Preliminary System Architecture Description

020.10.20.00.00-0002 REP

Status: **Released**

PREPARED BY	**ORGANIZATION**
R. Hiriart, T. Kusel, P. Kotzé, M. Archuleta, R. Selina	ngVLA, NRAO

APPROVALS	**ORGANIZATION**	**SIGNATURE**
P. Kotzé Systems Engineer	ngVLA, NRAO	Pieter Kotzé Pieter Kotzé (Jul 16, 2024 10:32 MDT)
E. Murphy Project Scientist	ngVLA, NRAO	Eric J. Murphy
R. Selina Project Engineer	ngVLA, NRAO	Rob Selina (Jul 16, 2024 12:58 MDT)
W. Hojnowski Project Manager	ngVLA, NRAO	William Hojnowski William Hojnowski (Jul 16, 2024 15:37 MDT)

RELEASED BY	**ORGANIZATION**	**SIGNATURE**
W. Esterhuyse Project Manager	ngVLA, NRAO	

Change Record

Version	Date	Author	Reason
1	2022-05-10	Kusel, Hiriart, Archuleta	First draft for internal review.
2	2022-06-03	Kusel, Hiriart	Update after informal review, based on RIDS.
A	2022-06-06	Kusel, Hiriart	First released version for System CDR.
A.1	2022-08-20	Kusel, Hiriart	First Baselined version, updated after System CDR, based on the review RIDS.
B	2022-09-02	Archuleta	Minor formatting edits; prepared document for release.
B.1	2024-04-02	P. Kotzé, R. Hiriart	ECR-0002 ECS chiller transfer of responsibility ECR-0005 Update of CSS architecture
C	2024-07-12	P. Kotzé, R. Hiriart, R. Selina	Minor corrections and edits for release.

Table of Contents

List of Figures

1 Introduction

1.1 Scope and purpose of this document

This document defines a preliminary architecture of the ngVLA system. The architecture is consistent with the system conceptual design [AD07], which is based on the system requirements as defined in [AD08].

This document represents a preliminary definition of the architecture at the time of the System CDR. It will evolve into a full system architecture definition during the preliminary design phase, to be baselined as a mature design at the time of the System PDR.

The scope of this preliminary system architecture document includes:

a) Definition of the system structure and how it is decomposed into subsystems and lower level parts.

b) Identification of system interfaces that require formal interface management.

c) Definition of the overall functionality and behavior of the system and how it is decomposed into subsystem functions.

This document defines the boundary and scope of each subsystem. This allows each subsystem team to independently develop their detailed designs, while ensuring that the overall system can be integrated successfully and that the integrated system will meet the requirements.

A further purpose of the system architecture definition is to harmonize the system development and the software development. For this purpose, it was decided to build a single System Model that is shared between the System team and the Software team. The System Model is defined using the SysML language and is implemented using the Cameo Systems Modeler tool. The System Model serves as the authoritative source for the system architecture.

This document gives an overview of the system architecture, but in some instances, the details are included in reference documents and in the System Model.

2 References

2.1 Applicable Documents

The following documents are applicable to this document to the extent specified and take precedence over this document. If not stated otherwise, the latest released version of the document in the repository is applicable.

Ref. No.	Document Title	Document Number
AD01	ngVLA Systems Engineering Management Plan	020.10.00.00.00-0001 PLA
AD02	ngVLA System Architecture Modeling Plan	020.10.20.00.00-0003 PLA
AD03	ngVLA Product Breakdown Structure	020.10.20.00.00-0004 DSN
AD04	ngVLA N-squared matrix	020.10.40.00.00-0001 DWG
AD05	Antenna Electronics Block Diagrams	020.30.00.00.00-0005 BLK
AD06	ngVLA Observing Modes Framework	020.10.05.05.00-0005 PLA
AD07	ngVLA System Conceptual Design Report	020.10.20.00.00-0001 REP
AD08	ngVLA L1 System Requirements	020.10.15.10.00-0003 REQ
AD09	ngVLA Stakeholder Requirements	020.10.15.01.00-0001 REQ
AD10	ngVLA System Concept Options and Trade-offs	020.10.25.00.00-0005 REP

2.2 Reference Documents

The following documents are referenced within this text or provide supporting context.

Ref. No.	Document Title	Document Number
RD01	ngVLA Configuration Management Plan	020.10.10.15.00-0001 PLA
RD02	Antenna to Antenna Electronics ICD	020.10.40.05.00-0011 ICD
RD03	ngVLA Calibration Plan	020.10.25.00.00-0006 PLA
RD04	ngVLA Monitoring and Control Concept	020.50.25.00.00-0002 DSN
RD05	Size-of-Computing Estimates for ngVLA Synthesis Imaging	ngVLA Comp. Memo #4
RD06	CASA Next Generation Infrastructure: https://cngi-prototype.readthedocs.io/en/stable	
RD07	High Performance Gridding	ngVLA Comp. Memo #5
RD08	Baseline HPG runtime performance for imaging	ngVLA Comp. Memo #7
RD09	Observing Modes Calibration Strategy	020.10.05.05.00-0006 PLA
RD10	Observing Modes Framework	020.10.05.05.00-0005 PLA
RD11	ngVLA Data Processing Concept	020.50.55.00.00-0001 DSN
RD12	A Notional Reference Observing Program	020.10.15.05.10-0001 REP
RD13	Amdahl GM (1967) Validity of the single-processor approach to achieve large scale computing capabilities. AFIPS Joint Spring Conference Proceedings 30 (Atlantic	

Ref. No.	Document Title	Document Number
	City, NJ, Apr. 18–20), AFIPS Press, Reston VA, pp 483–485.	
RD14	Gustafson (May 1988) Reevaluating Amdahl's law. Commun ACM, 31(5):532–533.	
RD15	Baseline-dependent averaging in radio interferometry, Monthly Notices of the Royal Astronomical Society, Volume 476, Issue 2, May 2018, Pages 2029–2039.	https://academic.oup.com/mnras/article/476/2/2029/4855945

3 Overview

3.1 System Architectural Elements

The system architecture is defined by the following elements:

1) **Structural architecture**, which includes:
   a. **Product structure**: defines how the system is decomposed into subsystems and lower level parts. The product structure is the primary structural definition for the system architecture. All other architectural elements are subordinate to the product structure.
   b. **Interfaces**: define the boundaries between items identified in the Product Structure. The interface definition includes the physical boundary and the flow of information, materials and energy across the boundary.
   c. **Physical structure:** defines the purely physical/mechanical view of the system and its decomposition. This perspective is important for parts of the system that have significant physical constraints or complex physical decomposition, such as the Antenna and Antenna Electronics.
2) **Functional architecture:** defines the overall functionality and behavior of the system, a hierarchical breakdown of the system functionality, relationships between functions and allocation of functions to products.

Although requirements are not considered to be an element of the system architecture, the relationship of the requirements to the architectural elements are important and are addressed in this document. The relationship between requirements and the architectural elements is defined and controlled in the System Model.

3.2 Roadmap for development of the system architecture

The level of detail of the system architecture definition is tailored to meet the needs of the project at the various stages of development. The staged development is defined to (a) support the development life cycle as defined in the SEMP [AD01] and (b) mitigate the high risk / high impact aspects of the architecture early to support a risk-based development.

3.2.1 Product Structure

The Product Breakdown Structure (PBS) is the primary structure for the system architecture. It defines a common reference structure for:

a) Organizational responsibilities: Responsibility for products in the PBS are allocated to organizational entities for their design, development, construction, operation and maintenance.
b) Product documentation and data: all documentation and data generated throughout the life cycle of the system (requirements, design documents, test reports, maintenance manuals, production data, etc.) is associated with specific items in the PBS.
c) Requirements decomposition and performance budgets: The structure for the decomposition of requirements and budgets follows the same structure as the PBS.
d) Architectural elements: such as interfaces, physical structure, allocated functions and behavior are associated with specific products identified in the PBS.

Scope: The scope of the PBS includes the complete hierarchy of the system, from the observatory level down to component level at which the components are procured as off-the-shelf items. However, the system architecture is defined by a subset of the products in the PBS, classified as type "Subsystems" as described in Section 4.3. This subset of products that are used to define the architecture are identified in the PBS.

The staged development for the PBS is defined as follows, in line with the SEMP [AD01]:

a) **System CDR**: The PBS should be developed to at least one level below the Subsystem level, so that the system architecture up to Subsystem level can be defined. Following the CDR, the PBS should be baselined for all architecture significant items.
b) **System PDR**: The PBS can remain at the same level as defined for the system CDR.
c) **Subsystem PDRs**: The PBS should be developed to a level of detail that complements the detailed design of each subsystem, at the time of its PDR.
d) **Subsystem FDRs**: The PBS should be fully developed to leaf level (procured items or manufactured items) and a preliminary physical configuration audit should be completed on the qualification prototype to verify the detailed PBS.

There are a number of factors that drive the design of the PBS:

a) At the upper levels of the PBS, its structure is determined mainly by a functional and domain-specific grouping (mechanical, cryogenic, RF, timing, etc.). This allows for the allocation of such high-level products or "subsystems" to be allocated to domain specialists who can design functionally coherent and performant subsystems.
b) The development of these high-level products should not only be driven by the division of design labor, but also by the envisaged contracting boundaries downstream for production / construction.
c) The structure of the PBS is also driven by the desire to keep the interfaces between subsystems as simple as possible.
d) At the lower levels, the structure is often determined by physical decomposition (for hardware systems) or by logical decomposition (for software systems).

3.2.2 Interfaces

Interfaces include all mechanical, electrical, electromagnetic and data exchange (software) interfaces between Subsystems. A system such as a radio telescope has many thousands of interfaces and only a subset of these interfaces is managed formally through the system architecture.

Scope: The formally managed interfaces are limited to interfaces across products that usually coincide with boundaries of organizational responsibility. These are typically subsystem-to-subsystem interfaces, but also include interfaces to all parts that are developed across organizations. The identification of interfaces that require formal management is an important part of the system architecture development. The identified subset of managed interfaces will be defined using Interface Control Documents (ICDs).

The stages of development of interfaces is defined as follows, in line with the SEMP [AD01]:

a) **System CDR**: Identification of all interfaces that require formal management. These are typically Subsystem interfaces.
b) **System PDR**: Completion of the first revision of ICDs for all interfaces identified for formal management. The first revision shall define all architectural aspects of the interface, but may lack implementation details.
c) **Subsystem PDRs**: Completion of the final revision of ICDs, including implementation details.

Development of ICDs involves multiple organizational entities (subsystem teams and/or contractors). The ICD between two parts is owned by the integrating part owner, who coordinates the development of the ICD. The integrating part owner should generate the first draft using a standardized template and including the contextual information from the system model. One of the integrating part design authorities is usually identified as the leading party for the ICD development. The ICD is approved by the design authorities of all the interfacing parts and the integrating part authority. Interfaces should be compliant with and/or re-use existing standards as far as possible.

3.2.3 Physical Structure

Physical structure includes the definition of the physical location of parts in relation to other parts, as well as the routing of physical interconnections between parts (cables and connectors). In radio telescopes, there are thousands of parts and not all physical structures are managed through the system architecture. Only complex physical structures that involve multiple subsystems are defined in the system architecture.

Scope: The definition of physical structure as part of the system architecture is limited to structures with complex layouts involving multiple subsystems, interfaces and shared resource allocation. For the ngVLA this will be limited to the following items:

a) Physical layout of Antenna Electronics for the Main Antenna and Short Baseline Antenna.
b) Physical layout of the equipment in the central electronics building where mixed-use of the facility resources (power, cooling, rack space, etc.) is expected by the central signal processor, computing technical infrastructure and signal reference systems.

The stages of development are defined as follows:

a) **System CDR**: Definition of the physical layout of the Antenna Electronics for the Main Antenna, as the Main Antenna is a risk, cost and schedule driving item.

b) **System PDR**: By system PDR, a baselined and mature physical layout of all items identified in the scope above should be completed.
c) **Subsystem PDRs**: Updates and refinements to align with the final subsystem designs.

3.2.4 Functional Architecture

Functional architecture includes the definition of all functionality required to support the requirements of the Telescope as a whole, broken down into a hierarchy of lower level functions. It also includes major behavioral aspects, such as observing modes and the impact of observing modes on functionality. The functional architecture also defines the major data flows between functions.

Scope: The scope of the functional architecture includes a decomposition of the system functions to a level where functions can be allocated uniquely to subsystems, and the structure of the major functionality of subsystems is clear. Data flow, including control and monitoring to and from these functions should also be identified. Functionality and data flow should be constructed in an architectural model as defined in [AD02].

The stages of development for the functional model are defined as follows:

a) **System CDR**: A comprehensive top-level functional model is developed and at least one level of hierarchy functional definition below the top level. Signal path functions are the highest priority and should be developed to a level where the signal path functional flow is clear and control and monitoring into and out of the signal path is defined. Observing modes should be defined and the mapping of signal flow functions to observing modes should be identified.
b) **System PDR**: A complete functional system functional architecture should be defined for the System PDR, including the full scope as defined above.
c) **Subsystem PDRs**: The system functional architecture should be refined and updated to align with the final subsystem designs as the individual subsystems reach maturity in the build-up to their PDRs.

3.3 System Architecture Model

The System Architecture Modeling Plan [AD02] defines the purpose and scope of the architectural model. The system architecture is modeled using the SysML modeling language, using the Cameo Systems Modeler tool. The model is the authoritative source for the architecture definition. The model is used to define the architecture; manage the system requirements and their relation to the architecture; verify the completeness and integrity of the architecture and to facilitate the management of architectural and requirements changes. The model will become the primary source for requirements and system architecture, with the goal to produce the requirements specifications and system architecture definition from the model.

One of the main reasons for using SysML as a modeling language, is that it can be used as a common framework for both the System team and Software team to develop their respective functional models. The Software team can translate the SysML model to UML and from there drive the software implementation, thus ensuring that it is aligned with the system architecture.

Guidance for the development of the model is provided in [AD02], but an overarching principle is that the diagrams should be simple enough to understand. If the diagram is too complex, it should be decomposed at the higher level (a general guideline is that each diagram should have less than 15 blocks).

3.4 Relationships between architectural elements

The relationships between architectural elements and the requirements in the system model is shown in Figure 1 below. The structural model is based on the PBS and is developed using a decomposition relationship. Interfaces connect different products. Data exchange interfaces transfer data items between products. The functional model is a hierarchical decomposition of functions. Functions are allocated to products through a "performed by" relationship. Functions send and receive data items to/from other functions. Products (with their allocated functions) satisfy the product requirements. Requirements are verified by verification requirements, which are performed at verification events. The verification requirements and events form the basis for verification plans for products.

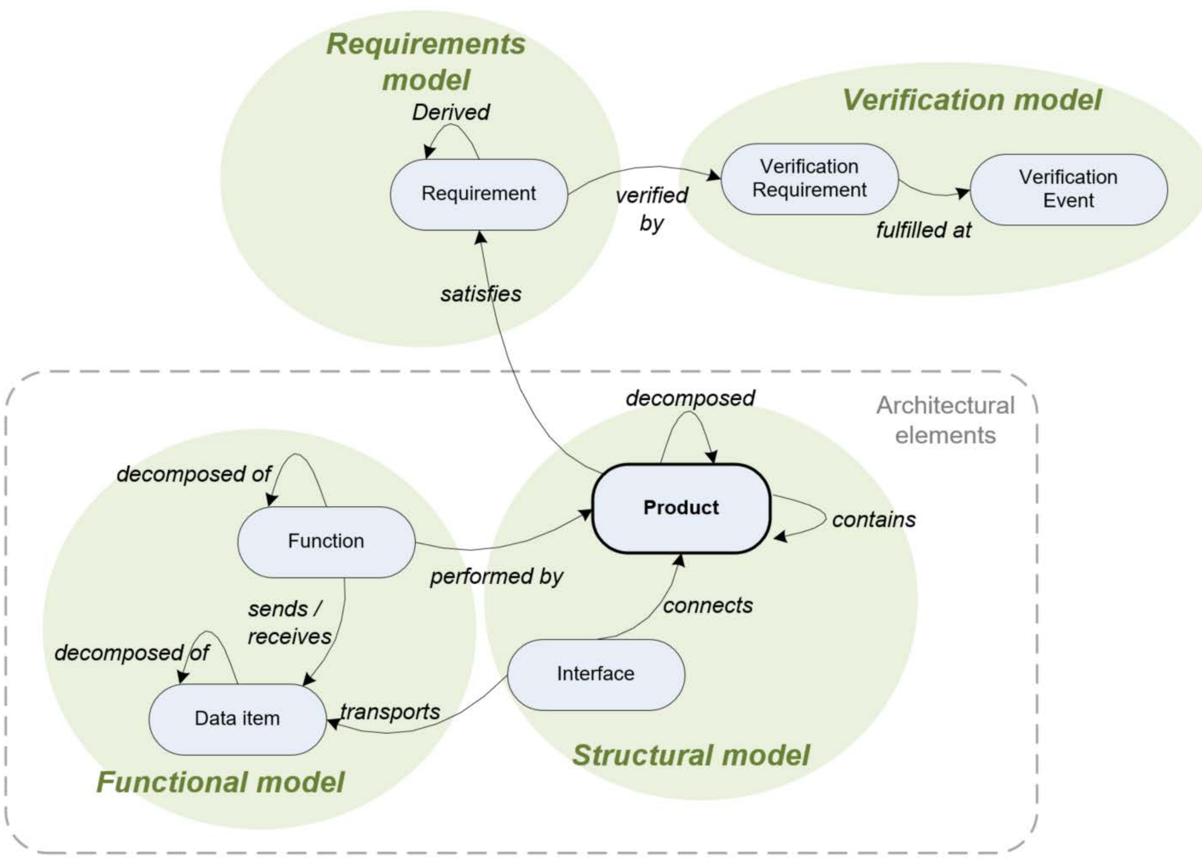

Figure 1: Representation of the system architecture in the system model

4 Structural Architecture

4.1 Product Breakdown Structure

The Product Breakdown Structure (PBS) is the main structure for the system architecture and defines a hierarchical decomposition of the system into parts down to a level of procured parts or manufactured parts.

Each item in the PBS can be treated as a product that is owned by an organization entity, that has a defined boundary of external interfaces and that is associated with a set of engineering data (specifications, design documents, as-built documents and operational documents). For production items, the products are also serialized and versioned. Each item is uniquely identified by name and configuration item number.

The PBS is maintained throughout the life cycle of the system, through development, construction and operations. All design, development, manufacturing and operational data will be stored in the Configuration Management System using the PBS as the organizing structure.

The PBS hierarchy starts at the observatory level and is expanded down to a leaf level where components are procured or manufactured. In cases where complex systems are procured from subcontractors (e.g. Antenna), the supplier product breakdown shall be incorporated into the product breakdown.

The preliminary PBS for the System CDR is defined in [AD03] and is not duplicated in this document.

On the top levels, the PBS is decomposed into the following parts:

a) ngVLA Telescope: is the prime equipment that is to be developed and includes the antenna arrays, central processing equipment, telescope software and telescope infrastructure.
b) ngVLA User Systems: includes operational systems that form part of the observatory, such as the maintenance and support systems, operational IT systems and science user systems.
c) ngVLA Enabling Systems: is software, equipment, tools and facilities that are needed for the development of the prime equipment, including AIV equipment, computing and software development systems and training systems.

A sample layout of the PBS is shown in Figure 2 below:

ngVLA Product Breakdown Structure (PBS) (1 2 3 4 5 6 7 <-- PBS level)	Configuration Item Number 020._	Code	Requirements level	Architecture layer	N^2 interfacing Item	Responsible IPT / WP	Location	CDR Baseline
ngVLA Telescope (Prime Equipment)	01.00.00.00		1	2				.
Main Antenna System	12.00.00.00	18AS		3				.
Main Antenna	25.00.00.00	ANT	2	4	y	ANT	ANT	.
Antenna Electronics	30.00.00.00					AE	ANT	.
Front End	30.05.00.00	FED	2	4	y	AE.FE	ANT.FED	.
Band 1 Front End - F501	30.05.10.00						ANT.FED	.
F511 - B1 Noise diode module								

Figure 2: Sample layout of the Product Breakdown Structure

The PBS represents the system as a multi-layered hierarchical structure. The specific levels (shown here as levels 1-7) intentionally don't have significant meaning or purpose, but are simply used to create a hierarchical structure.

In the upper levels of the product, the hierarchy breaks down through a simple tree structure with one-to-many breakdown relationship. Lower down in the product tree, it also contains many-to-many breakdown relationships because some parts at the lower levels are used by multiple higher-level products (i.e. common parts). A relational database tool is thus required to represent and manage the PBS, including common parts. The full PBS is defined and controlled in the Configuration Management System, which is also used to store all data related to the items in the PBS.

Column I identifies a unique configuration item number for each item in the PBS. The method for allocating configuration item numbers to products is defined in [RD01]. In the upper levels of the hierarchy, the numbers carry some structural information by representing the hierarchy of the system, although this is only for convenience (easy identification of parts by engineers and system users) and not needed to maintain the hierarchy. In the lower levels of the hierarchy, the item numbers carry less meaning and may become semi-randomized.

Column M identifies the subset of items that are used to define the system Structural Architecture, also indicating the level/layer of these items in the architectural hierarchy. The Structural Architecture is defined in section 4. For convenience of reference to components of the Structural Architecture, an abbreviation code is allocated in Column J.

Column N identifies the subset of items in the Structural Architecture that are used for the identification of significant interfaces that are managed formally through ICDs. Interfaces between these items are identified in Section 4.4.

The organizational entity responsible for the development of the items are indicated in column P.

4.2 System Product Breakdown

The product structure and interfaces are defined in this section, with the goal to define the boundaries between subsystems. By doing so, it allows the subsystems to proceed with independent development, while ensuring the integrity of the overall system structural architecture.

4.2.1 Telescope product structure

The Telescope is the prime equipment for the ngVLA and is decomposed as shown in Figure 3 below. It consists of:

1) Three types of Antennas deployed to form the antenna arrays:
    a) 244 identical **Main Antenna Systems**, each with a main reflector aperture diameter of 18m and a full suite of Antenna Electronics to cover the 6 frequency bands. 214 of the Main Antennas will be deployed in a main array distributed across ranges up to 1000km. 30 of the Main Antennas will be deployed in remote locations to form very long baselines (up to ~8860km) in 10 clusters to enable a high angular resolution capability.

b) An array of 19 identical **Short Baseline Antenna Systems** of 6m main reflector deployed in a compact array to fill in the sensitivity of the main array for large angular scales. For the CDR phase it is assumed that the Antenna Electronics for the Short Baseline Antenna is identical to the Main Antenna System, as indicated in the decomposition.

c) Four **Total Power Antenna (TPA) Systems** of 18m diameter aperture to fill the sensitivity gap at the zero spacings in the (*u,v*)-plane. The design of the Total Power Antenna System has not been finalized at the time of the System CDR, hence no product breakdown is provided in this version of the document. The goal is to keep the design as close as possible to the Main Antenna System. Modifications may be needed for the receivers (e.g. improved gain stability). However, the TPA system will have unique specifications and will have a unique product breakdown – thus it is considered to be an independent product, even though it will have many common parts with the Main Antenna System.

2) Central telescope processing and reference systems
   a) **Central time and frequency reference system**: includes a precision time generation system at the central processing facility that provides the system with a highly accurate absolute time reference for transient monitoring. It also includes the central frequency reference generation mechanism for the antennas. The frequency and time distribution system transmit the required time and frequency references to all the antennas.
   b) **Central signal processing system**: The Central Signal Processor (CSP) receives the data from all the antennas in the array and performs near real-time digital signal-processing to produce raw data products. The processing hardware is configured to produce different types of raw data products, depending on the observing mode.
   c) **Computing and Software Subsystem**: includes a wide range of software components, including: online and offline processing of data received from the CSP to produce observing data products; data product quality assurance; data product storage; data product extraction, discovery, analysis and visualization; proposal and observing management; telescope control, monitoring and calibration; telescope configuration management and maintenance management.
3) Supporting Infrastructure:
   a) **Environmental monitoring and characterization systems**: is a collection of different environmental monitoring equipment that is deployed around the array to characterize and monitor the environment, including weather, atmospheric phase, cloud cover, lightning and RFI.
   b) **Array infrastructure**: includes the physical infrastructure required to construct and operate the array, including roads, power supply utilities, power distribution and utilities for the optical fibers. Array infrastructure also includes the antenna foundations.
   c) **Fiber optic network infrastructure**: Includes optical fiber networks between the central processing facility and all the antennas in the array. This includes newly constructed end to end links for the central antennas as well as commercial links for remote antennas. It also includes data links from the central signal processor to the science data center and other satellite processing centers.
   d) **Buildings:** Various buildings are needed to support operations across the system, including buildings to house the centralized telescope equipment, maintenance operations, science operations and outreach activities.

NOTE: The Configuration Item (CI) numbers of products are abbreviated in the decomposition diagrams for simplicity, for example the Main Antenna System CI number 020.25.00.00.00 is abbreviated as "25", thus only indicating the unique part of the number.

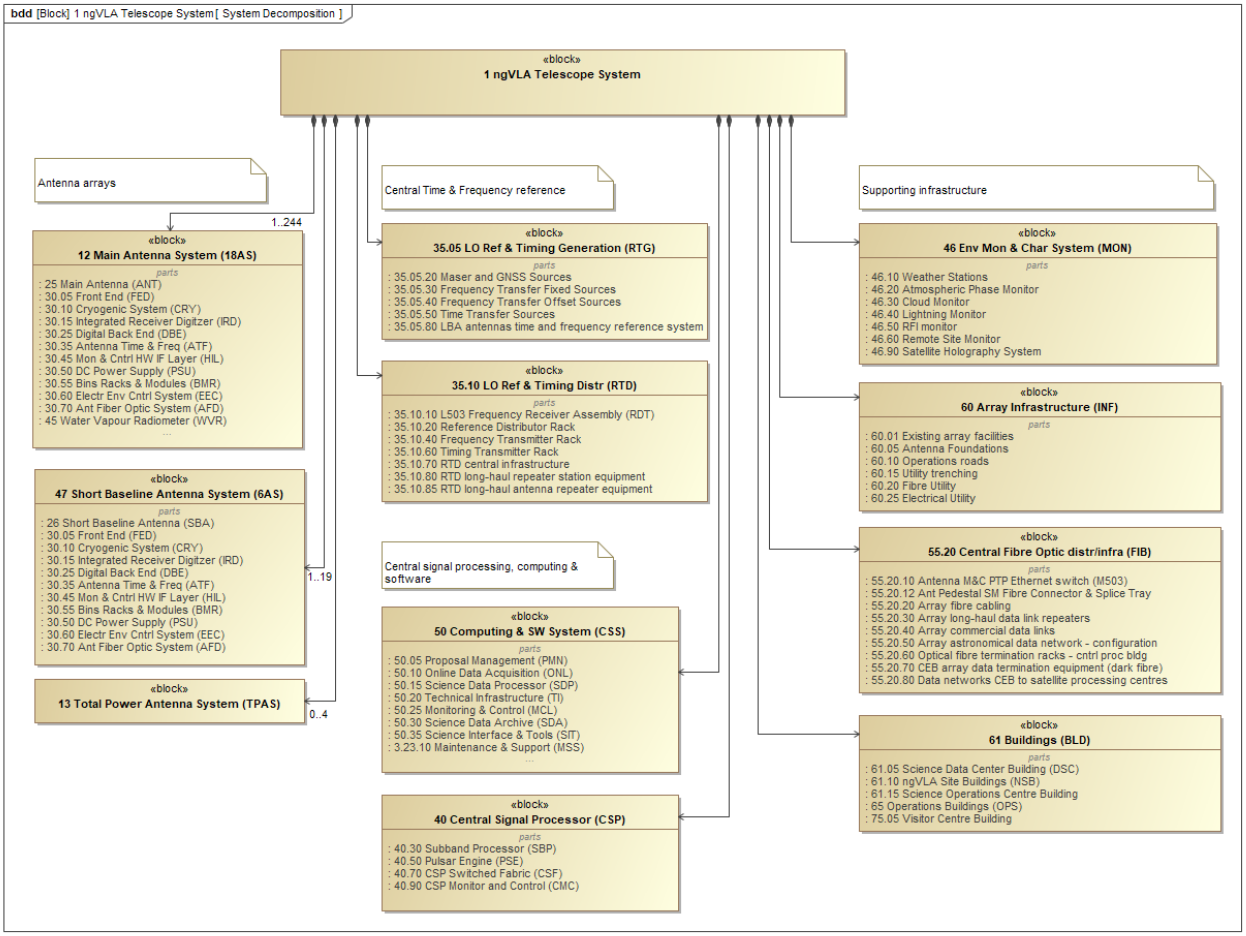

Figure 3: Product breakdown structure of Telescope System

4.2.2 Main Antenna System product structure

The product structure of the Main Antenna System is defined in more detail because it contains multiple subsystems and it is identified as a high priority item:

a) It carries a significant interfacing risk. It is composed of 12 major subsystems that are developed by different teams and therefore has many internal interfaces that need to be managed.

b) It carries significant cost risk: It represents a large portion of the construction cost. It also represents a large portion of the operational (maintenance) cost and will be deployed over a large geographical area.

A decomposition of the Main Antenna is shown in Figure 4 below. It includes the reflector system (main reflector and sub-reflector), the supporting structures (pedestal, turnhead, backup structure, feed arm), drive systems for all four motion axes (azimuth, elevation, feed indexing & feed focus), metrology and facilities for installing equipment such as AC power distribution. The Main Antenna is a contracted item and the decomposition and numbering is adopted from the contractor. (*Note: the Main Antenna System includes all the electronics, and the Main Antenna is only the mechanical structure and drives*).

The equipment on the Main Antenna System includes the signal path electronics (front-end analog receivers, digitizers and digital back-end), a cryogenic cooling system, time and frequency reference system for the antenna, control and monitoring infrastructure, a Water Vapor Radiometer and support equipment (optic fiber distribution, DC power supply system, environmental control system and equipment housing).

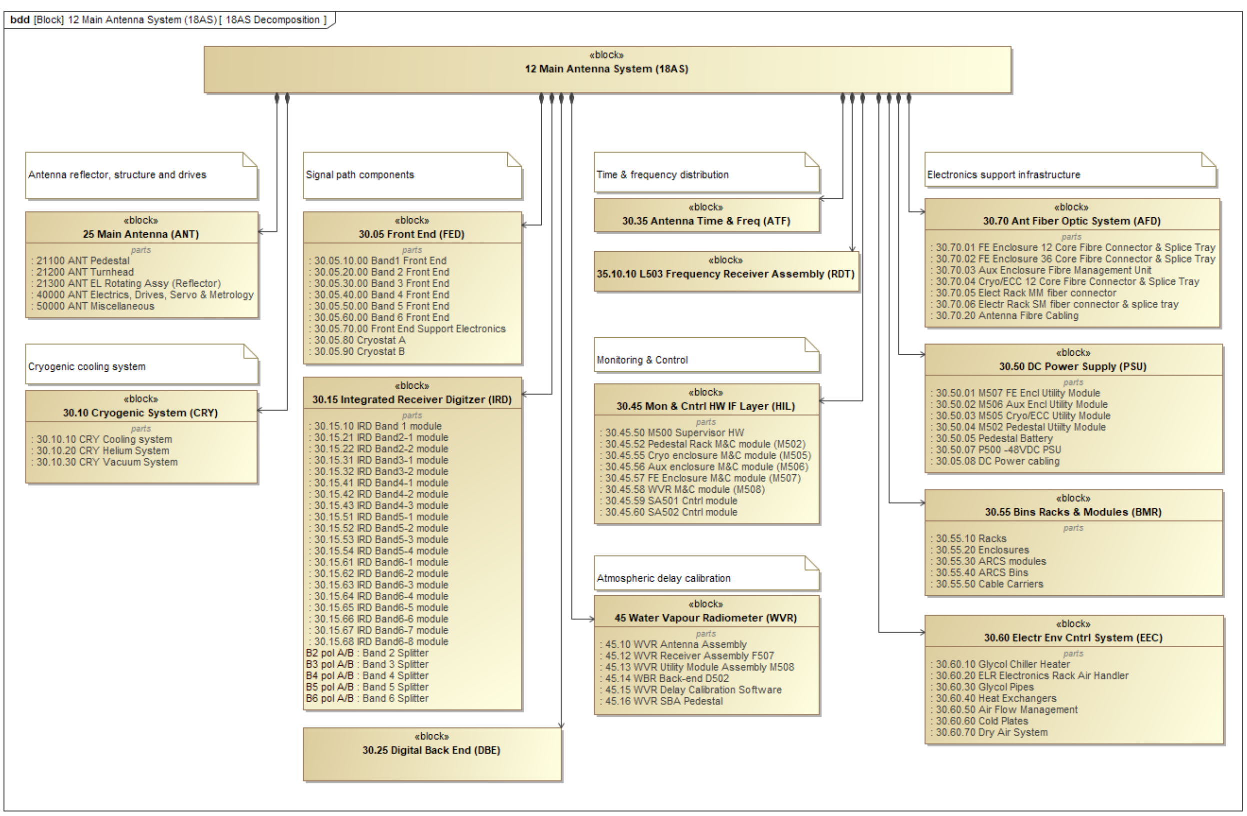

Figure 4: Product Breakdown Structure of Main Antenna System

Note: There are a number of aspects of the antenna design that are not considered to be separate subsystems, but rather as design that cuts across all the Antenna subsystems. Examples are RFI/EMI, earthing and lightning protection. Such design aspects will be owned at the system level and will be disseminated down to Antenna subsystems. System level design documents and System requirements will be formulated and these will flow down to subsystem specifications and designs.

4.3 Subsystems

A subset of items in the PBS are defined as "Subsystems". These subsystems are the main components of the system architecture and are allocated to different organizational entities for development. These subsystems form the basis for technical budget allocations, functional allocations, allocation of system requirements to subsystems, and for identifying system level interfaces. The ngVLA Subsystems are identified in Figure 5 below. The responsibility allocation of subsystems to organizational structure is indicated on the sides. The internal structure of each of these subsystems and the identification of their mutual interfaces is defined in subsequent sections.

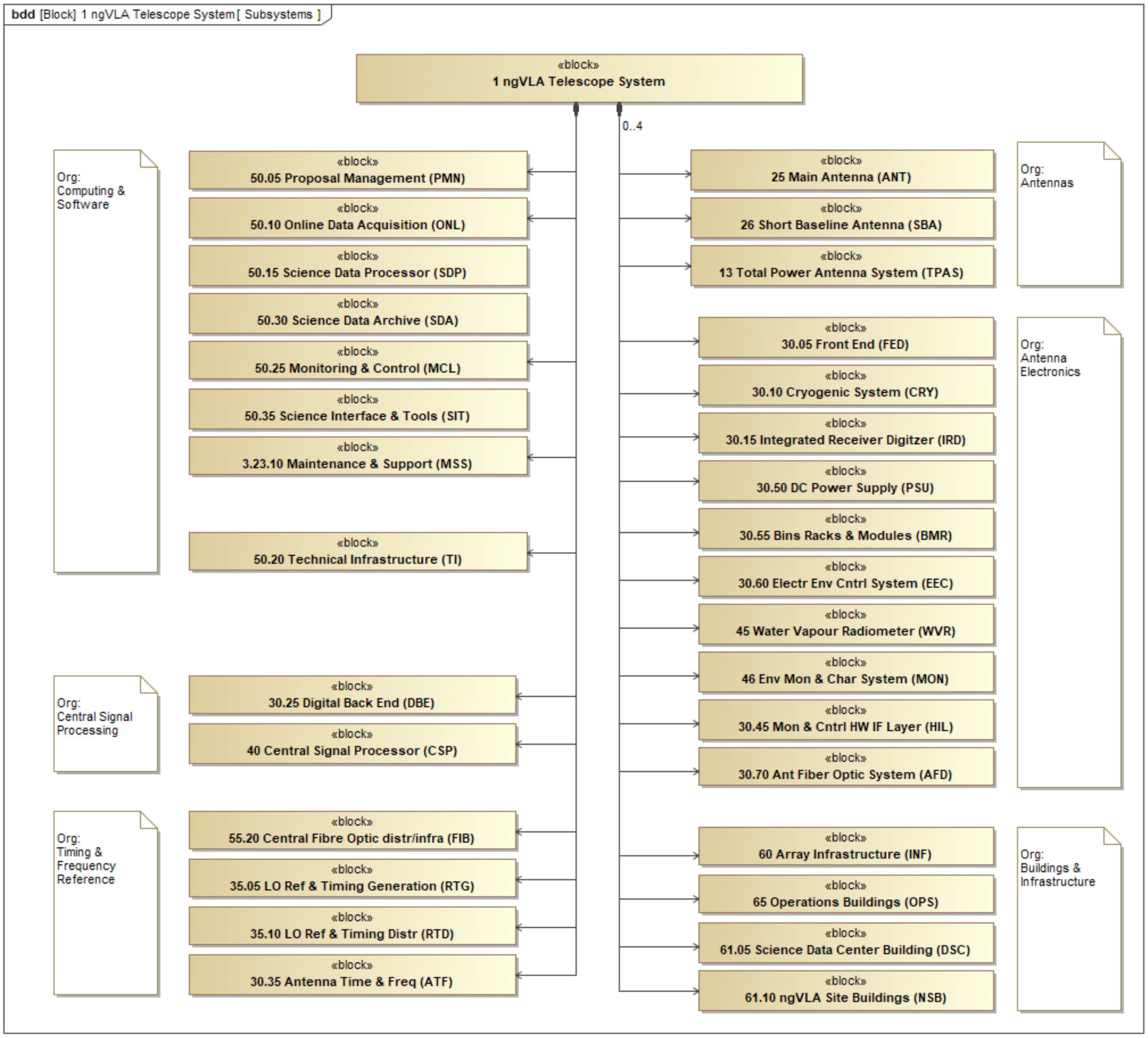

Figure 5: ngVLA Subsystems

4.4 System Interfaces

The N² matrix (where N represents the number of subsystems) below identifies all the Subsystem-to-Subsystem interfaces that need to be managed formally through ICDs. The diagonal cells identify the subsystems by their abbreviation. Each Subsystem-to-Subsystem interface is allocated a unique identification number to serve as a reference in documentation. Interfaces indicated with an “S” are secondary interfaces that will not be managed formally. In cases where multiple interfaces are defined in a single ICD, numbers are shown in blue italics. At the time of writing this version of the document, the Total Power Antenna interfaces were not yet identified.

	ANT	SBA	FED	CRY	IRD	PSU	BMR	EEC	WVR	MON	HIL	AFD	INF	OPS	DSC	NSB	MCL	PMN	ONL	SDP	SDA	SIT	MSS	TI	FIB	DBE	CSP	RTG	RTD	ATF
ANT			0130	0131		0132	0133	0134	0135	0137		0136	0030				0031						S						0139	TBC
SBA			*0032*	*0033*		*0034*	*0035*	*0036*	*0021*			*0037*	0038				0039						S							TBC
FED				0012	0004	*0014*	*0040*	0017			*0015*	*0041*					~~0042~~						S						0140	~~0016~~
CRY						*0043*	*0044*	0045			*0046*	*0047*		0126			~~0048~~						S							
IRD						*0006*	*0049*	0003			*0001*	*0050*					~~0051~~						S			0002				0005
PSU							*0052*	*0053*	*0022*		*0054*	*0055*					~~0056~~						S			*0057*			*0058*	*0059*
BMR								*0060*	*0023*		*0061*	*0062*													TBC	*0063*			*0064*	*0065*
EEC									0024		*0066*	*0067*					~~0068~~						S			0127			0069	0070
WVR										S	*0025*	*0026*	0138				~~0027~~		S				S			TBC			0128	0028
MON											*0071*		0072				*0073*		S				S							
HIL												*0074*					0075						S			~~0076~~		0129	0077	*0078*
AFD																							S		*0079*	*0080*			0153	*0081*
INF														0082		0083	0084						S	0141	0085					
OPS																	*0086*		~~0087~~				S	*0142*	*0088*					
DSC																	TBC	~~0089~~		~~0090~~			~~0091~~	*0093*	*0094*					
NSB																	*0095*		~~0096~~				S	*0143*	*0097*	TBC	*0098*	*0099*	*0100*	
MCL																ceb			0101				0102	*0103*		*0104*	0105	*0106*	*0107*	~~0108~~
PMN																			0109	0110		0146		*0111*						
ONL																				0112		0154		*0113*		S	0114	S		
SDP																			cbe		0147	0148		*0115*	~~0116~~					
SDA																						0149		*0144*						
SIT																								*0145*						
MSS																								*0117*		S	S	S	S	S
TI																									0150		0151			
FIB																										TBC	0119		0120	
DBE																											0121		~~0122~~	0152
CSP																												0123		
RTG																													0124	
RTD																														0125
ATF																														

Table 1: System interface identification

The mapping of interfaces to ICD documents is defined in [AD04]. In some cases there is a dedicated ICD for individual interface and in other cases, multiple interfaces are defined in one ICD. For each ICD, a leading party is identified who will lead the development of the interface.

