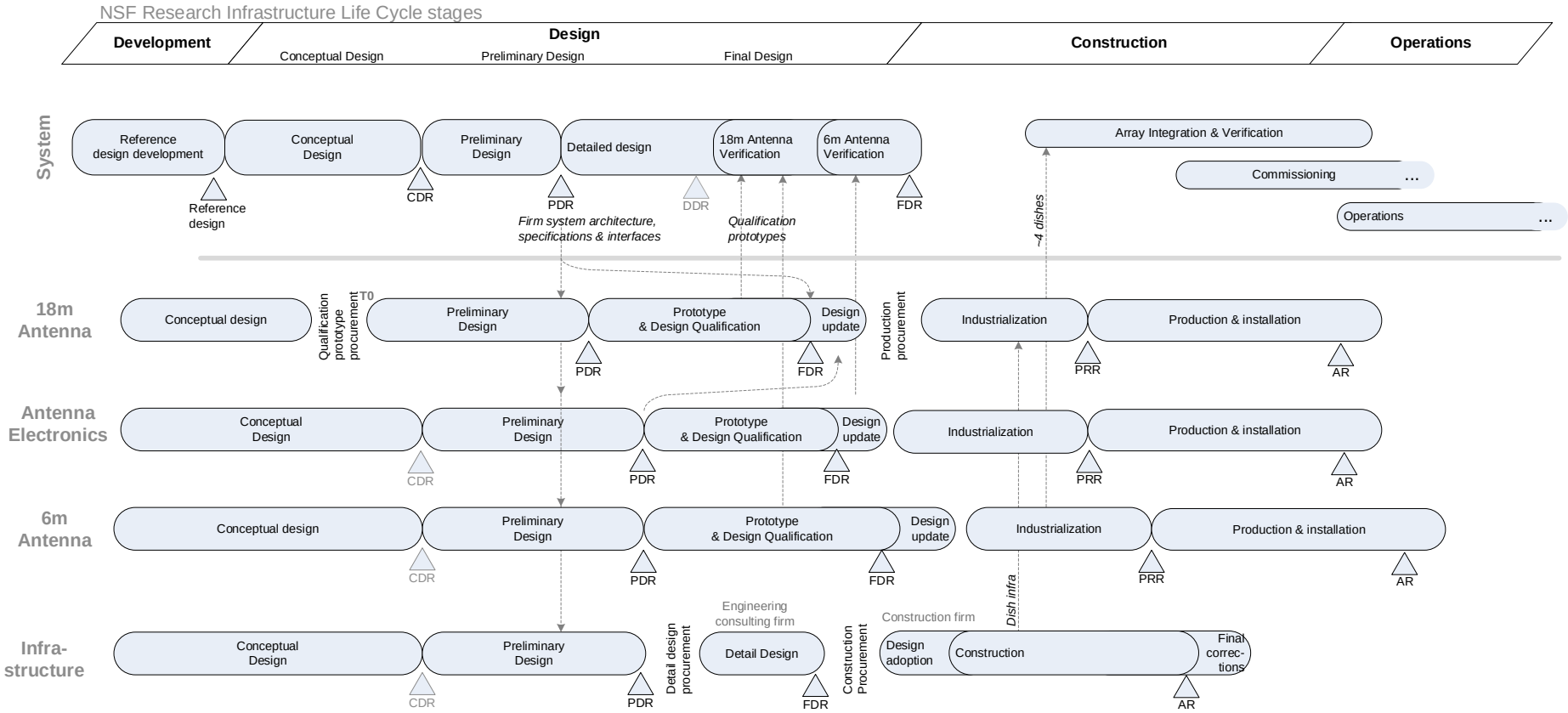

Figure 3: ngVLA Project Life Cycle – Antennas and Infrastructure

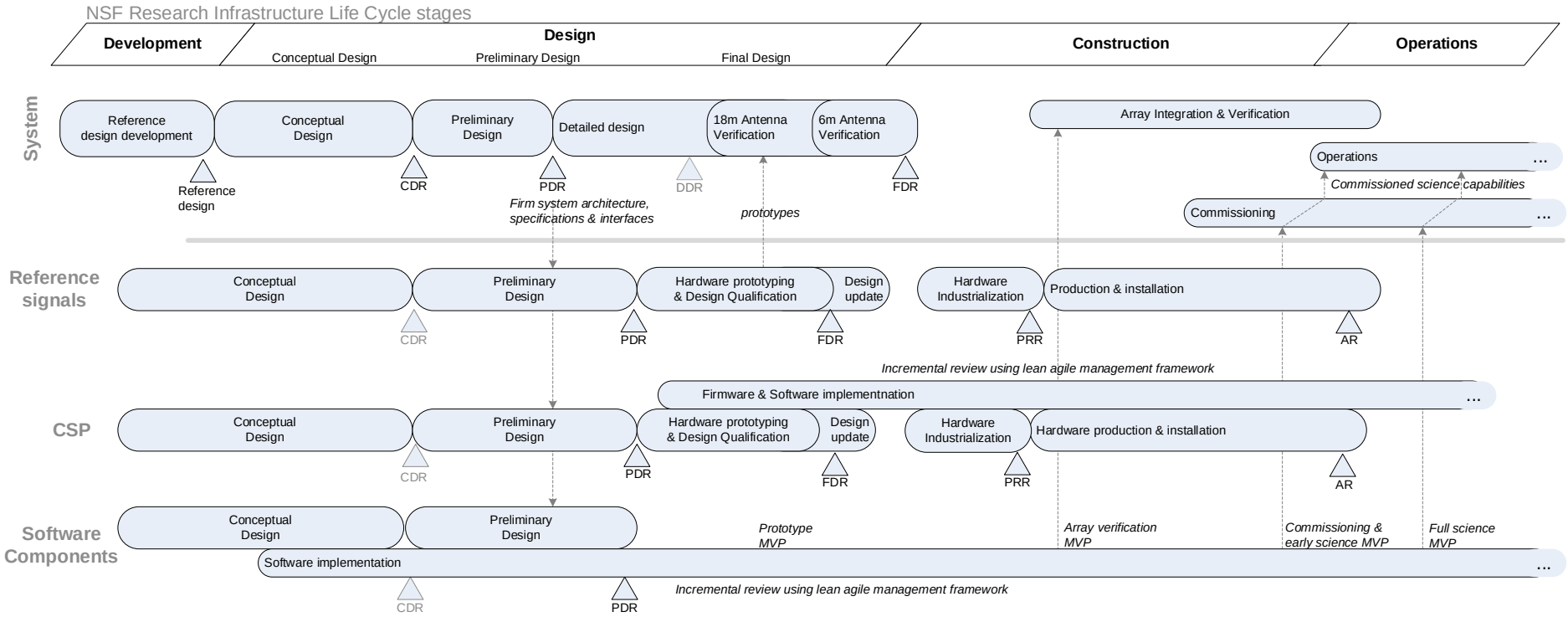

Figure 4: ngVLA Life Cycle – Central components and software

4.2 Subsystem Life Cycles

The following sections give a high-level overview of the life cycles of the major subsystems. More detailed life cycle plans may be required for individual subsystems or parts and will be determined on a case by case basis. In cases where such plans are required, the responsible person shall follow the principles set out in this document and shall deliver the life cycle plan at the subsystem CDR. Such development plans shall be approved by the ngVLA SE to ensure consistency of applying the SE process across the project.

4.2.1 18m Antenna development life cycle

The 18m Antenna life cycle drives the timeline for the project design phase. The schedule for the preliminary design, PDR, qualification and FDR are set as part of the procurement contract for the qualification prototype. The system PDR will only shortly precede the Antenna PDR and the Antenna Electronics PDR will occur after the Antenna PDR. This sequence imposes a risk on the Antenna design in terms of likely ECRs required for interfaces and requirements after its PDR. Some of these changes may have to be implemented after the FDR, in which case the changes will be implemented on the industrialization units.

Following the PDR, the qualification prototype is constructed on the VLA site and a comprehensive set of testing and inspections is performed on the Antenna to verify compliance to its requirements. This is followed by an Antenna FDR, which will be an internal review with community involvement. Following the FDR, a minimum set of changes will be implemented based on the non-compliances found during the use and verification of the qualification model.

The production procurement will be based on the detailed design as defined in qualification baseline established after FDR. Placement of the production contract is followed by an industrialization phase and PRR, after which full production may start.

4.2.2 6m Antenna development life cycle

The life cycle of the 6m Antenna will follow a similar structure to the 18m Antenna. The main difference is that the 6m Antenna is less critical than the main antenna. There are thus fewer constraints on the timeline, which allows for more flexibility to move activities on the timeline relative to the system timeline.

4.2.3 Antenna Electronics development life cycle

The life cycle of the Antenna Electronics follows a similar sequence to the Antennas. Close interaction between these teams is required to synchronize the designs. The commonality of the Antenna Electronics between the 6m and 18m Antennas will be maximized as far as possible to reduce the need for parallel development.

4.2.4 Infrastructure development life cycle

The design is likely to be contracted to a multi-professional construction engineering consulting firm through preliminary design and detailed design. The consulting firm should also help to prepare the construction tender and with the project management and supervision of the construction phase.

Following the construction procurement, the contracted construction contractor performs design adoption and verification before proceeding to site preparation and construction. Timing of the construction should ensure that the foundations are ready in time for the first antennas arriving at the site.

4.2.5 CSP and Reference signals development life cycle

Following the PDR, prototypes are built as required to qualify the hardware design. The qualification phase is concluded by a formal FDR before proceeding with industrialization and production for serial hardware production. The development of software and firmware may develop concurrently with hardware development, following the PDR. The delivery of CSP Minimum Viable Products (MVPs) is critical for system AIV and CSV activities.

4.2.6 Software components development life cycle

Software components will proceed through CDR and PDR phases to support the establishment of a firm functional architecture to support the System PDR. This includes the establishment of a firm set of requirements and boundary conditions for the software components. Implementation can commence concurrently at any time, following an iterative review process as defined in Section 5.8. The delivery of Software Minimum Viable Products (MVPs) is critical for system AIV and CSV activities.

5 Definition of Life Cycle Stages

This section defines the purpose, scope and deliverables for each of the life cycle phases. As described in Section 4.2, not all these stages are equally applicable to product items in the PBS and should be tailored and refined for each product item.

5.1 Conceptual Definition

Applicability: This phase is mainly applicable to the ngVLA System and the definition below is written from this point of view. Major subsystems will also go through a conceptual design phase to drive a down-selection of implementation options and to confirm key requirements, but these should be in support of the system level conceptual design (see Section 4.2). Subsystem conceptual designs will be completed and reviewed internally to the project. They should preferably be concluded ahead of the System CDR, but where this is not possible, the subsystems shall publish a specification and conceptual design in support of the System CDR.

Purpose: The purpose of the Concept Definition is to:

a) Define the reference science program
b) Firm up performance- and cost-driving requirements from science level through system level to subsystem level.

c) Evaluate different alternative solution options, trade off the options against an agreed value system and decide on a single implementation concept.
d) Describe the design of the chosen conceptual design that will satisfy the key requirements.
e) Establish performance budgets for the critical performance requirements for the chosen solution.
f) Define concepts of operation of the system.
g) Define the scope of the project (work, cost and schedule).
h) Define the key management plans that will be used to manage the project (including Project Execution Plan, SEMP and Configuration Plan).
i) Verify and validate the chosen concept through review by an independent panel of experts.
j) Baseline the conceptual design to serve as a firm foundation for the Preliminary Design phase.

Activities: Activities in this phase include:

a) Identify all key stakeholders in the funding, management, regulatory, user and implementation domains.
b) Define the science program and driving science requirements.
c) Define the concept of operations and the support concept, including requirements for reliability, maintainability and availability.
d) Define the concept of integration, verification and commissioning.
e) Identify the performance driving and cost driving system requirements through interaction with the identified stakeholders.
f) Analyze and clarify the system requirements and derive subsystem requirements that drive performance and cost. Note that this analysis does not need to involve a complete set of requirements, but only the concept driving requirements, which is usually a small subset.
g) Define a limited set of implementation options that can satisfy the driving requirements.
h) Trade off the options using a stakeholder value system and select an option as the reference solution (secondary options may be carried forward but this should only be done as an exception).
i) Produce a first order design definition of the selected option.
j) Produce a first order construction and operational costing of the selected option.
k) Produce models as needed to verify the feasibility of the selected option. The modeling should be focused on the cost and performance driving requirements and components.
l) Identify project risks and establish a risk register and mitigation plans.
m) Develop or update the management plans for the project, including the project execution plan, systems engineering management plan.

Conceptual Design Review (CDR): The system conceptual design phase is concluded by a stage gate with formal review by an independent panel of experts with expertise in both the stakeholder and implementation technology domains. The deliverables for the CDR include:

a) Science Program and Science Requirements (at least performance and cost driving requirements).
b) System Requirements Specification (at least performance and cost driving).
c) Subsystem Requirements (performance and cost driving).
d) Options tradeoff document(s).
e) System reference design.
f) Product Breakdown Structure down to subsystem level.
g) Operations and Support concept.
h) Integration, verification and commissioning concepts.
i) Construction and operational budgets.
j) Project Execution Plan.

k) Systems Engineering Management Plan.
l) Configuration Management Plan.
m) Risk register and mitigation plans.
n) Budget for development, construction and operations with risk-based contingency.

Concept Baseline (CoBL): Following the CDR, a formal baseline is established to manage the scope of the project (performance and cost driving requirements, system boundaries and budget) and the chosen implementation concept. After approval of the CoBL, any changes to this scope definition shall be subject to an ECR.

5.2 Preliminary Design

Applicability: This phase is applicable to all development items. The preliminary designs of the different products in the PBS typically follow a roll-down sequence. This enables the establishment of a firm requirements baseline and boundary definition for lower level items (via architecture definition at the next higher level), prior to finalization of the detailed design work, as illustrated in Figure 1.

Purpose: The purpose of the preliminary design phase is to perform a detailed analysis of all requirements and to design an architecture consisting of lower level items and their interfaces that, when integrated, can meet all the requirements. As part of the architectural design process, the requirements of the lower level product items are established. For items on the lowest level of the V-model, the design is established down to leaf component level. During this process, the method of verifying the requirements is defined and the verification plan is established. This phase is concluded with a Preliminary Design Review, which establishes the Design Baseline.

Activities: The activities during this phase include:

a) Establish a complete set of requirements for the product, including: functional and performance; interface; environmental; RFI/EMC; RAM and regulatory requirements. Traceability to higher level requirements is maintained.
b) Design of an implementation of the item of interest that will satisfy all the requirements and constraints.
c) Analyze requirements to derive a set of requirements for the lower level items.
d) Identify all major interfaces between the next lower level items that need to be managed formally and create interface control documents for these interfaces.
e) Define verification requirements for the item of interest and define an integration and verification plan that will be executed during the following phase (acceptance or qualification).

Preliminary Design Review (PDR): The PDR should be conducted by an independent panel of experts who have both the technological knowledge (for verification of the design) and the application domain knowledge (for validation of the design for science and operations). The deliverables for the PDR include:

a) Requirements specification.
b) External ICDs.
c) Architectural design document(s) including the following:
    - PBS down to next lower level (or down to leaf level as applicable).
    - Physical design.
    - Functional architecture.
    - Internal Interface Identification and ICDs (where applicable).

- Performance budgets and allocation of requirements to major components.
- Preliminary FMECA.
- Environmental design.
- RFI/EMC design, including identification of all RFI culprits and measurement of radiation levels to determine the required level of shielding in the design.
- Safety analysis.
- Architectural design models.

d) Configuration Item Definition (CID) document.
e) Compliance Matrix.
f) RAMS analysis report to demonstrate compliance to reliability, availability and maintainability requirements.
g) Integration and Verification Plan, including RFI/EMC test plan.

Preliminary Design Baseline (PDBL): Following the PDR, a formal baseline is established to enable control of changes to the design of the item. After approval of the DBL, any changes to the baseline shall be subject to an ECR.

5.3 Design Qualification

Design Qualification is equivalent to the NSF "Final Design" life cycle stage. The distinction is made here to emphasize that the purpose of this phase is primarily to verify an implemented design, rather than performing a design activity.

Applicability: The Design Qualification phase is applicable to items that will go into serial production. This phase is also applicable to systems that contain high volume production items (e.g. Correlator).

Purpose: The purpose of this phase is to verify that the realized/implemented design meets requirements before producing the item in large quantities, or before placing large procurement contracts. This is achieved by evaluating detailed justification evidence that the implemented design meets all the requirements. The evidence should as far as possible be in the form of test results from a qualification model (also called prototype or pre-production model). The evidence should give confidence that the item can go into industrialization or large-scale implementation without imposing significant risk on the project. Further goals are to verify that the design data is complete and accurate (in the form of a product/manufacturing data pack) and that the design is stable and unlikely to change before placing large construction/production orders.

Activities: The activities of the qualification phase typically include:

a) Build a qualification model (prototype) based on the DBL established after PDR.
b) Perform a Test Readiness Review when the qualification model is ready for testing.
c) Perform the qualification tests on the prototype in a representative environment.
d) Complete the verification through other means as required (analysis, inspection, demonstration) and produce a qualification report.
e) Produce the product/manufacturing data pack down to leaf level in accordance to the agreed CID.
f) Perform a preliminary physical configuration audit (PCA) to verify that the manufacturing data pack is in line with the qualification model.
g) Develop management documentation for the industrialization/production phase, including an integration and acceptance plan.

Test Readiness Review (TRR): A TRR shall be conducted after the qualification model is completed, and before formal qualification testing commences. This is typically an internal project review. The purpose of the review is to:

a) Approve the Qualification Test Procedures;
b) Verify that the qualification model configuration and the test configuration are mature and stable; and
c) Verify that the definition of the data pack is mature, based on a preliminary PCA of the qualification model.

Final Design Review (FDR): The qualification review is performed after all the qualification activities have been completed. The review should be conducted by an independent panel of experts who are familiar with the application domain, implementation technologies and the production environment. The FDR deliverables shall include:

a) Qualification Results Report.
b) Compliance Matrix.
c) Updated CID document.
d) Data Pack, containing the following data in a complete PBS structure:
    - Requirements specifications for all major components.
    - Design documents for major components (including performance budgets and analysis reports as required).
    - Assembly drawings for all assembled components.
    - Parts list for assembled components.
    - Procurement specifications for major procured parts.
    - Electrical diagrams for all electrical systems.
    - Manufacturing drawings for manufactured items.
    - Schematics for printed circuit boards.
e) Manufacturing, acceptance testing and installation plan for the production phase.
f) Models used for design analysis.
g) Updated RAMS analysis report.
h) Hazards analysis report and site installation safety plan where applicable.
i) Preliminary PCA report, including software configuration report.
j) Draft user documentation including operating and maintenance manuals.