4.4.1 Antenna Electronics monitoring and control interfaces

The Antenna Electronics monitoring and control interfaces are complex and require a more detailed level of identification. The following figures show initial examples of the physical configuration of the monitoring and control interfaces from the Monitoring and Control (MCL) subsystem to the Antenna Electronics subsystems, via the Monitoring and Control Hardware Interface Layer (HIL) subsystem. Next lower level interfaces are identified, based on the N[2] interface identifications. For example, the interface 0015 between FED and HIL is expanded into lower level interfaces (0015.01, 0015.02, etc.)

During the preliminary design phase, these interfaces will be modelled and maintained in the System Architecture Model to represent their physical, functional and data structures, as illustrated in an example in the Appendix B section 7. The Interface Control Documents (ICDs) will serve as the authoritative source for interface definitions.

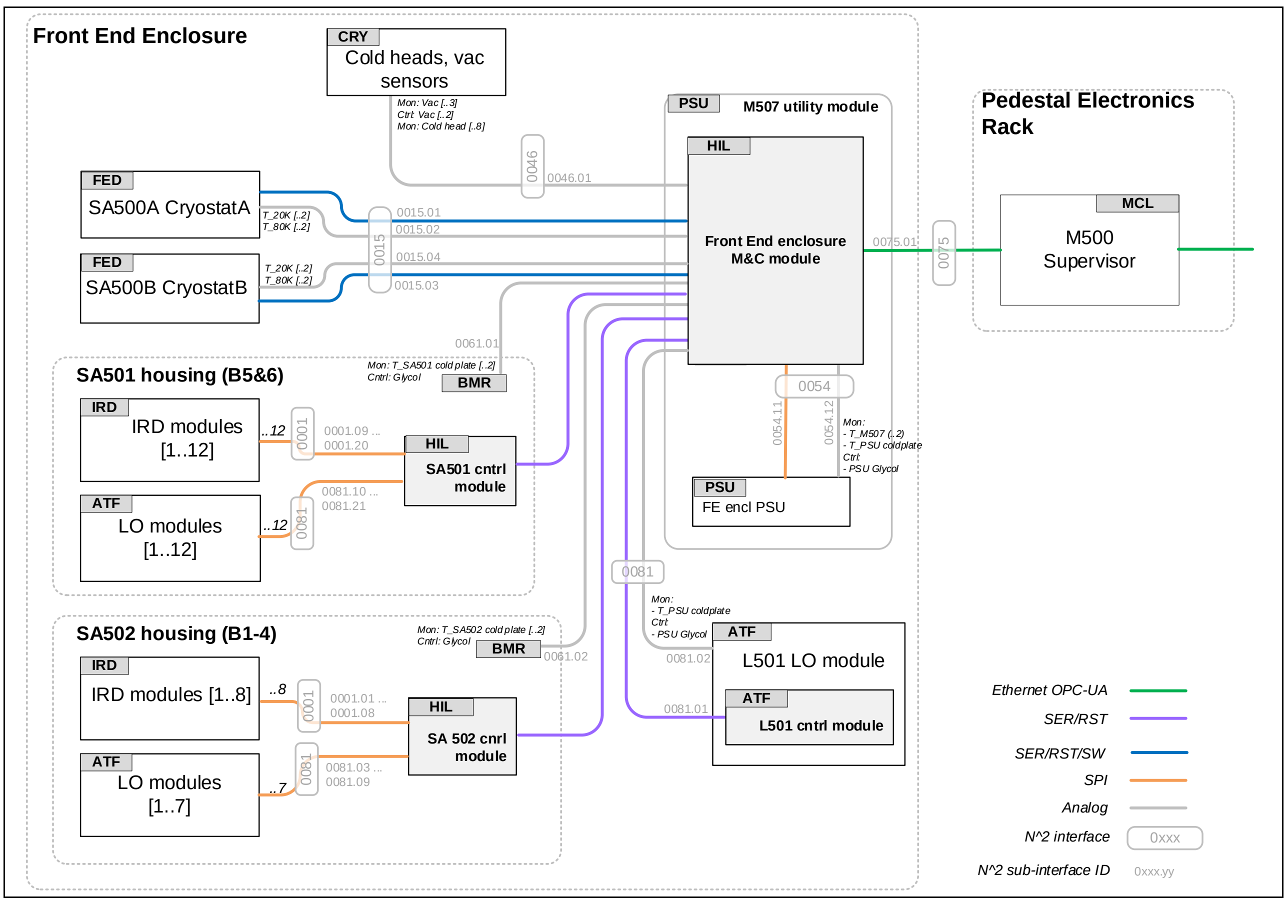

Figure 6: Front-end control and monitoring interfaces

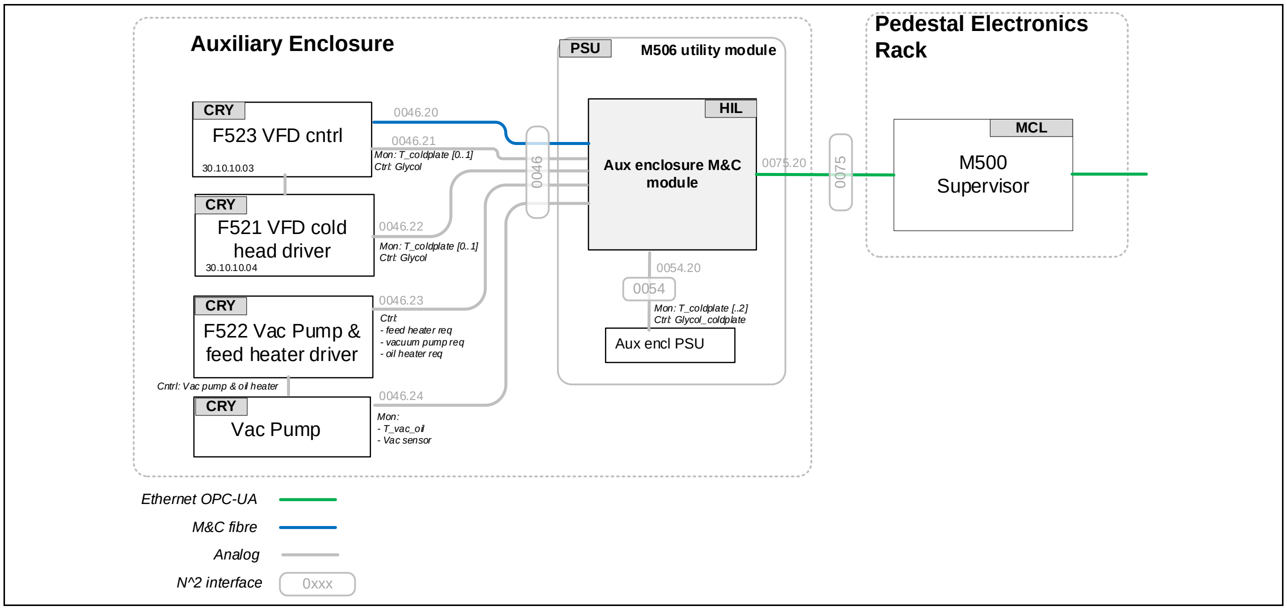

Figure 7: Auxiliary enclosure control and monitoring interfaces

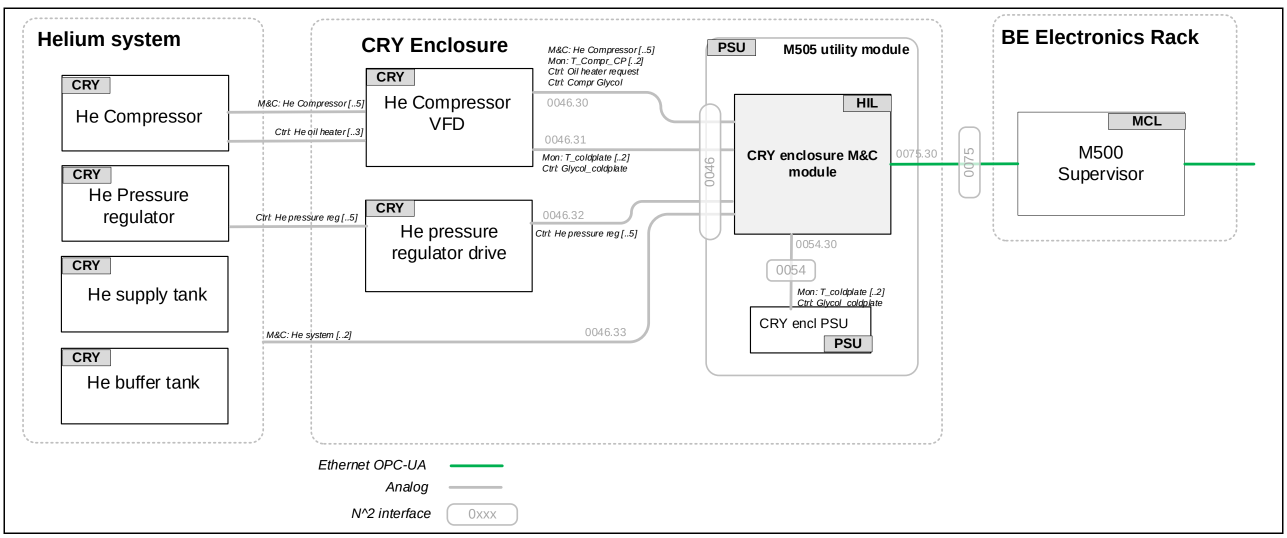

Figure 8: Cryogenics enclosure control and monitoring interfaces

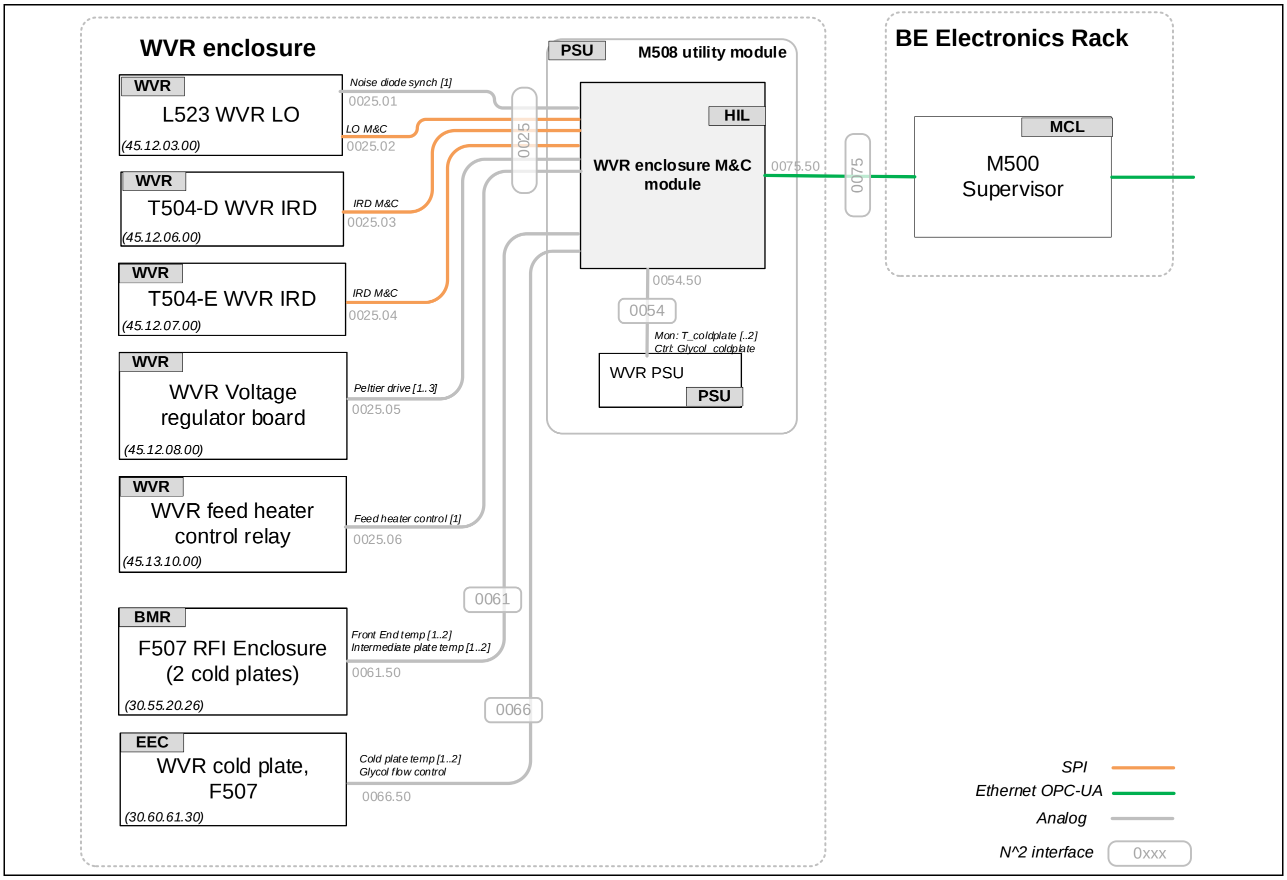

Figure 9: WVR Control and Monitoring Interfaces

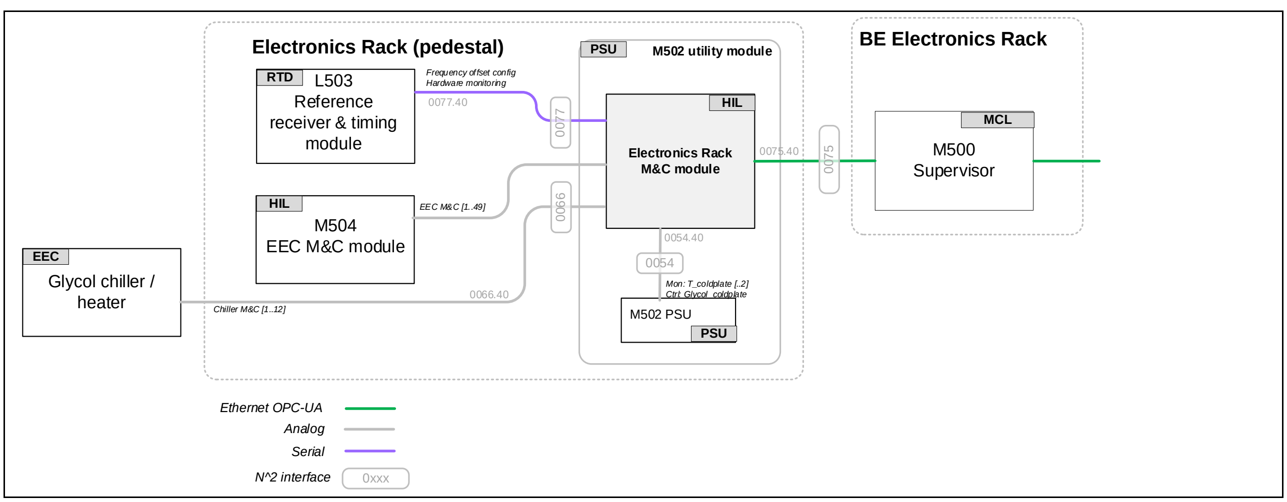

Figure 10: Electronics Rack control and monitoring interfaces

4.5 Physical Architecture

The product breakdown structures defined in the previous section are often functionally driven to enable the specification, design and verification of functionally coherent and performant systems. Many of these systems are physically distributed (e.g. the reference signal system). In some cases (specifically in the case of the Antennas), where multiple functional systems are co-located in a constrained environment, the physical configuration of these systems becomes complex and it is necessary to define the physical configuration of these systems.

For the CDR phase of the project, only the Main Antenna System physical architecture has been defined in more detail, to enable the conceptual and preliminary development of the Antenna and Antenna Electronics. This information is not included in this document, but is detailed in reference documents as described below.

4.5.1 Main Antenna System physical architecture

The Main Antenna System consists of the antenna structure (ANT) and eleven Antenna Electronics Subsystems. Most of the Antenna Electronics subsystems are physically distributed across the structure. The physical configuration of the Main Antenna System is defined in the following reference documents:

a) CAD model of the Antenna (ANT) Subsystem, developed by the ANT contractor. This model is reviewed informally throughout the development, with formal review at the ANT PDR.
b) CAD models of the Antenna Electronics enclosures. These models are reviewed informally throughout development, with formal review at the Antenna Electronics PDRs for the various subsystems.
c) ICD between ANT and Antenna Electronics [RD02] defines the space, volume and mass requirements of the antenna electronics components as installed on the Antenna. This ICD has been formally reviewed and is under configuration control.
d) Antenna Electronics Block Diagrams [AD05] Define the physical locations and configurations of the Antenna Electronics parts in relation to each other, including interconnections between components. These block diagrams are formally reviewed at the CDR and are placed under configuration control after inputs from the review.

4.6 Subsystem Product Breakdown Structures and Interfaces

The following sections briefly define the scope and product structures of all the Subsystems and identify their external interfaces.

4.6.1 Main Antenna (ANT)

The scope of the Main Antenna includes all the structural elements and actuators that are required to: establish an efficient reflector system; to accurately point the reflector; to position the receiving feed antennas for the different frequency bands; and to provide infrastructure to house the Antenna Electronics.

The Main Antenna is decomposed into the following items as shown in Figure 11:

a) Elevation Assembly, which includes all the mechanical parts above the elevation bearing. This includes the Main reflector surface, back-up structure, boom arm connecting the main and sub-reflectors, sub-reflector assembly, feed indexer system and alignment of the reflectors and receiver. The feed indexer includes a two-dimensional positioning platform for mounting the Front End. The Elevation Assembly also includes the basic infrastructure to house the WVR and auxiliary electronics enclosure.
b) Turnhead, which includes all the mechanical systems between the Azimuth and Elevation axes, including the gearboxes and bearings for both axes as well as the lubrication system to service these axes. It also includes an environmentally protected enclosure in which some of the electronics will be housed (including the helium compressor).
c) Pedestal, which includes the Azimuth wrap and creates an environmentally protected and EMI shielded space to house electronics components. The pedestal interfaces with the foundation and the services that are provided through the foundation, including power and fiber cable entries.
d) Antenna electrics, drives, servo and metrology: These are systems that are physically distributed across the structure. This item includes the drive electronics, cables and motors that drive the three axes (Az, El and indexer). It includes the I/O units and metrology systems. This item will also include an HVAC system that will provide a controlled ambient environment for the pedestal and turnhead spaces. It also includes an RFI shielded electronics rack which contains the antenna drive electronics and other antenna electronics. This item also includes the AC power distribution to all the components throughout the Main Antenna. The integrated design for the safety system is included, which includes the central safety control system (PLCs), E-stops and interlock safety circuits.
e) Miscellaneous items include supporting equipment needed for the installation, integration and verification of the Main Antenna.

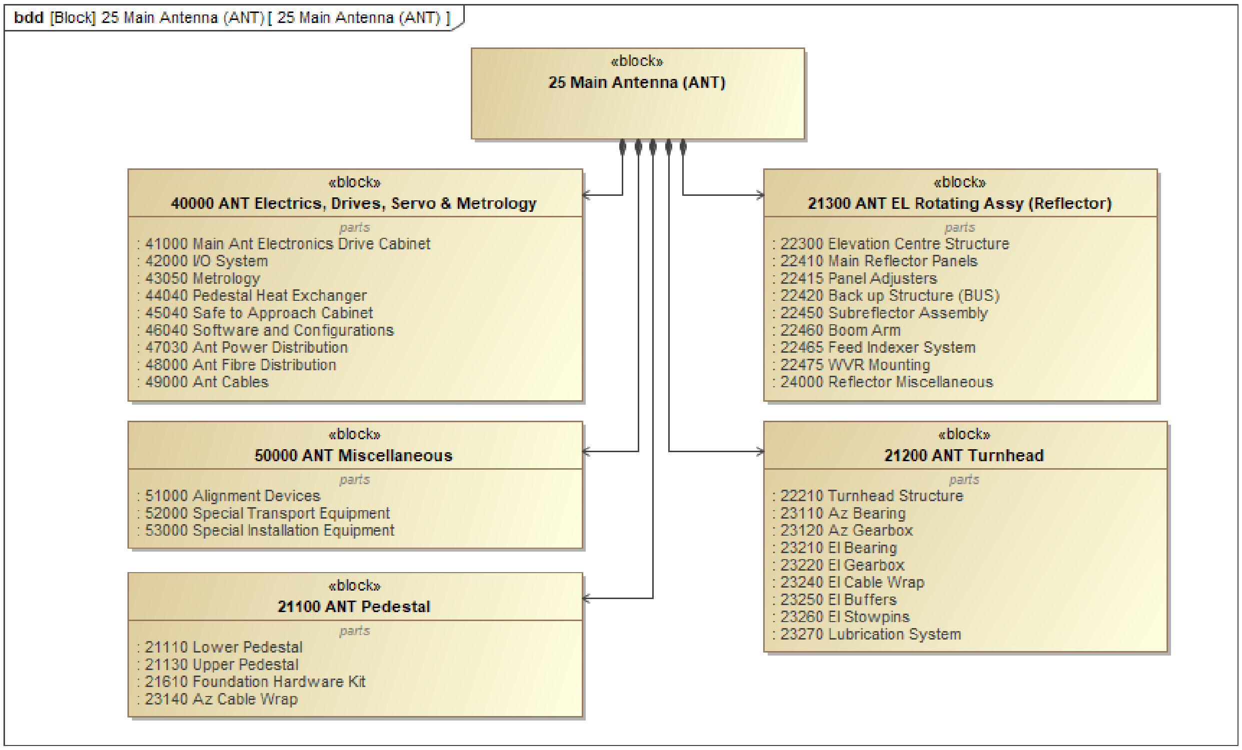

Figure 11: Main Antenna decomposition

The external interfaces of the Main Antenna are shown in Figure 12 below:

a) Antenna Electronics: the most complex interface is with the Antenna Electronics components. These components impose significant constraints and requirements on the design of the structure, especially the receiver components that are located on the feed indexer, which impose positioning accuracy requirements and are subject to mass limitations.
b) Infrastructure (INF) provides the foundation and working platform for the antenna, roads to the antenna sites, power to each antenna and conduits for fiber cabling. The interface to the foundation has important performance implications, specifically on pointing and survival loading. Foundation stiffness and survival load requirements will be defined in the ANT/INF ICD and these performance requirements should be verified during qualification by the foundation contractor.
c) Monitoring and control (MCL) for the monitoring and control of the antenna over a general ethernet network. Note that the provision of a PTP time reference is also provided via this network, but the configuration of the network for this purpose is provided by the RTD system.

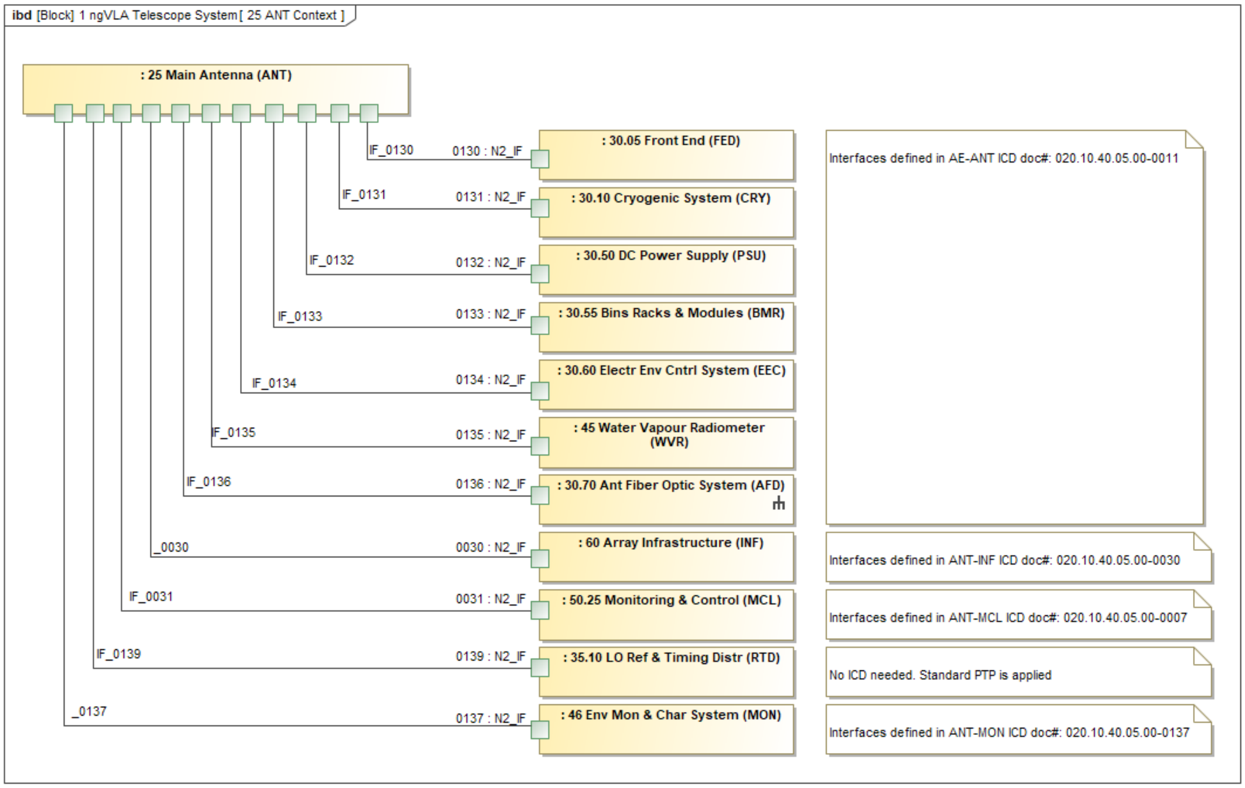

Figure 12: Main Antenna external interfaces

4.6.2 Short Baseline Antenna (SBA)

The scope of the 6m aperture Short Baseline Antenna is similar to the Main Antenna and the product breakdown will be similar to that shown for the main antenna in Figure 11. The details of the decomposition of the SBA will be defined during the preliminary design phase.

The goal is to keep the Antenna Electronics for the SBA as similar as possible to the Main Antenna – thus the SBA will have to provide similar facilities to host the Antenna Electronics. Interfaces to the Antenna electronics will be similar, as shown in Figure 13 below. Because the SBA antennas are much smaller than the Main Antenna, the method of hosting the equipment may differ from the main antenna and some equipment may have different environmental specifications (e.g. the helium compressor may operate in the ambient environment). Another difference is that the WVR will not be mounted on the SBA antennas, but on their own separate pedestals close to the short baseline array.

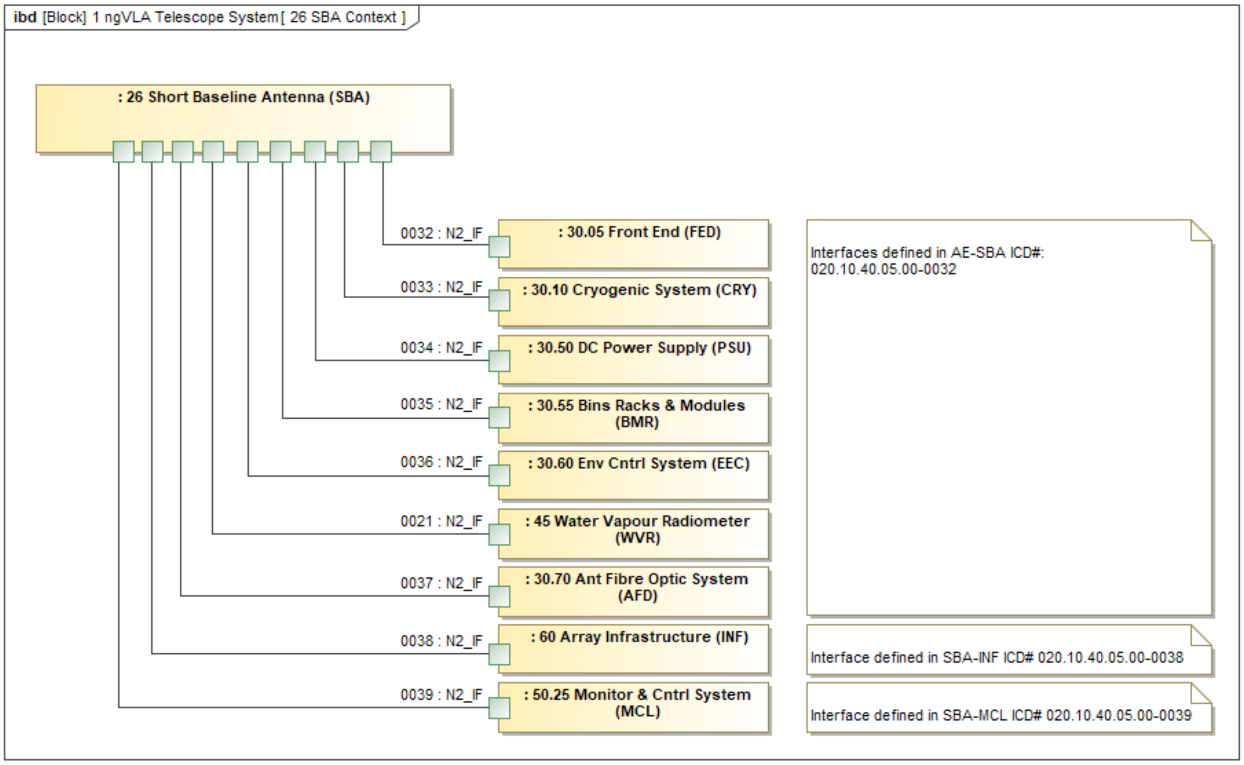

Figure 13: Short Baseline Antenna external interfaces

4.6.3 Antenna Electronics: Front-end (FED)

The Front-End subsystem consists of six receivers that cover the 1.2 – 116 GHz frequency range, with a gap between Band 5 and 6 at the atmospheric absorption band between 50.5 – 70 GHz. The receivers for each band include the feed horn, OMT, low noise amplifiers, calibration noise module, LNA bias controls and the sensors necessary to operate and maintain each receiver. The receivers are housed in two separate Cryostats: Cryostat A for Band 1 and Cryostat B for Bands 2-6. Cryostat B is designed to mount the Bands2-6 receivers as removable cartridges. The cartridge concept enables easy replacement of receivers, but also enables manufacturing, final test, and repair of receiver cartridges independent of the Cryostat. The Front End supplies the two integrated Cryostats, which are located inside the Front-end enclosure. The Front-end enclosure is mounted on a linear indexer at the secondary focus of the antenna. The Front-end enclosure is mounted on the indexer platform (platform is provided by ANT), which allows for two dimensions of linear motion: one for the switching between bands and the other for focal adjustment. The product decomposition of the Front End is shown in Figure 14.

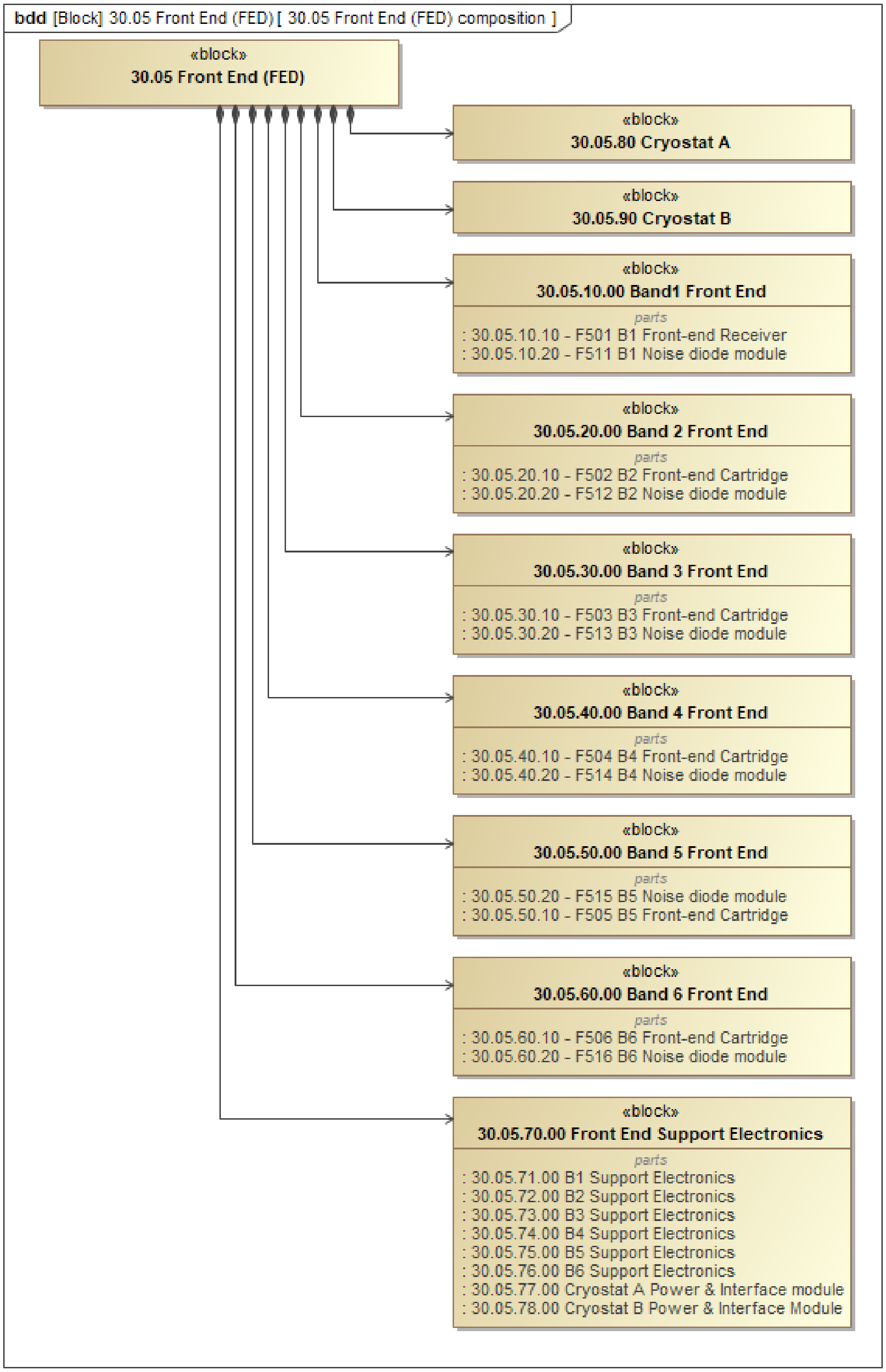

Figure 14: Front-end Decomposition

The Front End has interfaces with the following subsystems, as shown in Figure 15:

a) Mechanical interface with the Antenna, including mass and volume constraints and positioning accuracy of the receiver feed antennas.
b) Mechanical and thermal loading interface with the cold head which is supplied by CRY. Also included in this interface is the supply of vacuum by the CRY subsystem.
c) RF signal output interface to the IRD for all six bands.
d) Requirements for cooling from the EEC.
e) Provision of space, mounting mechanisms, environmental shielding, RF shielding and surge protection by the Front-End Enclosure, which is supplied by BMR.
f) Control and monitoring supplied via HIL to the MCL system.
g) Supply of DC power to the Front End from PSU.
h) Connection of all the fiber cabling to the Front End by AFD.

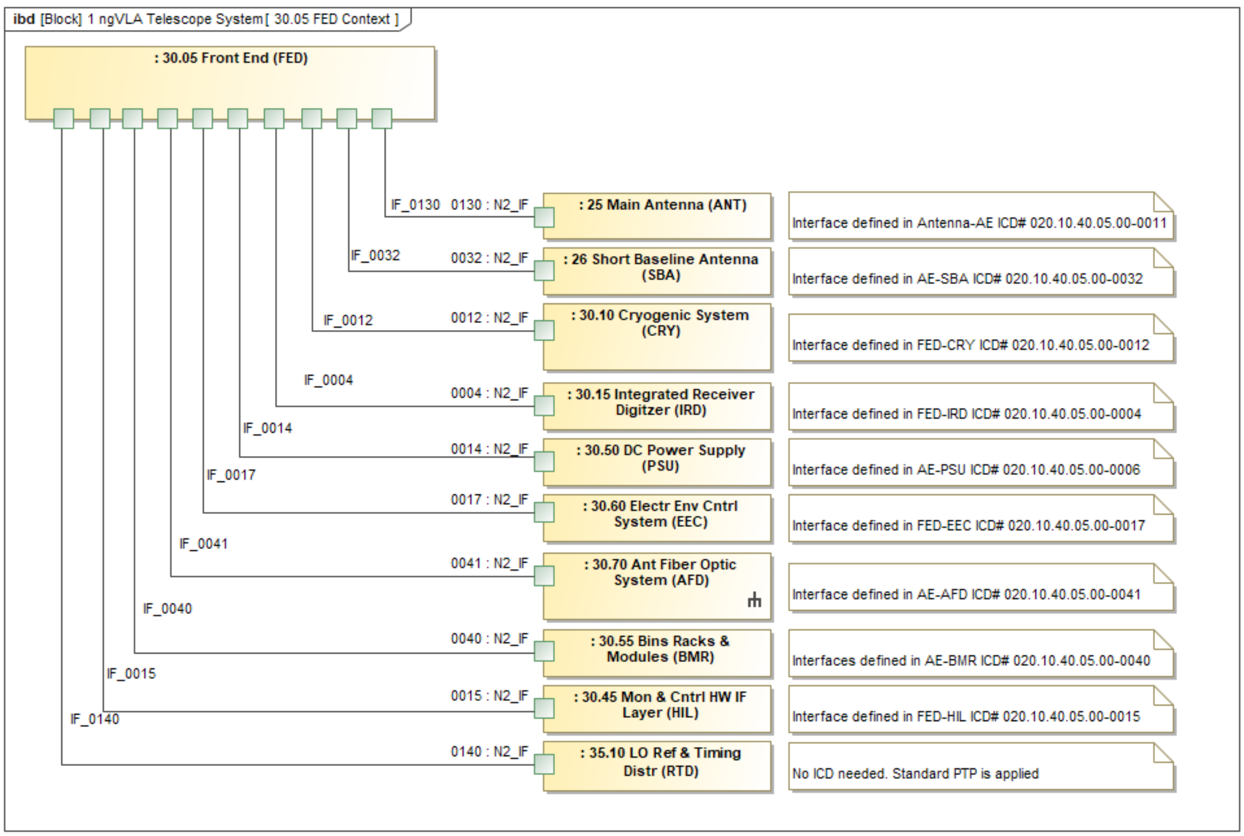

Figure 15: Front-end Context

4.6.4 Antenna Electronics: Cryogenic Subsystem (CRY)

The purpose of the cryogenic subsystem is to cool the Front-End electronics to a low temperature (20K) to minimize self-generated noise and improve the telescope's overall sensitivity. The subsystem is composed of components that are distributed across the antenna. Its main components are cryogenic cooling system, vacuum system and helium system. The decomposition and locations of these parts are shown in Figure 16 below.