Final Design Baseline (FDBL): The Final Design Baseline is established after the FDR documents have been updated with the FDR observations and approved for release.

5.4 Industrialization

Applicability: This phase is applicable to all serial production items, including the Antennas and Antenna Electronics.

Purpose: The purpose of the industrialization phase is to set up a production line that is able to produce the qualified design and to verify that the production line is capable of producing compliant items. As part of this process, the full set of production documentation is developed. A limited number of items are produced and thoroughly tested in a representative environment. The set of tests should include all or most of the qualification tests.

Activities: The activities in the industrialization phase include:

a) Production of a limited number of items.
b) Verification of the production items.
c) Completion of the data pack to include all the production process documentation.
d) Conducting a First Article Inspection to ensure that the production data is compliant with the production plan.
e) Physical Configuration Audit (PCAs) to ensure that the product documentation is in line with the as-built configuration.

Production Readiness Review (PRR): Following the testing of the industrialization units, a Production Readiness Review (PRR) is conducted to determine whether the manufacturing process is sufficiently mature to proceed to full scale production. The PRR panel should include expertise in production management and quality management systems. The deliverables for the industrialization phase include:

a) Production Plan.
b) Quality Assurance Plan.
c) Test Reports for all the industrialization units.
d) List of all non-conformances and Concessions.
e) Compliance Matrix.
f) First Article Inspection Report.
g) PCA report.
h) Complete Production Data Pack as defined in the CID, including the following:
    - Production test procedures.
    - Assembly Procedures for all assembled items.
    - As-built manufacturing files (for the industrialized items).
    - Built-to register (for the industrialized items).
    - Production Routing Cards (for the industrialized items).

Production Baseline (PBL): The PBL is established after the PRR documents have been updated with the observations and approved for release.

5.5 Production and Installation

Applicability: This phase is applicable to all serial production items, including the Antennas and Antenna Electronics.

Purpose: The purpose of the Production phase is to serially manufacture the items, install and accept the items for operation. Verification of the items occurs throughout the manufacturing process, before shipment from the factory, after shipment on arrival (where applicable) and after installation, as agreed in the production plan.

Activities: The activities in the production phase include:

a) Serial production of the full quantity of items.
b) Factory acceptance testing of all the items.
c) Transportation, installation, integration and site acceptance testing.
d) Ongoing product assurance in factory and on site.
e) Delivery of product documentation in line with the production plan.

f) Physical configuration audits (PCAs) to ensure that the production documentation is in line with the as-built configuration.

Acceptance Review (AR): An acceptance Review is conducted near the end of the production and installation phase. The AR is a gate for formal acceptance of the product and contractual deliverables by the Observatory. The deliverables for the AR should include all the documentation and information that is required to transition the product to the operational phase including:

a) Accepted and installed production items.
b) Factory and Site Acceptance Reports for all delivered items.
c) List of all non-conformances and Concessions.
d) As-built documentation for all deliverables as defined in the CID.
e) Final user documentation including operating and maintenance manuals.
f) PCA report.
g) Spares required for the operations phase.
h) Support equipment required for the operations phase.

At the completion of the AR, the Project Manager (with input from the Systems Engineer and Project Engineer) recommends the acceptance of the component to the Project Director, who in turn signs off on acceptance.

Following the Acceptance Review and acceptance of the product:

a) The Operational and Support Baseline (OSBL) is established for the product.
b) The use of the product is transferred to the system AIV team for system integration and then commissioned by the CSV team.
c) The maintenance of the item becomes the responsibility of the operational maintenance team.
d) The warranty period for the delivered product starts. The supplier shall be available to repair all latent defects during the agreed warranty period.

5.6 Installation and Acceptance of central systems

Applicability: This phase is applicable to all central (one-off) systems such as the CSP and Reference signals, but excludes the Infrastructure which is defined in Section 5.7.

Purpose: The purpose of the installation and acceptance phase is to produce the hardware at full scale, install the hardware and to deploy a first operational version of software. The end result is a first full-scale operational version of the product that can be accepted for initial operations.

Activities: The activities in the production phase include:

a) Full scale production of the hardware components.
b) Factory acceptance of the hardware components.
c) Installation and integration of the hardware on site.
d) Ongoing product assurance in factory and on site.
e) Installation of a first operational version of the software and verification of the integrated system.
f) Completing all required product documentation.
g) Physical configuration audits.

Acceptance Review (AR): An Acceptance Review is conducted after integrated system testing. The AR is a gate for formal acceptance of the product by the Observatory. The deliverables for the AR should

include all the documentation and information that is required to transition the product to the operational phase including:

a) Final verification reports for the integrated product.
b) List of all non-conformances and Concessions.
c) As-built documentation as defined in the CID.
d) Final user documentation including operating and maintenance manuals.
e) PCA report.
f) Spares required for the operations phase.
g) Support equipment required for the operations phase.

At the completion of the AR, the Project Manager (with input from the Systems Engineer and Project Engineer) recommends the acceptance of the component to the Project Director, who in turn signs off on acceptance.

Following the Acceptance Review and acceptance of the product:
a) The Operational and Support Baseline (OSBL) is established for the product.
b) The use of the product is transferred to the system AIV team for system integration and then commissioned by the CSV team.
c) The maintenance of the item becomes the responsibility of the operational maintenance team.
d) The warranty period for the delivered product starts. The supplier shall be available to repair all latent defects during the agreed warranty period.

5.7 Infrastructure Detail Design and Construction

Applicability: This phase is applicable to the infrastructure subsystem.

Detail Design activities: Following the PDR, the detailed design for the infrastructure is typically contracted to a construction engineering consulting firm. The consulting firm produces a detailed design and helps the client to prepare the required construction tender documentation and draft construction contracts.

Detail Design Review (DDR): A DDR is conducted to verify the design and construction tender documentation. The DDR deliverables include:
a) Requirements specification.
b) Detailed design documentation and construction drawings.
c) Building information model.
d) Construction schedule.
e) Construction costing.
f) Compliance Matrix.
g) Verification Plan.
h) Draft tender documentation.

Construction activities: The DDR is followed by construction procurement and the appointment of a construction contractor. During this phase, the consulting firm that performed the detailed design will typically be appointed as an independent consultant to help the client with overseeing the construction – this includes the evaluation of tender responses and supervision of the construction works. The construction phase activities include the following:

a) The successful bidder adopts and verifies the design before starting with site establishment and construction. A design review with the contractor may be needed if changes are made to the detailed design.
b) During construction, any changes to the design shall be agreed according to a change control process. The detailed design documentation shall be kept up to date to reflect the changes and the as-built status.
c) As the construction progresses, the contractor performs continuous verification of the implementation as defined in the Verification Plan. The supervisors oversee the construction and ensure that the verification procedures are executed appropriately.
d) During construction as the individual parts are completed, the client and consultant perform PCAs to ensure that the final as-built documentation is in line with the built configuration.
e) Towards the end of construction an Acceptance Review is conducted to review the delivered infrastructure and documentation. At the review, a list of non-compliances are identified which have to be corrected before the final contract payment is concluded.

Infrastructure Acceptance Review (AR): The deliverables for the AR should include all the documentation and information that is required to transition the infrastructure to the operational phase including:

a) Compliance Matrix.
b) Verification Reports.
c) PCA Reports.
d) As-built documentation and infrastructure information models as agreed in the contract.
e) List of all non-conformances and Concessions.
f) Maintenance and operator manuals.
g) Spares required for the operations phase.
h) Support equipment required for the operations phase.

At the completion of the AR, the Project Manager (with input from the Systems Engineer and Project Engineer) recommends the acceptance of the component to the Project Director, who in turn signs off on acceptance.

Following the Acceptance Review and acceptance of the infrastructure:

a) The Operational and Support Baseline (OSBL) is established.
b) The use of the product is transferred to the system AIV team for system integration.
c) The maintenance of the infrastructure becomes the responsibility of the operational maintenance team.
d) The warranty period for the delivered product starts. The supplier shall be available to repair all latent defects during the agreed warranty period.

5.8 Software implementation

Activities: Software implementation starts early in the project in parallel with the conceptual and preliminary designs. Following the PDR, the software development shall be managed using a recognized agile software development management framework (e.g. SCRUM or SAFe). The framework shall support the following management mechanisms:

a) Defining a team structure with clear roles and responsibilities.
b) Facilitating regular (typically 3-monthly) reviews to report on progress and to plan the following cycle.

c) Setting long-term scheduled goals for deliverables required by the project (e.g. minimum viable product for array integration).
d) Involving the ngVLA Project Manager, Project Engineer and Systems Engineer as stakeholders to evaluate progress and to define priorities for the following cycle and long-term goals.
e) Implementing a test framework that supports the ongoing verification of the requirements. The verification process should indicate the level of requirements coverage of the current implementation in the form of a compliance matrix.
f) Generating sufficient documentation to maintain and update the software in future.
g) Establishing a software build environment to make the software easy to maintain and update.
h) Applying rigor to interface management, since software is often the "glue" that links various components of a system together.