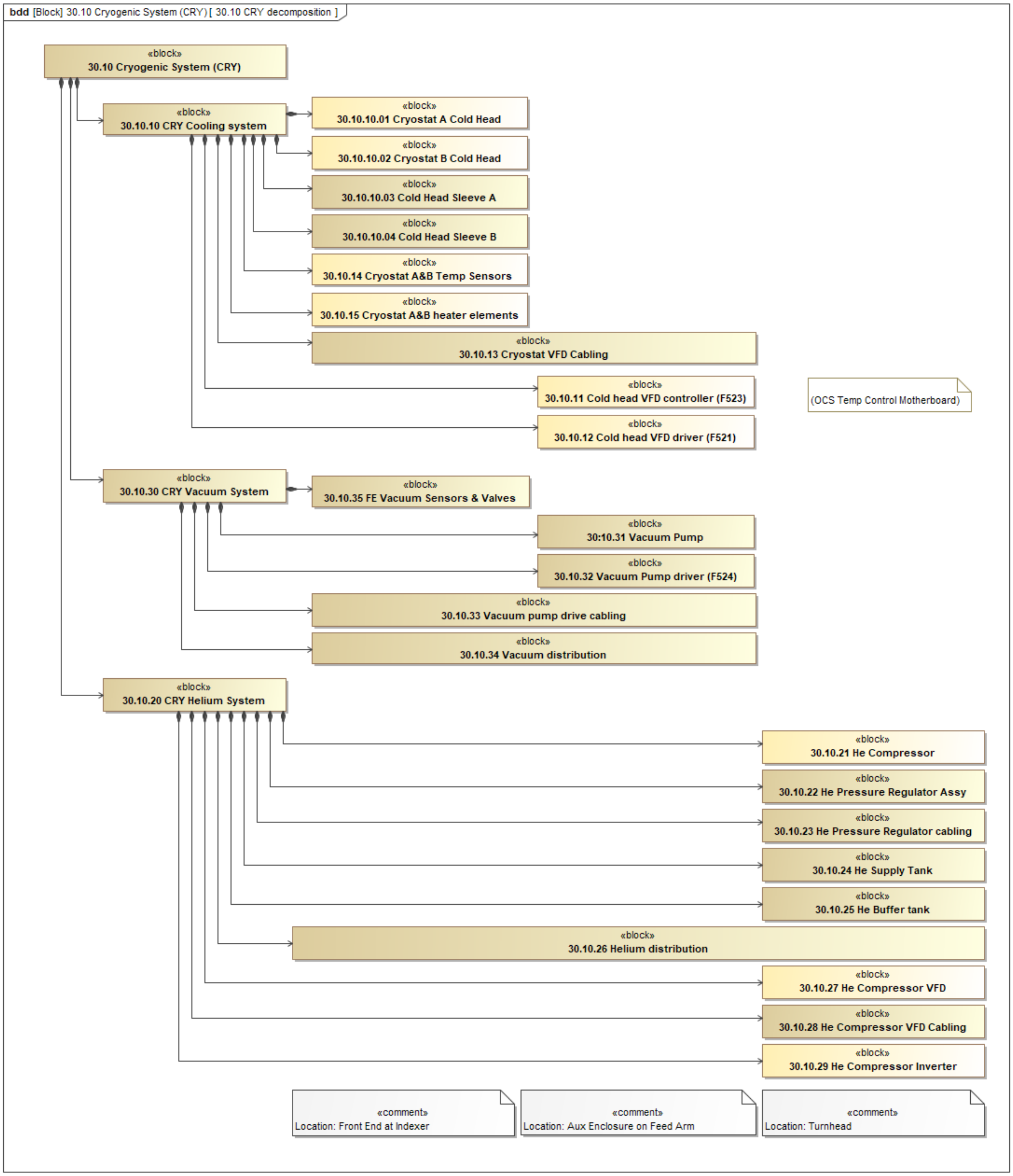

Figure 16: Cryogenic Subsystem decomposition and location

Its primary functional component is the **Cryogenic Cooling System**, with the cold heads supplying the cooling for the receivers. These are integrated in the Front-End assembly at the focal location on the dish on the feed indexer. The Cryostat A cold head serves to cool Band 1 while the Cryostat B cold head cools the receivers for Bands 2 to 6. A variable speed controller is located in the auxiliary enclosure on the feed arm to maximize the efficiency of the system by varying the speed of the cooler, thus reducing power consumption.

The **Vacuum System** supplies the system with the capability to apply a vacuum to the Cryostats in case their vacuum needs to be re-generated after a warm-up cycle. This system includes a vacuum pump and vacuum pump driver at the auxiliary enclosure and vacuum distribution to the two Cryostats.

The **Helium System** supplies high pressure helium to the cold heads. The helium compressor, pressure regulator, supply and buffer tanks and compressor variable speed controller are located in the turnhead above the azimuth bearing.

The functionality of the Cryogenic subsystem is defined in more detail in Section 5.2.3.

The Cryogenic subsystem interfaces to other subsystems on the antenna as shown in Figure 17:

a) To the Antennas (ANT and SBA) for making provision for mounting and working space for the various components and mass allocations for the items that are mounted on the indexer. The Antennas also distributes AC power to some of the CRY components.
b) BMR provides environmentally and RFI shielded enclosures for some of the CRY components, specifically the control electronics.
c) CRY interfaces to FED via the cold head (mechanical and thermal) and the supply of vacuum to the Cryostats.
d) CRY relies on the EEC subsystem for the supply of cooling capacity for many of its parts. One of the major cooling interfaces is the supply of liquid cooling to the compressor, which has a high heat load.
e) AFD provides the fiber optic distribution infrastructure for communication to the various CRY devices.
f) PSU supplies DC power to various CRY components.
g) CRY is controlled and monitored from MCL via the HIL subsystem.

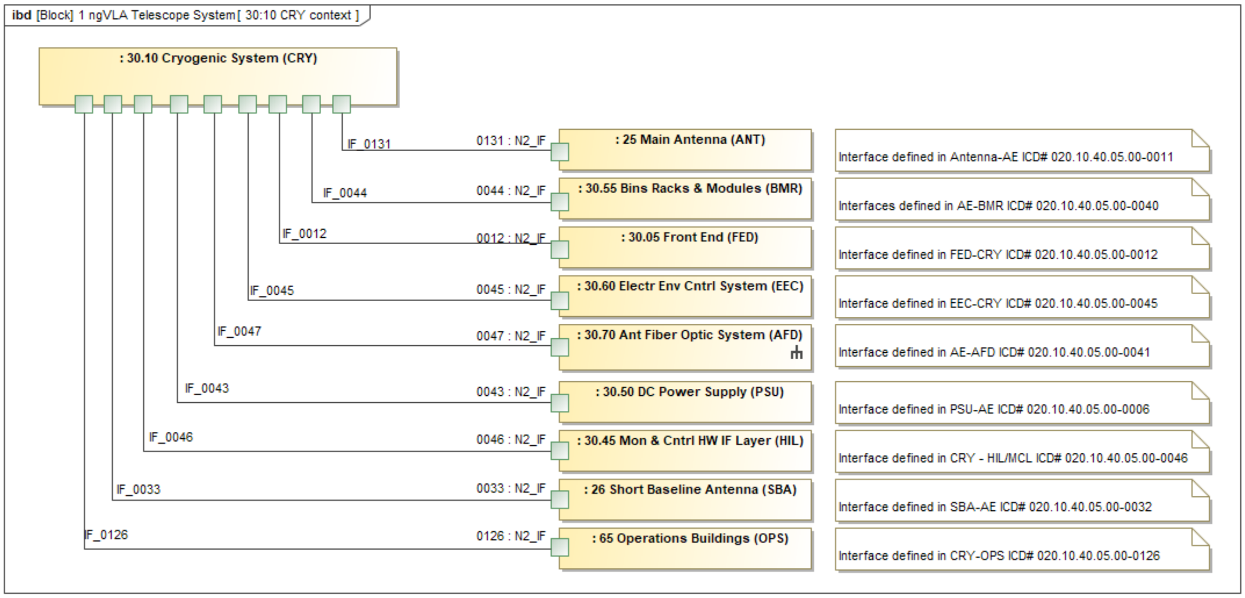

Figure 17: Cryogenic Subsystem external interfaces

4.6.5 Antenna Electronics: Integrated Receiver Digitizer (IRD)

The IRD receives the analog RF signal from the Front End and applies amplification and level adjustment, then down-converts the signal (for bands 2-6), and digitizes it. The signal is then serialized and sent to the Digital Back-End. IRD has modules that are dedicated to the six frequency bands and the digitization process runs independently between the frequency bands, allowing the switching between bands without losing coherency. The functional overview of the IRD is provided in Section 5.2.2.3. The IRD is decomposed into 20 modules to service all the frequency bands, as shown in Figure 18 below.

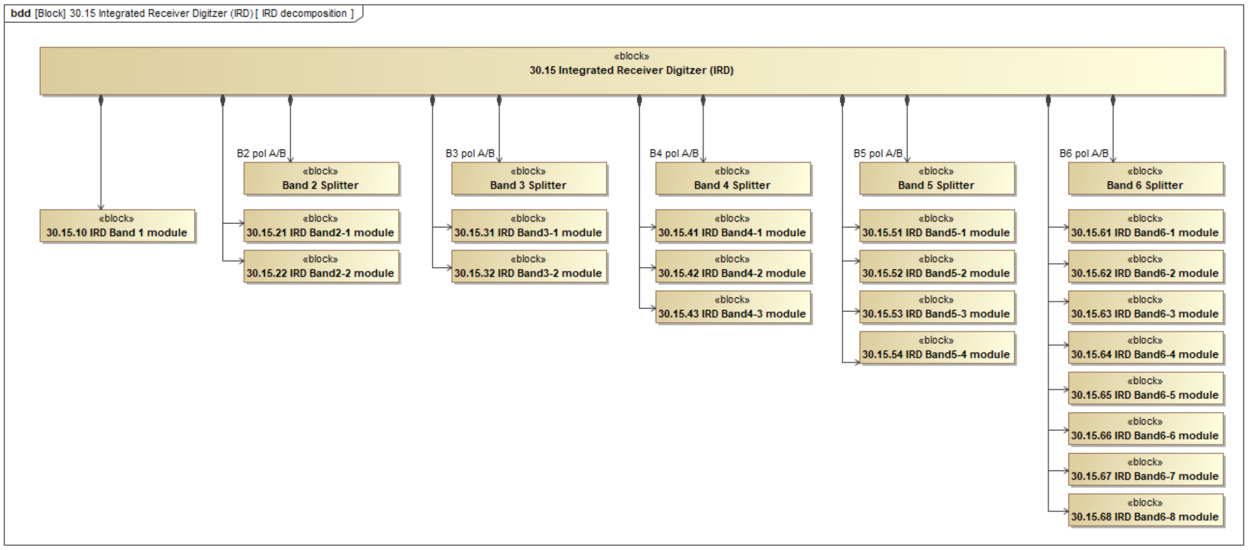

Figure 18: IRD decomposition

The IRD modules are all located in the Front-end enclosure at the focus of the antenna and rely on a shielded and thermally controlled environment and the supply of regulated DC power. The IRD modules receive an LO for down-conversion and sampling clock from the Antenna Time and Frequency system.

The external interfaces of the IRD are shown in Figure 19 below:

a) RF input signal from the Front-end which will define power levels and mechanical aspects of the RF connection (Coaxial or waveguide).
b) Characteristics of the power supplied by PSU, including voltage levels and supply stability.
c) BMR hosting of the IRDs, including definition of space requirements, mechanical interfaces, RF shielding requirements, surge protection, etc. that are provided by the enclosure.
d) Cooling capacity required from the EEC.
e) Control and monitoring interfaces to the MCL system via the HIL system.
f) Provision of optical fibers to the IRD modules by the AFD.
g) Signal data interface between IRD and DBE.
h) Characteristics of the time and frequency reference signals provided by ATF.

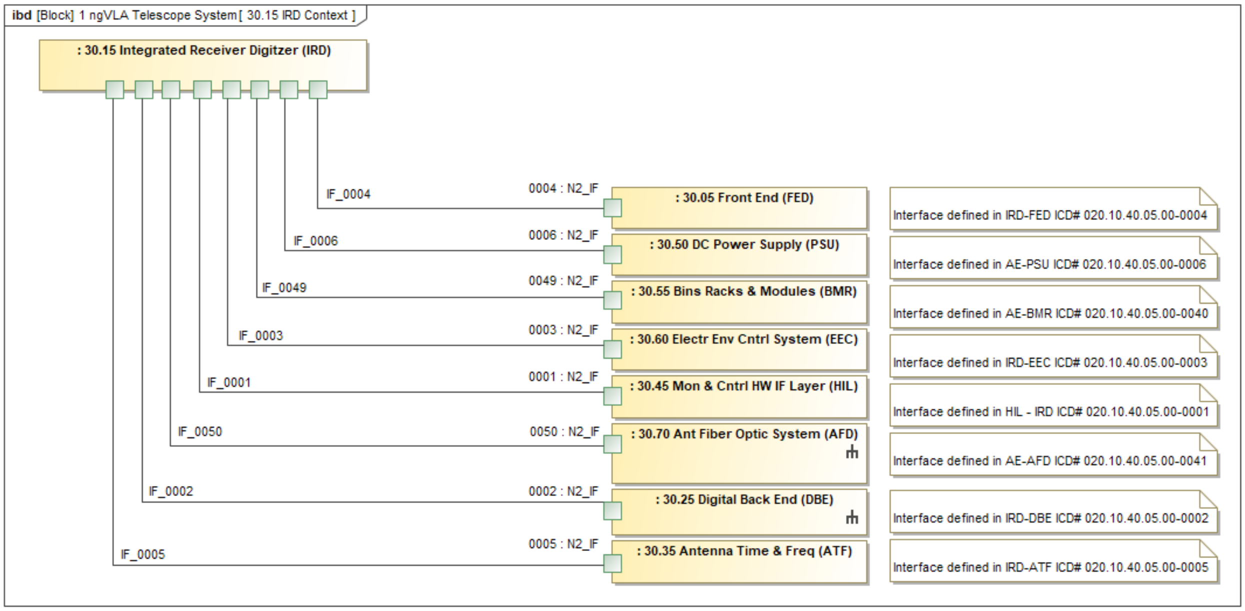

Figure 19: IRD external interfaces

4.6.6 Antenna Electronics: Water Vapour Radiometer (WVR)

The purpose of the WVR is to measure the atmospheric contribution of RF delays on a high cadence at each antenna. This is an important delay calibration mechanism for the array to enable the coherent combination of signals from different antennas, and reduces the frequency needed to switch to calibrator sources during an observation.

A WVR is deployed on each Main Antenna, on the elevation structure on the side of the main reflector. WVRs will not be mounted on the SBA antennas directly, but a few WVRs will be mounted on stand-alone pedestals with positioners in the area surrounding the short baseline array.

The WVR is an independent radiometer with its own antenna, low noise receiver, digitizer and signal processor. The receiver and digitizer are located at the WVR antenna. The signal processor is located in the pedestal of the main antenna. The delay calibration software is run centrally as an integral part of the offline software of the telescope computing software.

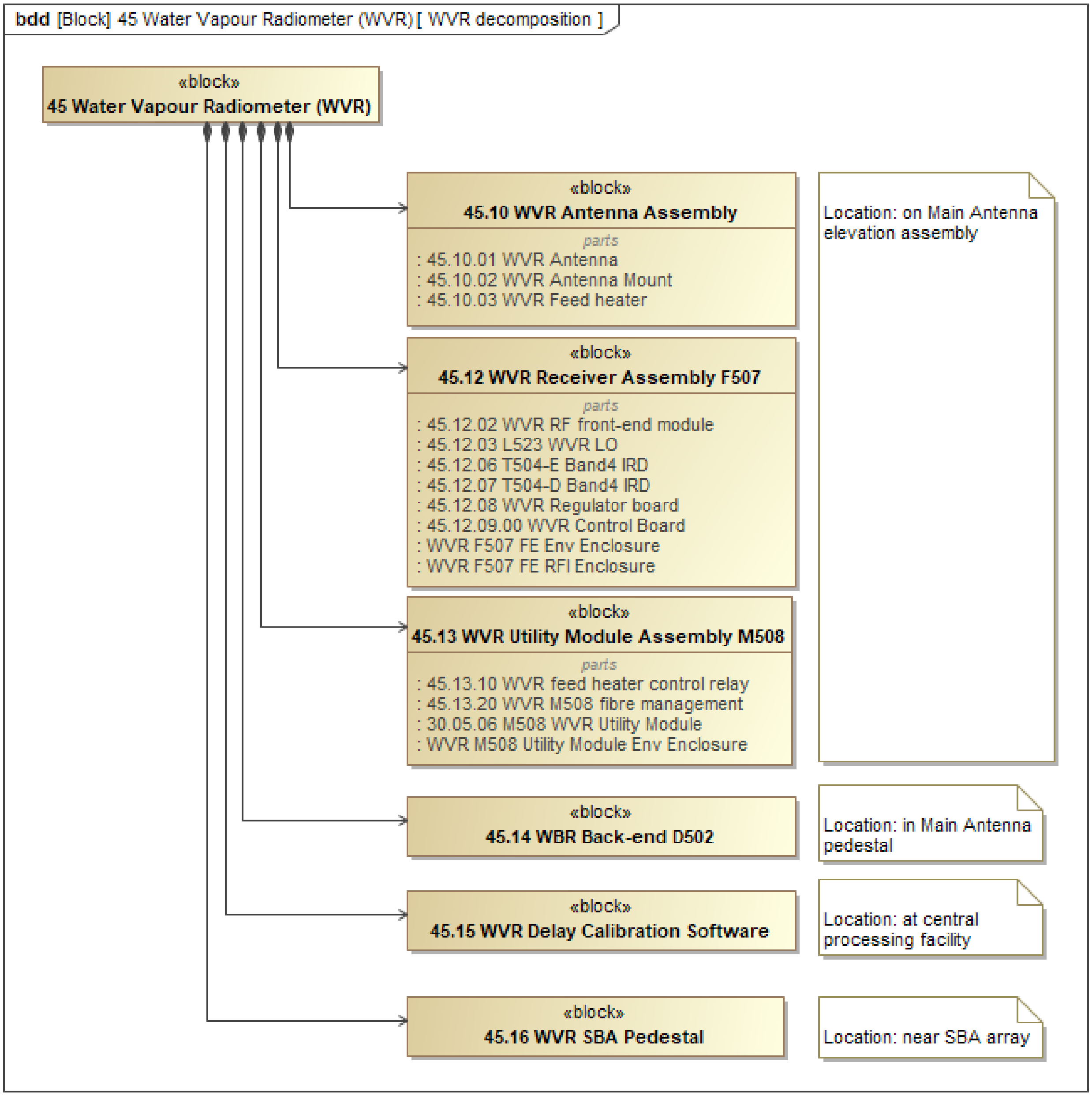

Figure 20: WVR decomposition

The WVR external interfaces are shown in Figure 21 below and include:

a) Mechanical interfaces to the ANT for the mounting of the WVR components on the Antenna structure and for the provision of AC power.
b) Supply of DC power by the PSU subsystem.
c) Supply of cooling for the WVR electronics by EEC.
d) Provision of environmental and RFI shielding for the WVR electronics by the BMR.
e) Control and monitoring of the WVR electronics via the HIL subsystem.
f) Connection to the antenna fiber infrastructure via the AFD.

g) Provision of LO and sampling clock references by the ATF, for the down-conversion and sampling of the received signal.
h) Provision of an accurate time reference (PPS) by the RDT to the WVR back end for the time stamping of the WVR data in the pedestal.
i) Infrastructure required for the SBA WVR stations.

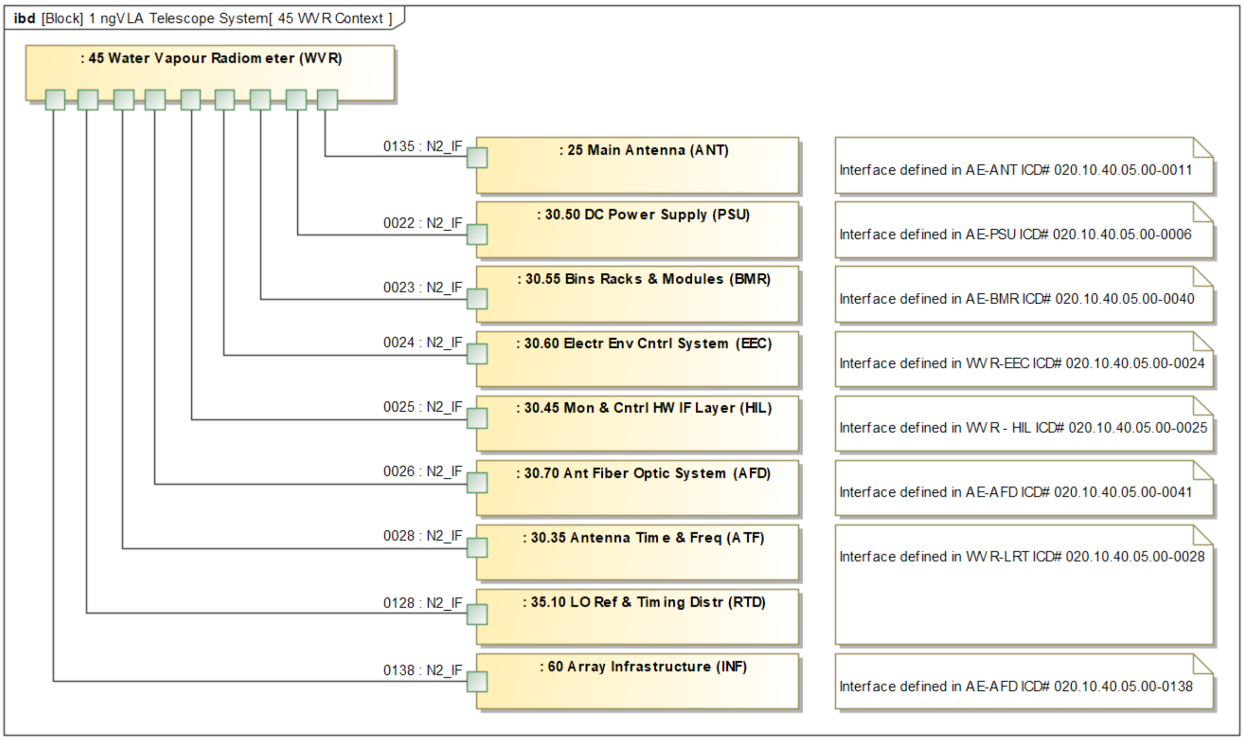

Figure 21: WVR external interfaces

4.6.7 Antenna Electronics: Monitoring and Control Hardware Interface Layer (HIL)

The HIL provides "Level 1 – Intelligent Device Layer" control and monitoring functionality as defined by the Monitoring and Control Concept [RD04]. It interacts with the various hardware devices (Level 0 devices) in the Antenna via a combination of (a) analog sensing and control and (b) their native serial communication protocols. On the other end, the HIL communicates via OPC-UA over ethernet, with the MCL system in the Antenna, which acts as the Supervisory system (Layer 2).

The HIL consists of various control and monitoring hardware:

a) Five monitor and control (M&C) interface modules (M502, M505, M506, M507, M508) distributed across the Antenna. Front-end enclosure, Auxiliary enclosure, WVR control and monitoring enclosure, cryogenics control enclosure and pedestal electronics enclosure. These interfacing units are contained within Utility Modules. See Section 4.4.1 for details of how these five HIL modules interface with the various hardware components.
b) Two control and monitoring boards inside the SA501 and SA502 enclosures that contain the IRDs and the LO modules, to provide control and monitoring for these electronics.
c) Antenna supervisor computer (HIL provides the hardware only. MCL provides the software).

The decomposition of the HIL subsystem and the location of its components is shown in Figure 22.

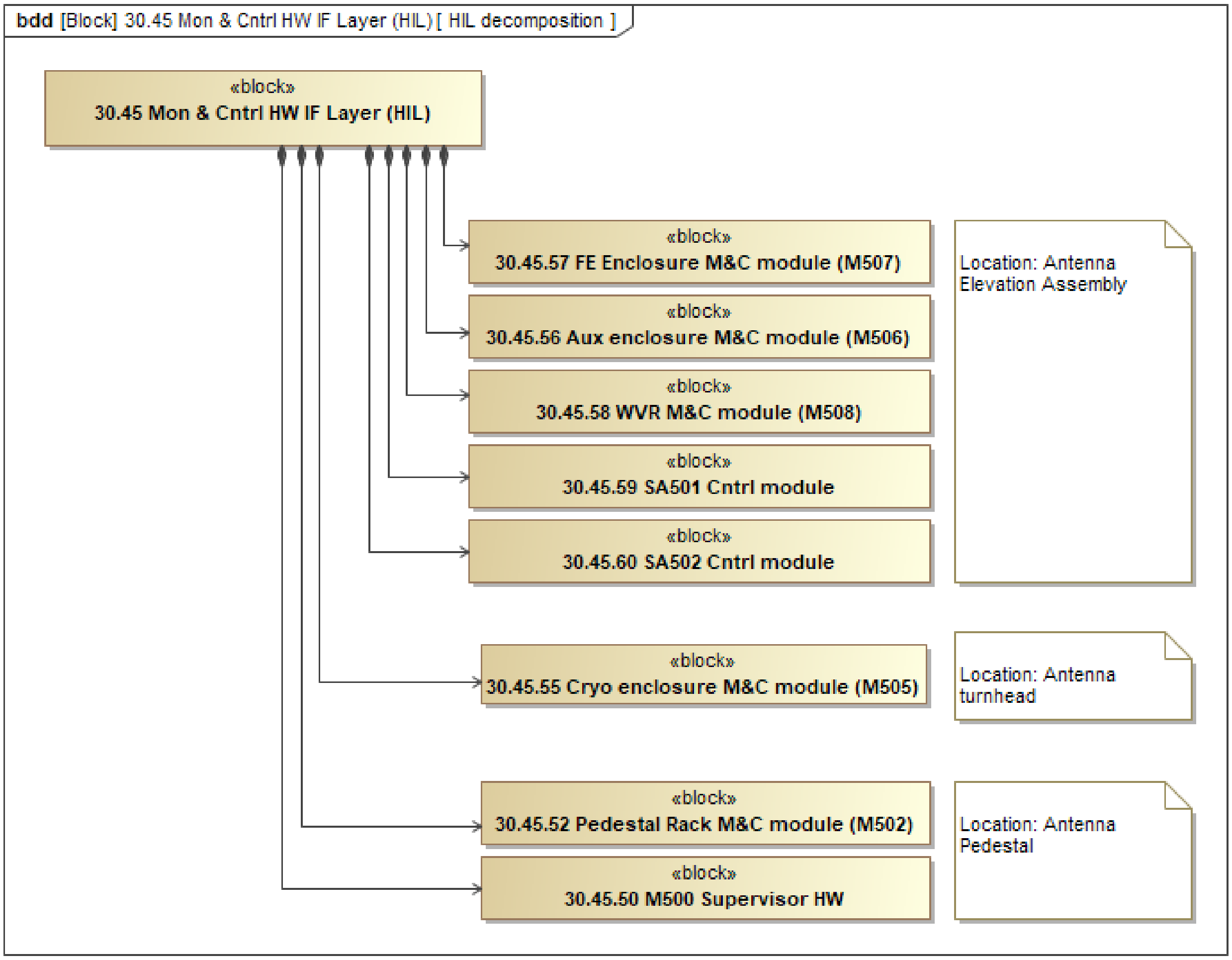

Figure 22: HIL decomposition

The HIL has external interfaces as shown in Figure 23, which includes:

a) M&C of the FED components located in the Front End Enclosure.
b) M&C of CRY: Cryogenics components located in the Front End Enclosure and Cryogenics Enclosure.
c) M&C of the IRD and ATF inside the SA501 and SA502 modules
d) The PSU subsystem is responsible for the Utility Modules, which will provide housing and DC power for the HIL modules. The HIL modules in turn provide monitoring and control interface for the DC power supply.
e) Interfaces to the BMR for the provision of the SA501/2 control module housing and shielding, and for the mechanical interfaces between the supervisor computer in the pedestal.
f) Interfaces to the EEC for provision of cooled airflow for the supervisor computer and for cooling of the SA501/2 control units.
g) M&C of the WVR components in the WVR enclosure.

h) M&C of MON components.
i) AFD for the provision of fiber interconnect infrastructure in the antenna.
j) MCL for the relay of all M&C data to/from the antenna supervisor computer.
k) M&C of the RTD components in the antennas pedestal and central processing facility.
l) M&C of the RTG components in the central processing facility.

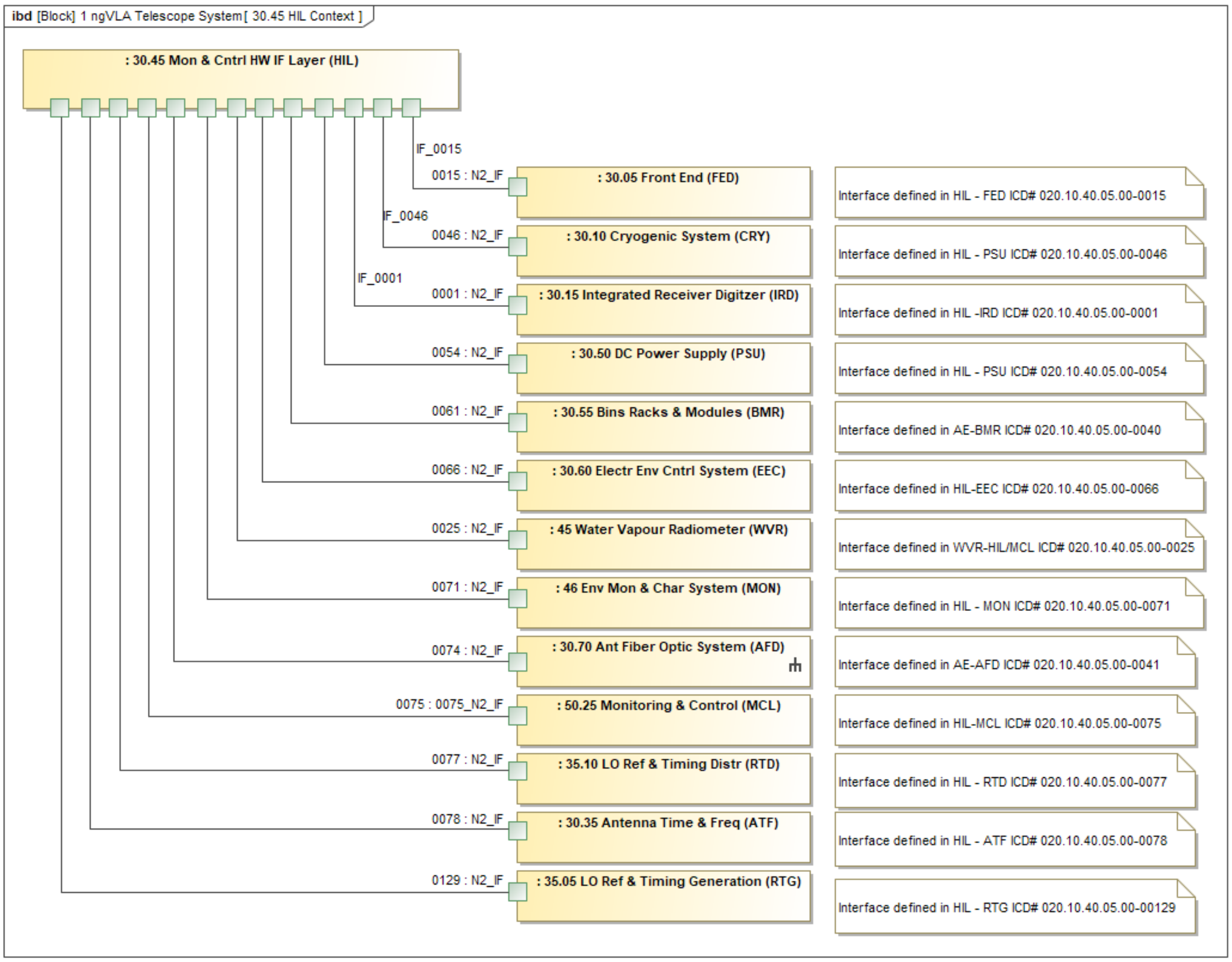

Figure 23: HIL external interfaces

4.6.8 Antenna Electronics: DC Power Supply System (PSU)

The DC Power Supply System has the following functions:

a) Converting the incoming 208V 3 phase AC power to -48 VDC power and serve as the central source of DC power in the antenna. This is provided by the P500 power supply unit that is located in the pedestal. This unit also charges the battery system.
b) Providing an uninterrupted DC power supply to the antenna for use by critical components in case of a power failure at the antenna. This is accomplished by a lithium battery unit in the pedestal.

c) In each enclosure, converting the -48 VDC to the various DC voltages that are required by the Antenna Electronics components in the enclosures. There are four Antenna Electronics DC power supply units at the various locations on the antenna: in the front-end enclosure, in the auxiliary antenna electronics enclosure, in the cryogenics control enclosure and in the pedestal electronics enclosure. The units are called Utility Modules, because they also each contain an HIL M&C unit, so each unit provides power, control and monitoring facilities for the enclosures.

The decomposition of the PSU subsystem is shown in Figure 24 below. Note that the WVR utility module M508 is shown here for subsystem development responsibility, but it forms part of the WVR PBS.

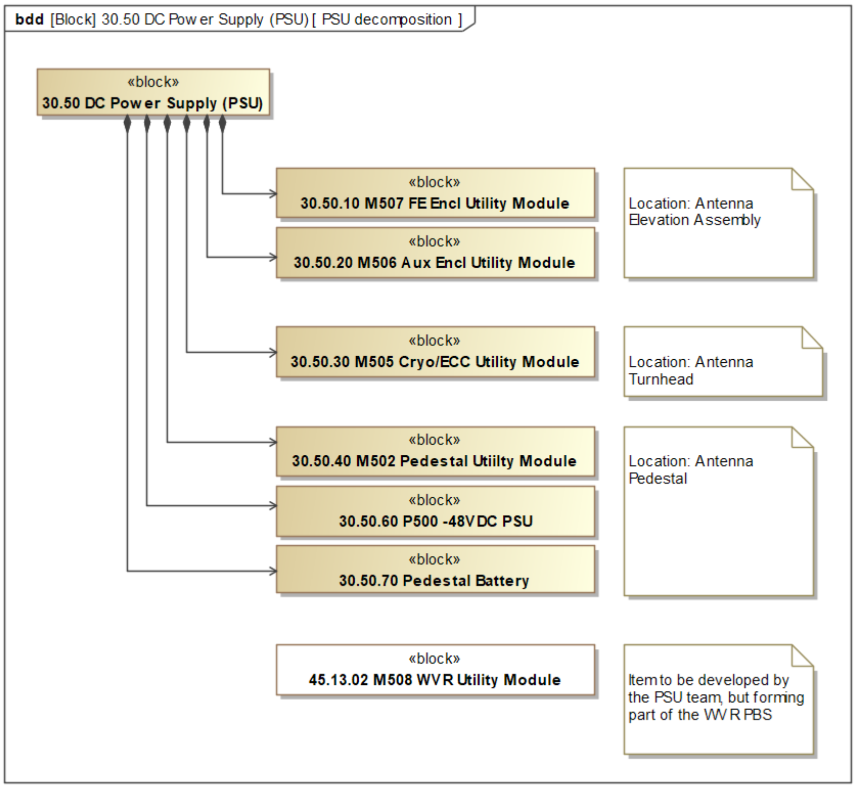

Figure 24: PSU decomposition

The external interfaces of the PSU subsystem are shown in Figure 25 below and include:

a) Interfaces from the Main Antenna and SBA for the supply of AC power and for the mechanical interfaces of the PSU equipment.
b) DC power supply interfaces to the Antenna Electronics (IRD, FED, CRY, WVR, DBE, RTD, ATF)
c) PSU cooling and mounting interfaces supplied by the EEC and BMR respectively.
d) Mechanical and power supply interfaces between PSU and HIL. HIL will be hosted inside of the utility modules.

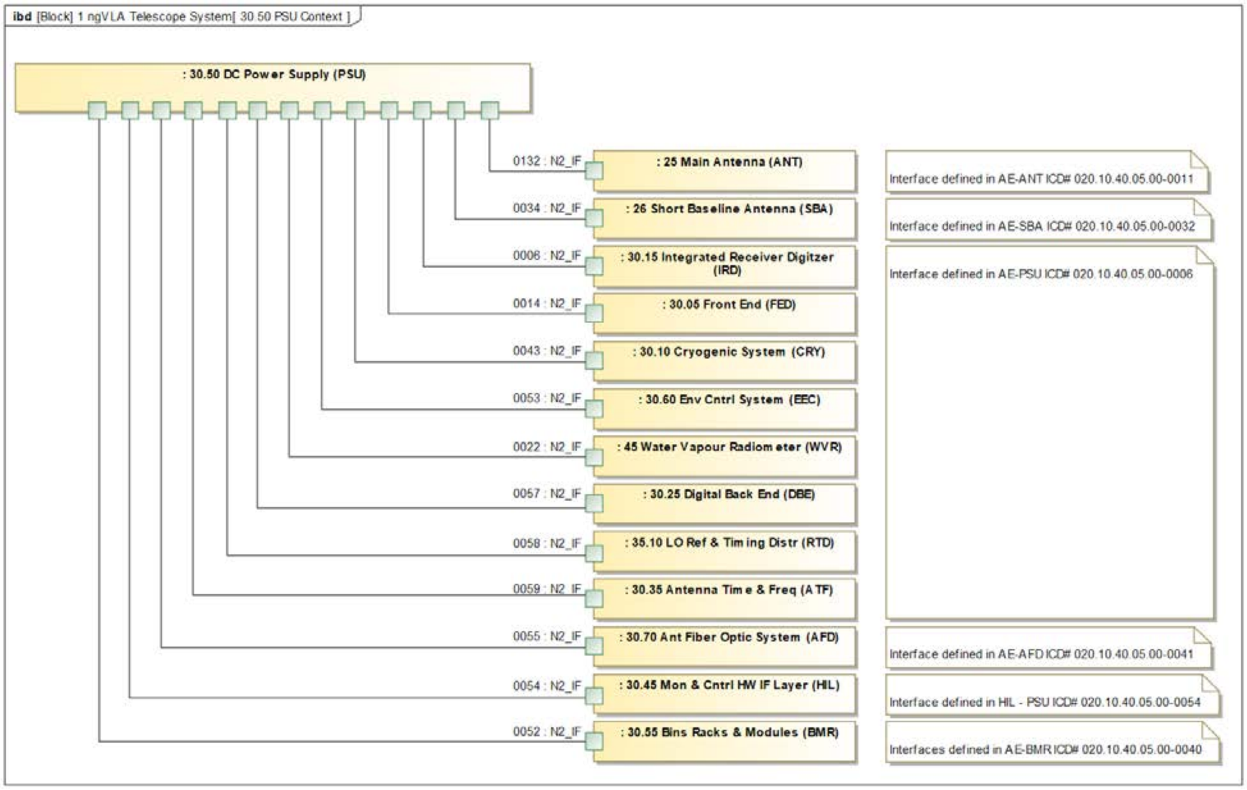

Figure 25: PSU external interfaces

4.6.9 Antenna Electronics: Bins, Racks and Modules (BMR)

The BMR subsystem provides enclosures for hosting the antenna electronics on the different locations on the antenna. The various enclosures are shown in the decomposition in Figure 26. Some of the modules are designed for specific purposes while others are generic module enclosures that are used on multiple locations.

The BMR provides the following functions:

a) Environmental protection against the elements (sun, moisture, etc.).
b) RF radiation shielding.
c) Earthing of enclosures.
d) Surge protection on all conductive lines entering the enclosure.
e) Entry points for fiber optic penetrations.
f) Mechanical mounting mechanisms.
g) Mechanisms to regulate the temperature in the enclosures (through glycol or air ventilation).

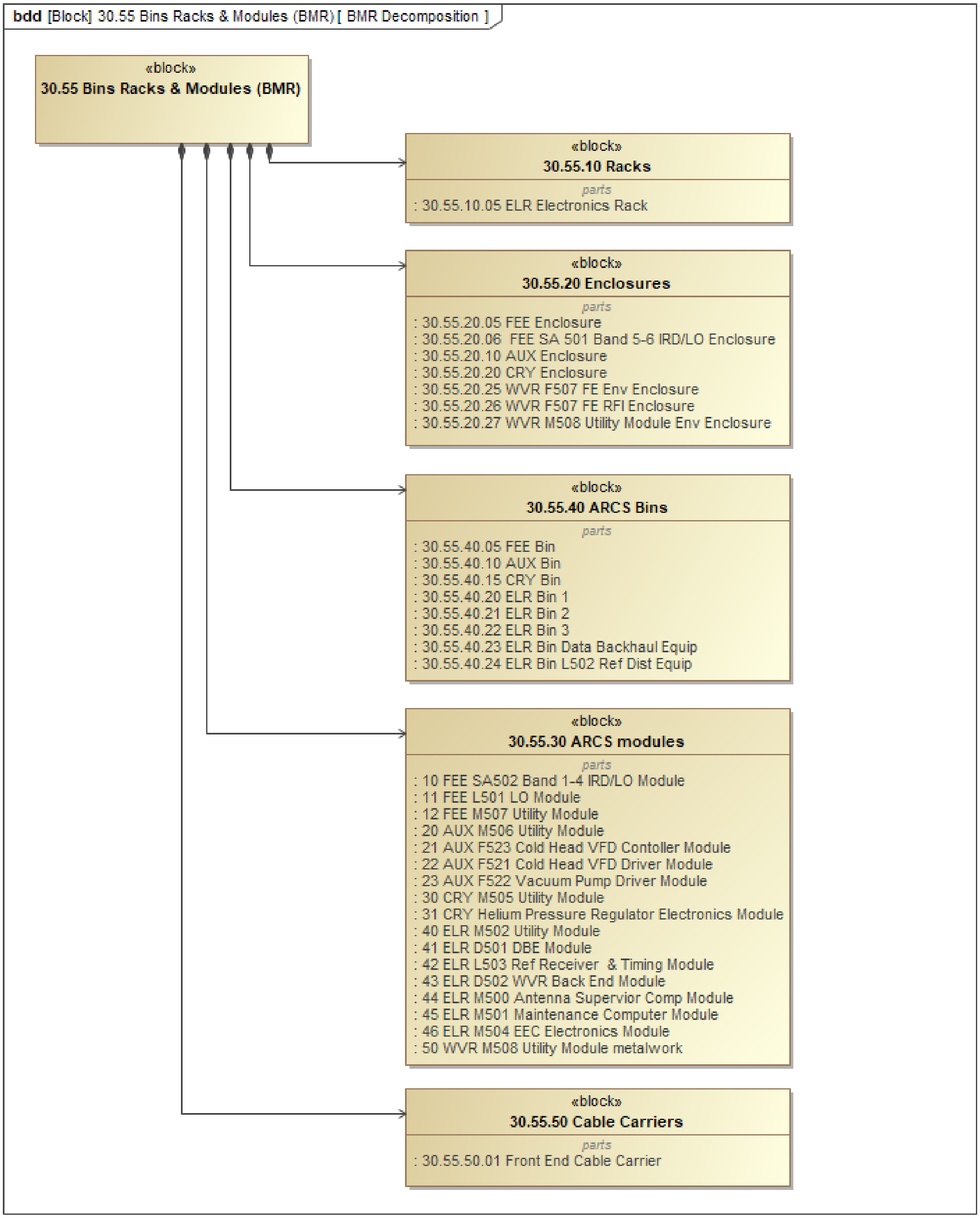

Figure 26: BMR decomposition

The external interfaces of BMR are show in Figure 27 below. The BMR interfaces with:

a) Antenna Electronics that are housed inside the modules/enclosures.
b) Main Antenna and SBA: mechanical interfaces for the mounting of enclosures, AC power connections and earthing connections.
c) Penetrations of the modules/enclosures by the antenna fiber optic cable network (AFD).

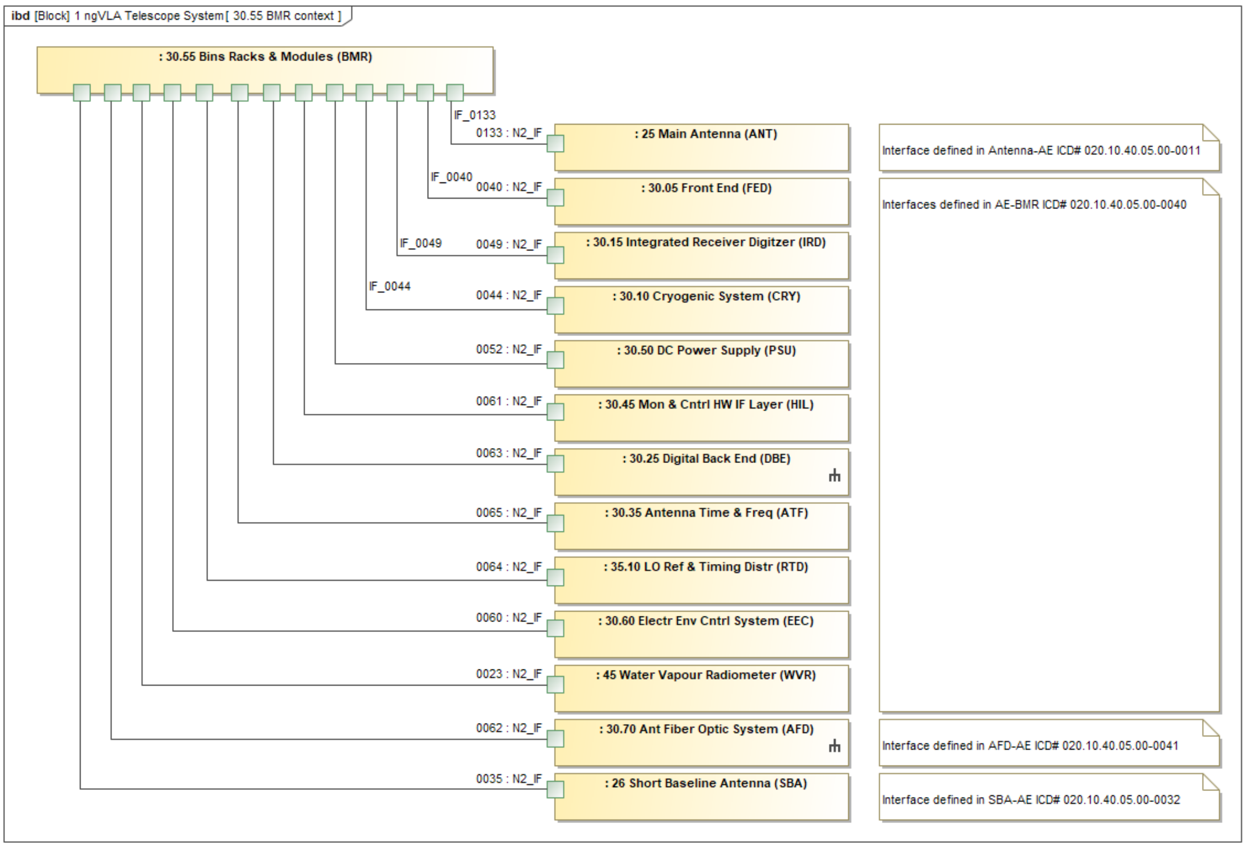

Figure 27: BMR external interfaces

4.6.10 Electronics Environmental Control System (EEC)

The EEC provides cooling for all the components housed in the antenna, including Antenna Electronics and Main Antenna components, as shown in Figure 28. It uses a glycol Chiller (located in a next to the antenna) as the primary source of heat extraction. A propylene glycol / water mix is used to avoid the environmental concerns that come with the more common and toxic ethylene glycol.

The glycol is circulated throughout the antenna to the various enclosures that house electronics. Inside each enclosure, the glycol is further distributed to cold plates on individual modules. Controllers inside the enclosures sense the temperature of individual modules and control the flow of glycol to individual modules.

The Helium compressor is one of the major heat loads. It is located in the turnhead and is also glycol cooled.

The electronics rack in the pedestal may use a combination of air cooling (via a rack cooler) and direct glycol connection to high power modules (e.g. DBE).

An air conditioner is used to cool the ambient air in the turnhead and pedestal to keep the motors and other Antenna components at the specified operating temperature.

The total heat load of the system is approximately 17kW. Figure 28 shows a first order heat load budget across the antenna.

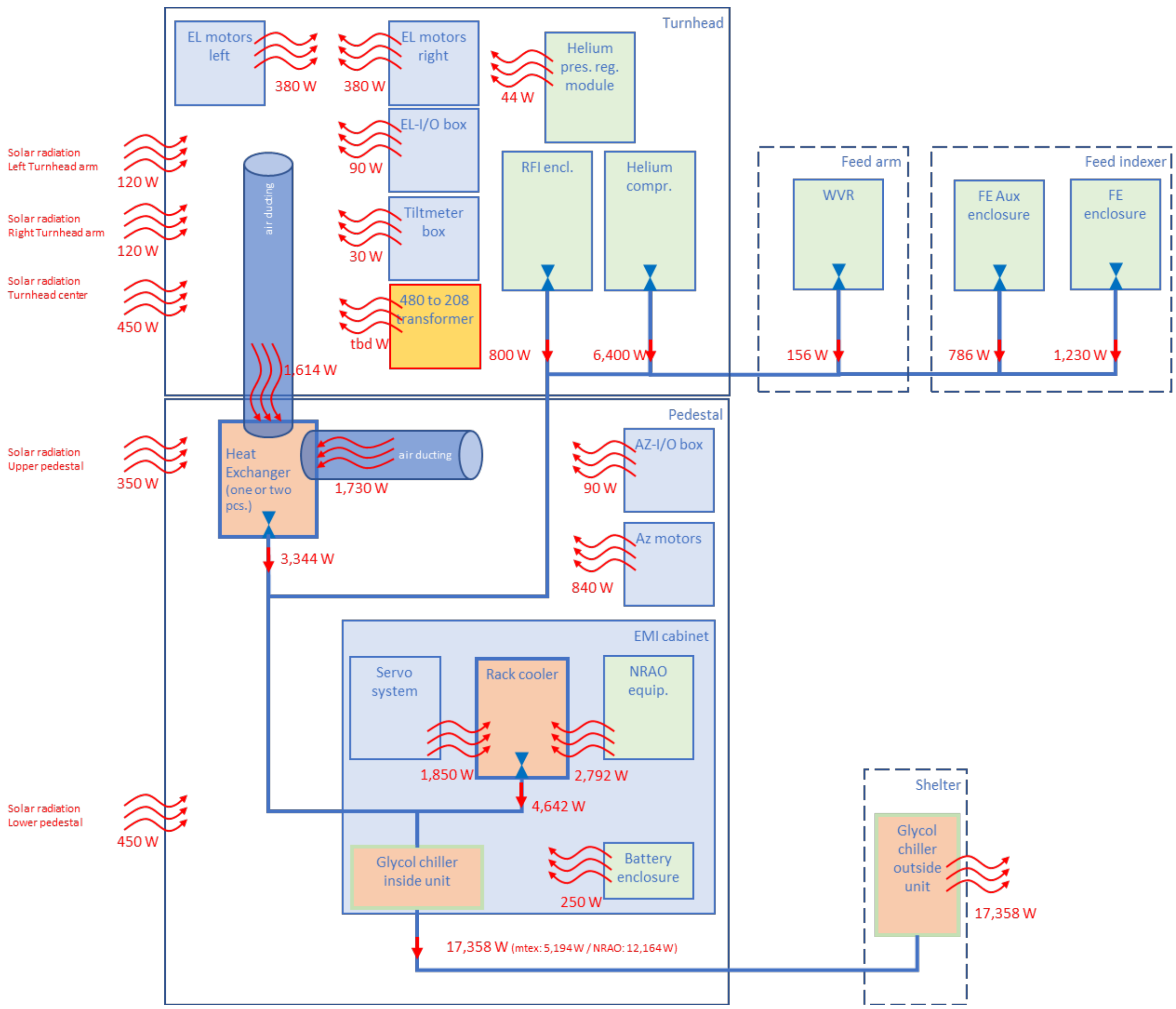

Figure 28: Overview of the Antenna Environmental Control System

The product breakdown structure of the EEC is shown in Figure 29. To ensure that the cooling system is integrated with the antenna's design and operation, the prototype antenna contractor is providing the design and installation of the chiller and the fixed glycol distribution lines. Components supplied by the antenna contractor are shown in blue in the EEC decomposition of Figure 29.

A more detailed breakdown of components can be found in the PBS.

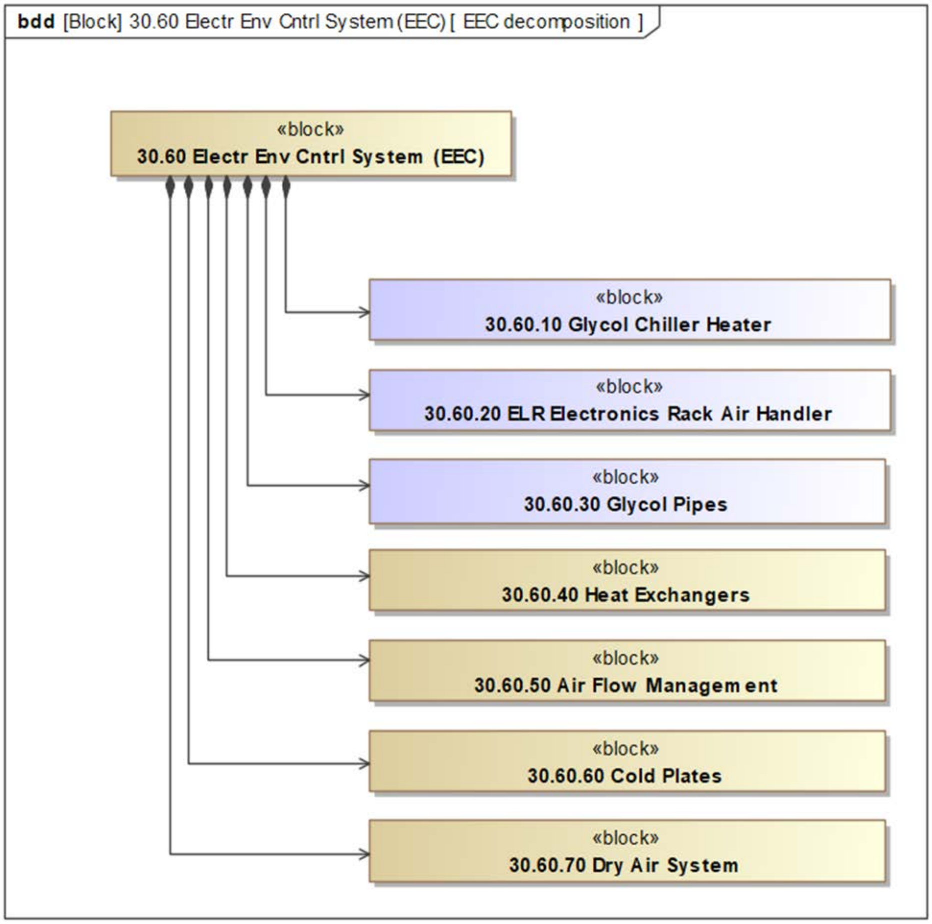

Figure 29: EEC product breakdown structure

The external interfaces of the EEC are identified in Figure 30 below. The interface definitions cover broadly the following:

a) Heat loads, glycol flow rates and glycol coupling specifications for all the electronic components (FED, CRY, IRD, PSU, BMR, WVR, HIL, AFD, RTD, ATF, DBE).
b) Heat load and glycol flow rate for the compressor (CRY).
c) Mechanical interfaces, glycol routing and heat loads for the Antenna equipment (ANT and SBA).

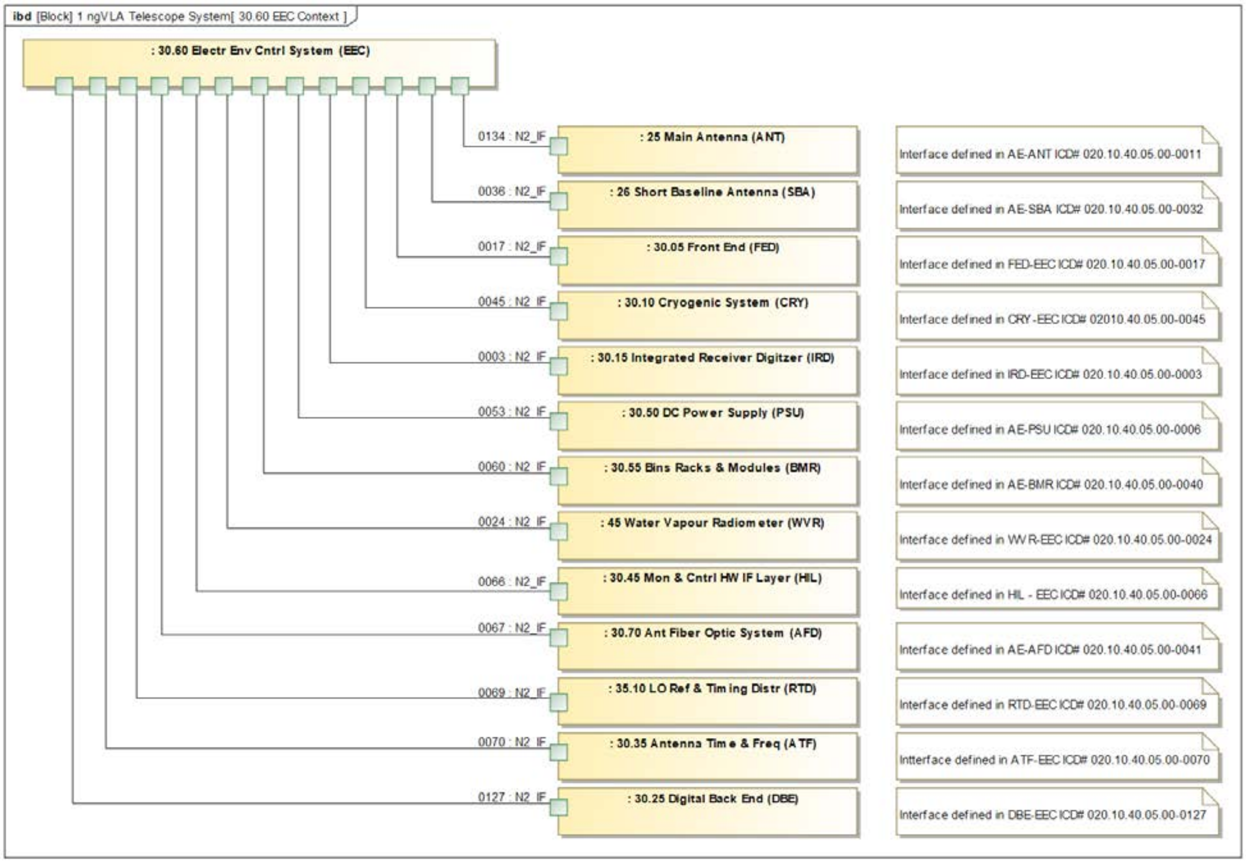

Figure 30: EEC external interfaces

4.6.11 Antenna Electronics: Antenna Fibre Distribution (AFD)

The AFD subsystem consists of the optical fiber cabling and optical fiber connection/splice trays that connect the Antenna Electronics components on the antenna. The decomposition of the AFD and location of components is shown in Figure 31 below. Note that the fiber connection/splice trays that connect directly to the externally entering fibers in the pedestal are provided by the FIB subsystem.

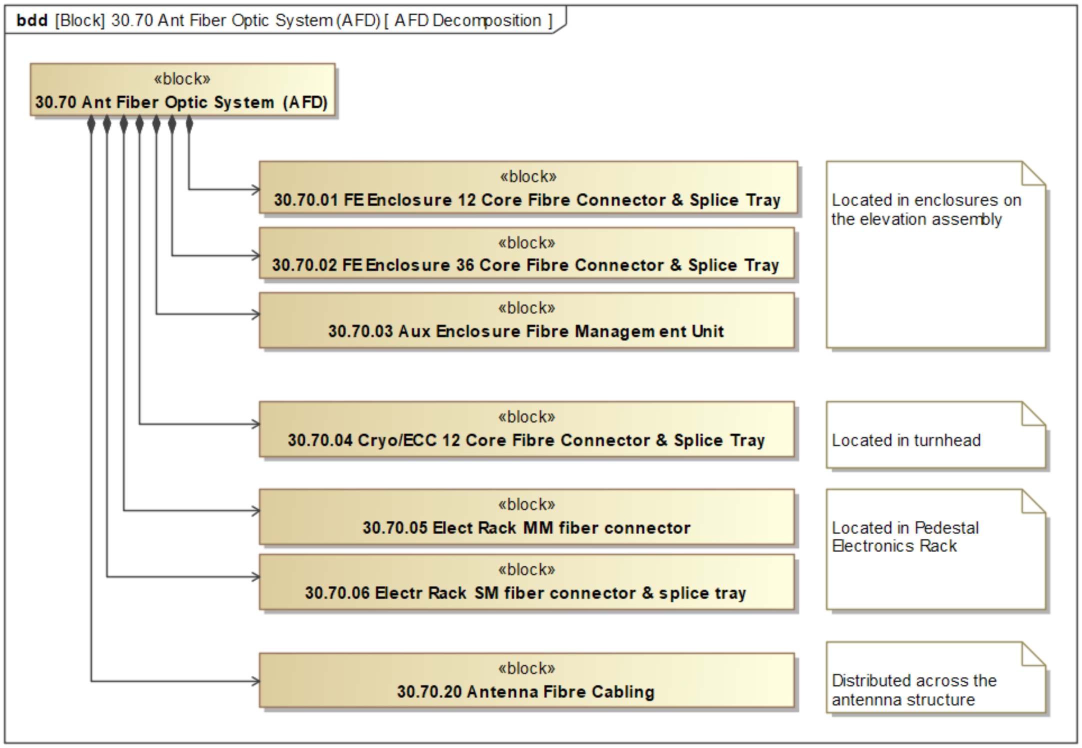

Figure 31: AFD decomposition

The external interfaces of the AFD are shown in Figure 32 below:

a) The antennas (ANT and SBA) provide the infrastructure to route the fiber optic cables throughout the antenna between enclosures, including the wraps across the three axes of motion.
b) The AFD provides fiber optic connectivity to the FED, CRY, IRD, PSU, EEC, WVR, ATF, HIL and DBE subsystems.
c) There are fiber routing interfaces and enclosure penetration interfaces between AFD and BMR for all the Antenna Electronics enclosures.

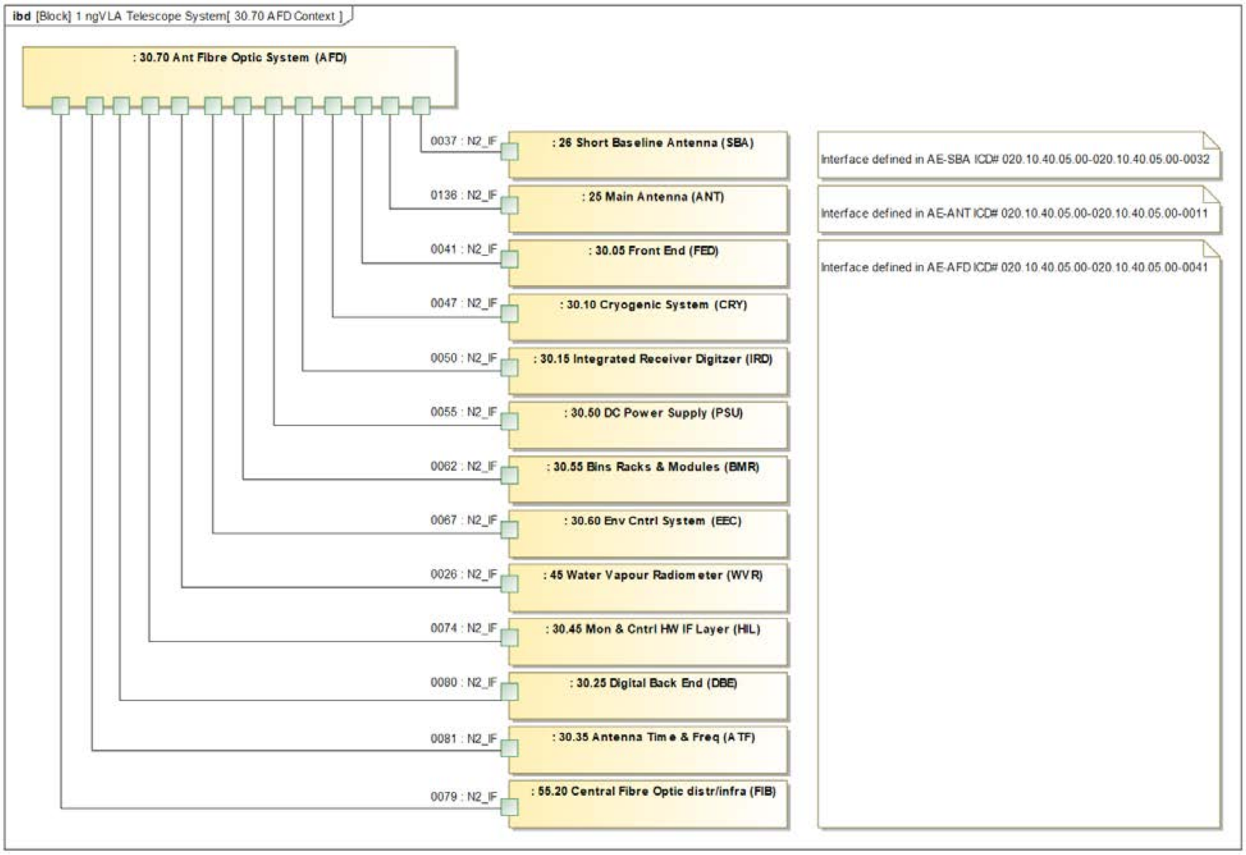

Figure 32: AFD external interfaces

4.6.12 Environmental Monitoring and Characterization System (MON)

The MON subsystem is a collection of different environmental monitoring equipment that is deployed around the array to characterize and monitor the environment, including weather, atmospheric phase, cloud cover, lightning and RFI. This equipment is located at the central part of the array and also distributed along the mid baseline array as needed to cover the monitoring needs. This subsystem also includes a mobile satellite holography system that can be moved to any antenna location for holographic testing for antenna verification after installation or maintenance. The decomposition of the MON subsystem is shown in Figure 33 below.

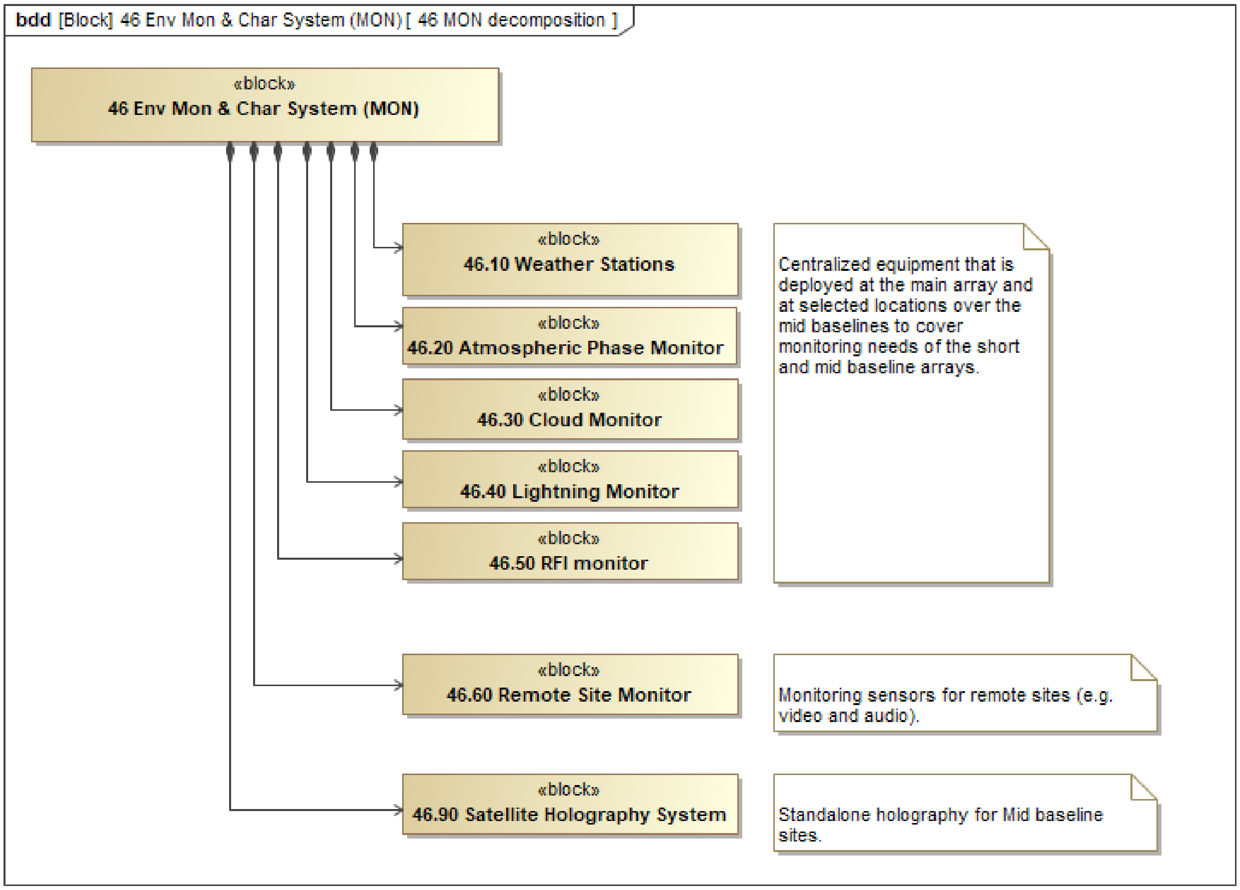

Figure 33: MON decomposition

The MON subsystem has interfaces to:

a) The HIL and MCL subsystem for the transfer of the environmental data and for the control of the MON equipment.
b) The INF subsystem for the provision of physical infrastructure, power and fiber connections, as shown in Figure 34 below. Note that the power and ethernet connections may come from the closest antenna, but INF supplies the cabling.

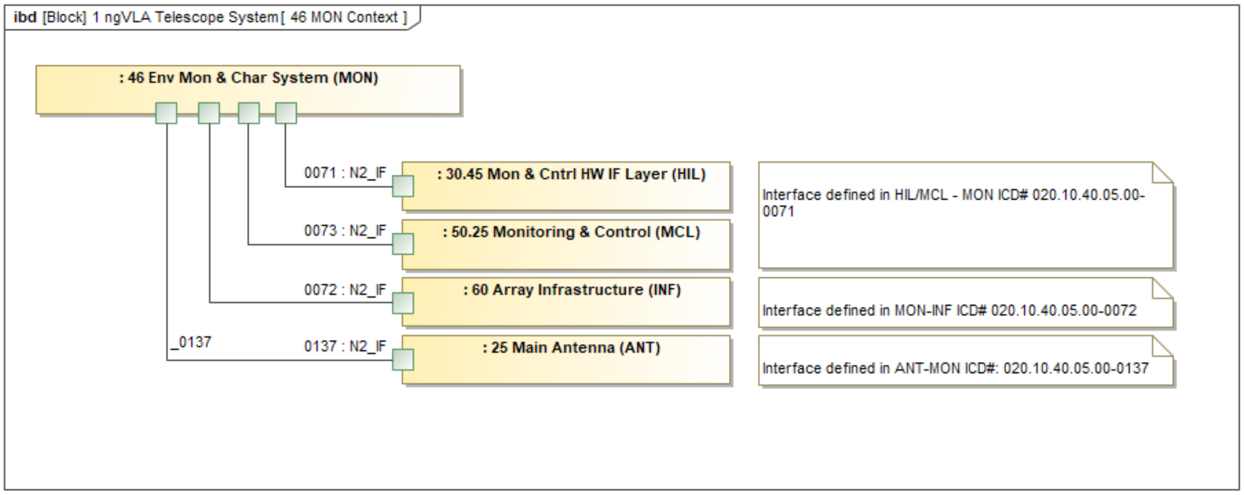

Figure 34: MON external interfaces

4.6.13 Array Infrastructure (INF)

The Array Infrastructure subsystem will support system operations, including scientific and array operations, array maintenance and engineering, and array development. Five primary components have been identified for Array Infrastructure:

a) **Antenna Foundations** serve as physical anchors to support stability requirements for the antennas in the ngVLA system. This component also includes the foundations necessary to support other system elements like the glycol chiller, transformer pads, and weather station pads.

b) **Operations roads** provide unrestricted access to operational facilities, antennas, and other array infrastructure to support maintenance and operational activities.

c) **Utility Trenching** houses electrical and fiber cabling between array facilities and antennas, likely with specific focus to areas near the array. Interfacing with existing power and fiber infrastructure will likely be necessary outside of the array core.

d) **Fiber Utility** identifies the components required to support fiber installation, support, and maintenance. Interfacing with existing power and fiber systems will likely be necessary outside of the array core. At the array, FIB will inform high-level design of fiber infrastructure.

e) **Electrical Utility** identifies the elements required to support electrical cabling installation, support, and maintenance, as well as central generator back up capabilities and associated switch gear.

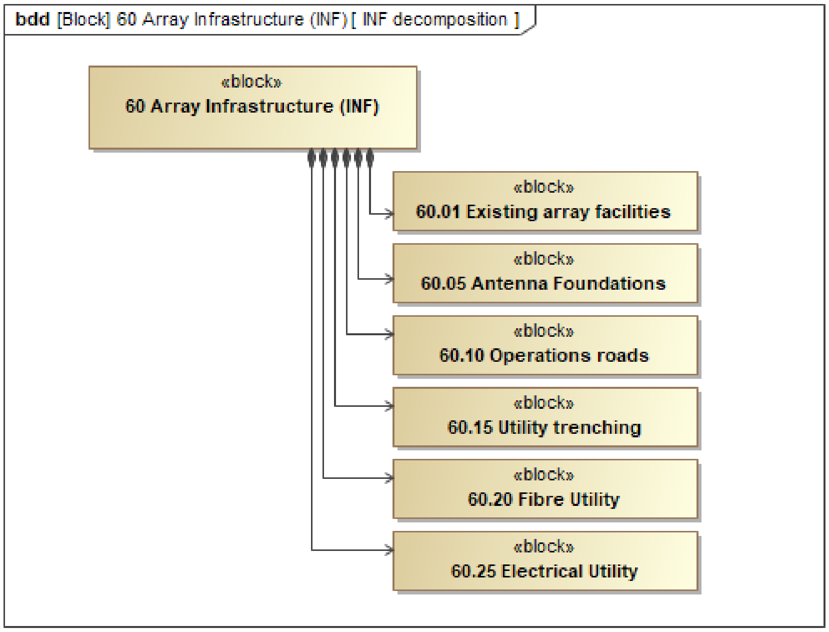

Figure 35. Array Infrastructure Subsystem Decomposition

INF interfaces to other subsystems, and associated ICD information, are shown in the context diagram in Figure 36 below.

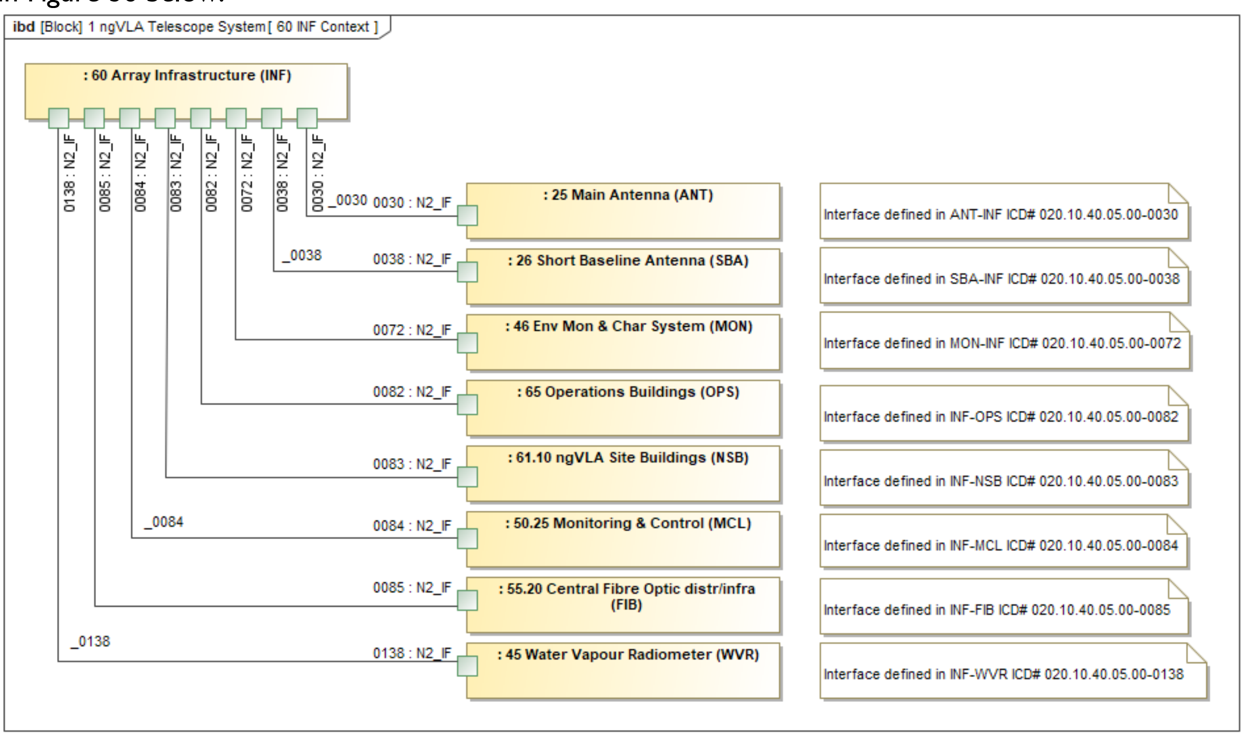

Figure 36. Array Infrastructure Context Diagram

4.6.14 Buildings (BLD)

Various buildings are needed to support operations across the system as shown in Figure 37 below. These include buildings to support the hosting of telescope equipment, maintenance operations, science operations, and outreach activities.

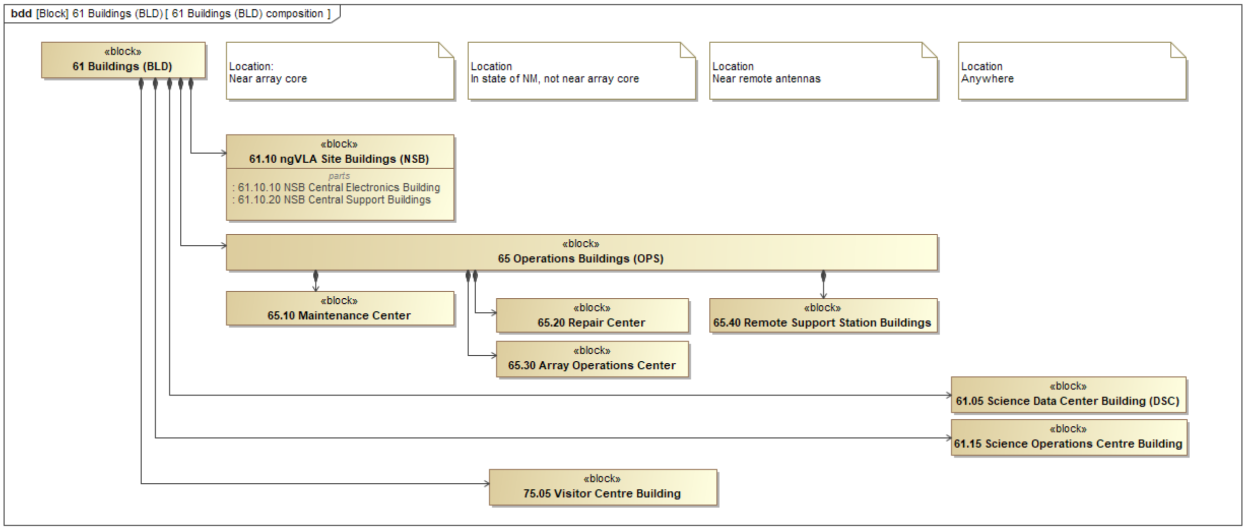

Figure 37: Buildings decomposition and location

4.6.14.1 ngVLA Site Buildings (NSB)

The major facility for NSB is the Central Electronics Building that will house the central signal processor (Correlator), centralized IT infrastructure, and time and frequency generation and distribution equipment.