Deliverables: at the software program increments shall include:
a) Progress report, including verification results and requirements coverage in the form of a compliance matrix.
b) Interface control documents as required.
c) Prioritized list of tasks for the following increment.
d) Definition of long-term goals (e.g. MVPs).

6 SE Process Management

6.1 Product Breakdown Structure (PBS)

Management of the PBS is a high priority SE process. The PBS defines a hierarchical structure for the configuration items of the system. The structure used in the configuration management system shall be in line with the PBS. The upper layers of the PBS should be defined as early as possible in the project and shall be baselined at the CDR. All engineering data produced during the life cycle of a product shall be associated with the configuration items identified in the PBS. This includes specifications, interfaces, design data, architectural models, verification data, production data and support data.

The ngVLA PBS is defined in [AD08]. The lead ngVLA Systems Engineer shall maintain the PBS document that defines the following aspects of the product hierarchy:
a) Hierarchical configuration item breakdown of the ngVLA System, including the prime equipment, user systems and enabling systems.
b) Numbering of configuration items.
c) Identification of configuration items that should be included in the system architectural definition and identification of the architectural level of the item.
d) Identification of configuration items that require significant development effort and thus require SE management oversight. Such items shall be designated as Development Items
e) Identification of the level of specification for Development Items.

6.2 Stage Transition Management

The Product Life Cycle in Section 4 defines the stages, stage gates and major reviews for the system and its components. The process of transitioning between stages is defined in this section and is illustrated in Figure 5.

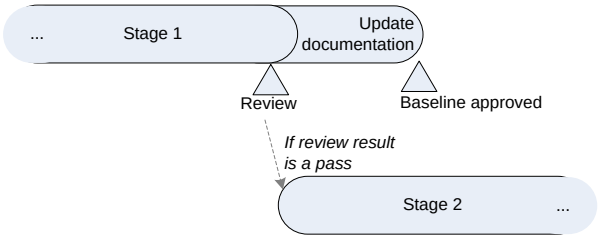

Figure 5: Stage transition process

The stage transition process involves the following steps:

a) The team that is responsible for the item under review organizes the stage gate review in consultation with the lead Systems Engineer. Formal reviews should be managed as defined in Section 6.3. As part of the planning process, a subset of documents is identified as baseline documents in consultation with the lead SE.
b) Following a passed review, the team updates the documentation to incorporate the changes as agreed at the review. When all the documentation is updated, the baseline documents are approved and the baseline is approved in the configuration management system. Baselines should be managed as defined in Section 6.4.
c) If the review result is an unconditional pass, the activities of the following stage may proceed concurrently, but priority should be given to updating the documentation and finalizing the baseline.

6.3 Formal Reviews

Formal reviews are intended to assess the results of the stages of the ngVLA System Lifecycle Model to ensure the system is on track to meet its technical performance goals and the project schedule. A formal review can be one of the following:

f) ***Internal formal reviews***, which are scheduled and managed by ngVLA project personnel and involve review panels and stakeholders internal to the project;
g) ***Internal formal reviews with the community***, which are scheduled and managed by ngVLA project personnel and include subject matter experts from the scientific and/or technical communities external to the ngVLA project;
h) ***External formal reviews***, which are scheduled and managed by the NSF as part of their MREFC Lifecycle stage and phase gates. For more information on the external NSF reviews, see the NSF's Major Facilities Guide [RD01].

These reviews will be executed on system- and subsystem-levels and are essentially the gates the system must pass through before proceeding to the next stage of its lifecycle.

6.3.1 Formal Review Process

Formal reviews should be managed in the following sequence:

a) A review plan is agreed with the Project Office, sufficiently ahead of the review in time to allow panel members to participate. The review plan should identify
    a. Scope and purpose of the review
    b. Panel charge
    c. Panel composition and panel chair
    d. Location and date of the review

e. Participants, roles and responsibilities
f. Review documentation list and identification of baseline documents

b) Documents are reviewed internally by the team and by quality assurance to ensure that the documentation is on a good level of quality.
c) Documents and RIDS are released to all panel members and reviewers ahead of the review to allow sufficient time for reviewing the documents.
d) If the review involves a large number of documents, the documents should be released with an overview sheet with links to all the documents and RIDS via one spreadsheet – the spreadsheet should give a clear structure of the documentation and indicate which documents are for context and which are for review.
e) Panel members and reviewers review the documents and list all observations in the RIDS.
f) The project team responds to the observations in the RIDS and identifies specific observations that require discussion at the review.
g) The panel chair communicates to the team ahead of the review specific topics that should be included in the agenda.
h) The review agenda is agreed with the panel chair and should include time to discuss specific topics identified by the chair and unresolved observations.
i) The panel chair chairs the review meeting and at the end of the meeting provides a feedback session summarizing the outcome of the review.
j) At the end of the review, all actions should be agreed, or there should be a clear plan of how to resolve all the unresolved observations.
k) The panel issues a review report summarizing the main outcomes of the review, typically a few weeks after the review meeting.

Formal Reviews should have either one of the following outcomes:

a) Unconditional pass: the team can proceed with implementation of the agreed actions. No further interaction with the panel is required.
b) Conditional pass: a small number of critical items have been identified and need to be corrected. The panel will reconvene (usually via teleconference) to evaluate additional information or updated documentation addressing the specific high-risk items before declaring the review a pass.
c) Fail: there are significant deviations from the scope of the review or high-risk items. The review should be repeated with the panel at a future date after the issues have been dealt with.

6.4 Baseline Management

Technical baselines are an important mechanism to manage changes following a major review. After each major review, a subset of the reviewed documents is identified as "baseline documents". These baseline documents are updated with inputs received at the review, approved and then together form a "baseline" or stable foundation for the following phase of engineering work (see Section 6.2 for the transition process between phases). The baseline is an approved set of documents with specific revision numbers. Changes to the baselined documents are managed formally through the change management process (see Section 6.7) as defined in the Configuration Management Plan [AD03]. All changes to baselined documents shall be traceable to a ECR or CN (See Section 6.7).

6.5 Requirements Traceability

Maintaining traceability of requirements through the product structure is a high priority SE process. Requirements traceability ensures that all the user requirements are covered and that there are no gaps

in the design of components. It also ensures that the verification process is complete and enables a thorough assessment of the impact of changes. Figure 6 shows the different types of requirements traceability that should be maintained in the product structure.

a) A set of requirements is defined for each Development Item in the PBS. These requirements govern the design and verification of the item. Traceability of requirements needs to be maintained across the vertical hierarchy of the Development Items to ensure the completeness and non-redundancy of requirements at the various levels. This is defined here as the "contractual" requirements traceability (black items in Figure 6). The contractual requirements traceability shall be maintained formally in a requirements management tool. Baselining of requirements shall be done at least on the requirements documents. It is preferable to also have a mechanism of baselining requirements in the requirements management tool to manage changes to baselined requirements.

b) The architectural design of a product defines how its requirements are broken down into lower level requirements and how the functional architecture satisfies functional requirements. This includes performance budgets and functional decomposition, but generally includes the breakdown and allocation of all requirements through a design process. For software systems, the traceability between functional requirements and functional architecture is particularly important. The logic of this breakdown and allocation of requirements is defined here as the "analysis" requirements traceability (blue items in Figure 6). It is not mandatory that the traceability between the design and the requirements be traced formally in a database tool, but shall at least be captured in the compliance matrix at the design review. The compliance matrix shows how each requirement is addressed in the design by referencing the relevant section(s) in the design documentation.

c) The verification of an item is derived from its requirements specification, and the traceability between the requirements and verification method should be maintained to ensure that the verification completely covers all requirements. This traceability is defined here as the "verification" requirements traceability (green items in Figure 6). The method of verification (Analysis, Inspection, Test or Demonstration) is indicated in the specification document. Traceability between the verification procedures and the requirements shall be captured in the verification procedure documents.