The ngVLA Site Buildings also include Central Support Buildings to support maintenance operations on site, such as heavy equipment storage, garages, depot, security facilities, and a small medical clinic.

The NSB also includes the supply of water and sanitation services. Potable water is supplied from a well and is made available at all facilities at the VLA via an onsite closed-loop system. The sanitary sewer system consists of a gravity collections system that serves the control building, visitor center, and most of the other site buildings.

NSB interfaces to other subsystems, and associated ICD information, are shown in the context diagram in Figure 38. These interfaces pertain mainly to the interfaces to the Central Electronics Building:

a) Interfaces between array infrastructure and the Central Electronics Building, including power supply interfaces and fiber utilities.
b) Central Electronics Building interfaces to hosted equipment for the supply of space, power, cooling, etc.

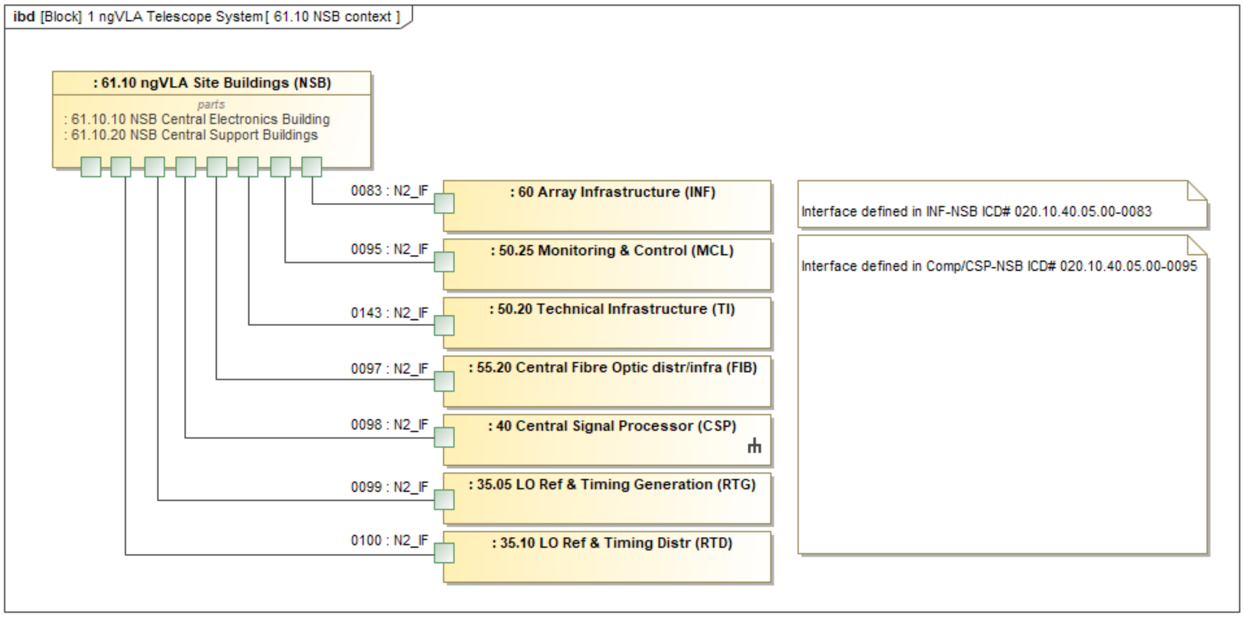

Figure 38. ngVLA Site Buildings Context Diagram

4.6.14.2 Operations Buildings (OPS)

Operations buildings encompass a wide range of buildings to support array operations and maintenance across the full physical extent of the array. These include:

- Near the array core:
  - Maintenance Center.
- Within the State of New Mexico:
  - Array Operations Center.
  - Repair Center.
- At LBA stations and remote antenna sites
  - Remote Support Station Buildings.

The **Maintenance Center** will serve as a central location for safety, security, and maintenance personnel, as well as maintenance activities and ready spare storage. The Maintenance Center will include garages for heavy equipment and vehicles.

The **Array Operations Center** provides office and laboratory space, as well as storage and transfer capabilities, and computing infrastructure for approximately 250 staff. It will be co-located with the Repair Center.

The **Repair Center** is anticipated to be collocated with the Array Operations Center. It will serve as the location for diagnostic, repair, and test activities for electronic LRUs and other equipment. Parts that fail will be sent to the Repair Center for repair, and then will be returned to the Maintenance Center as ready spares.

The **Remote Support Stations** will include all the operations buildings that are required for the long baseline antennas and for antennas in remote locations that cannot be serviced from the Maintenance Center.

OPS interfaces to other subsystems, and associated ICD information, are shown in the context diagram in Figure 39.

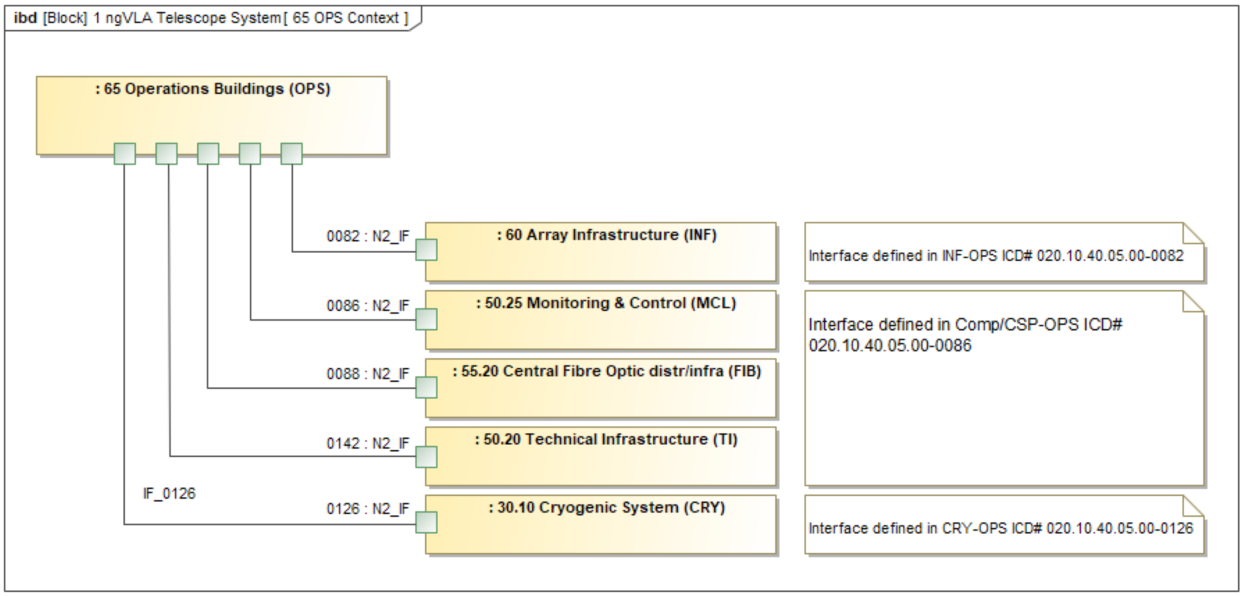

Figure 39. Operations Building Context Diagram

4.6.14.3 *Science Operations and Data Centre Building (DSC)*

The **Science Operations and Data Center Building** will likely be located in a large metropolitan area. It hosts mainly two activities:

a) ngVLA Science Operations. This includes research, development, and software operations for approximately 175 staff and will primarily consist of office space. It will host staff that do not need regular access to the antenna sites, such as staff scientists, firmware and software engineers and staff responsible for the maintenance of the data center.
b) Science Data Center which will house high performance computing equipment for the offline processing system that is responsible for post-processing data products and data archiving.

DSC interfaces to other subsystems are shown in the context diagram in Figure 40 below. The managed interfaces are mainly related to the hosting requirements of the computing equipment including space, power and cooling interfaces.

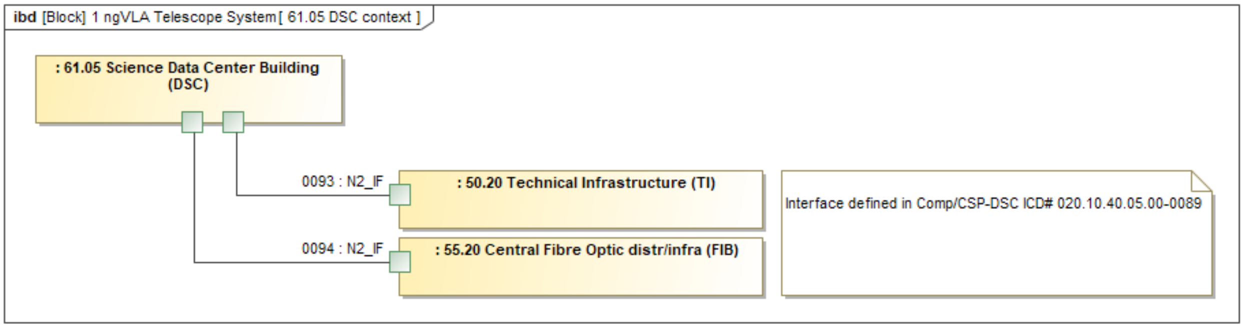

Figure 40. Data Science Center Building Context Diagram

4.6.14.4 Visitors Center

The Visitors Center supports public outreach and engagement with radio astronomy technology. The location of this building is still TBD, and it may use existing available buildings if found suitable. Locating this building at a distance from the core, while still maintaining proximity to the array, would minimize radio frequency emission impact to the array while still encouraging interaction with the array.

4.6.15 Computing and Software System (CSS)

Figure 41 shows all the subsystems in the scope of the CSS IPT.

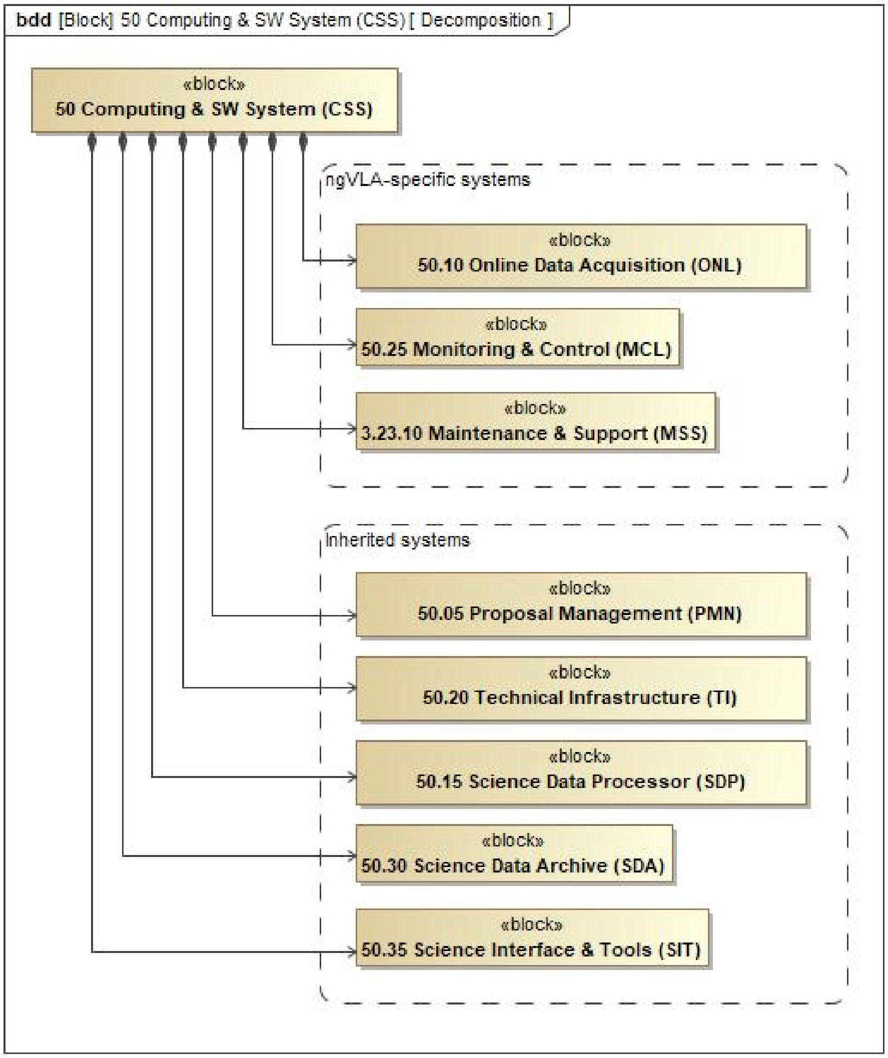

Figure 41: Decomposition diagram for the Computing and Software (SW) Subsystem.

The system is divided between "ngVLA-specific systems" and "inherited systems". The ngVLA-specific systems (ONL, MCL and MSS) will be implemented from the ground-up, specially constructed to comply with ngVLA requirements. The inherited systems (PMN, TI, SDP, SDA and SIT) represent systems that are already in operation in NRAO and will be upgraded for ngVLA. Typically, the inherited systems are designed to service not only ngVLA, but other NRAO facilities (like ALMA) as well.

The subsystems defined in these diagrams are:

(a) **50 Computing & SW System (CSS)**: This block represents all the software and computing equipment in the scope of the ngVLA Computing and Software IPT.

(b) **50.05 Proposal Management (PMN)**: The PMN system supports the ngVLA telescope time allocation processes, including the solicitation of proposals for each observing cycle, the proposal submissions from PIs, the review, time allocation, approval and closeout processes. It supports these processes through the Telescope Time Allocation Tools (TTAT), a common NRAO system for all its supported telescopes. The ngVLA Proposal Management System extends the TTAT system to comply with its specific requirements.

The PMN system is constituted by the augmented TTAT and the Observation Preparation subsystem. The TTAT does not generate Scheduling Blocks, as these are telescope-specific structures. Instead, it creates telescope-agnostic Observation Specification structures that are transformed into Scheduling Blocks by the Observation Preparation subsystem.

(c) **50.10 Online Data Acquisition (ONL)**: The ONL system schedules and controls the execution of observations, receives science data from the Central Signal Processor (CSP), processes the science data to generate calibration tables, applies RFI mitigation strategies, formats the data into the science data format, and dumps the datasets on a temporary buffer, to be transported to the Science Data Center by the Data Transport Middleware (part of TI). It also optionally performs the last stage of data averaging. But for a few exceptions, the ONL system is mostly composed by dynamic components that are instantiated per-subarray.

(d) **50.15 Science Data Processor (SDP)**: The Science Data Processor system provides interfaces to select and execute workflows that accomplish specific processing use cases (e.g. imaging, calibration, etc.). A workflow consists of one or more tasks - usually comprising preprocessing, processing, and post-processing steps. Workflows can mix parallel application invocations with instantiations of single threaded processes. Parallel application invocations will involve delegating applications to the resource manager. The resource manager is responsible for allocating physical resources to applications as well as scheduling and monitoring workflow executions. Applications will consist of CASA API libraries, parallel processing libraries, and any other dependencies (e.g. zarr, Dask, etc.)

(e) **50.20 Technical Infrastructure (TI)**: The Technical Infrastructure system includes all computing, storage and networking hardware for which the CSS IPT is responsible. All the other systems are pure software systems. This organization reflects modern software development and operational practices for large computing facilities, where there is a separation between software development activities and the responsibility of specifying, procuring, installing and maintaining technical infrastructure up and running. The use of containerization and virtualization strategies has allowed the abstraction of deployment details from software development, enabling more efficient use of computational resources and more streamlined software operations. The paradigm is for software development groups to define the capabilities that their systems need, while the aggregated resources that these capabilities require are specified and maintained by the TI group as shared resources. Besides hardware resources, the technical infrastructure group is also responsible for maintaining non-domain, crosscutting software infrastructure such as logging, IT monitoring systems, data transport middleware, and communication middleware.

(f) **50.25 Monitoring & Control (MCL)**: The MCL system provides supervisory control components which interact with hardware elements using protocols such as Open Platform Communications Unified Architecture (OPC UA), and expose their functionality in APIs. The APIs isolate the low-level details involved in accessing the hardware from the ONL software responsible for executing observations. These supervisors are mostly static components, in contrast with the ONL components which are mostly dynamic and subarray-based. The MCL provides highly available services for the Array Operator, which include a Supervisory Control And Data Acquisition (SCADA) system that interacts both with the supervisor components and OPC UA servers in HIL, ANT, SBA, DBE, and CSP systems. The MCL receives monitoring data streams from these subsystems, storing and processing them to support diagnostics, troubleshooting and preventive maintenance operations.

(g) **50.30 Science Data Archive (SDA)**: The SDA system provides data management software needed to support the science data archive, the final repository for the science data products produced by the ngVLA telescope. Examples are ingestion software, data retrieval interfaces, and services to perform queries over the metadata. Note that the archive physical storage systems are included in the TI system, while the SDA system only provides software infrastructure.

(h) **50.35 Science Interface & Tools (SIT)**: The SIT system provides an integrated science interface allowing users to easily and effectively interact with the science data and their colleagues, track the progress of their projects and interact with ngVLA scientific staff. The SIT system also includes tools and services needed for commissioning, quality assurance, data analysis and visualization.

As explained in RD04, the ngVLA monitoring and control concept adopts a layered architecture based on ISA-95 and the Purdue model for cybersecurity. The layers have been defined as:

- Level 0 - Hardware Device Layer: The hardware elements that are directly involved in the physical processes involved in an astronomical observation.
- Level 1 - Intelligent Device Layer: Intelligent devices for sensing and manipulating. Involves the hardware elements that sense, manipulate and convert the signal path. These are HIL boards, the CSP, DBE and ACU. The processes involved in these operations have typical time-frames of less than a second (ms and us).
- Level 2 - Supervisory Control and Monitoring: Control systems for monitoring and supervision. The systems that supervise, monitor and control the physical processes. Includes Distributed Control Systems (DCS), Human-Machine Interfaces (HMI), Supervisory Control and Data Acquisition (SCADA) software. The time-frame is typically seconds to minutes.
- Level 3 - Observation Operation Layer: Systems involved in managing the observation workflows to produce the desired science datasets. The typical time-frame is minutes to hours.
- Level 4 - Observatory Planning and Logistics Layer: Manages the activities of the observatory operation. This includes the telescope time allocation process, establishing the long-term observatory schedules, etc. The time frame is days and months.

Following this architecture, the ONL system includes all Level 3 components, while Level 2 components conform the MCL system. The PMN system resides in Level 4. The other levels are composed by sub-elements belonging to other IPTs. This organization is shown in Figure 42.

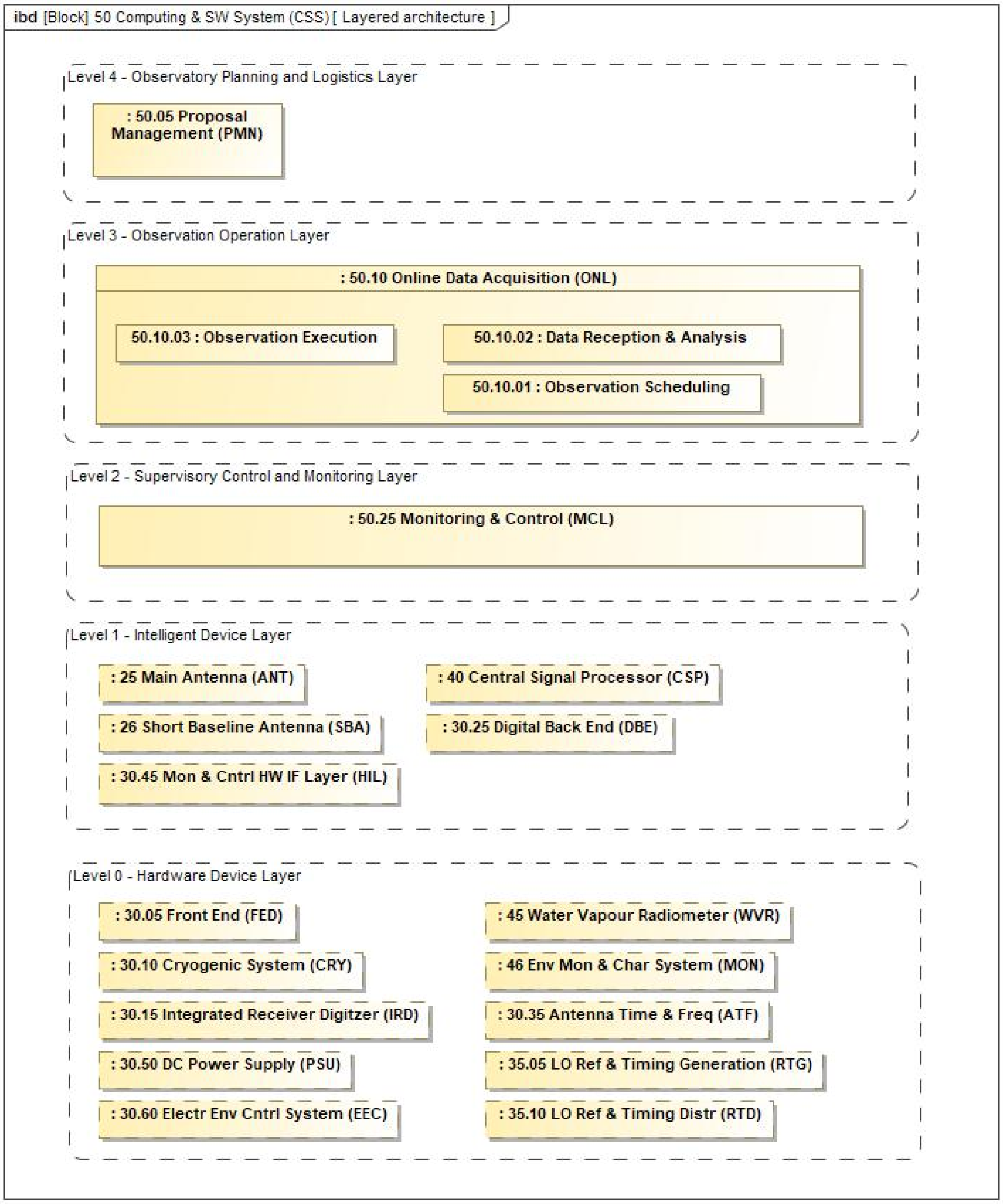

Figure 42: Monitoring and control conceptual layered architecture.

Figure 43 show the main interfaces between the CSS systems.

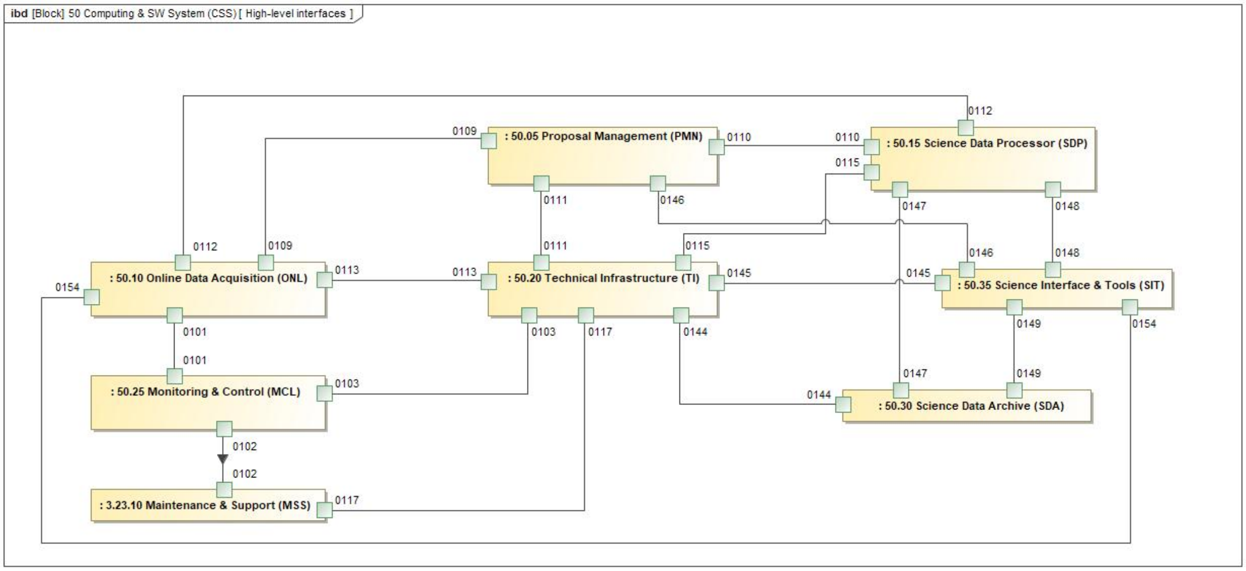

Figure 43: High-level interfaces between CSS systems.

These interfaces are described below.

(a) 0113, 0103, 0117, 0144, 0145, 0115, 0111: All software systems have interfaces with TI. The specification of these interfaces defines software deployment requirements for the technical infrastructure. This should include the definition of the processes that will be deployed and an estimation of their computing power, memory, input/output, and storage requirements. Although preliminary estimations can be obtained by analysis, realistic figures will most probably require measurement and extrapolation using existing systems or prototypes.

(b) 0112 - Interface between ONL and SDP: The dynamic scheduling algorithm considers the SDP current processing jobs, processing queue, and the available capacity of intermediate buffers as inputs to decide the next observations to avoid overloading this system. This requires a service in the SDP to expose this information. Additionally, triggered observations may require an interface for the ONL scheduling component to pause running jobs in the SDP, although this may be handled just by assigning a very high priority to the triggered observation processing jobs.

(c) 0109 - Interface between ONL and PMN: ONL downloads Scheduling Blocks from PMN. A service is provided by ONL to support long-term scheduling simulations for the Time Allocation Committee (TAC). Other interfaces may be necessary to support triggered observations.

(d) 0101 - Interface between ONL and MCL: The ONL system sends high-level control commands to the MCL system, which translates them into low-level commands to the hardware. It also sends calibration results to be applied in the hardware. The MCL sends to ONL selected monitoring data streams (e.g. water vapor radiometer (WVR) and pointing data).

(e) 0102 - Interface between MCL and MSS: The MCL system receives monitoring data from hardware elements and streams this data to the MSS system for storage and further processing and visualization.

(f) 0110 - Interface between PMN and SDP: The TTAT structures include detailed processing instructions to generate high-level data products. Note that these data structures will most probably be included in the science datasets, but are specified formally in this ICD.

(g) 0146 - Interface between PMN and SIT: SIT provides interfaces to track the status of PMN objects. PMN sends notifications of changes to SIT through this interface.

(h) 0147 - Interface between SDP and SDA: The SDP system retrieves and ingest data products into the SDA.

(i) 0148 - Interface between SIT and SDP: The SIT uses SDP services to re-process data and perform quality assurance operations.

(j) 0149 - Interface between SIT and SDA: The SIT uses SDA services to provide query, retrieval, visualization and analysis interfaces for datasets stored in the SDA.

(k) 0154 - Interface between ONL and SIT: SIT provides interfaces to track the status of ONL objects, such as observation executions. ONL sends notifications of changes to SIT through this interface.

The monitoring and control interfaces between CSS and other external system elements are shown in Figure 44.

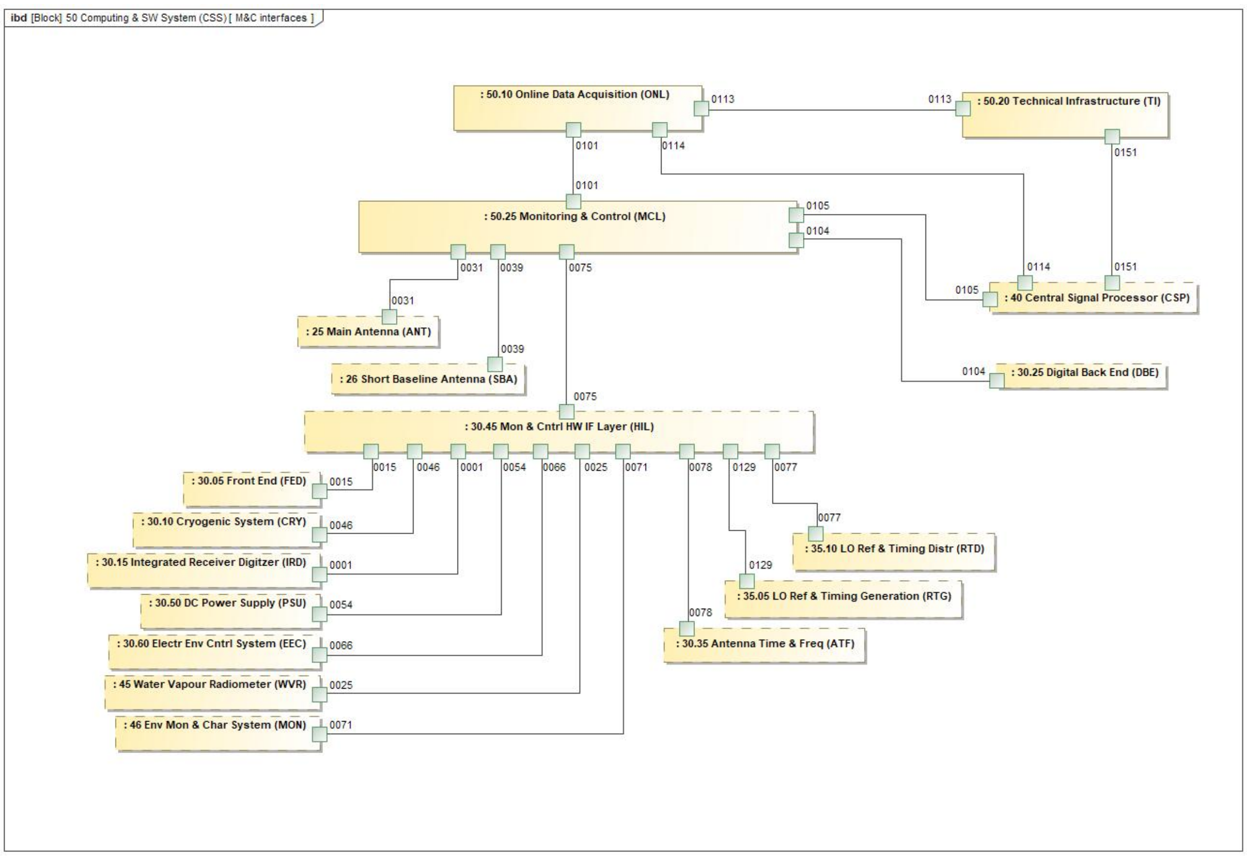

Figure 44: CSS monitoring & control interfaces.

The MCL system communicates with several electronic systems through OPC UA interfaces. These interfaces are 0031, 0039, 0075, 0104 and 0105.

The interface 0075 acts like an aggregation interface for the low-level interfaces between HIL controller boards and FED, CRY, IRD, PSU, EEC, WVR, MON, ATF, RTG and RTD. The HIL implements OPC UA servers that connect with MCL through the 0075 interface.

The CSP sends interferometry, pulsar search/timing, and VLBI data to physical computer nodes in TI through the 0151 interface. While the 0151 interface specifies the physical aspects of the transmission of the science data, the format of these data structures and any other software-level details of the transmission process are specified in the 0114 interface between CSP and ONL.

Lastly, the interfaces between CSS systems and external building and infrastructure systems are shown in Figure 45.

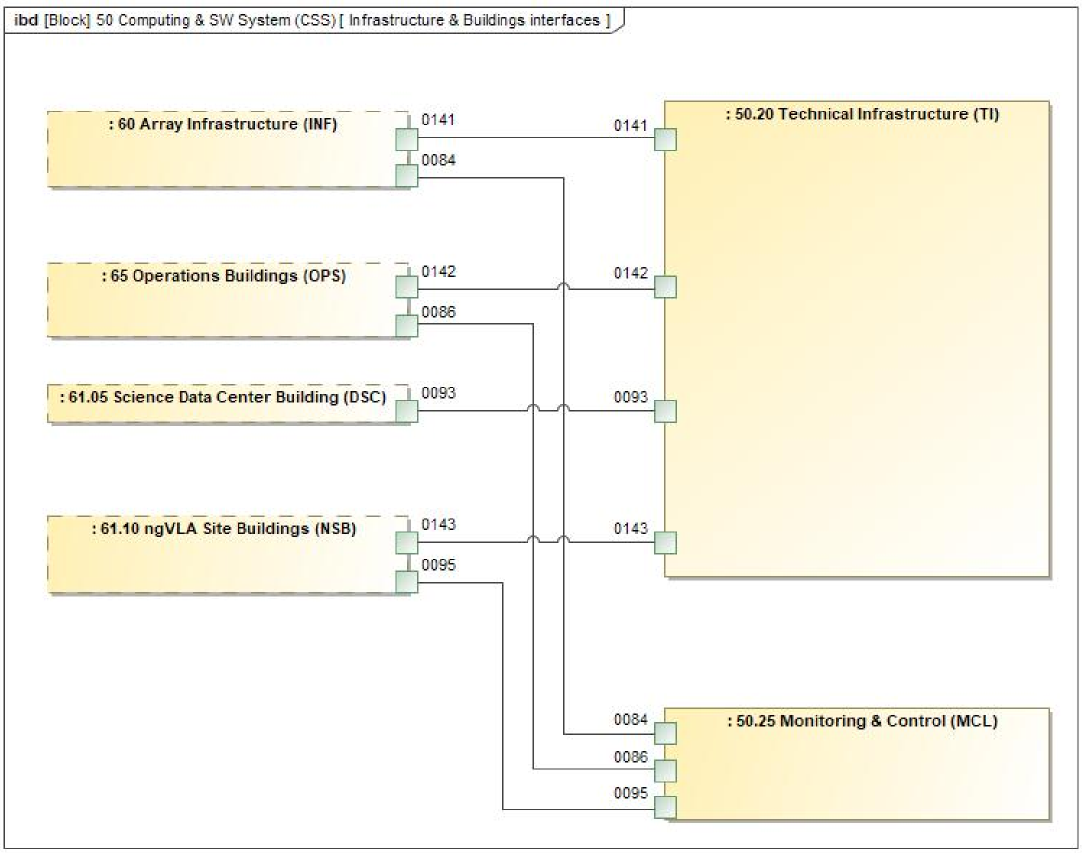

Figure 45: Interfaces between Infrastructure and Buildings and CSS elements.

As hardware elements specified in TI will be installed on different buildings, the specific requirements pertaining to rack space, cooling and power are specified in the interfaces between TI and INF (0141), OPS (0142), DSC (0093) and NSB (0143).

In addition, these buildings and infrastructure elements include monitoring points and alarms (e.g. fire alarm systems, intrusion alarm systems, UPS) that need to be monitored by the MCL system. As the MCL system is not a safety-critical system, it does not control these systems, just collects monitoring data and alarms to be presented to the Array Operator.

4.6.15.1 Proposal Management Subsystem (PMN)

The Proposal Management (PMN) system receives proposal submissions from PIs and provides software to support review, scoring, and allocation in observing seasons. It also provides software to simulate several weather scenarios and how they affect the schedule of observations in several timescales. Proposals accepted for observation are transformed into one or more scheduling blocks. This process transforms the proposal's science requirements into the technical configurations necessary to perform the observation in the telescope.

Figure 46 shows the PMN decomposition in subsystems.

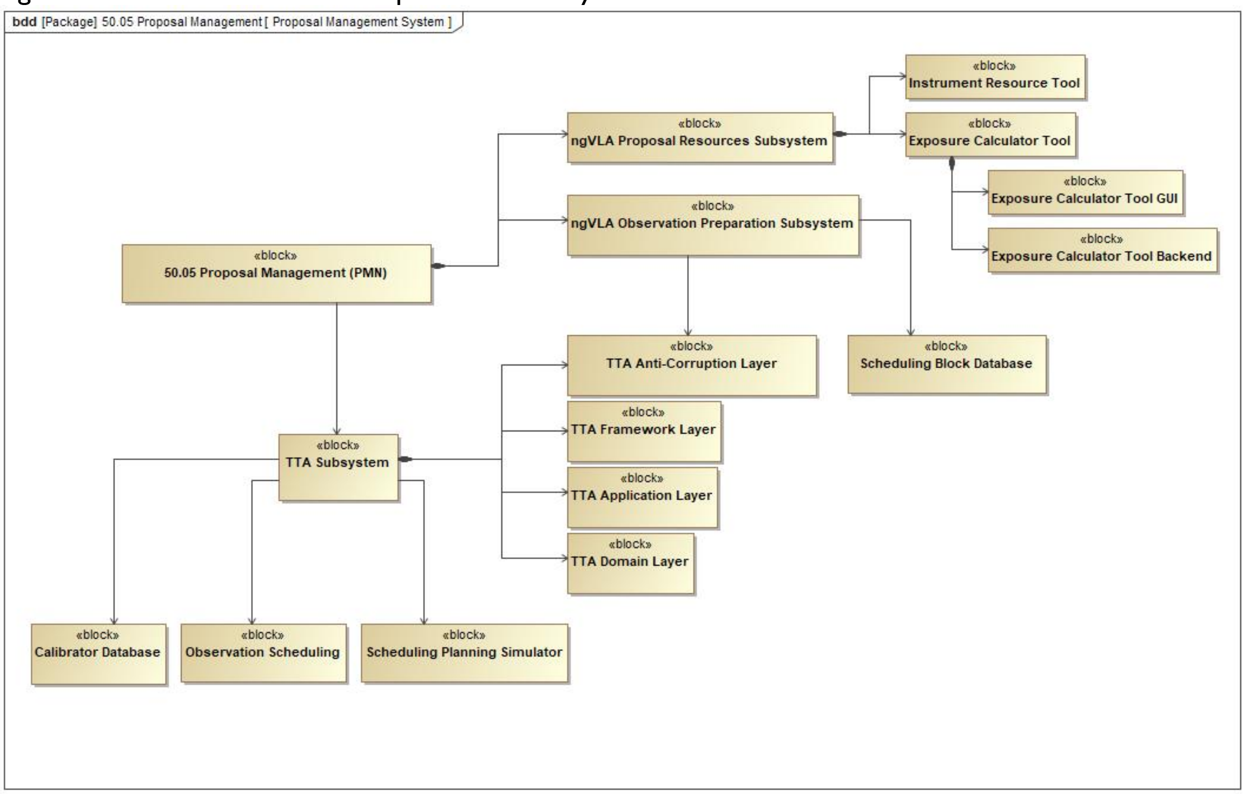

Figure 46: PMN structural decomposition.

The ngVLA Proposal Management System extends the core services provided by the common Telescope Time Allocation (TTA) System. This system *only handles the proposal process*. A separate ngVLA Observation Preparation System manages the translation of proposals to scheduling blocks.

The subsystems of PMN are:

(a) **Exposure Calculator Tool**: The ngVLA Exposure Calculator tool helps observers perform calculations that estimate the total time - not only the time on the sources of interest, but also time spent observing calibrators, slew time between sources, and various types of setup times - needed for a proposed observation.

(b) **Exposure Calculator Tool Backend**: The Exposure Calculator Tool Backend consists of all the server code needed to implement the calculations, persistence, and interactions with the GUI.

(c) **Exposure Calculator Tool GUI**: The Exposure Calculator Tool GUI provides a front end to the users that guides them through the required calculations.