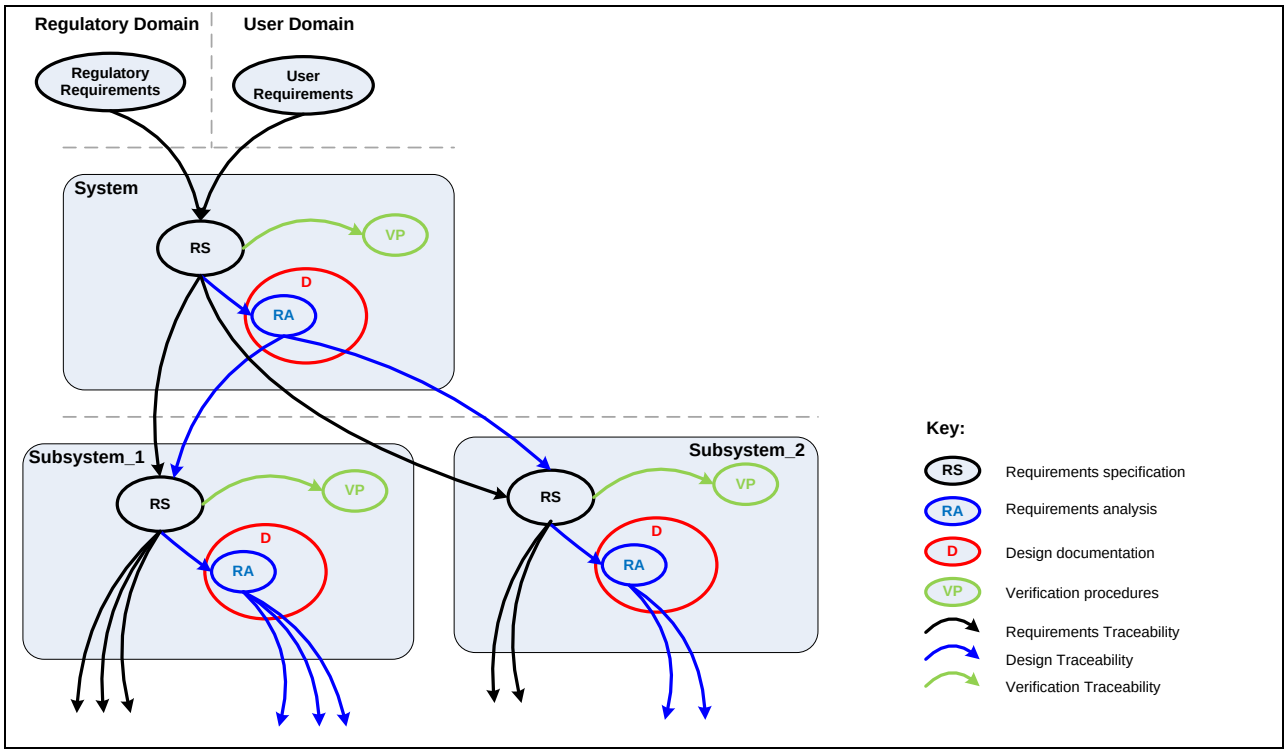

Figure 6: Requirements Traceability

6.6 Configuration management

Configuration Management (CM) ensures that the configuration of the system is managed over the entire life of the product.

"Configuration" refers to all the technical data that is associated with all items in the PBS. The PBS forms the structure of the configuration. The configuration data of an item includes its specifications, designs, models, verification data, manufacturing data, as-built information, software and user and operating instructions. For serial production items, the configuration includes all the serialized item data.

"Management" refers to the control of the configuration data to ensure that:

a) Configuration items and documents are identified and numbered according to the agreed standards and in line with the PBS.

b) All changes to the structure of the configuration, configuration data or baselines are controlled in line with the approved change management procedures, roles and responsibilities.

c) Versions are managed for all configuration items, documents, drawings and other versioned configuration data according to change management procedures.

d) The latest approved set of configuration data is accessible to all authorized project participants.

e) All concessions are managed according to the concession procedures.

CM embraces the elements of order, discipline, and control to issue numbering, prevent unauthorized changes and expedite implementation of valid changes. The CM process described in the Configuration Management Plan [AD03] provides a flexible and comprehensive methodology for the ngVLA Project Team to manage and control system configuration. Document management, which is a subset of CM, is described in more detail in the ngVLA Document Management Plan [AD02].

The CM Plan incorporates five interrelated functions which, when collectively applied, maintain consistency between the physical as-built system and the information relating to the system throughout development, design, assembly and integration, testing, construction, operations and maintenance, and retirement. The five CM functions are:

a) Configuration Identification
b) Configuration Management
c) Configuration Change Management
d) Configuration Status Accounting
e) Configuration Verification and Audit

A suitable configuration management tool should be acquired for the project that can support these functions.

6.7 Change management

The change management function involves managing changes to the approved system configuration for a subsystem/product, using a structured process. The configuration change management function applies to all layers of the PBS hierarchy and to all of the ngVLA System Lifecycle Model stages. The Configuration Management Plan [AD03] defines the detailed procedures for change management. A summary is provided in this section.

The purpose of the change management process is:

a) To evaluate whether a proposed change is necessary and adds value to the project.

b) To evaluate the full technical and programmatic implications of the change.

c) To ensure the involvement of all affected stakeholders in the process of approving and implementing the change.

d) Assign responsibilities for implementing the change.

e) If approved, to ensure that the change is implemented completely and within the agreed timeframe.

All changes to baselined documents or product configurations shall be implemented through a controlled change management process, as defined in the Configuration Management Plan [AD03], either through a Engineering Change Notice (ECN) or an Engineering Change Request (ECR). Depending on the scope of the change, an Authority is identified for making the approval decision, with inputs and a recommendation from a change control board.

6.7.1 Engineering Change Notice (ECN)

ECNs are applicable in cases where the impact of the change is limited to the product itself (i.e. it does not affect other products in the PBS at the same or higher level), it is limited to only a small number of

documents, and it has minimal or no impact on cost, schedule or performance. ECNs are an efficient method of implementing small changes, without having to resort to the more formal ECR process.

a) The SE shall maintain an ECN register that defines the current state of all ECNs and associated actions.
b) The CM shall maintain an ECN definition for each change, which includes a motivation for the change, change description and a list of all affected documents.
c) All affected parties shall be notified of the change. If no objections are raised within a set period, the change may be implemented.
d) All ECNs shall be recorded in the configuration management tool and linked to all affected documents.

6.7.2 Engineering Change Request (ECR)

The ECR process applies if a change impacts multiple product items, a large number of documents or if it significantly affects the scope of the project (cost, schedule or scope).

a) The SE shall maintain an ECR register that defines the current state of all ECRs and ECR actions.
b) The ECR shall include: A description of the proposed change; motivation why it is needed; complete impact assessment; list of impacted documents with revision numbers; and a list of actions with responsibilities and dates.
c) The ECR shall be distributed to all affected parties and the configuration manager for input before submission for approval.
d) A CCB shall be constituted to review and approve ECRs.
e) If approved, the responsible CM shall track all ECR actions and shall report the number of uncompleted ECRs.
f) All ECRs shall be managed using the configuration management tool.

6.8 Interface management

Interface management is a high priority SE activity. As the product structure and architectural design develops, the SE identifies a list of interfaces that need to be managed formally. Note that not all interfaces should be managed formally. Interfaces should be managed formally in cases where:

a) The interface is complex and/or presents a risk.
b) The interface crosses organizational boundaries (either across organizations or across teams within one organization).

ICDs are sometimes developed over time and details of the interface are added as the details of the items on either side of the interface emerge. A typical pattern of such an ICD development is shown in Figure 7.

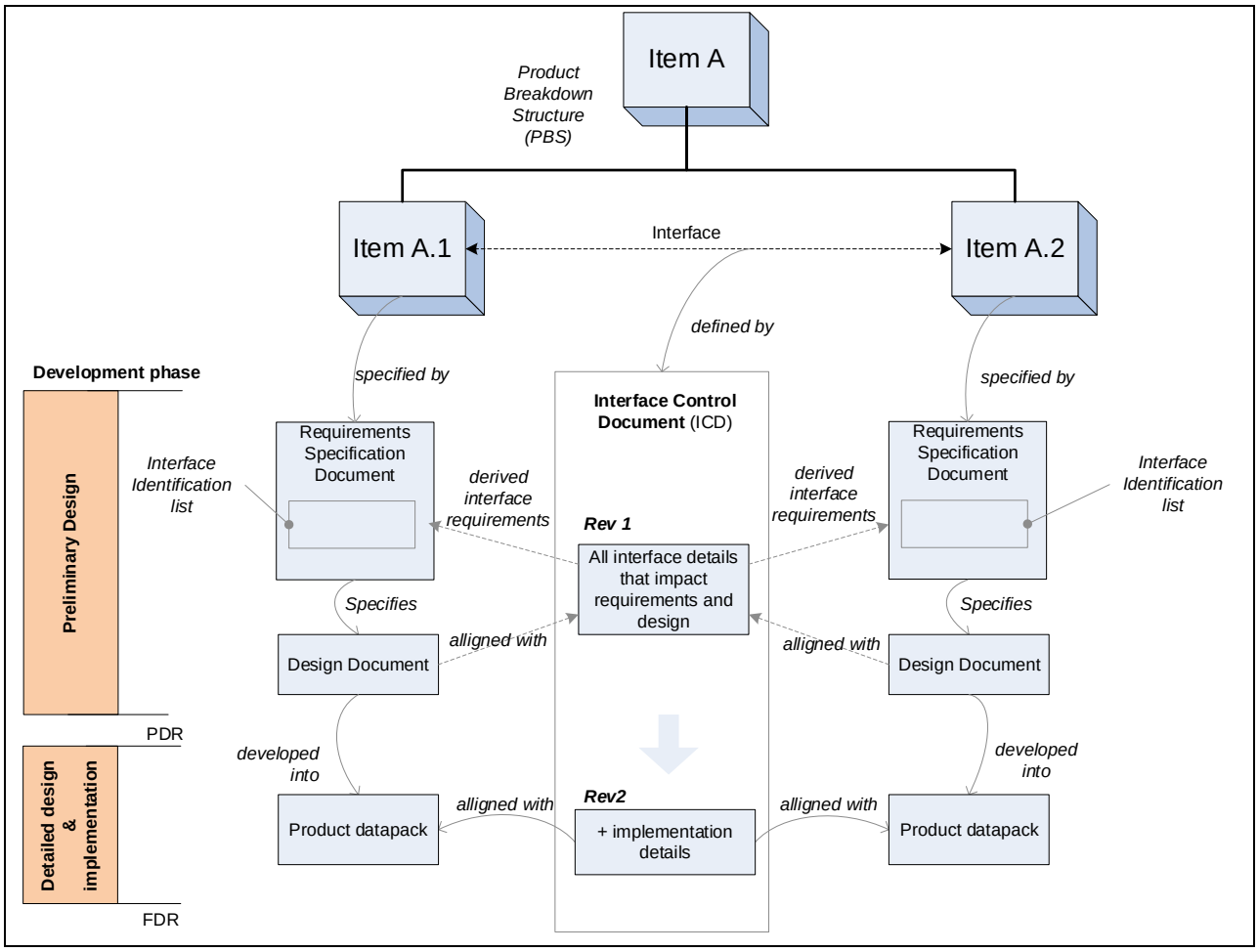

Figure 7: ICD development

During the preliminary design, interfaces are identified and the requirement-driving interface definitions are captured in the first revision of the ICD. This ICD is used to derive interface requirements for the interfacing items (Item A.1 and A.2 in Figure 7). The final implementation detail is sometimes only added to the ICD during the detail design phase (e.g. detailed interface drawings for mechanical interfaces), or during the implementation phase (e.g. data items flowing across software interfaces).