(d) **Instrument Resource Tool**: The Instrument Resource Component contains the telescope-specific information that allows other components to find the resources available for a solicitation.

(e) **ngVLA Observation Preparation Subsystem**: This system transforms observation proposals into scheduling blocks, data structures that specify all the details necessary to perform observations in the array. This system also allows editing scheduling blocks or creating them from scratch.

(f) **ngVLA Proposal Resources Subsystem**: This module encapsulates all the tools needed to support proposal management. This subsystem has functionality specific for ngVLA.

(g) **TTA Anti-Corruption Layer**: The TTA System must support different radio astronomy facilities, which over the course of many years have developed their own unique conceptual models for creating and executing projects.

The TTA system will use the Anti-corruption Layer (ACL) strategy to create an isolating layer to provide other systems with information or functionality in terms of their own domain model. This strategy allows TTA to maintain a highly unified core conceptual model while supporting any facility which may have different development teams, concepts, requirements, etc. ACL will be instantiated in the TTA Framework layer and will consist of some combination of services, translators, adaptors, or facades.

(h) **TTA Application Layer**: Entities in the Application Layer orchestrate the use of entities found in the Domain Layer. The Application Layer also adapts requests from the Framework Layer to the Domain Layer.

(i) **TTA Domain Layer**: The Domain Layer contains entities (Domain Objects) comprising a Domain Model derived from the TTA domain and expressed as Domain-Driven Design primitives. The Domain Objects represent "business logic" - the rules the application must follow - and define how the Application Layer can interact with them.

Additionally, the Domain Layer can contain supporting domain logic such as Domain Events (events fired at important points in the business logic) and use-cases (definitions of what actions can be taken on the application).

(j) **TTA Framework Layer**: The Framework Layer includes entities that are not part of the Domain Model but are needed to satisfy system requirements. Specific Framework Layer entity examples include UX, persistence, messaging, job processing, or other systems.

(k) **TTA Subsystem**: The TTA system is a common system to support the time allocation processes for all NRAO telescopes. It provides common model and services, which need to be extended for each telescope.

Figure 47 shows the interfaces between the PMN system and external system elements.

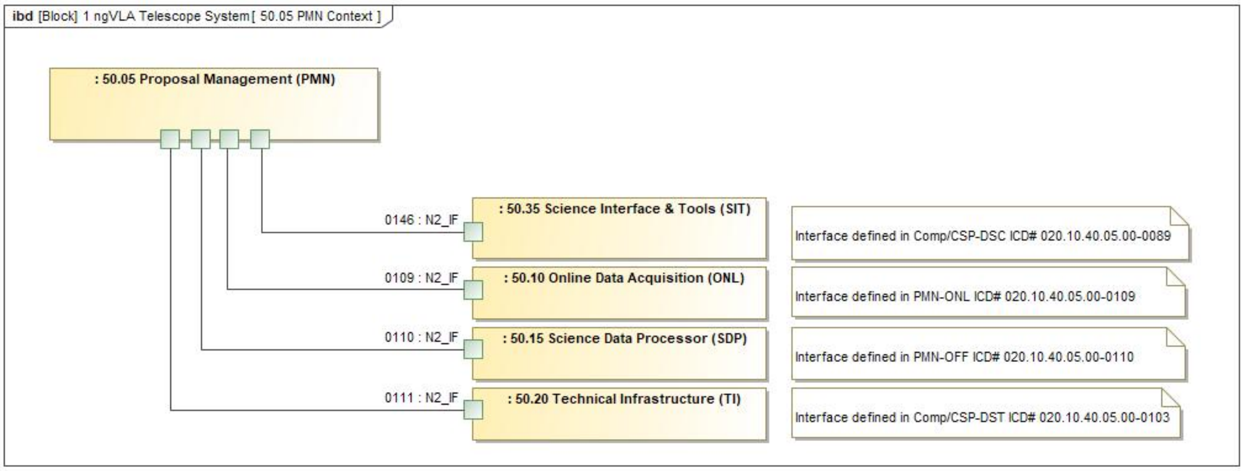

Figure 47: Context diagram for the Proposal Management System, showing the interfaces between this system and other system elements.

These interfaces are:

(a) **0109**: Interface with ONL: The interface between the PMN and ONL subsystem is mainly through the scheduling blocks that are generated by PMN and stored in the Proposal Management Database. In addition, ONL exposes an interface for PMN to execute the scheduling algorithm, in long-term mode, for TTA simulations.

(b) **0110**: Interface with SDP: The interface between the SDP subsystem and PMN is mainly through the data structures stored in the Proposal Management Database. If other interfaces are necessary between PMN and SDP, they should be specified in this ICD.

(c) **0111**: Interface with TI: Specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software infrastructure elements (e.g. logging, IT monitoring, communication frameworks, container orchestration).

(d) **0146**: Interface with SIT: ONL sends notifications of changes to SIT through this interface. SIT provides interfaces for users to track the status of their observation executions.

4.6.15.2 Online Data Acquisition System (ONL)

The ONL system is decomposed in subsystems as shown in Figure 48.

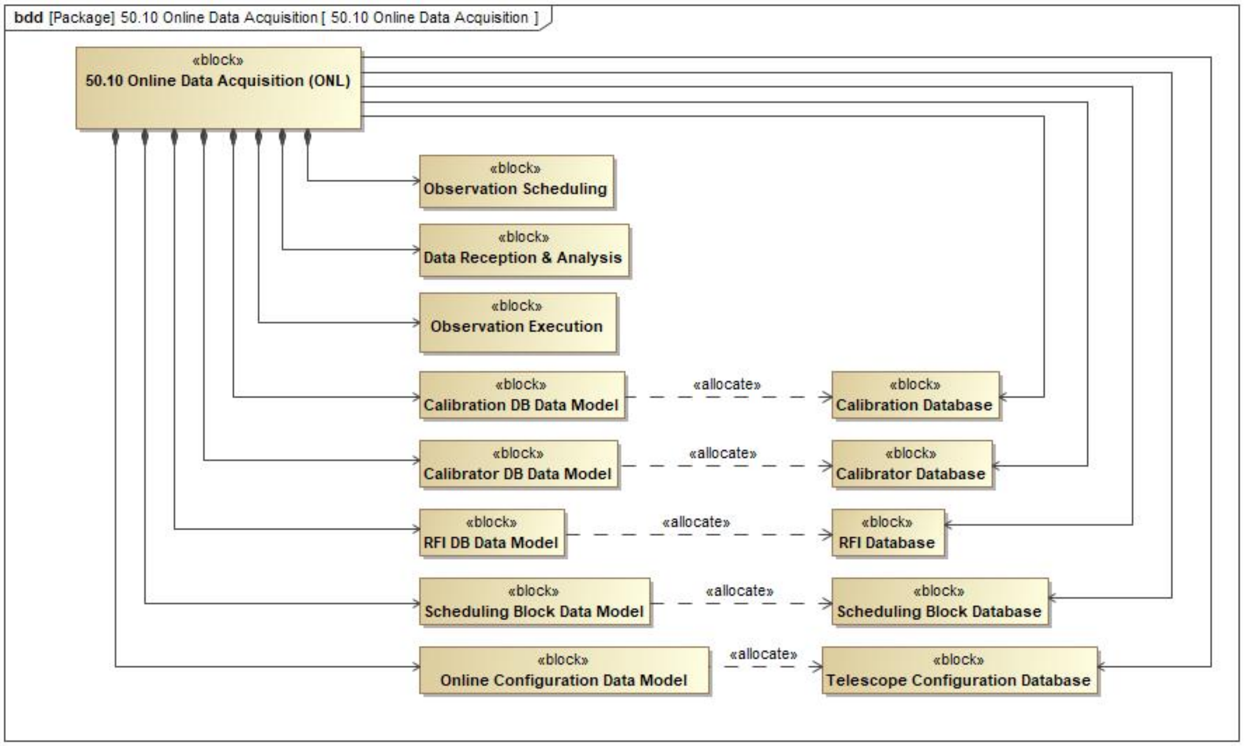

Figure 48: ONL system decomposition.

These subsystems are:

(a) **Data Reception & Analysis**: The Data Reception & Analysis subsystem receives the CSP data and performs any final step of processing and formatting to create the final science datasets. It includes calibration solvers to produce online calibration tables (a.k.a. TelCal solutions).

(b) **Observation Execution**: The Observation Execution subsystem is responsible for executing astronomical observations, receiving a schedule of Scheduling Blocks or Scan Blocks from Scheduling and coordinating the operations that are performed in the hardware elements to execute the observation. This system is tightly integrated with Scheduling.

(c) **Observation Scheduling**: The Observation Scheduling subsystem solves for an optimal schedule of sub-arrays and the observations to be executed on each one of them for a given timeframe (a few hours for dynamic scheduling, an observing season for the long-term scheduler), based on numerous inputs (e.g., the pool of observable Scheduling Blocks, weather information, hardware availability, expected RFI interferers).

Also shown in the diagram are the data models owned by the ONL system and their database allocations.

Figure 49 shows the interfaces between the ONL sub-element and external system elements.

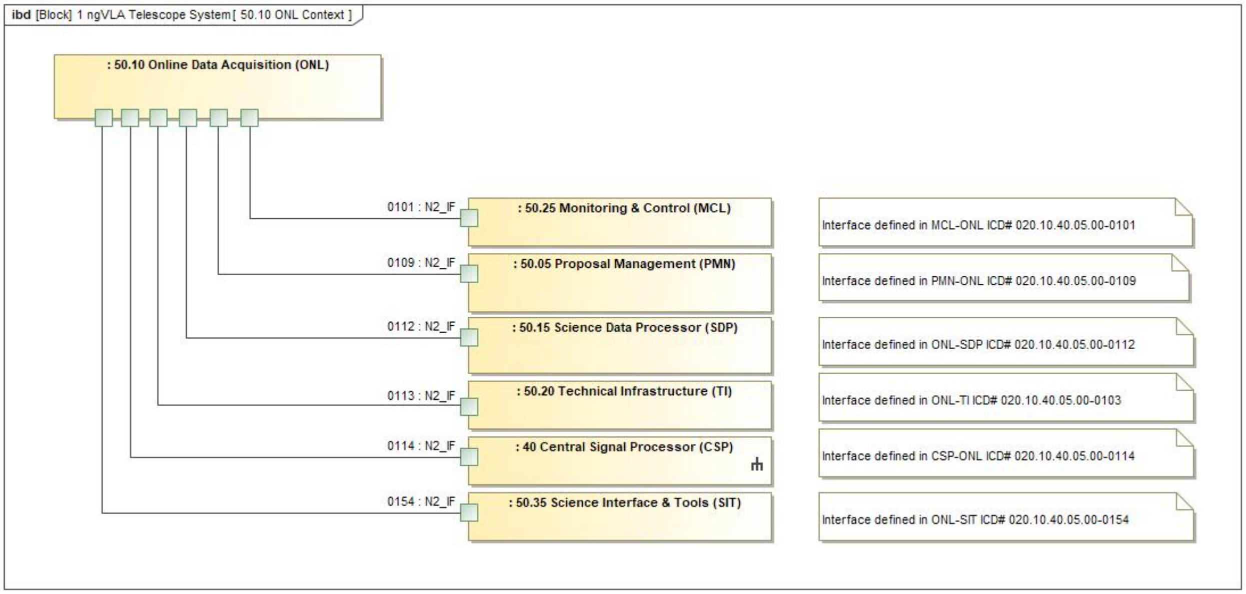

Figure 49: Context diagram for the ONL sub-element, showing the interfaces between this sub-element and other system elements.

These interfaces are:

(a) **0101**: Interface to MCL. Sends high-level hardware commands and receives a subset of the monitoring data.

(b) **0109**: Interface to PMN. Receives Scheduling Block data structures. Handles coordination to execute triggered observations.

(c) **0112**: Interface with SDP. The ONL system queries the status of the SDP processing resources for observation scheduling purposes.

(d) **0113**: Interface with TI. This interface specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software infrastructure elements (e.g. logging, IT monitoring, communication frameworks, container orchestration).

(e) **0114**: Interface with CSP. This interface specifies the software aspects of the transmission of the CSP data (interferometric, phased, and pulsar data), including the specification of their data format. The physical aspects (networking interface) are specified in interface 0151, between CSP and TI.

(f) **0154**: Interface with SIT. ONL sends notifications of changes to SIT through this interface. SIT provides interfaces for users to track the status of their observation executions.

Figure 50 show the main data flows in the ONL system.

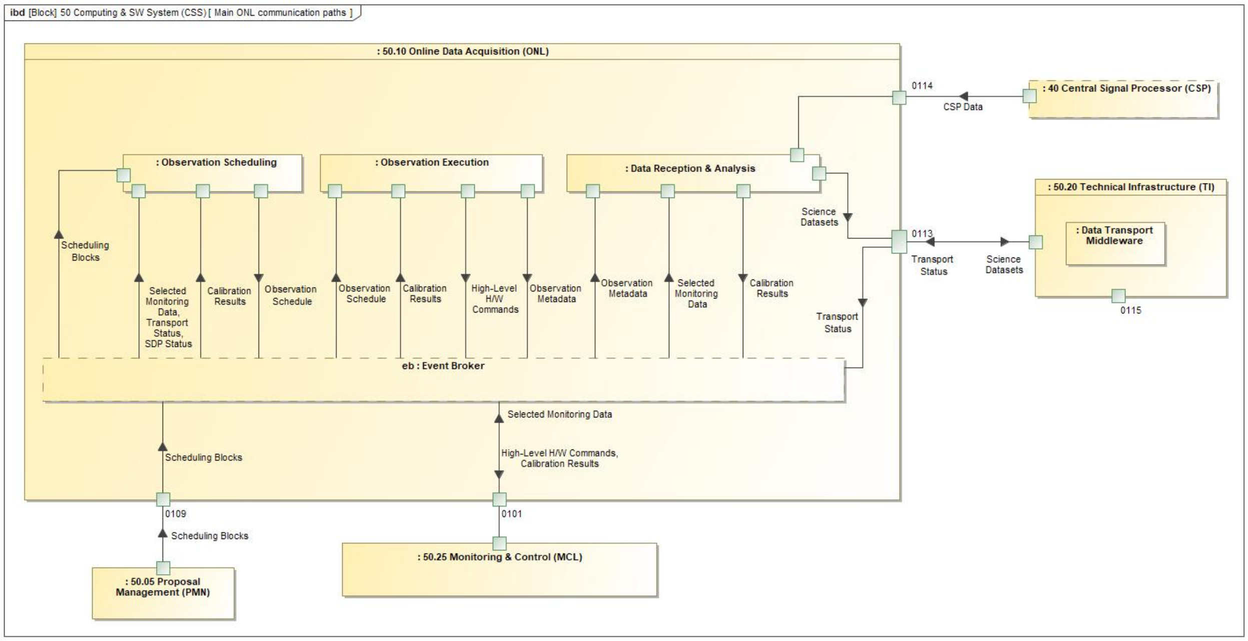

Figure 50: Main data flows involving the Online Data Acquisition system.

All the communications internal to the ONL system, with the exception of the CSP data (interface 0114) and the final science output datasets (interface 0113), are routed through the Event Broker. This is a shared component between ONL and MCL, so the data that flows through interface 0101 is transmitted through internal topic streams inside the Event Broker. For the purpose of the architecture definition, the Event Broker is represented as part of MCL, but it is actually shared between ONL and MCL. The Event Broker provides a low-latency, highly scalable streaming framework for the ONL and MCL systems. All the events flowing through the Event Broker are persistent, which allows the implementation of high-availability strategies and facilitates the collection of metadata and troubleshooting information.

The ONL system receives ngVLA-specific Scheduling Blocks from the PMN system. The Observation Scheduling subsystem reads the pool of Scheduling Blocks and produces an optimal Observation Schedule, which is executed by the Observation Execution subsystem. The execution generates a flow of high-level H/W commands that are sent to the MCL system, which translates them into protocol-specific (OPC UA) low-level commands to the hardware systems. The Scheduling subsystem also receives calibration results, monitoring data that includes weather data and WVR values, the status of the SDP and data transport middleware, and other streams that for simplicity are not shown in this diagram.

As the observation scans are executed, the CSP generates data that is received by the Data Reception & Analysis subsystem. Note that this interface (0114) specifies the logical, software interface, in contrast to the physical interface (the actual bits of data flowing through network interfaces) that is specified between the CSP and TI.

The Data Reception & Analysis subsystem (optionally) performs the last stage of visibility averaging and combines the data from the CSP with the Observation Metadata received from the Observation Execution subsystem, formatting it in the final Science Data Format (which is being defined by the XRADIO project). The data is then sent to the Data Transport subsystem, which transmits it to the SDP. The Data Reception

& Analysis subsystem generates calibration results (a.k.a. Telescope Calibration (TelCal) results), which are propagated to other modules through the Event Broker. The reception of the CSP data and the execution of analysis algorithms are coupled in the same subsystem because we expect to process the data in-memory as it is being received, avoiding unnecessary I/O operations. The CSP data will be likely transmitted directly to memory buffers by means of a high-performance protocol such as Remote Direct Memory Access. Calibration results are included in the output science datasets and broadcasted to other online components that needs them (e.g., the CSP supervisor, for array phasing).

A number of selected and configurable monitoring data streams, e.g. the WVR data, needed by TelCal; or the weather data and the antenna status data, used by Scheduling, are received from the MCL system.

4.6.15.3 Monitor and Control System (MCL)

The Monitoring & Control (MCL) system encompasses static components that interact with the telescope hardware to provide automated and highly available services to the array operator, support engineers, and the ONL system, which in contrast is mostly dynamic and sub-array based.

One of the goals of this separation between ONL and MCL is reuse. Executing an observation can be developed and tested independently of the underlying hardware protocols. It may possible the reuse of software components from JVLA or ALMA – at least initially in the construction project – after adapting them to interact with the MCL, which is hardware-dependent and specific for ngVLA. Conversely, the separation between ONL and MCL makes it possible to change the MCL layer as the system evolves, without affecting ONL. Enabling the possibility of software reuse is an important goal, given expected staffing and time constraints in the project. A couple of other strategies aid in this direction: the use of commercial-off-the-shelf (COTS) components in MCL (one of the reasons behind choosing the standard protocol OPC UA was to allow this interoperability), and the use of code-generation techniques to synthesize control components.

The MCL system is decomposed in subsystems as shown in Figure 51.

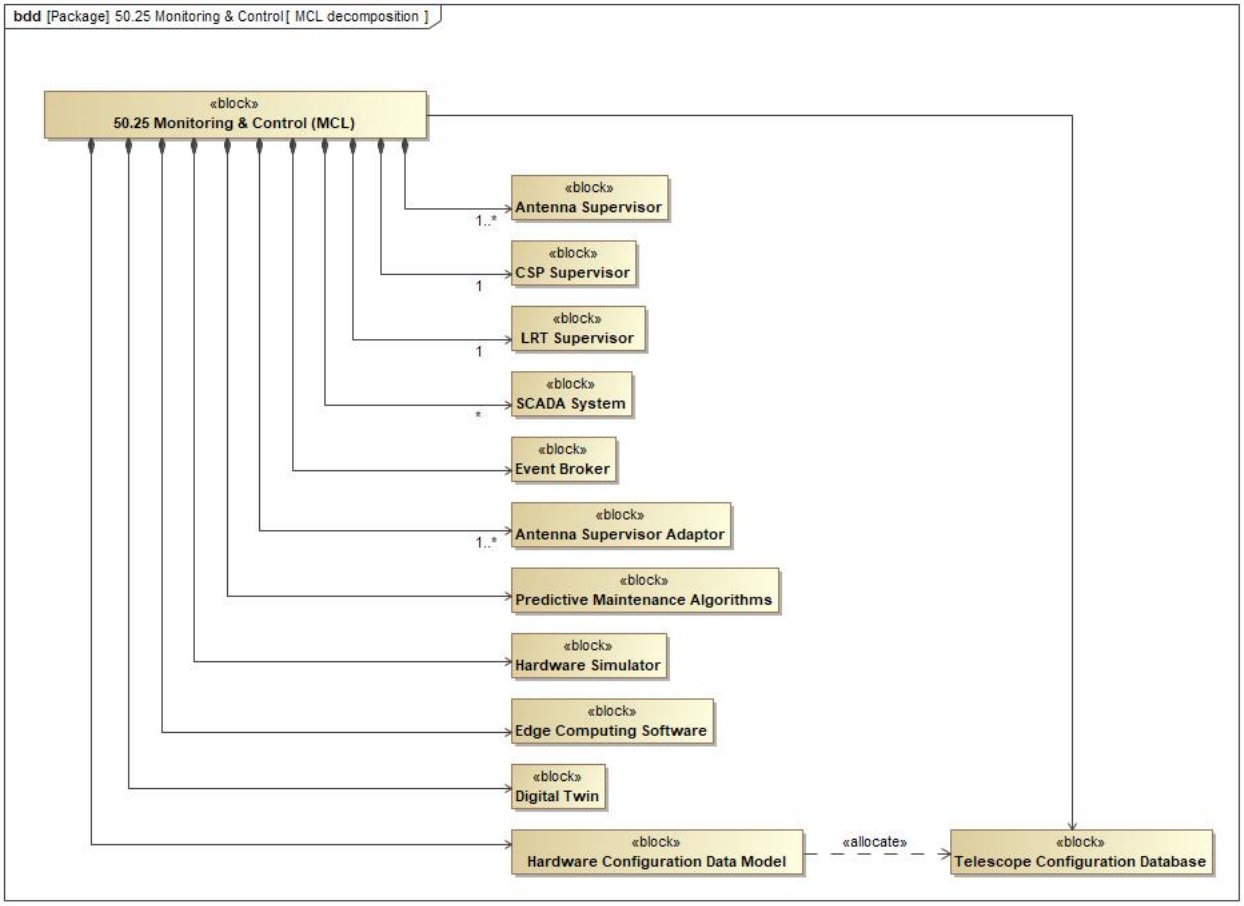

Figure 51: Subsystem decomposition of the MCL system.

These subsystems are:

(a) **Antenna Supervisor**: This subsystem controls the antenna hardware elements. It interacts with several OPC UA servers in the antenna, translating the High-Level Commands received from the ONL system into OPC UA commands. It monitors alarm conditions that depend on multiple devices. It loads and updates configuration data, synchronizing it with the central repository maintained in the Telescope Configuration Database.

(b) **Antenna Supervisor Adaptor**: This adaptor translates the protocol used by the Event Broker (e.g. Kafka streams) into a protocol suitable for communicating with the remote Antenna Supervisor, over a WAN network. This is not necessary to the other supervisor components, which are co-located with the Event Broker. It is not clear yet that this component may be needed, or whether it will be needed for all antennas (directly connected antennas can probably use the Event Broker native protocol, while long baseline antennas on the other hand may need this adaptation). It is likely that this component can be found already as part of the Event Broker provided adaptors (for instance, Kafka messages can be translated into MQTT using a provided sink).

(c) **CSP Supervisor**: This subsystem controls the CSP, through its OPC UA interface. It translates High-Level Commands received from the ONL system into OPC UA commands. It loads and updates configuration data into the CSP, synchronizing it with the central repository maintained in the Telescope Configuration Database.

(d) **Digital Twin**: The digital twin provides a virtual model of the real telescope. It can detect deviations in the monitoring data from expected behavior. It provides a model for the latencies involved in the execution of commands sent to the hardware, which include an application timestamp set in the future.

(e) **Edge Computing Software**: Software deployed on antenna edge devices (e.g., the M502 single-board computer) that execute predictive maintenance algorithms and other diagnostics and troubleshooting functions (such as the oscilloscope function) that require high-frequency data.

(f) **Event Broker**: An event broker (e.g., Kafka) is a system that receives events, stores them in a partitioned event stream (append only, similar to a database commit log), and provides them for consumption by other processes. Event broker systems suitable for large-scale processing follow a model where multiple, distributed event brokers work together in a cluster to provide several essential features:

- Scalability. Additional event broker instances can be added to increase the cluster's production, consumption, and data storage capacity.
- Durability. Event data is replicated between nodes. This permits a cluster of brokers to both preserve and continue serving data when a broker fails.
- High availability. A cluster of event broker nodes enables clients to connect to other nodes in the case of broker failure. This permits the clients to maintain full uptime.
- High-performance. Multiple broker nodes share the production and consumption load. In addition, each broker node must be highly performant to be able to handle hundreds of thousands of writes or reads per second.

The event data stored by the event broker (for any period of time that it may be practical) constitutes the "single point of truth" of the processing system.

(g) **Hardware Simulator**: A simulator to be used in software development, for the application of hardware-in-the-loop testing techniques.

(h) **LRT Supervisor**: This subsystem controls the ATF, RTG and RTD devices through their HIL OPC UA interfaces. It translates High-Level Commands received from the ONL system into OPC UA commands.

(i) **Predictive Maintenance Algorithms**: These algorithms analyze monitoring data to detect possible hardware maintenance issues that need to be attended before they become faults.

(j) **SCADA System**: The Supervisory Control and Data Acquisition system used by Operators to control the array and monitor its health.

Also shown in the diagram are the data models owned by the MCL system and their database allocations.

Figure 52 shows the interfaces between MCL and other system elements.

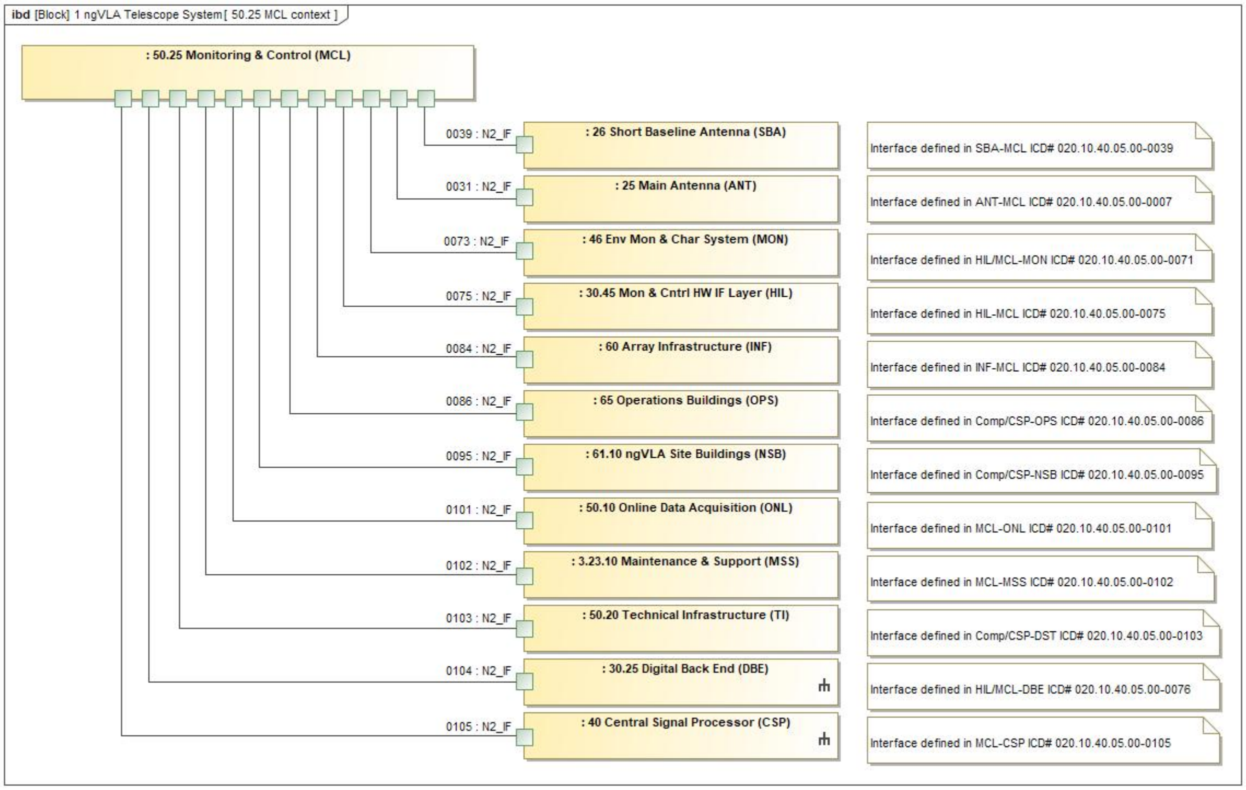

Figure 52: Context diagram for the MCL system, showing the external interfaces between this system and other system elements.

These interfaces are:

(a) **0031**: OPC UA interface with the Main Antenna (ANT).

(b) **0073**: OPC UA interface with the Environmental Monitoring and Characterization (MON) system.

(c) **0075**: Interface with HIL. This interface aggregates all the OPC UA interfaces for the systems controlled by the HIL boards.

(d) **0084**: Interface with Array Infrastructure (INF), most probably OPC UA interfaces to PLCs that control fire alarm systems, intrusion alarms and UPS systems.

(e) **0086**: Interface with Operations Buildings (OPS), most probably OPC UA interfaces to PLCs that control fire alarm systems, intrusion alarms and UPS systems.

(f) **0095**: Interface with ngVLA Site Buildings (NSB), most probably OPC UA interfaces to PLCs that control fire alarm systems, intrusion alarms and UPS systems.

(g) **0101**: Interface with the ONL system. This interface is used to transmit high-level commands from the ONL system to the MCL system, and selected monitoring data in the reverse direction.

(h) **0102**: Interface with MSS. This interface is used to transmit monitoring data and generated maintenance tickets from the MCL to the MSS system.

(i) **0103**: Interface with TI. It specifies software deployment requirements for the MCL components to be deployed on TI hardware, defining computational power, input/output, and storage requirements for them.

(j) **0104**: OPC UA interface to the DBE.

(k) **0105**: OPC UA interface to the CSP.

(l) **0039**: OPC UA interface with the Short Baseline Antenna (SBA).

Figure 53 shows the main data flows involved in the MCL supervisory control.

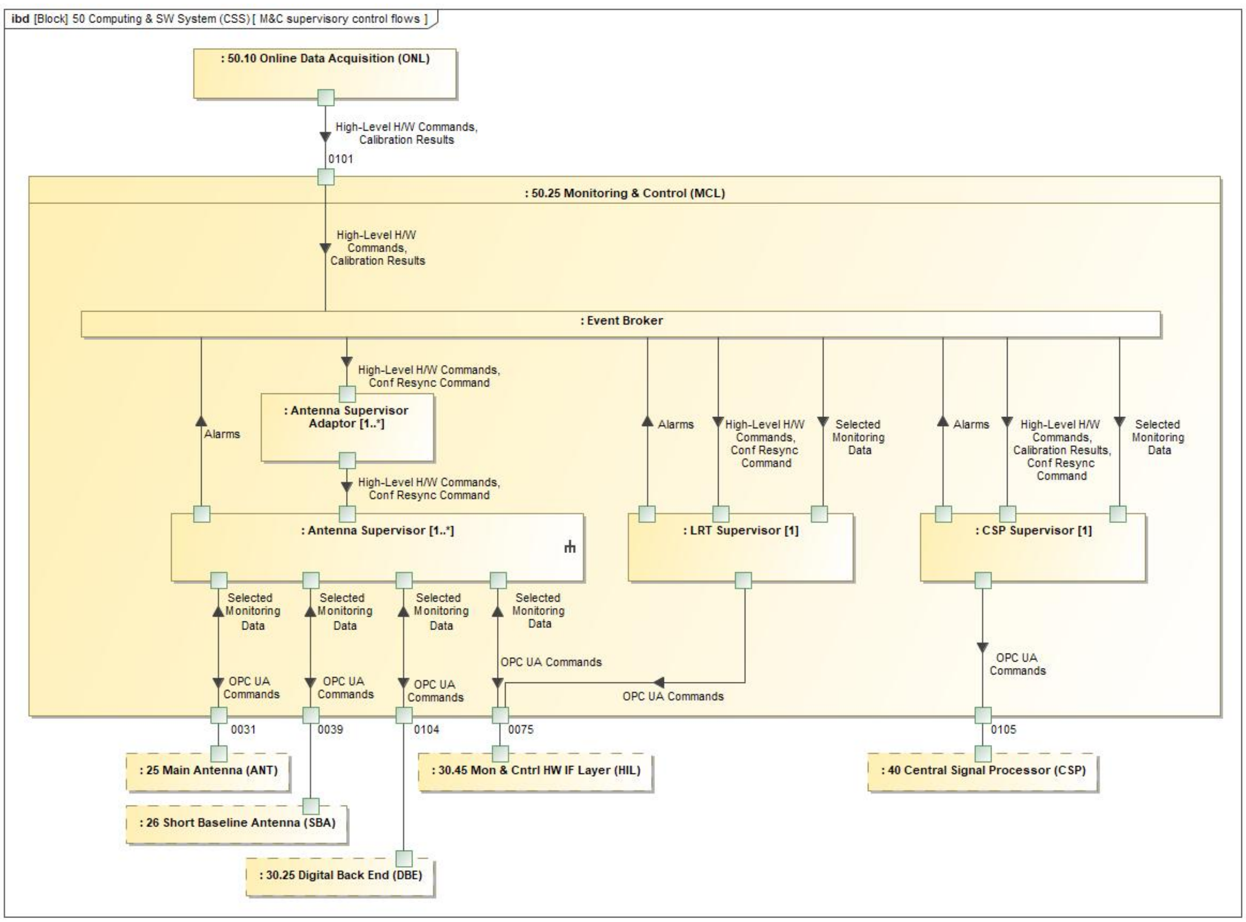

Figure 53: Monitoring and control supervisory flows.

The backbone of the system is the Event Broker. This system receives and distributes a number of streams organized by topic. Some of these topics are created dynamically, while others are static. Topics related with MCL are mostly static, while ONL topics are dynamic. Dynamic topics are usually organized by subarray, and include:

- the high-level observation commands
- calibration results

The static topics, on the other hand, are organized by antennas and devices, including:

- monitoring data
- flags
- alarms and events
- configuration data synchronization commands

High-level commands are received from the ONL system and distributed to the supervisory components, which translate them into OPC UA commands. Some of the monitoring data streams collected from devices are received by the supervisor components to check for alarms or alert conditions that depend on multiple devices. (On the other hand, checking for alarms for single devices is a responsibility of Layer 1 components.) If these conditions are triggered, alarms are created and sent to the Event Broker.

The Telescope Configuration Database is a distributed database that keeps configuration data under version control. Data is kept in a central repository, which is synchronized with remote repositories local to the supervisory components. Synchronizing remote repositories with the central repository is accomplished by sending a Configuration Resync command when changes need to be propagated. Upon receiving this message, the supervisor components update their local repositories.

Figure 54 shows the main data flows involved in the MCL monitoring function.

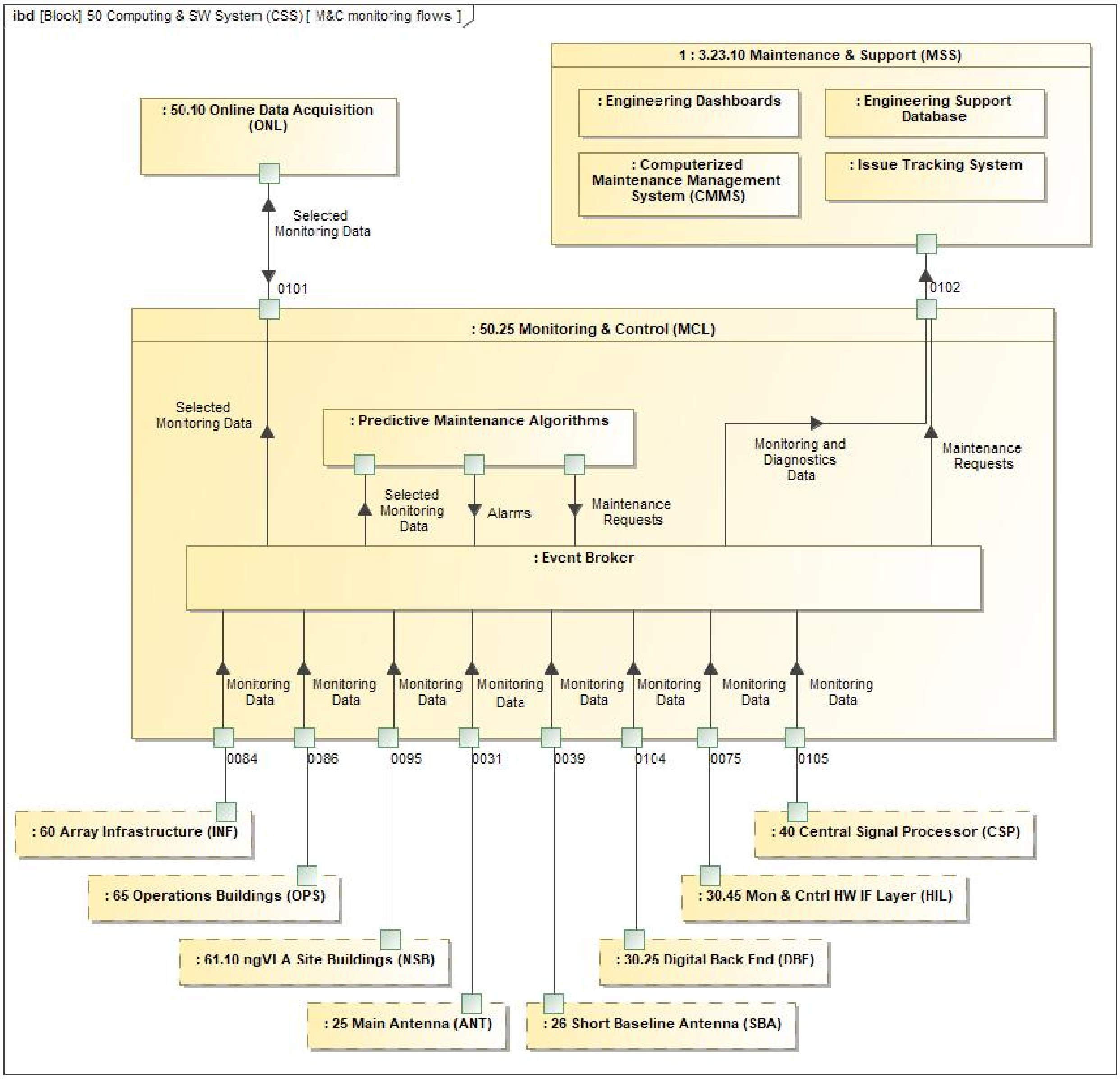

Figure 54: Main monitoring data flows in the MCL system.

The Event Broker receives monitoring data from Layer 1 controllers. A selection of the monitoring data (e.g., the WVR streams and the pointing data streams) are sent to the ONL system, to be used by TelCal. Some of the monitoring data streams are used by predictive maintenance algorithms, which generate alarms and maintenance request tickets. All the monitoring data, along with other diagnostic data (e.g., delay tracking commands) are sent to the MSS system for long-term storage, further processing, and visualization. These data, which provide an integrated and complete database of the functioning of the telescope, are made available through troubleshooting interfaces. Maintenance requests are sent to the MSS system as well, for consumption by the Issue Tracking System.

Figure 55 shows the main data flows involved in the MCL SCADA function.

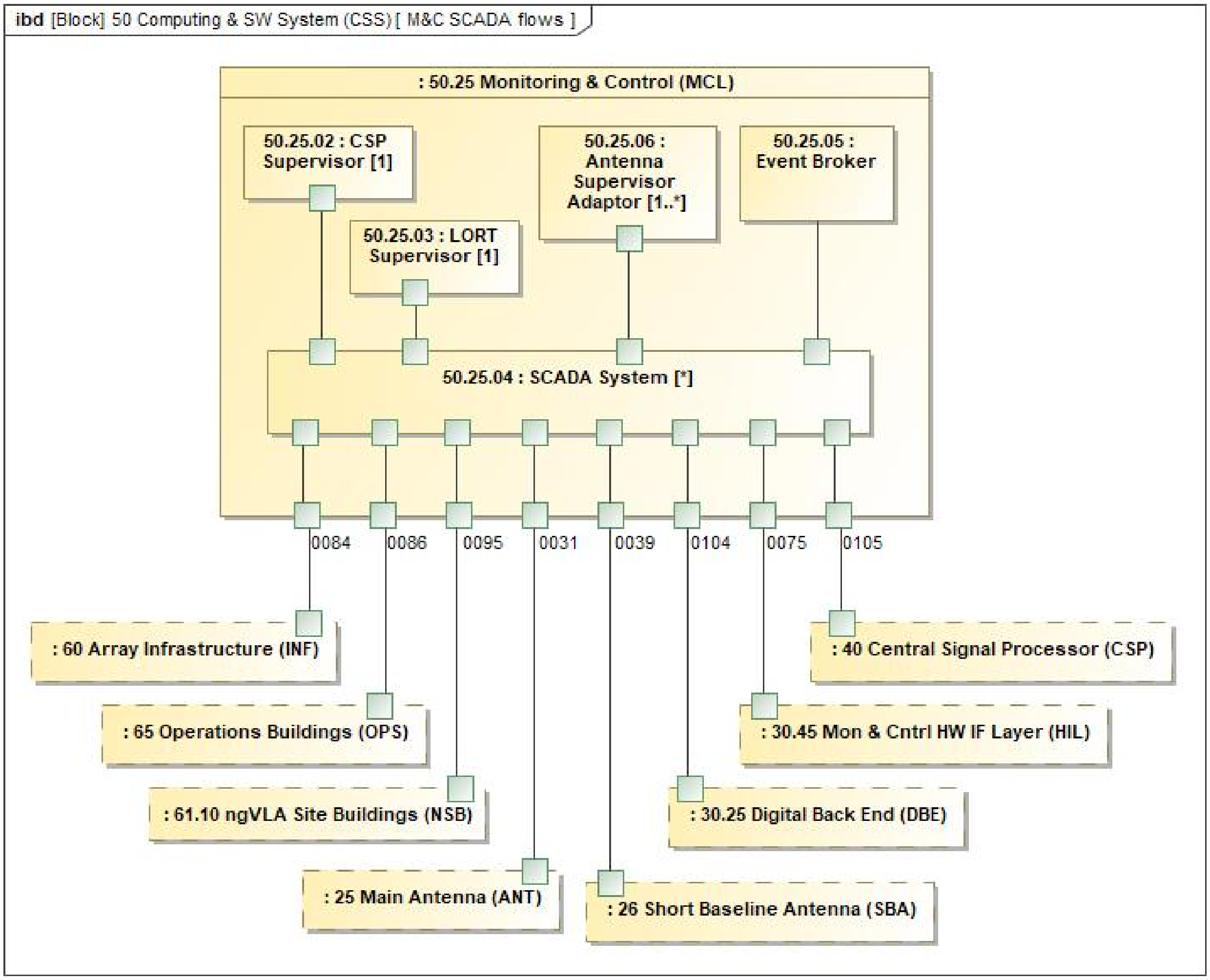

Figure 55: SCADA-related connections and data-flows.

A SCADA system provides interfaces for the array operators to visualize the state of the array, troubleshoot problems, and recover the system in case of problems. Note that controlling the array follows two different paths:

- The automated or semi-automated observation execution commands, which are sent from the ONL system.
- Operator interactive commands from the SCADA system.

It may be needed to configure device locking in some cases, depending on the level of authorization of the user. This can be done through standard OPC UA mechanisms.

The SCADA system connects to the Layer 1 components directly through OPC UA interfaces. The SCADA system incorporates panels depicting different telescope sub-systems at different levels of detail, along with textual and graphical representations of "live" values from the field. It may also incorporate a short-term historian database, in order to provide plots to the operator. The long-term storage for monitoring data, however, is the Engineering Database in the MSS system, which can also be integrated with the SCADA system if necessary.

4.6.15.4 Maintenance and Support Subsystem (MSS)

The MSS system is decomposed in subsystems as shown in Figure 56.

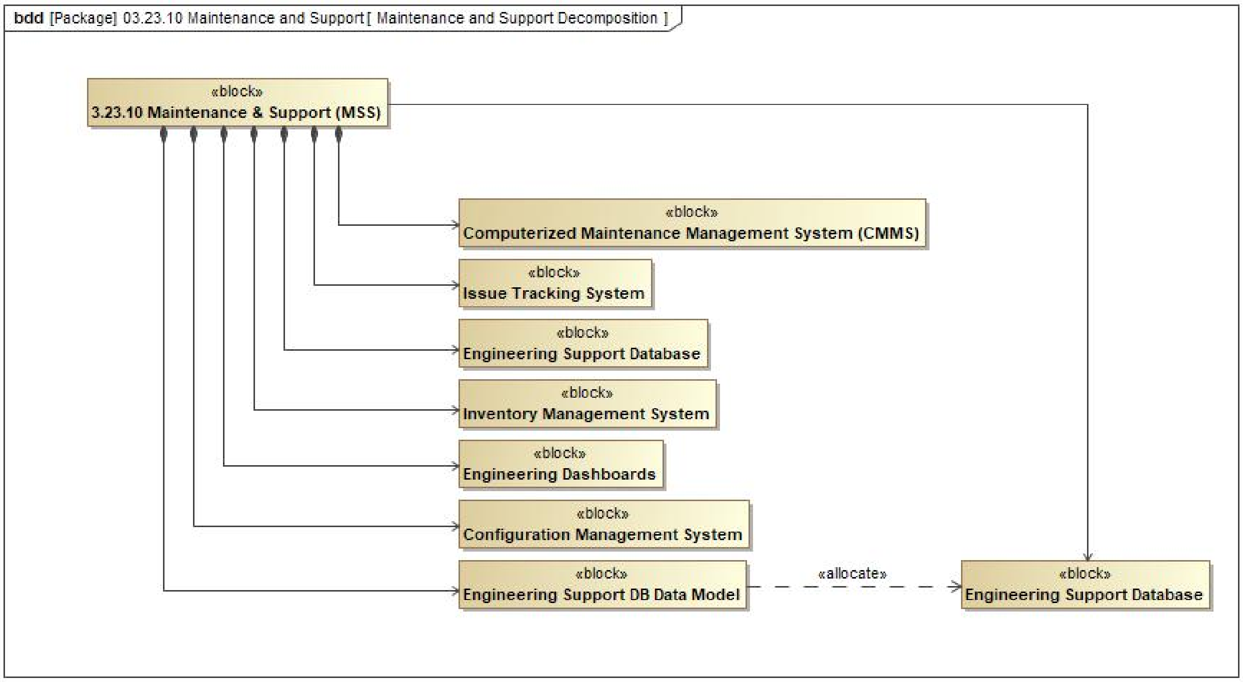

Figure 56: High-level decomposition of the Maintenance and Support Subsystem.

These subsystems are:

(a) **Computerized Maintenance Management System (CMMS)**: This system provides several functions aimed to effectively organize maintenance operations. It usually integrates functions such as asset management, predictive maintenance, reliability centered maintenance, monitoring, and maintenance activity scheduling.

(b) **Configuration Management System**: This system tracks the configuration of each telescope equipment (antennas, CSP, etc.) deployed within the array over time.

(c) **Engineering Dashboards**: This system provides an interface for engineering support staff to construct visualization panels for the array systems, query the Engineering Support Database, plot time-series data, etc.

(d) **Engineering Support Database**: This database stores logs, alarms, and monitoring data. It provides query interfaces to support maintenance operations.

(e) **Inventory Management System**: The Inventory Management System tracks the location and availability of spare LRUs, sub-assemblies, critical components, and consumables across the array logistic centers (warehouses, maintenance center, repair center, RSS, etc.)

(f) **Issue Tracking System**: This system manages maintenance requests and provides interfaces to report problems, assign requests to support staff, update their status, attach relevant information, and coordinate the process of solving problems effectively.

Also shown in the diagram are the data models owned by the MSS system and their database allocations.

Figure 57 shows the interfaces between MSS and other system elements.

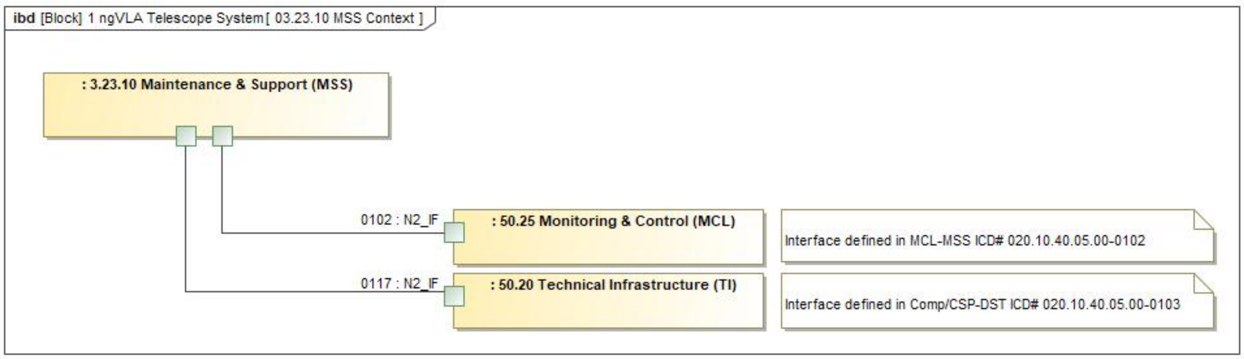

Figure 57: Context diagram of the Maintenance and Support Subsystem, showing the interfaces between this subsystem and other system sub-elements.

These interfaces are:

(a) **0102**: Interface with the Monitoring and Control Subsystem (MCL): This interface specifies how monitoring, alarm/event and logging data is transmitted from MCL to MSS.

(b) **0117**: Interface with TI: This interface specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software infrastructure elements (e.g. logging, IT monitoring, communication frameworks, container orchestration).

4.6.15.5 Science Data Processor (SDP)

The SDP system provides software components that, running on the Technical Infrastructure (TI)-provided hardware infrastructure, process observational or archived data to provide ngVLA science users with a range of quality assured products, from coarsely calibrated visibilities to High-Level Data Products (HLDPs), suitable for analysis with no further processing required by users.

The SDP system is decomposed in subsystems as shown in Figure 58.

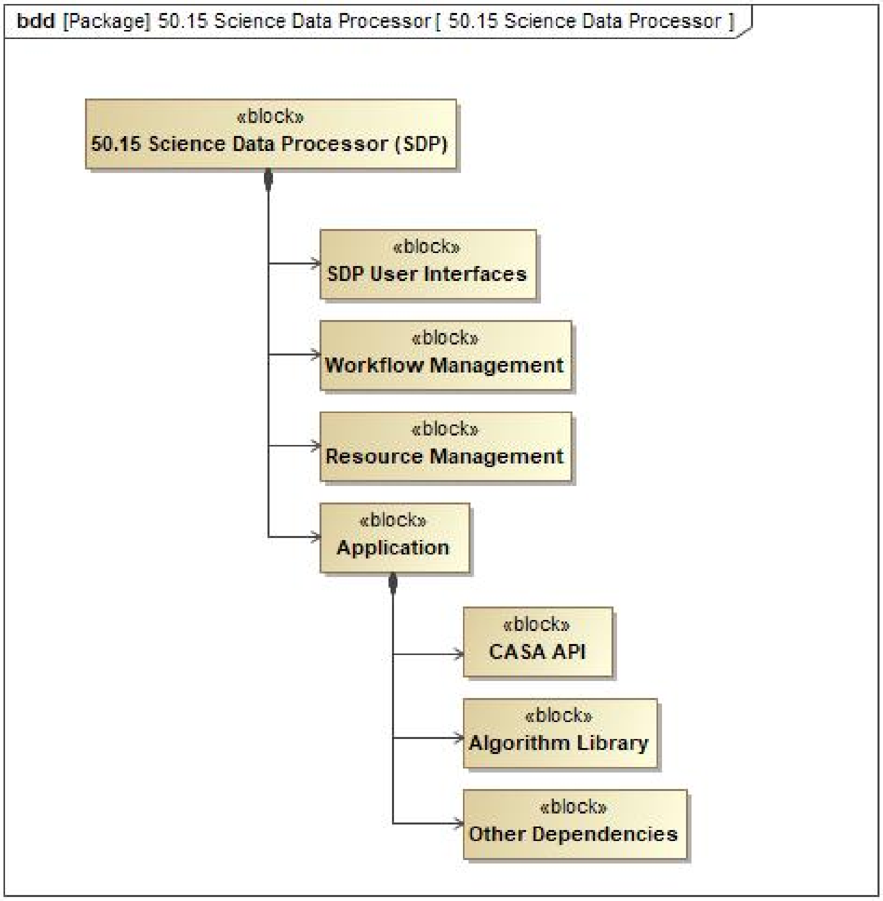

Figure 58: SDP system decomposition.

These subsystems are:

(a) **Algorithm Library**: The algorithm library includes any frameworks or algorithms needed to support the Common Astronomy Software Applications (CASA) API.

(b) **Application**: Applications are built using the CASA API library and the radio astronomy algorithm library and accomplish any radio astronomy processing task. The application, CASA library, or algorithm library may have other dependencies. Applications are executed as workloads in a compute environment.

(c) **CASA API**: The CASA API consists of all radio astronomy domain code needed to accomplish imaging, calibration, etc.

(d) **Other Dependencies**: This block includes any other open source or COTS dependencies needed for an application to function.

(e) **Resource Management**: Resource managers perform three principal functions:

– resource allocation - assigning physical hardware, ranging from a fraction of a machine to an entire system, to jobs based on user-configurable policies,

– workload scheduling - efficiently launching via optimized mechanisms thousands or more processes across a comparable number of nodes, and

– workload monitoring - overseeing application execution and tracking resource usage.

(f) **SDP User Interfaces**: SDP user interfaces will enable users to select and monitor workflows.

(g) **Workflow Management**: The SDP is designed to be a multi-tenant system which means more than one tenant - multiple users from an organization or group - shares common hardware and software infrastructure.

The following definitions are used to represent the minimum, lowest-common-denominator industry standard terms for use in a conceptual architecture supporting multitenancy:

– Job - A job is a self-contained work unit with associated input data that produce output data after execution. Jobs may mix parallel application invocations with instantiations of single threaded processes. Jobs may be executed interactively, involving user presence at an interface to provide additional input a runtime, or use automated processing where all necessary parameters and inputs for job execution are specified before it is launched.

– Task - Jobs may be monolithic or subdivided into a number of smaller steps called tasks. Tasks can be associated with the launch of a specific application program. Tasks do not have to be identical in terms of used resources or duration of execution.

– Workload - The resources and tasks required to run a job in a computing environment.

The following terms are adapted specifically to the radio astronomy data processing domain:

– Pipeline - A pipeline is a task involving the calibration or imaging of single dish or interferometric radio astronomy data.

– Workflow - A workflow is a job. Radio astronomy data processing workflows typically consist of one or more preprocessing tasks, one or more pipeline tasks, and one or more post processing tasks.

Workflow managers define, schedule, execute, and monitor workflows. They also orchestrate the execution of multiple, simultaneous workflows, scaling up or down dynamically based on demand. In terms of fault tolerance, these platforms include mechanisms for retrying failed tasks and handling errors gracefully; users can configure retry policies, specify error handling strategies, and define fallback actions to ensure robustness during workflow execution.

Figure 59 shows the interfaces between SDP and other system elements.

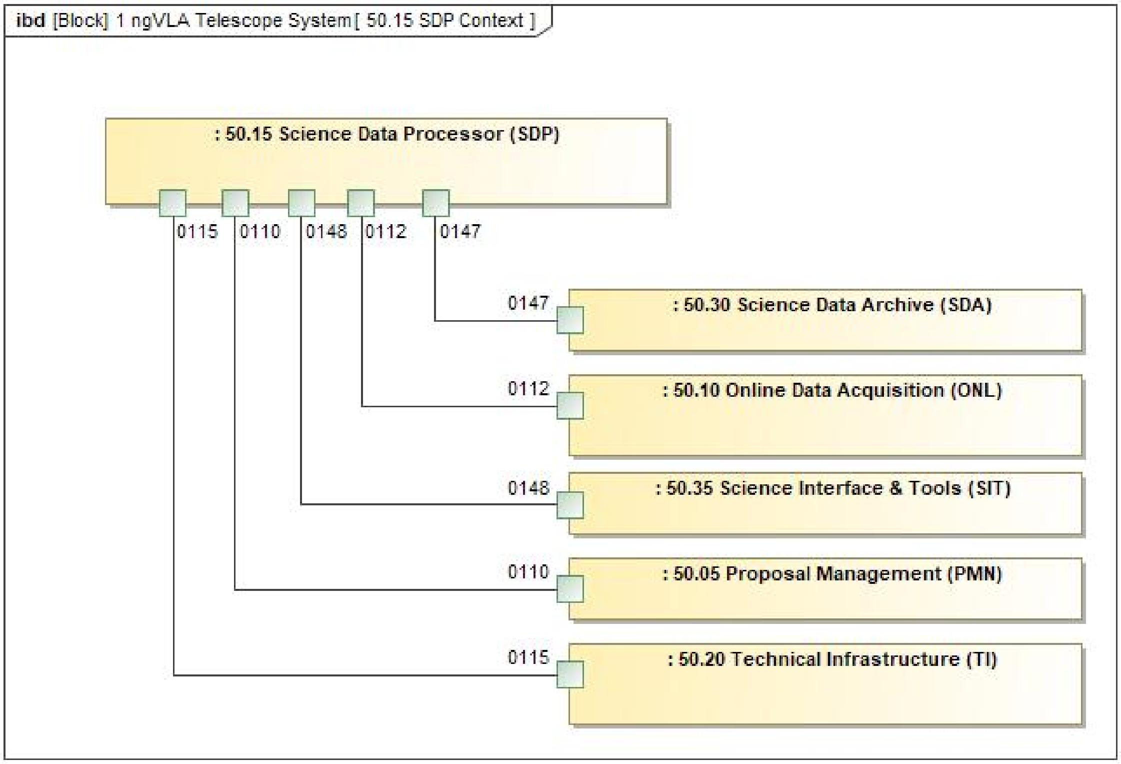

Figure 59: SDP context diagram.

These interfaces are:

(a) **0110**: Interface with PMN. The interface between the SDP subsystem and PMN is mainly through the data structures stored in the Proposal Management Database. If other interfaces are necessary between PMN and SDP, they should be specified in this ICD.

(b) **0112**: Interface with ONL. The ONL system queries the status of the SDP processing resources for observation scheduling purposes.

(c) **0147**: Interface with SDA. The SDP system accesses archived datasets from SDA to be processed and ingests data products through this interface.

(d) **0148**: Interface with SIT. SIT provides interfaces to track the status of processing jobs. Using this interface, SDP notifies SIT of changes in the state of the processing jobs.

(e) **0115**: Interface with TI. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software infrastructure elements (e.g. logging, IT monitoring, communication frameworks, container orchestration).

4.6.15.6 Science Data Archive (SDA)

The SDA system provides data management software needed to support the science data archive, the final repository for the science data products produced by the ngVLA telescope. Examples are ingestion software, data retrieval interfaces, and services to perform queries over the metadata. Note that the archive physical storage systems are included in the TI system, and the SDA system only provides software infrastructure.

The SDA system is decomposed in subsystems as shown in Figure 60.

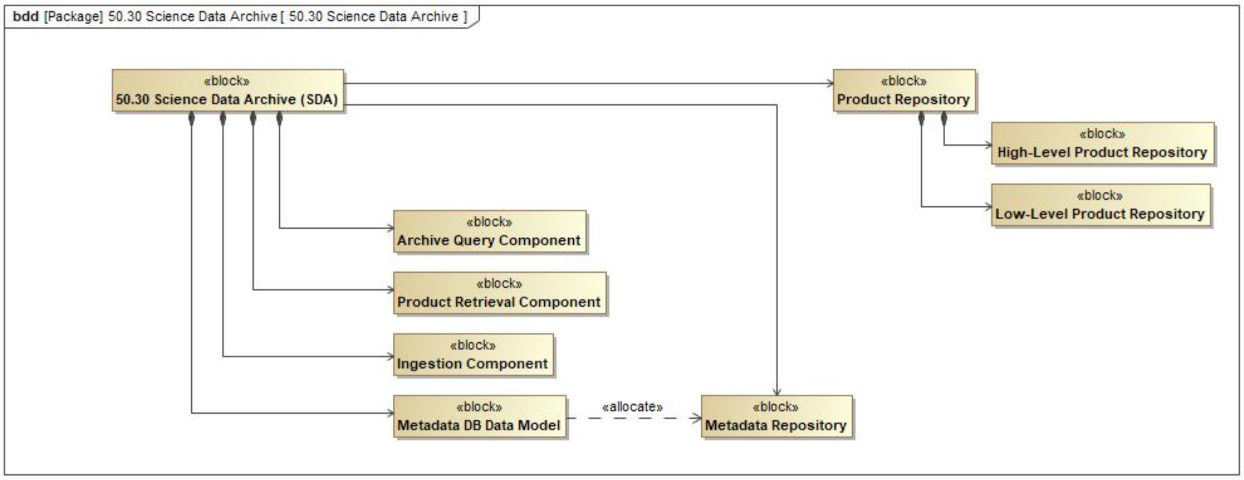

Figure 60: SDA decomposition diagram.

Also shown in the diagram are the data models owned by the SDA system and their database allocations.

These subsystems are:

(a) **Archive Query Component**: The Archive Query Component allows users and other components to construct queries to retrieve data through the Product Retrieval Component.

(b) **Ingestion Component**: The Ingestion Component receives high-level and low-level products and metadata packages for storage in the Science Data Archive hardware component of the Technical Infrastructure (TI) system. The Ingestion Component checks the data, its format, documentation, metadata, and auxiliary information and creates the additional documentation needed for the archiving purposes.

(c) **Product Retrieval Component**: The Product Retrieval Component allows users and other components to retrieve products and associated metadata from the Product and Metadata Repositories.

Figure 61 shows the interfaces between SDA and other system elements.

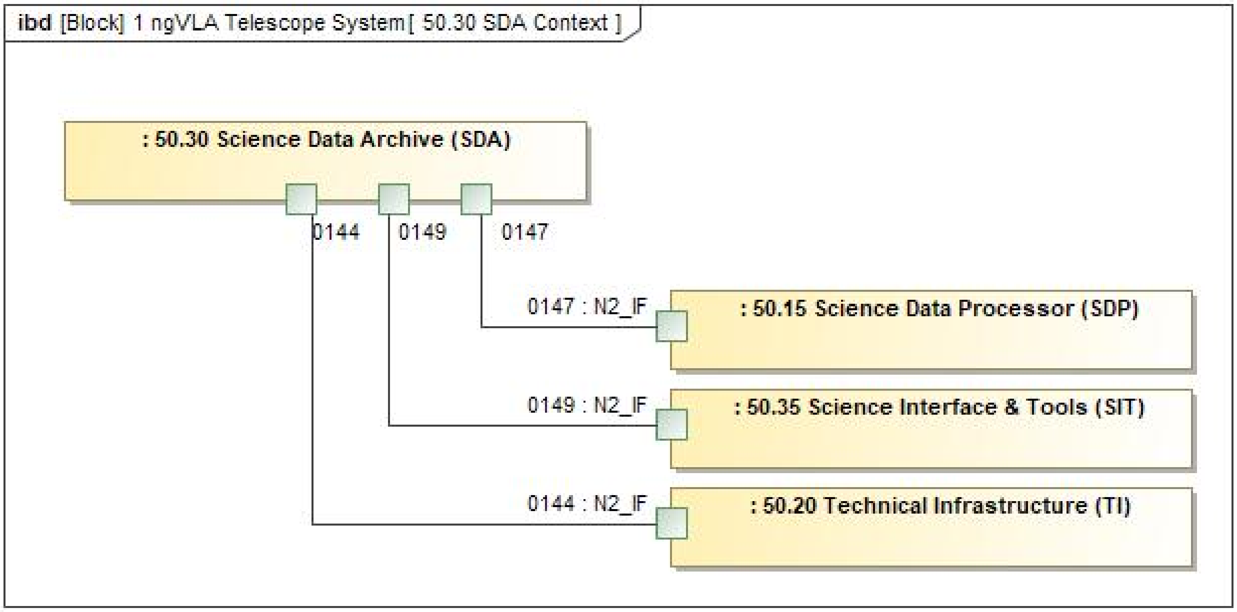

Figure 61: SDA context diagram.

These interfaces are:

(a) **0147**: Interface with SDP. The SDP system accesses archived datasets from SDA to be processed and ingests data products through this interface.

(b) **0149**: Interface with SIT. The SIT system provides a user interface to query, visualize, analyze and retrieve archived products from SDA using this interface.

(c) **0144**: Interface with TI. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software infrastructure elements (e.g. logging, IT monitoring, communication frameworks, container orchestration).

4.6.15.7 Science Interface and Tools (SIT)

The Science Interface & Tools (SIT) system is the main user interface for scientists and support staff. The functionality includes: Observatory interfaces for end users to search and access science data products, data product visualization, analysis and re-processing interfaces, interfaces for principle investigators to see the status of their accepted proposals and access their data products. SIT also includes scientific scripts and tools needed for commissioning.

The SIT system is decomposed in subsystems as shown in Figure 62.

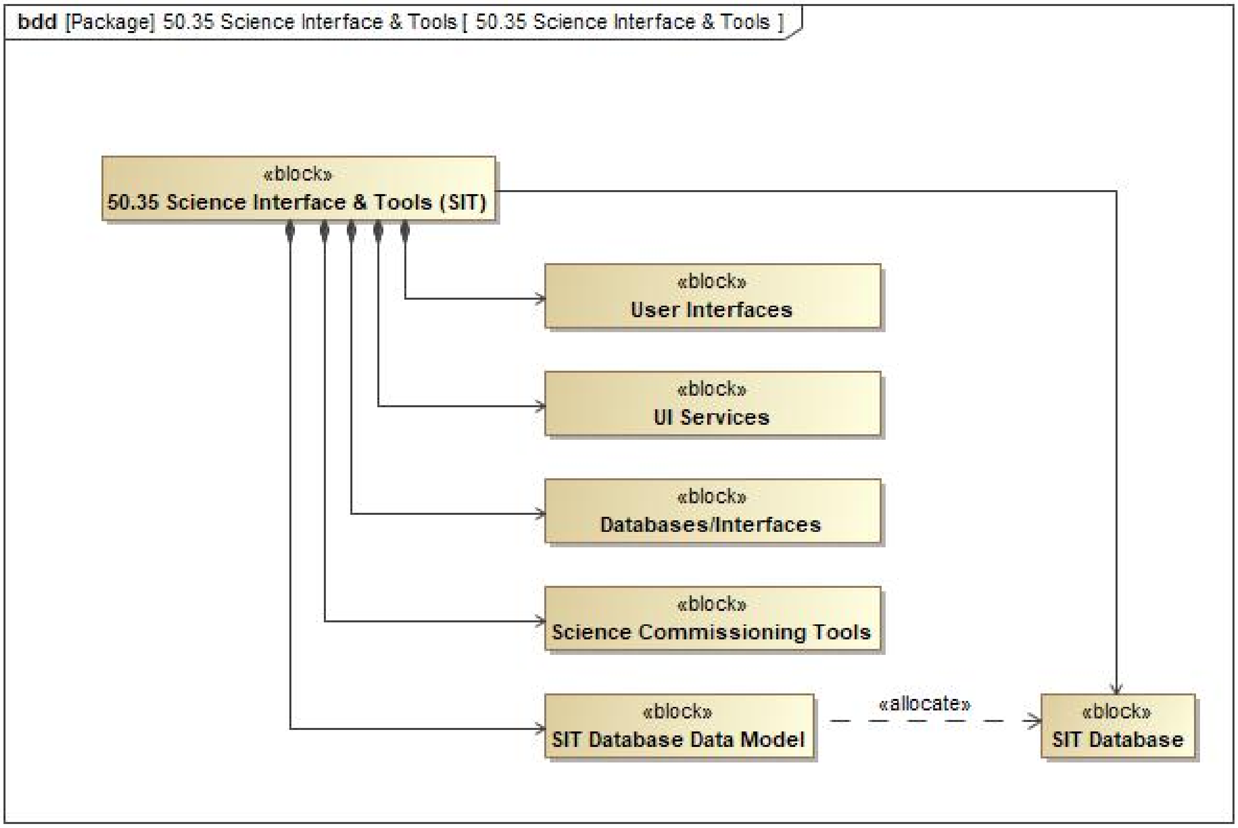

Figure 62: Science Interface & Tools decomposition.

These subsystems are

(a) **Databases/Interfaces**: The Databases/Interfaces layer interfaces to the other databases in the relevant computing systems, like the Proposal Management System (PMN), Online Data Acquisition System (ONL), and Science Data Archive (SDA). Any databases used only by SIT would also be accessed in this layer.

(b) **Science Commissioning Tools**: Scientists have developed, and will continue to develop, a host of scripts, tools, and graphical user interfaces for Assembly, Integration and Verification (AIV) testing and Commissioning Science and Validation (CSV). These key pieces of software will comprise the Science Commissioning Tools and are expected to evolve throughout the lifetime of the project.

(c) **UI Services**: UI Services are all the services needed to support the User Interfaces. This extensible list includes all the services needed to support interfaces to the project lifecycles, processing lifecycles, and quality assurance processes. It is envisioned that the logic part of the system that tracks the state of an execution needed to support the different lifecycles is part of the UI Services subsystem. The information in the state system would be persisted in the Science Data Archive (SDA). The services can be single session or shared sessions to support single or multi-user environments, respectively, depending on the requirements.

(d) **User Interfaces**: The User Interfaces are designed to support a variety of users, both internal and external. The users and key features identified so far are:

Users

The User Interfaces need to support the following categories of users:

- Pipeline Operators – monitor workflow and pipeline jobs, manually control jobs when necessary, and assign jobs for review.
- Quality Assurance (QA) Reviewers and Data Reduction Staff – perform quality checks, investigate problems, and re-run pipelines when necessary.
- Developers – build and test new tools and investigate problems in deployed software.
- Commissioning Scientists – prototype heuristics, test unreleased software, and investigate problems in deployed software.
- External Users – inspect and analyze their products, track projects, review processing steps, interact with support staff, and sometimes run custom processing jobs. To meet the needs of the diverse group listed above, the User Interfaces need to provide the ability to: query the archived data sets, submit jobs to the Science Data Processor (SDP), analyze and visualize science data, track the progress of projects, interact with support staff, perform quality assurance, perform development and commissioning of new software releases, and troubleshoot deployed software.

Key Features

The User Interface will likely contain an integrated, browser-based, modularized collection of standard tools and interfaces including data manipulation and analysis tools. In addition, other key features include:

- Open Environment – a single-user environment used for development, commissioning, and deep QA investigations.
- Science Platform – a cohesive platform which allows access to astronomical data from the ngVLA as well as data from other facilities. This platform will be available across collaborations so that remote users at different locations can access, analyze and manipulate data products. It will contain a "sandbox" functionality for users to bring in their own software analysis tools or code to analyze their ngVLA products. It is intended to support multiple, simultaneous users in a single environment.
- Lifecycle Tracking – allows the Principal Investigators (PIs) and external users to monitor the status of their project through the project lifecycle: from proposal acceptance to execution(s) and archiving the raw data, through data processing workflows, to the production of high-level data products. It is envisioned to be a rich interactive application to provide a broad overview to both internal and external users of the status of their projects.

Also shown in the diagram are the data models owned by the SIT system and their database allocations.

Figure 63 shows the interfaces between SIT and other system elements.

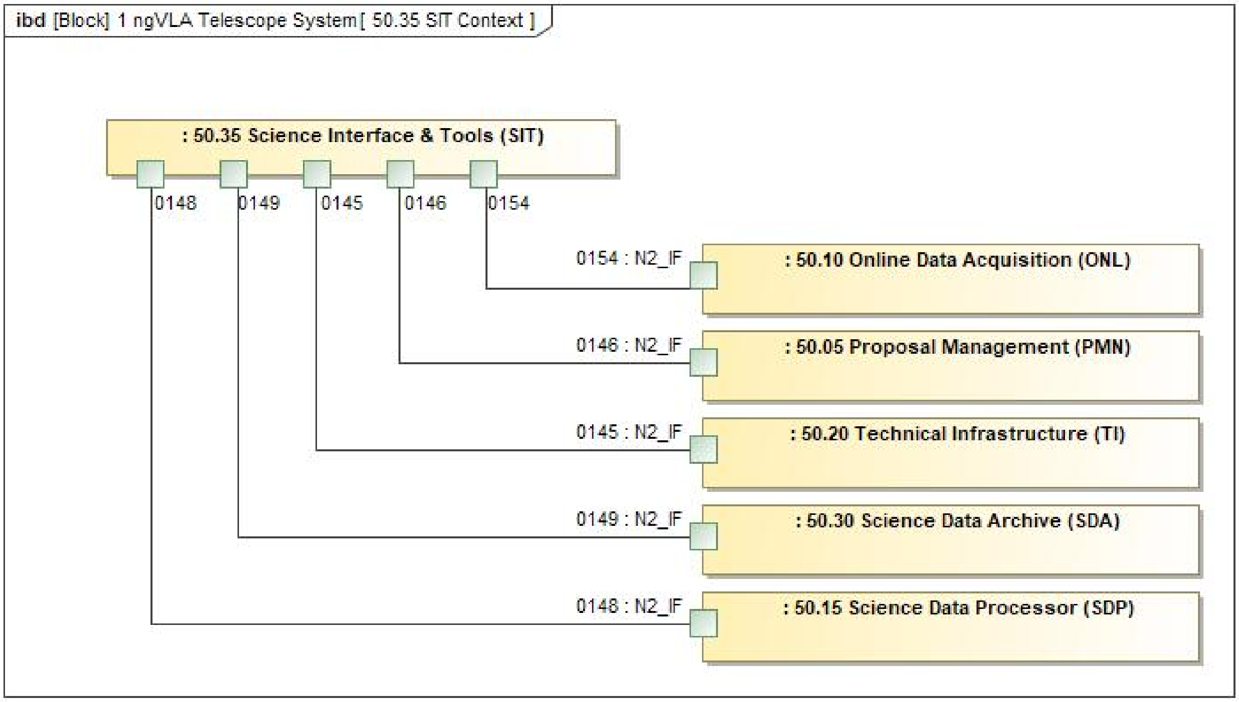

Figure 63: SIT context diagram.

These interfaces are:

(a) **0148**: Interface with SDP. SIT provides interfaces to track the status of processing jobs. Using this interface, SDP notifies SIT of changes in the state of the processing jobs.

(b) **0149**: Interface with SDA. The SIT system provides a user interface to query, visualize, analyze and retrieve archived products from SDA using this interface.

(c) **0145**: Interface with TI. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software infrastructure elements (e.g. logging, IT monitoring, communication frameworks, container orchestration).

(d) **0146**: Interface with PMN. SIT provides interfaces to track the status of proposals. Using this interface, PMN notifies SIT of changes in the proposal status.

(e) **0154**: Interface with ONL. SIT provides interfaces to track the status of observations. Using this interface, ONL notifies SIT of changes in the observation status.

4.6.15.8 Technical Infrastructure (TI)

The TI system includes all the computing and networking infrastructure required by the CSS software systems, including software development infrastructure, and all the system databases and file repositories. TI also maintains external (i.e. not developed in-house) software middleware.

The TI system is decomposed as shown in Figure 64, Figure 65, Figure 66 and Figure 67.

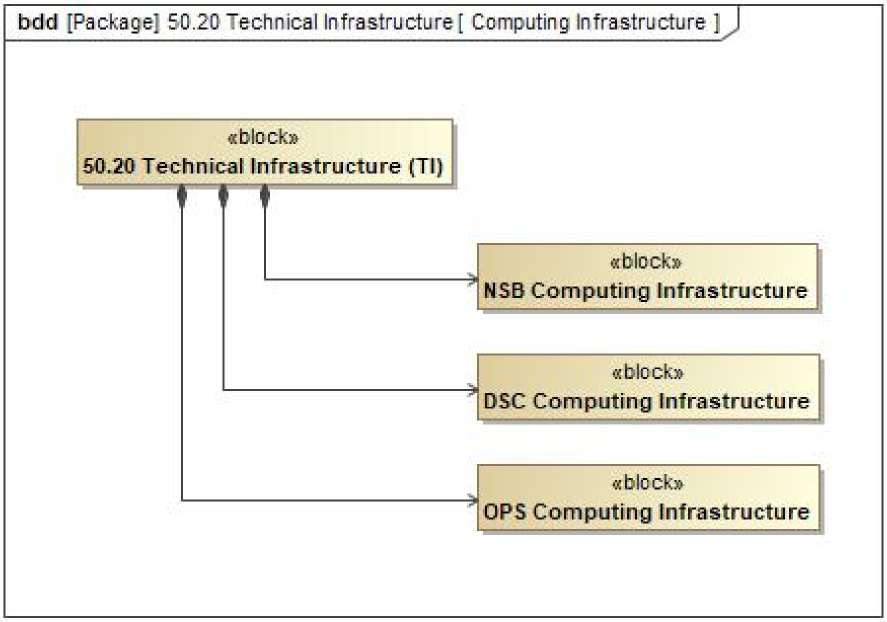

Figure 64: TI decomposition for computing infrastructure.

The computing infrastructure elements are:

(a) **DSC Computing Infrastructure**: Computing and networking infrastructure in the Science Data Center (DSC).

(b) **NSB Computing Infrastructure**: Computing and networking infrastructure in the ngVLA Site Buildings (NSB), mostly located in the Central Electronics Building.

(c) **OPS Computing Infrastructure**: Computing and networking infrastructure in the Operations Buildings (OPS). The operations buildings are the Array Operations Center, Remote Support Station Buildings, Maintenance Center and Repair Center.

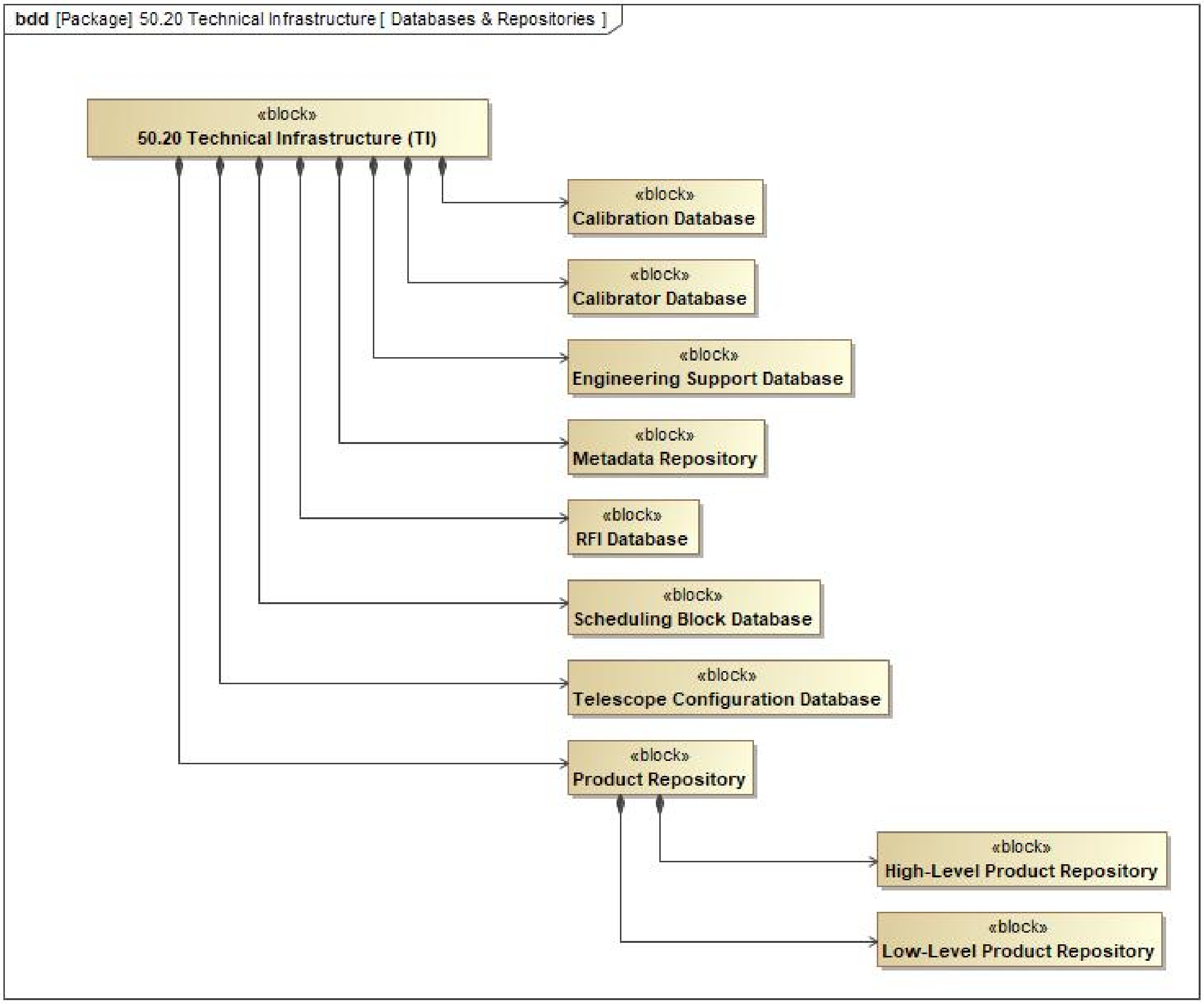

Figure 65: TI decomposition for databases and file repositories.