ICDs should only contain interface definitions and not interface requirements. Interface requirements should be derived from the ICD by the interfacing item engineers and stated in the requirements specifications of product items, where they can be managed, traced and verified. Interface requirements have been omitted from ICDs because this causes problems with requirements ownership, traceability and verification. Interface definitions shall have a unique number identification to allow traceability between interface definitions and derived requirements.

The following interface management principles shall apply on the ngVLA project:

a) The SE responsible for the interface (SE of Item A in Figure 7) shall identify a list of interfaces that require formal management during the preliminary design phase.
b) The responsible SE (Item A) shall facilitate the writing of ICDs for all the identified interfaces, with inputs from the interfacing item SEs (Items A.1 and A.2).

c) ICDs shall not contain requirements, only interface definitions.
d) Interface requirements shall be derived (by each interfacing item SE individually – for Items A.1 & A.2) from ICDs and included in the item Requirements Specifications (which is approved by the higher-level SE – Item A).
e) Verification of the interfacing requirements is the responsibility of the interfacing item SEs (Items A.1 & A.2), as part of their normal requirements verification process.

The responsible SE (Item A) should report the completion status of all ICDs to the project manager on a regular basis.

6.9 Quality Assurance

The Quality Assurance (QA) and Quality Control (QC) processes are documented in the ngVLA Quality Management Plan [AD07]. These processes include product quality assurance, review protocols, quality constraints placed on deliverables from vendors and partner institutions, incoming inspections on procurements, programmatic and project process audits, vendor audits, IPT workflows, and other quality-related processes. Quality processes have two priorities: assure the quality of the deliverables, and assure the quality of processes used to produce the deliverables.

Product Assurance is a subset of the Quality Assurance activities. Product Assurance specifically focuses on the quality aspects of the product, whereas the Quality Assurance includes the wider organizational functions (finance, supply chain, human resourcing, etc.).

Product Assurance shall be overseen by the designated ngVLA Quality Manger and supported by the lead Systems Engineer. The emphasis of Product Assurance varies across project stages and across different technologies as follows:

a) ***Product design and design qualification up to FDR - All subsystems***: Product assurance during this phase is ensured through the implementation of the SEMP supported by rigorous and independent reviews for the CDRs, PDRs and FDRs.
b) ***Industrialization and Production – Contracted items*** (e.g. Antenna): The main responsibility for quality assurance is with the contractor, who shall appoint a quality manager to ensure proper implementation of a recognized Quality Management System (QMS). The quality manager shall ensure implementation of quality management mechanisms for the industrialization and production processes including factory and site activities. The contracted organization shall involve the ngVLA Quality Manager and Systems Engineer in key events such as first article inspection during industrialization and key inspection points during production. Important quality management aspects for the ngVLA specifically include:
    a. Management of tolerances for mechanical parts that drive performance.
    b. Management of mechanical joints and moving parts that are prone to mechanical failure.
    c. Management of workmanship in the implementation of RFI design features (filters, enclosure joints, cable braiding, connectors, etc.)
c) ***Industrialization and Production – In-house developed items***: (e.g. Antenna Electronics & Reference Signals). The responsibility for quality assurance is shared between the IPTs that produce the products and the ngVLA Quality Manager. The IPTs shall develop the required quality management mechanisms and agree these mechanisms at the Production Readiness Review. Important quality management aspects specifically for the ngVLA include:
    a. Implementation of production verification processes that detect latent weaknesses and defects (e.g. environmental stress screening)
    b. Management of workmanship in the implementation of RFI design (filters, enclosure joints, cable braiding, connectors, etc.)

d) ***Construction of infrastructure***: The responsibility of quality assurance lies with the construction contractor and is overseen by the construction management entity. The construction manager will deploy supervisors to oversee the quality of the construction process on an ongoing basis and approve the construction work in phases as agreed in the contract. The construction management entity could either be the ngVLA infrastructure IPT or an engineering consulting firm, but should ensure that it has the necessary supervision skills in the different domains (buildings, roads, foundations, power, HVAC, etc.).

e) ***Software***: The software team will define a Software Quality Assurance Plan, encompassing the following:

- Specific quality assurance and quality control tasks (e.g., review and testing strategies).
- Control of software work products and changes (change and release management, error reporting and tracking).
- Applicable software development standards and procedures to ensure compliance (when applicable).
- Measurement and reporting mechanisms.

These activities will be defined and performed in close collaboration with the Quality Manager.

6.10 Verification and Validation

Verification and Validation are defined in the Defined Terms in Section 11.2.
The purpose of Verification and Validation is to perform an overall evaluation of the system and its subsystems and assemblies. This includes the evaluation of the requirements, design and built systems. The evaluation of built systems includes performing assembly- and component-level testing to verify that detailed design technical requirements have been met, integration testing to verify all subsystem- and system-level interfaces, system-level verification testing to confirm the design meets the system requirements, and validation to ensure the system fulfills its purposes. The strategy and plan for all activities involved in ngVLA Verification and Validation are described in the ngVLA Verification and Validation Plan [AD05].

Verification and Validation occurs throughout all the project phases:

a) Concept Definition Stage:

- The conceptual design is verified for compliance to performance-driving and cost driving requirements by means of analysis and modelling. The viability of the concept, budget and system boundary definition is also verified through peer review at the CDR.
- Validation is continuously performed throughout the concept definition phase through:
  i. Ongoing interaction with the science stakeholders via the Project Scientist.
  ii. Ongoing interaction with funding stakeholders via the Principle Investigator.
  iii. Involvement of the support operations team and CSV team during the CDR.

b) Preliminary Design Stage:

- Requirements are verified for consistency, completeness, accuracy and quality. This is done through the requirements analysis process and through peer review at the PDR.
- The correctness and compliance of the design is verified by means of analysis, modelling and peer review during the preliminary design phase. The design compliance matrix is an important compliance checking tool for the design review.
- Validation of the requirements and design occurs through:
  i. Continuous engagement of the project scientist and involving science representatives as needed.

ii. Involving the support operations team and CSV team during the PDRs.

c) Design Qualification Stage:
- Compliance of the design to requirements should be verified through testing of a qualification model in a representative operational environment, or by inspection or demonstration of the qualification model. Verification through analysis should only be done in cases where testing is not possible, too expensive or impractical.
- Validation during this stage is done through:
  i. Involvement of the project scientist during the testing of the prototype and interpretation of test results.
  ii. Involvement of the support operations team and CSV team during the verification of the prototype to evaluate the design from a supportability point of view.

d) Production Stage:
- Verification during production is mainly a quality assurance function as defined in Section 6.9.
- Validation during this stage is mainly at the system level, where the science commissioning team is heavily involved in the array integration and testing activities.

6.11 Non-compliance management

Non-compliance management applies specifically to serial production items during the production stage.

Up to the FDR, non-compliances of the design are dealt with through ECRs by changing either the design or the specification to resolve a non-compliance.

When the item is in production, the specifications and designs should be regarded as static to avoid the use of different versions or configurations of the product. In cases where the manufactured item has non-compliances to the specification, but is nevertheless deemed acceptable for use, the supplier shall apply to the client (NRAO) for a Concession. Concessions will be reviewed by a Non-compliance Review Board. The review of the Concession may have one of the following outcomes:

a) ***Accepted:*** The items are accepted for use with the non-compliance as stated in the concession request. The concession request shall list all the serial numbers of the items that are affected by the non-compliance. The non-compliance shall be linked to all serial numbers in the configuration management system.
b) ***Rejected:*** The items are not accepted by the client. In this case the supplier shall either:
   a. Discard these items.
   b. Modify the items until they are fully compliant.
   c. Modify the items until they are deemed acceptable for use and apply for a new Concession.

Note that the terms "Waiver" and "Deviation" have been eliminated and replaced by a single term "Concession" to avoid confusion and because these processes do not differ significantly.

6.12 Contractor Management

The Procurement Management Plan [RD14] describes the technical control of suppliers and vendors. This includes the approach and methods to devolve requirements, manage interfaces, control quality, build long-term relationships, and assure participation on integrated teams where appropriate.

All technical development contracts that are placed on external organizations shall be managed according to sound SE principles, in particular:

a) All such contracts shall contain a set of development process requirements that form part of the contractual agreement. These development process requirements should be based on a tailored SEMP for the contracted product.
b) Fulfillment of the development process requirements shall be linked to payment milestones.
c) The contractor shall produce a SEMP that is in line with the development process requirements within two months of project kick-off, to be approved by the ngVLA lead SE.
d) The contractor shall involve the ngVLA Project Engineer and lead SE in all major design reviews as panel members.

6.13 Risk Management

The Project Office is responsible for managing risks on the ngVLA project. The risk management methodology for the Project is based on the standard processes used in project management for risk mitigation. The process uses the following steps:

a) Identify risk issues and concerns.
b) Identify the responsible risk owner, stakeholders.
c) Analyze the risks for their impact and probability, then prioritize them.
d) Decide on the risk treatment and mitigation strategy for top risks.
e) Assign actions to mitigate risk as appropriate.

Risks are controlled by regular reviews and communication to ensure implementation of mitigation plans and actively retirement of risk from the Risk Register.

The Project Manager will capture and manage risks on the project with support from the Project Engineer, Systems Engineer and IPT leads. Further detail on the risk management process can be found in the ngVLA Risk Management Plan [RD12].

6.14 Technical Performance Tracking

Key Performance Parameters (KPPs) represent critical system capabilities or characteristics. KPPs are a critical subset of the performance parameters that are so significant that failure to meet the intended performance value can be cause to reassess the project. KPPs are typically system requirements that are decomposed to key subsystem requirements, which are also treated as KPPs at subsystem level. Each KPP must have a threshold range and objective value. The project team designs the system to meet the objective value; however, performance within the threshold range is considered acceptable. If the developer of an item finds that a KPP cannot be achieved within the threshold range, he/she shall immediately notify the Project leadership. The KPPs shall be identified in the requirements specification of all development items. The lead Systems Engineer shall ensure that there is traceability for all KPPs through the PBS.

6.15 Technical Readiness Assessment

Technical Readiness Levels (TRLs) are defined in Table 1 to assist project and technical managers in making decisions on system maturity throughout the formal review process and in preparation for external reviews with the customer and major stakeholders. TRLs will be assigned at the subassembly or component levels and be able to be aggregated to the subsystem levels.

Subsystem TRLs can then be aggregated to the system level, resulting in an overall system-level TRL. TRLs are especially useful when new technological innovations are selected as part of a design that carries inherent complexities and risks if they have not been proven in similar systems.

Systems Engineering will work with the Project Engineer and IPT Leads to assign and update TRLs on the component level, as well as agree on a method for aggregating multiple TRLs into a top-level TRL. TRL levels required for major project milestones include:

- Development Stage
  - Reference Design = TRL 4[1]
- Design Stage
  - Conceptual Design Review = TRL 3
  - Preliminary Design Review = TRL 5
  - Final Design Review = TRL 6, 7*
- Construction Stage
  - Infrastructure installation and onsite acceptance tests completed = TRL 8
  - Science validation and commissioning of installed system completed = TRL 9

* System maturity at the time of NSF's Final Design Review will either be at level 6 or level 7, depending on whether an operational environment is permitted and available for testing.

Table 1: Technical readiness levels.

Technical Readiness Level		Description
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component validation in laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component validation in relevant environment.	The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.

[1] Technologies are intentionally required to be in a more advanced state for the Reference Design than the Conceptual Design Review since this is primarily a costing exercise using readily available, low-risk technologies.

6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment (i.e. normal atmospheric conditions). Examples include testing a prototype antenna with astronomical signals.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. Examples include integrated verification testing to determine if it the system meets design specifications.
9	Actual system proven through successful science operations.	Actual application of the technology in its final form and under operational conditions. TRL 9 can only be achieved following completion of Commissioning and Scientific Validation (CSV).

7 Technical Project Organization

The ngVLA Project Execution Plan [RD03] and Project Resource Management Plan [RD05] describe the organization of the project team, including roles and responsibilities for each position. Note that these documents supersede the SEMP from the standpoint of the organizational structure. The ngVLA RACI Matrix [RD06] provides details on which personnel are responsible [R], accountable [A], consulted [C], or informed [I] for various tasks within the project.

The technical portion of the project team consists of the following personnel and groups.

7.1 Lead Systems Engineer

The Lead Systems Engineer has the overall responsibility for managing the Systems Engineering team and the processes and activities outlined in this document. The Lead SE will oversee the implementation of the ngVLA System Lifecycle (Section 4) and supporting processes to ensure the technical aspects of the project is managed efficiently and effectively.

The Lead SE will have overall responsibility and oversight from a process perspective for facilitating requirements management and system design activities, testing activities, providing quality control for systems engineering and other technical project documentation. The Lead SE will work with the Project Team to ensure timely completion of ngVLA deliverables in accordance with project's internal formal review and release processes. By owning the design/development processes, the SE team will ensure that the design embodies systems engineering best practices, to include:

a) minimizing and simplifying interfaces;
b) clear/concise hierarchically structured requirements;
c) consistency and conformity with the science goals and use cases; and
d) ensuring the design can be properly integrated, verified, validated and delivered to meet the stakeholders' needs.

The Lead Systems Engineer will work in close coordination with the Project Engineer and Project Scientist to deliver an optimal system solution.

The Lead Systems Engineer will manage the technical product baseline process, including the integration and coordination of updates and changes to the technical product baseline.

The lead SE will also be a major technical stakeholder in the review/approval process for the sub-system level design, and verification.

Additional responsibilities include the following:

a) Facilitating cross-functional collaboration and coordination
b) Working with the Project Engineer to resolve system-wide engineering and technical issues
c) Reviewing project technical documents and designs for accuracy and consistency
d) Participating in, and chairing as appropriate, internal design reviews

7.2 Systems Engineering Team

The systems engineering team supports the Lead Systems Engineer and is responsible for executing the following lifecycle activities:

a) Performing system-level requirements definition, decomposition and management activities
b) Documenting and managing the system-level architecture.
c) Defining and tracking the project KPPs.
d) Planning and overseeing integration, verification, validation and commissioning activities.
e) Planning and executing system integration and verification test activities.
f) Actively participating on Integrated Product Teams (IPTs) to help document and analyze designs, and to execute and oversee formal testing activities.
g) Leading and participating in formal design reviews and document reviews.

The Project Resource Management Plan [RD05] contains information on staffing management and hiring efforts for the project. New personnel in project office and technical support roles will require training on systems engineering tools, methods, and procedures to ensure compliance with the approach being used on the ngVLA project and NRAO systems engineering policies. The Lead Systems Engineer will create a training plan for all applicable personnel that is tailored to each role. At a minimum, this will include a thorough understanding of the SEMP and subordinate documents.

7.3 Project Engineer

The Project Engineer provides engineering subject matter expertise to the project development, system design, documentation, project office, and proposal activities. The Project Engineer is responsible for the technical definition and delivery of ngVLA system design materials. The Project Engineer is also responsible to generate the initial performance budgets, after which the performance budgets will be transferred to and managed by the SE team. The Project Engineer will evaluate the technical impact of changes as part of the change management process. The Project Engineer will act as an important stakeholder to the IPTs and will perform technical coordination with the project teams to facilitate timely completion of design deliverables. The Project Engineer acts as a liaison between the ngVLA project office and the ngVLA Technical Advisory Committee (TAC).

7.4 Integrated Product Teams (IPTs)

The IPT Leads will own the detailed subsystem-level designs. The ngVLA Project Execution Plan [RD03] contains information on the membership and conduct of IPTs within the project.

Each IPT will identify a person as the systems engineering representative for the IPT. The role of the IPT systems engineering representative will be to ensure the work done by the IPT is executed in line with this SEMP. The IPT systems engineering representative will interact with the Lead SE as a contact person for all SE related activities in the IPT.

As part of this role, the systems engineering representative will help the IPT to define the subsystem requirements, architecture, interfaces, track KPPs and oversee the planning and execution of integration and verification activities.

The IPT systems engineering representative will have the ability to escalate design and test issues that impact the greater ngVLA system as needed to the attention of the Lead Systems Engineer and Project Engineer.

7.5 Quality Team

The Quality Team is responsible for developing, implementing and enforcing the ngVLA Quality System and for guiding the ngVLA project staff that have Quality Assurance/Quality Control (QA/QC) responsibilities. Quality personnel shall also participate on IPTs as appropriate. More information on QA/QC processes and activities can be found within the ngVLA Project Execution Plan [RD03] and the ngVLA Quality Management Plan [AD07]. The Quality Team will be led by a ngVLA Quality Manager. The ngVLA Quality Manager should have reporting structure that is independent of the project execution reporting line and should report directly to the Project Director.

7.6 Technical Advisory Committee (TAC)

The TAC is the interface between NRAO and engineering and computing experts within the radio astronomy community who will provide feedback and guidance during the design of the ngVLA. Their charge includes, but is not limited to:

a) Consulting with the computing and engineering communities to provide advice to the ngVLA Project Office on technical issues related to the ngVLA design.
b) Reviewing and commenting on technical designs.
c) Helping translate science requirements into technical requirements.
d) Providing recommendations on technical design options.

7.7 Technical Subcontractors

Subcontractors will be involved at various stages of the project and may contribute to IPTs as subject matter experts.

7.8 Project Scientist

The Project Scientist provides scientific subject matter expertise to the project and supports use case development, scientific requirements, documentation, and proposal activities. The Project Scientist will be responsible for the scientific definition, evaluating impact of changes in scientific definition or scope, and facilitating interactions with the ngVLA community. The Project Scientist will participate in formal reviews where he fulfills a critical role of validating the requirements and designs.

7.9 Project Manager

The Project Manager will participate in all formal reviews to ensure that the project management aspects (scope, cost, schedule, risk, etc.) of the project are adequately addressed at the reviews. The Project Manager will ensure that the project planning documents are aligned with the SEMP. Specifically, the Work Breakdown Structure, Statement of Work and Schedule should be clearly aligned with the Life Cycle Plan. The Project Manager shall be involved on the Change Control Board and is a decision stakeholder for all changes that impact scope, cost or schedule.

7.10 Project Director

The Project Director is the final decision-maker on the project and should be involved in any decisions that impact significantly on performance, scope, cost or schedule. For all formal internal reviews, the Project Director has discretion on acceptance of the review outcome and determining next steps.

8 SE Tools and Models

8.1 Model Based Systems Engineering (MBSE)

MBSE is a tool and methodology that helps the SE to manage some (but not all) of the SE information. MBSE provides a means to manage multi-dimensional system information in a database. The system information can be viewed from different perspectives, while maintaining a single source of truth for the information that is used consistently throughout all the different views.

The MBSE tool should be used to define the following:

a) Product hierarchy for all architectural items identified in the PBS.
b) Definition of requirements for all development items identified in the PBS.
c) Traceability of all requirements through the PBS for development items.
d) Identification of interfaces and ICDs between all interfacing items identified in the PBS.
e) Functional model: Hierarchical functional model of the System and allocation of the functions to development items and functional requirements.
f) Verification Traceability: traceability between requirements and verification requirements and verification procedures for all development items.

The MBSE tool should be used to facilitate the following SE management functions:

a) Managing all requirements from stakeholder to subsystem requirements.
b) Generating requirements specifications.
c) Generating requirements traceability matrixes.
d) Generating artifacts required for architectural design and documentation (e.g. context diagrams, functional flow block diagrams and interface diagrams).
e) Definition of functional interfaces.
f) Evaluating the impact of changes to requirements or architecture.
g) Generating verification plans.

9 Logistics Engineering

A maintenance and support system shall be developed concurrently with the development of the prime equipment (telescope), to ensure that the necessary support can be provided to the telescope throughout the integration, verification and operational stage (as soon as the products are accepted by

the observatory). This will be achieved by the management of specific activities of design and development (logistic engineering activities), in close coordination with the other system engineering activities.

The support system should be designed to be cost effective while maintaining high system availability and safe operation. The details of the logistics engineering effort shall be described in a separate Logistics Engineering Management Plan [AD09].

Important interactions between the logistics engineering and systems engineering activities include:

a) Requirements analysis: Definition, analysis and allocation of RAM requirements.
b) Design: Design influence to ensure that the product is easy to maintain and has sufficiently high reliability to support the operational budget and can meet the availability requirements.
c) Qualification phase: Data pack definition and preliminary physical configuration audits.
d) Production / Construction phases: final physical configuration audits.
e) Final acceptance review: establishment of the operational support baseline.

Logistics Engineering includes the management of Reliability, Availability and Maintainability as defined in the following sections.

9.1 Availability

Operational availability is the proportion of time that the system is available for its intended end use. One of the key requirements of the system is to have a high operational availability.

The system requirements for operational availability and how this translates to system and subsystem requirements is defined in [RD15].

9.2 Reliability

Reliability of a system or component is the probability that it can perform its intended function without failure or maintenance for a specified time period, under stated conditions.

High reliability is important for two reasons:

a) It impacts on the operational availability if failures are critical.
b) It impacts on the maintenance workload and thus on the operational cost.

System reliability requirements are derived from the operational availability and operational cost requirements as defined in [RD15].

During the Preliminary Design phase, the reliability of the subsystems are derived through a process of Failure Modes and Effects Analysis (FMEA) analysis. The purpose of FMEA analyses is to identify potential failures and determine how to preventively address them in the design, if possible. If failures cannot be "designed out," then their effect is included in the system reliability budget.

9.3 Maintainability

Maintainability of a component refers to how easy it is to maintain. Components that need regular maintenance should be designed to be easily repaired.

Maintainability is important because it impacts on the maintenance workload and thus on operational cost.

In the field maintenance is more expensive due to the remote location of some equipment and due to the more difficult working environment. For this reason, wherever possible, field maintenance should be achieved through remove and replace mechanisms with easy access. For remote equipment, automated maintenance mechanisms should be considered during design (e.g. automatic lubrication). Maintainability will be reviewed as part of the design review process.

10 Safety

The plan and approach for safety, including personnel safety and training programs, across the project will follow the guidelines contained in the AUI Environment, Safety, and Security Program Manual [RD13].

10.1 Functional Safety

The objective of Functional Safety is to ensure that the system is designed to be safe to construct and operate. Functional Safety ensures that safety risks are adequately identified, assessed, minimized, and accepted during the design phase. Functional Safety is implemented by applying a safety program at the system level which ensures that:

a) Safety requirements, including safety regulations, are identified.
b) Safety requirements are implemented in the design.
c) Hazards are identified during the design process and categorized using the mishap risk assessment defined in [RD16]. All hazards categorized as "High" or "Serious" shall be eliminated or, where this is not possible, minimized and mitigated through operational procedures.
d) Safety controls are adequately implemented in the verification plan.

11 Appendix

11.1 Abbreviations and Acronyms

Acronym	Description
AD	Applicable Document
AIV	Assembly, Integration, and Verification
ALMA	Atacama Large Millimeter-submillimeter Array
AR	Acceptance Review
AUI	Associated Universities, Inc.
BOM	Bill of Materials
CAD	Computer Aided Design
CCB	Change Control Board
CID	Configuration Item Definition
CM	Configuration Management
CDR	Conceptual Design Review
CSP	Central Signal Processing
CSV	Commissioning and Scientific Validation
DDR	Detail Design Review
ECN	Engineering Change Notice
ECR	Engineering Change Request
EMC	Electromagnetic Compatibility
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FDBL	Final Design Baseline
FDR	Final Design Review
HVAC	Heating, Ventilation and Air Conditioning
ICD	Interface Control Document
IPT	Integrated Product Team
IRR	Industrialization Readiness Review
KPP	Key Performance Parameter
MBSE	Model-Based Systems Engineering
MeerKAT	MeerKAT Karoo Array Telescope
MREFC	Major Research Equipment and Facilities Construction
MTBF	Mean Time Between Failure
ngVLA	Next Generation VLA
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
PBS	Product Breakdown Structure
PBL	Production Baseline
PCA	Physical Configuration Audit
PDBL	Preliminary Design Baseline
PDR	Preliminary Design Review
PRR	Production Readiness Review
QA	Quality Assurance

QC	Quality Control
QMS	Quality Management System
RACI	Responsible, Accountable, Consulted, Informed
RAM	Reliability, Availability and Maintainability
RD	Reference Document
RF	Radio Frequency
RFI	Radio Frequency Interference
RIDS	Review Item Discrepancy Sheet
RVTM	Requirements Verification Traceability Matrix
SAC	Science Advisory Committee
SE	Systems Engineer
SEMP	Systems Engineering Management Plan
SKA	Square Kilometer Array
SME	Subject Matter Expert
SRR	System Requirements Review
StRR	Stakeholder Requirements Review
TAC	Technical Advisory Committee
TBD	To Be Determined
TPM	Technical Performance Measure
TRL	Technical Readiness Levels
TRR	Test Readiness Reviews
VLA	Jansky Very Large Array
WVR	Water Vapor Radiometer

11.2 Defined Terms

Term	Definition
Baseline	A baseline is a reference point in a product's development life cycle defined by an approved set of versioned documents. The objective of a baseline is to reduce a project's vulnerability to uncontrolled change by fixing and formally change controlling the set of documents after a major review.
Concession	A specific written authorization by the client to accept an item from a manufacturer which, during verification, is found to depart from its specified requirements, but nevertheless is considered suitable for use, either permanently or for a specified time period.
Configuration Item	A component of the system that is identified in the Product Breakdown Structure and that requires the management of its configuration data.
Configuration Item Definition	A document that identifies the complete set of data that defines a Configuration Item.
Physical Configuration Audit	The formal examination of the as-built configuration of a configuration item against its approved configuration data.
Product Breakdown Structure	A list defining the hierarchical decomposition of the Configuration Items of a product.
Qualification	An instance of Verification that is applicable for physical items that will go into serial production. Qualification is the verification of a product's design to ensure that it meets all its requirements, before industrializing the product. The evidence shall include tests results from a qualification model that is representative of the final design, tested in a representative operational environment.
Validation	Confirmation, through the provision of objective evidence, that the system and/or its design meets the needs of the stakeholders. It answers the question: "Was the right system built?" This activity spans the full development life cycle.
Verification	Confirmation, through the provision of objective evidence, that a system and/or its design meets its specified requirements. Verification is performed at each level of the system hierarchy. It answers the question: "Was the system built right?" This activity spans the full development life cycle.

020.10.00.00.00-0001-C-PLA-SEMP

Final Audit Report 2022-01-30

Created:	2022-01-18
By:	Thomas Kusel (tkusel@nrao.edu)
Status:	Signed
Transaction ID:	CBJCHBCAABAA4C3-Rue7J0uCy_B8CJ9P9nUPSvJ8ujb3

"020.10.00.00.00-0001-C-PLA-SEMP" History

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