The databases and repositories are:

(a) **Calibration Database**: This database manages calibration data such as antenna positions and their relative offsets to focal plane, antenna pointing parameters, delay/phase models, etc. This database stores calibration models derived from observations to be reused in subsequent observations.

(b) **Calibrator Database**: This database stores calibrator sources along with their characteristics.

(c) **Engineering Support Database**: A database to support engineering operations, storing data such as monitoring streams, alarms, and system logs.

(d) **High-Level Product Repository**: The high-level products are calibration tables, images, high-level data products, and other artifacts produced from the visibility data. These high-level products have different availability requirements than the low-level products.

(e) **Low-Level Product Repository**: The low-level products are the visibility (binary) data which are physically stored in hardware within Technical Infrastructure (TI) in a variety of hardware mediums based on the lifetime of the data.

(f) **Metadata Repository**: The Metadata Repository stores metadata associated with each data product and its provenance (e.g. proposal and observation execution information).

(g) **Product Repository**: The Product Repository stores, maintains and retrieves low-level and high-level data products, assigns them to locations in a hierarchical storage system in the hardware component of Technical Infrastructure (TI) and provides access to them through the Product Retrieval Component in SDA.

(h) **RFI Database**: The RFI database stores characteristics of both expected and observed RFI for reuse as well as to provide a long-term record of emitters visible to the array.

(i) **Scheduling Block Database**: This database stores Scheduling Block structures.

(j) **SIT Database**: This database stores persistent data used by the Science Interface and Tools (SIT) system.

(k) **Telescope Configuration Database**: This distributed database provides a central repository for the configuration and calibration data needed by ONL and MCL components. This data is kept under version control and changes are propagated to distributed repositories across the system.

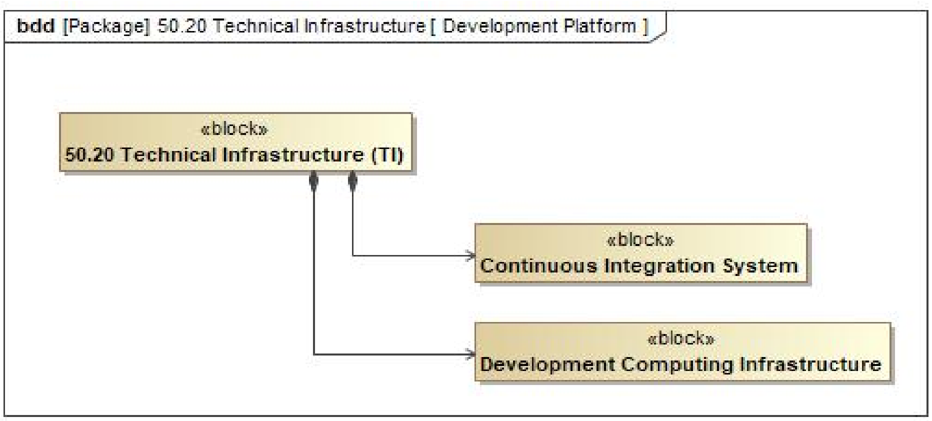

Figure 66: TI decomposition for the development platform elements.

The development platform elements are:

(a) **Continuous Integration System**: This system executes test suites automatically when software changes are made, and reports results to the responsible developers.

(b) **Development Computing Infrastructure**: Computing infrastructure to support software development activities.

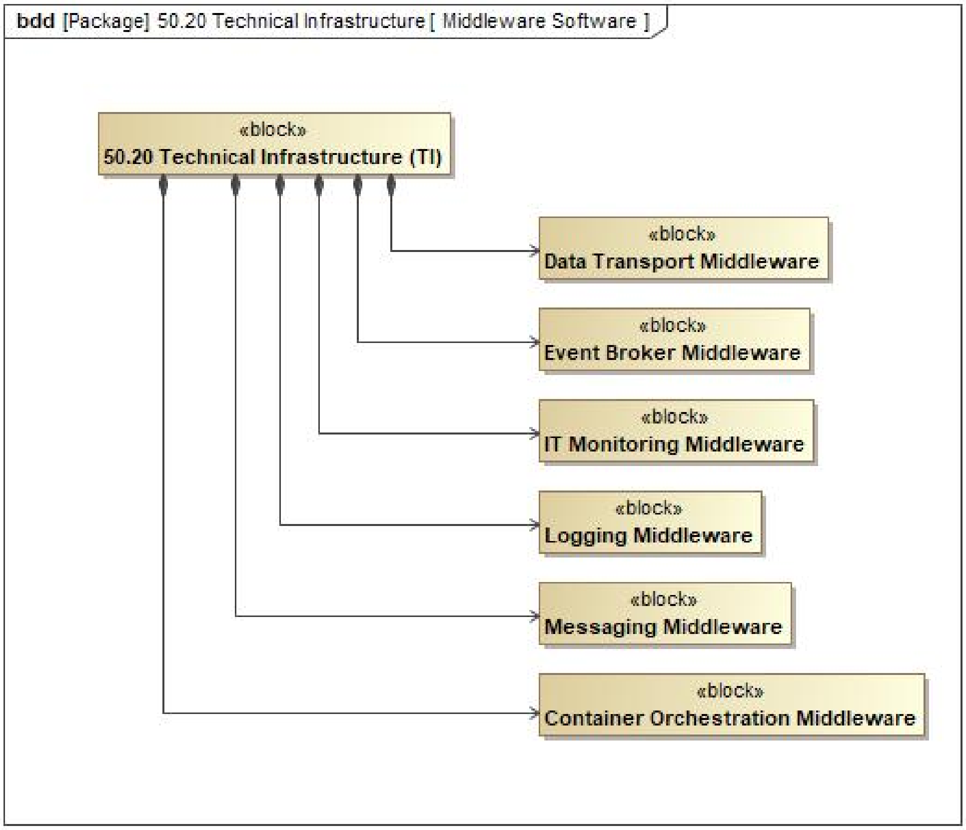

Figure 67: TI decomposition for middleware software.

The middleware software elements are:

(a) **Container Orchestration Middleware**: A container Orchestrator (e.g. Kubernetes) manages a pool of computational resources, allocating containerized applications to execute on them. It implements reliability strategies, e.g., re-starting and re-allocating applications in case of hardware or software failures.

(b) **Data Transport Middleware**: The Data Transport Middleware transports low-level data products from the Central Electronics Building to the Science Data Center for archiving and post-processing.

(c) **Event Broker Middleware**: An event broker (e.g. Kafka) provides a low-latency, highly scalable streaming framework. All the events flowing through the Event Broker are persistent, which allows the implementation of high-availability strategies and facilitates the collection of metadata and troubleshooting information.

(d) **IT Monitoring Middleware**: Middleware to monitor the state of computational and networking resources.

(e) **Logging Middleware**: Middleware to support the collection, storage and presentation of system logs.

(f) **Messaging Middleware**: Middleware to support asynchronous or synchronous communication between components in a distributed architecture.

Figure 68 shows the interfaces between TI and other system elements.

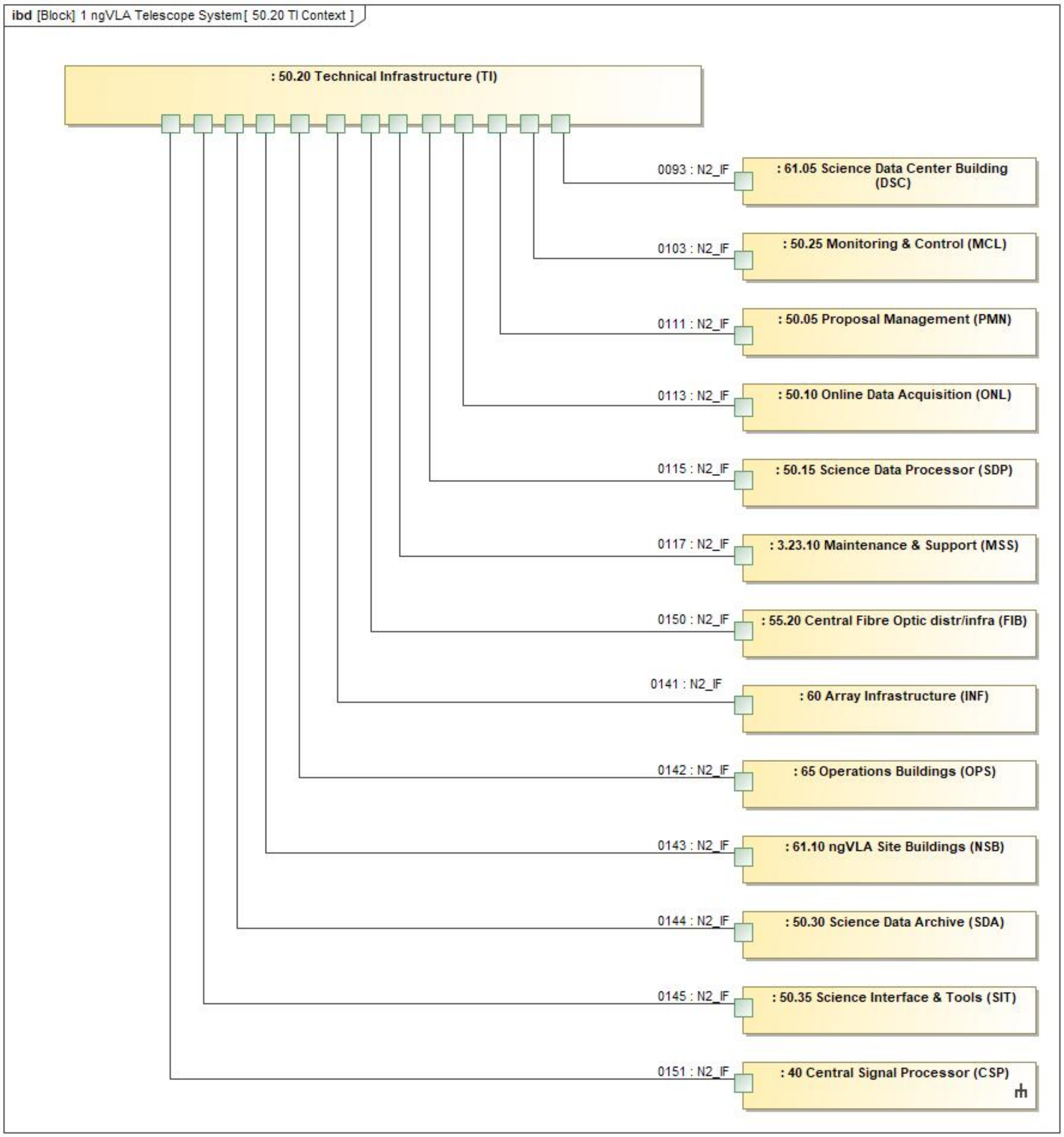

Figure 68: Context diagram for the TI subsystem, showing the interfaces between this subsystem and other system sub-elements.

These interfaces are:

(a) **0093**: Interface between TI and DSC. It specifies requirements for rack space, cooling and power for the Data Science Center buildings.

(b) **0103**: Interface between TI and MCL. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(c) **0111**: Interface between TI and PMN. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(d) **0113**: Interface between TI and ONL. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(e) **0115**: Interface between TI and SDP. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(f) **0117**: Interface between TI and MSS. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(g) **0150**: Interface between TI and FIB. Specifies requirements for the connectivity of "above ground" fiber and TI systems, e.g. M&C connectivity from the Central Electronics Building computing nodes; and data transport connectivity between Central Electronics Building and Data Science Center.

(h) **0151**: Interface between TI and CSP. It specifies requirements for the transmission of CSP data from the CSP Switched Fabric to the ONL Data Reception & Analysis computing nodes.

(i) **0145**: Interface with TI and SIT. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(j) **0144**: Interface between TI and SDA. It specifies software deployment details and computational, networking and storage requirements, and the interfaces to common software middleware.

(k) **0141**: Interface between TI and INF.

(l) **0142**: Interface between TI and OPS. It specifies requirements for rack space, cooling and power for the Operations Buildings.

(m) **0143**: Interface between TI and NSB. It specifies requirements for rack space, cooling and power for the ngVLA Site Buildings.

The software deployment is shown in Figure 69, Figure 70 and Figure 71.

	DSC Computing Infrastructure	NSB Computing Infrastructure	OPS Computing Infrastructure
50.05 Proposal Management	11	1	
Exposure Calculator Tool	↗		
Exposure Calculator Tool Backend	↗		
Exposure Calculator Tool GUI	↗		
Instrument Resource Tool	↗		
ngVLA Observation Preparation Subsystem	↗	↗	
ngVLA Proposal Resources Subsystem	↗		
TTA Anti-Corruption Layer	↗		
TTA Application Layer	↗		
TTA Domain Layer	↗		
TTA Framework Layer	↗		
TTA Subsystem	↗		

Figure 69: Software deployment table for the PMN system.

	30.45.59 SA501 Cntrl module	30.45.60 SA502 cntrl module	Development Computing Infrastructure	DSC Computing Infrastructure	NSB Computing Infrastructure	OPS Computing Infrastructure
50.10 Online Data Acquisition					3	
Data Reception & Analysis					↗	
Observation Execution					↗	
Observation Scheduling					↗	
ONL Data Models						
50.25 Monitoring & Control	2	1	1		8	1
Antenna Supervisor	↗					
Antenna Supervisor Adaptor					↗	
CSP Supervisor					↗	
Digital Twin					↗	
Edge Computing Software	↗	↗			↗	
Event Broker					↗	
Hardware Simulator			↗			
LORT Supervisor					↗	
MCL Data Models						
Predictive Maintenance Algorithms					↗	
SCADA System					↗	↗

Figure 70: Software deployment table for the ONL and MCL systems.

	Computing Infrastructure	DSC Computing Infrastructure	NSB Computing Infrastructure	OPS Computing Infrastructure
50.15 Science Data Processor		7		
Algorithm Library	1	↗		
Application	1	↗		
CASA API	1	↗		
Other Dependencies	1	↗		
Resource Management	1	↗		
SDP User Interfaces	1	↗		
Workflow Management	1	↗		
50.30 Science Data Archive		4		
Archive Query Component	1	↗		
Curation Component	1	↗		
Ingestion Component	1	↗		
Product Retrieval Component	1	↗		
SDA Data Models				
50.35 Science Interface & Tools		4		
Databases/Interfaces	1	↗		
Science Commissioning Tools	1	↗		
SIT Data Models				
UI Services	1	↗		
User Interfaces	1	↗		

Figure 71: Software deployment table for the SDP, SDA and SIT systems.

4.6.16 Central Signal Processing (CSP)

The Central Signal Processor (CSP) is a heterogeneous subsystem consisting of various digital signal-processing sub-elements that convert the digitized voltage from each digitizer at the antenna into raw data products. The raw data products are sent to the computing and software system for further processing or for storage.

Functionally, the CSP includes the Digital Back-End (DBE) at each antenna, which receives the signal data from the digitizer (IRD) and performs sub-banding, time stamping and signal conditioning functions (See Section 5.2.2.4), before packaging the data for transmission to the central signal processor.

The CSP consists of three main sub-systems that perform the central signal processing functions as defined in Sections 5.2.2.5, 5.2.2.6 and 5.2.2.7:

a) A CSP Switched Fabric (CSF) serves as a central hub for all the data routing from the DBEs and between the CSP processing nodes.
b) An array of Sub-band Processor (SBP) modules that perform parallel processing on the sub-banded DBE data. The SBP modules perform different functions, depending on the observing modes. In the interferometric mode, they perform channelization and correlation to produce visibilities. In the beamforming modes, they produce channelized data per beam.
c) Pulsar Engine (PSE): The pulsar engine uses beamformed data as an input and performs transient processing to produce either pulse profiles, or transient search data products, depending on the observing mode.

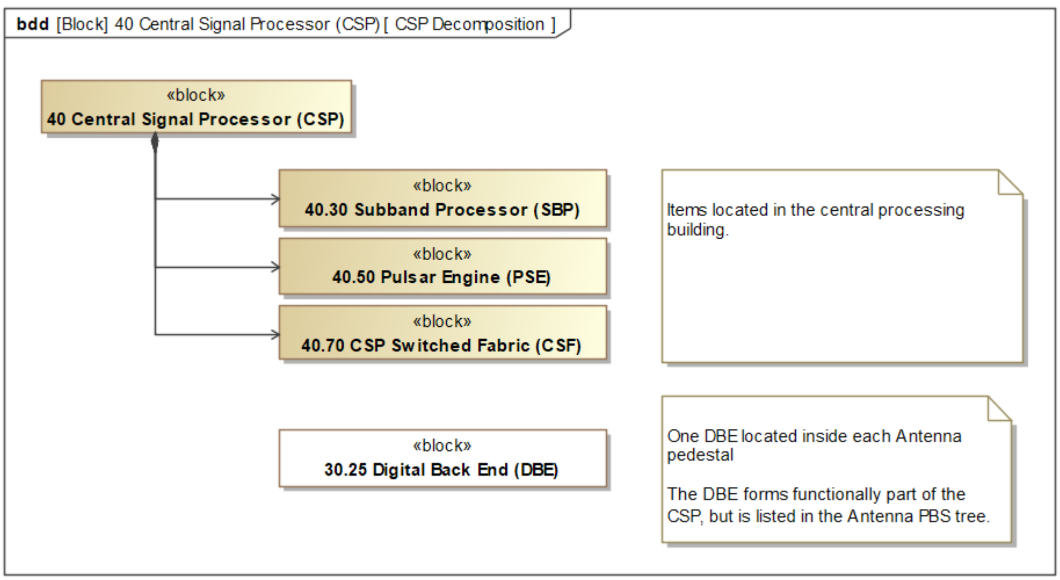

Figure 72: CSP product breakdown

The external interfaces of the DBE are shown in Figure 73 below:

a) Incoming digitized voltage data from the IRD.
b) Outgoing sub-banded and packaged data to the CSP.
c) Fiber connectivity to all systems via the AFD.
d) Power supply from PSU.
e) Environmental conditioning from EEC and BMR.
f) Configuration and monitoring of the DBE from the MCL.
g) Timing reference from ATF.

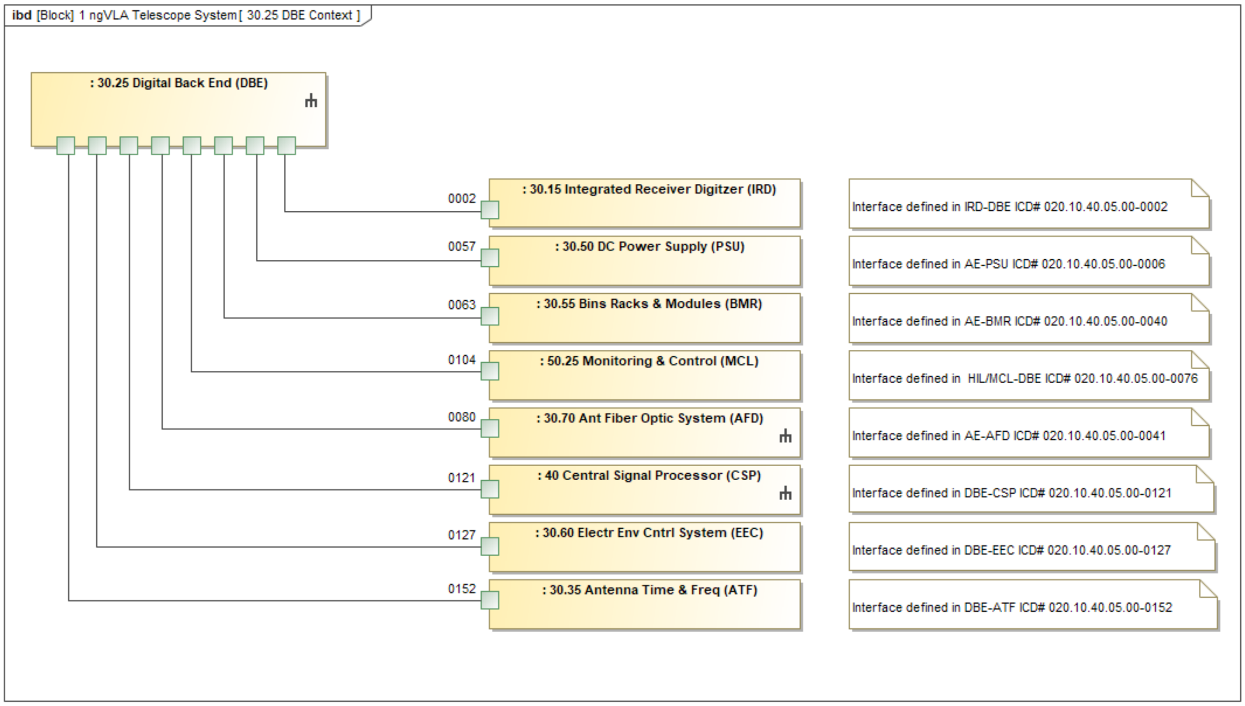

Figure 73: DBE external interfaces

The external interfaces of the central CSP components are shown in Figure 74:

a) Incoming data from DBE.
b) Outgoing data to ONL.
c) Fiber connectivity for incoming data from the antennas via FIB.
d) Monitoring and control from MCL.
e) Supply of timing reference from RTG.
f) Hosted space, power and cooling from NSB.

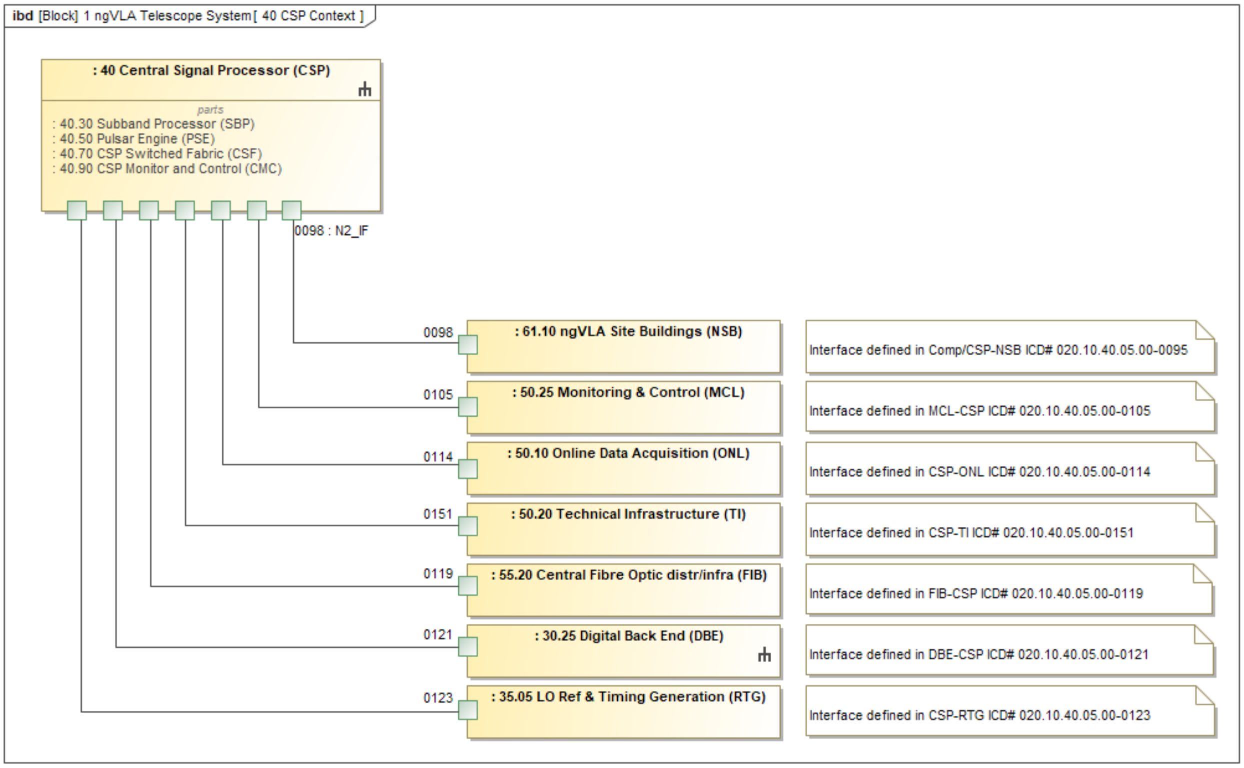

Figure 74: CSP external interfaces

4.6.17 Central Fiber Optic Distribution infastructure (FIB)

The FIB subsystem includes:

a) The data networks to connect the antennas to the central processor building:
   i. Optical fiber termination racks and trays at the central processor building, where the optical fibers from the antennas terminate.
   ii. Optical fiber cables from the central processor buildings to all the short and mid baseline antennas. Note that the fibers will be specified by the FIB subsystem, but installed and tested by the INF contractor.
   iii. Data link repeaters and splice termination trays for long-haul optical fiber links – these will in some cases be located at or inside antennas along the spiral arms, and in other cases in repeater huts along the fiber routes.
   iv. Fiber splicing/connection trays in the antenna pedestals where the array fiber cables terminate in the antenna.
   v. Ethernet data switches in all the antennas. Note that these switches need to be PTP compatible.
   vi. Commercial data links for long baseline antennas for the transfer of astronomical and M&C data between the antennas and the central processor building.
   vii. Network configuration setup for all the astronomical data links between the central processor building and the antennas.

b) The data networks to distribute the astronomical data from the central processor building to the data center for offline data processing.

Note that even though FIB will be responsible for the design, procurement and installation of these components, the LO Reference and Timing Distribution (RTD) system will use the FIB infrastructure for the distribution of timing and frequency references. RTD will thus impose requirements on the FIB system and will be closely involved in its design.

The decomposition of this subsystem is shown in Figure 75 below.

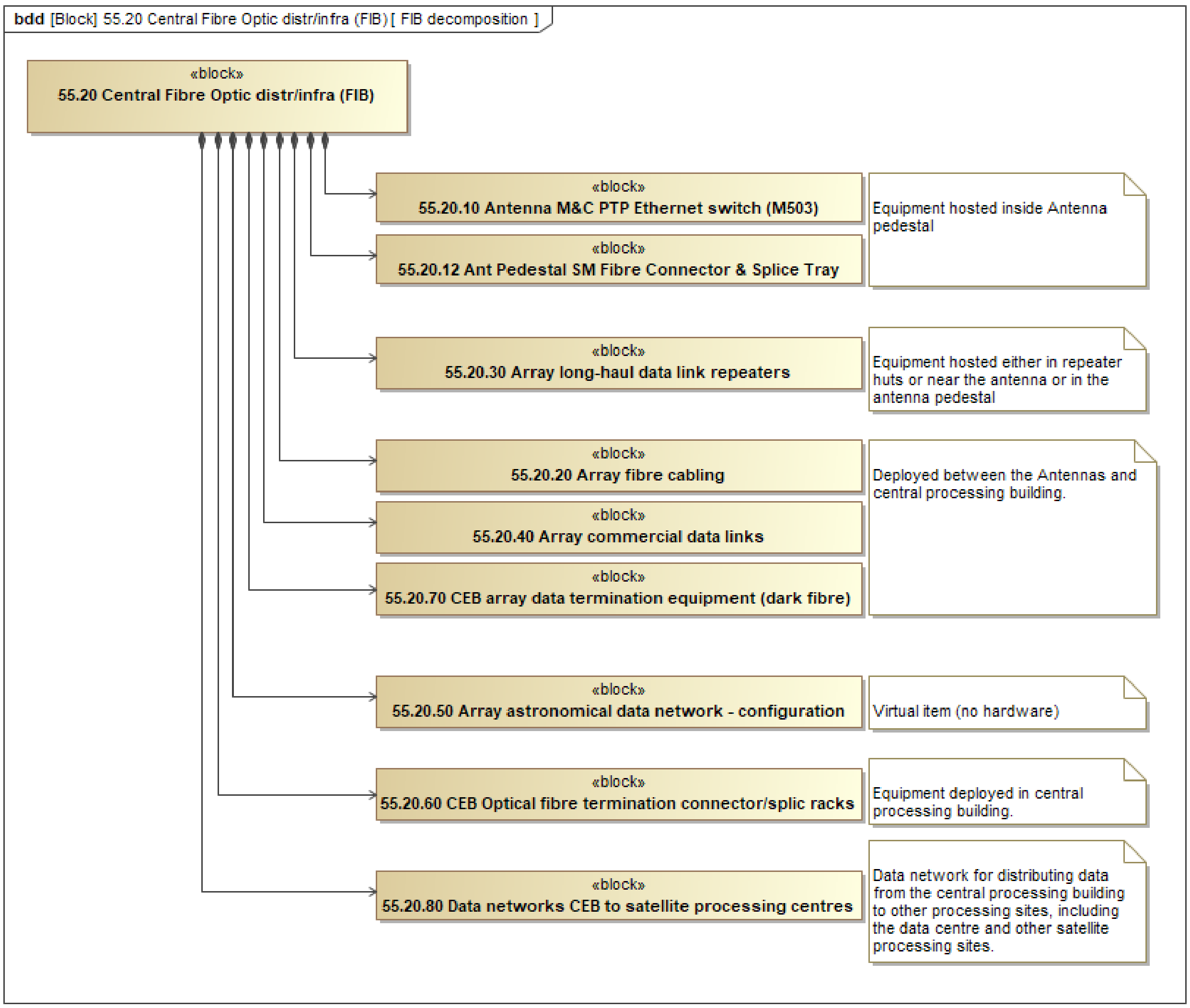

Figure 75: FIB decomposition

FIB has interfaces to the following subsystems, as shown in Figure 76:

a) To INF for the installation of the array fiber cables in the conduits or trenches that are provided by INF.
b) To NSB for hosting fiber racks and terminal equipment in the central processor building.
c) To DSC for hosting fiber racks and terminal equipment in the data center.

d) To TI for the transfer of data from the central processing center to the data center.
e) To CSP for the transfer of astronomical data from the antennas to CSP.
f) To RTD for the specification of optical fiber cables that will carry the frequency reference signals.
g) To AFD for the connection of the antenna hosted equipment to the local antenna fiber distribution network.

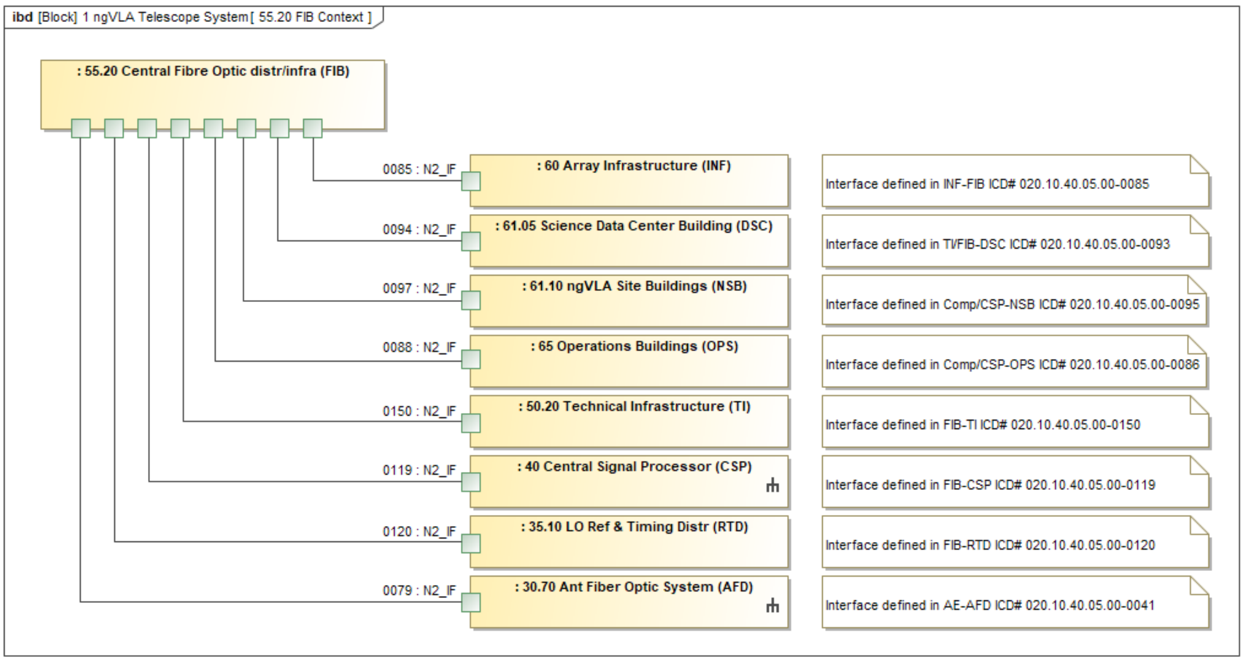

Figure 76: FIB external interfaces

4.6.18 LO Reference & Timing Generation (RTG)

The RTG includes the following components:

a) Maser and GNSS sources at the Central Electronics Building to generate a stable common frequency source for the system and to generate an accurate central system clock domain.
b) Fixed frequency transfer sources for the transmission of fixed frequency reference to central signal processor and all antennas.
c) Time transfer sources for transmission of various time references for the central signal processor and all connected antennas, in the various formats that are required, including PPS and a coded timescale for the data network.
d) Frequency reference and time generation equipment for all stand-alone antennas (antennas not connected via direct fiber to the Central Electronics Building) and for the LBA stations.

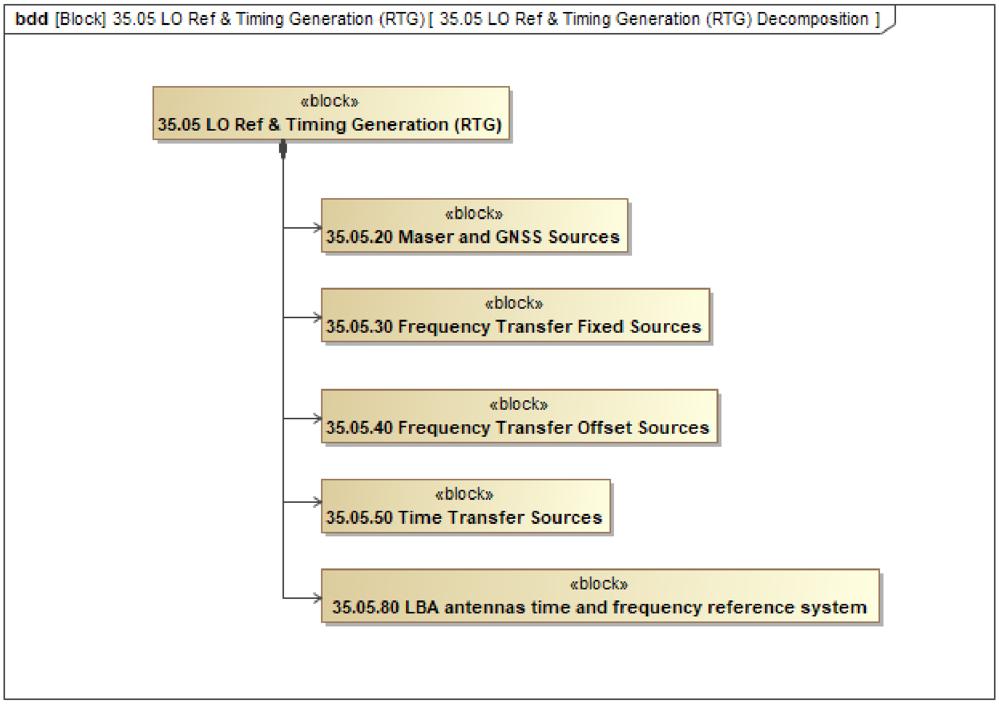

Figure 77: RTG decomposition

The interfaces of the RTG to other subsystems are shown in Figure 78:

a) To the ngVLA Site buildings at the Central Electronics Building, for hosting the central RTG equipment, including space, power and environmental control.
b) To the MCL system for the monitoring and control of the RTG hardware.
c) To the CSP for the provision of time and frequency references to the CSP.
d) To the RTD system to supply the time and frequency sources for distribution to all fiber connected antennas.
e) To the HIL for control and monitoring of the RTG hardware components.

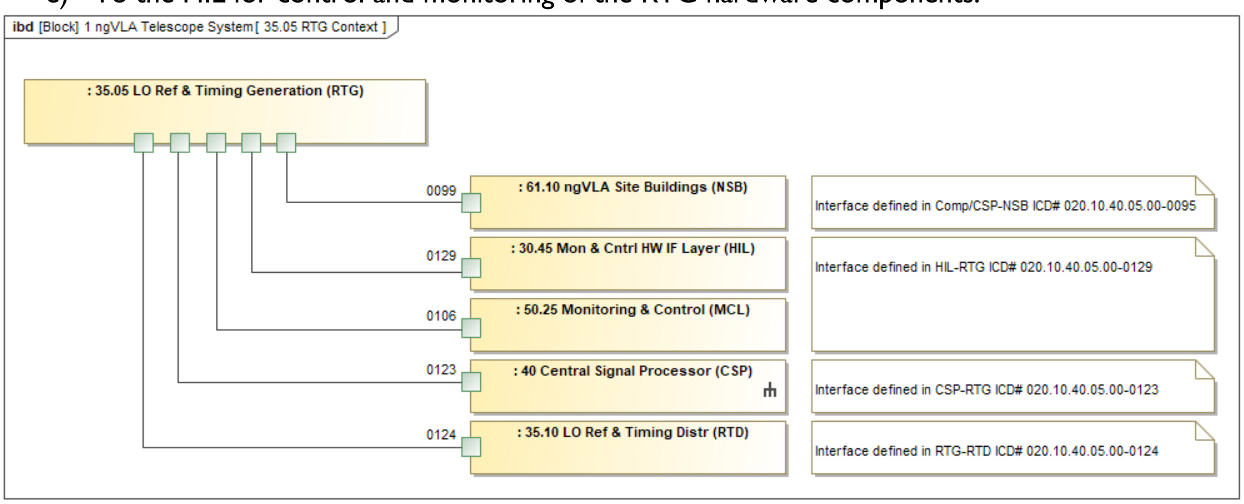

Figure 78: RTG external interfaces

4.6.19 LO Reference & Timing Distribution (RTD)

The RTD includes the following components:

a) Reference distribution equipment to split up the time and frequency sources received from the RTG into multiple sources required for all the antennas. This equipment also performs round trip time and frequency measurements to/from the fiber connected antennas.
b) Transmitter equipment to amplify the frequency and time reference signals for transmission to antennas.
c) Infrastructure to support the RTD equipment at the Central Electronics Building, such as racks and cabling.
d) Reference signal repeater and amplification equipment for long haul fiber optic links, to be housed either in huts along the distribution route or in antennas along the way.
e) Receiver equipment located in each of the antennas to receive the reference signals and condition them for the Antenna Time and Frequency (ATF) subsystem.

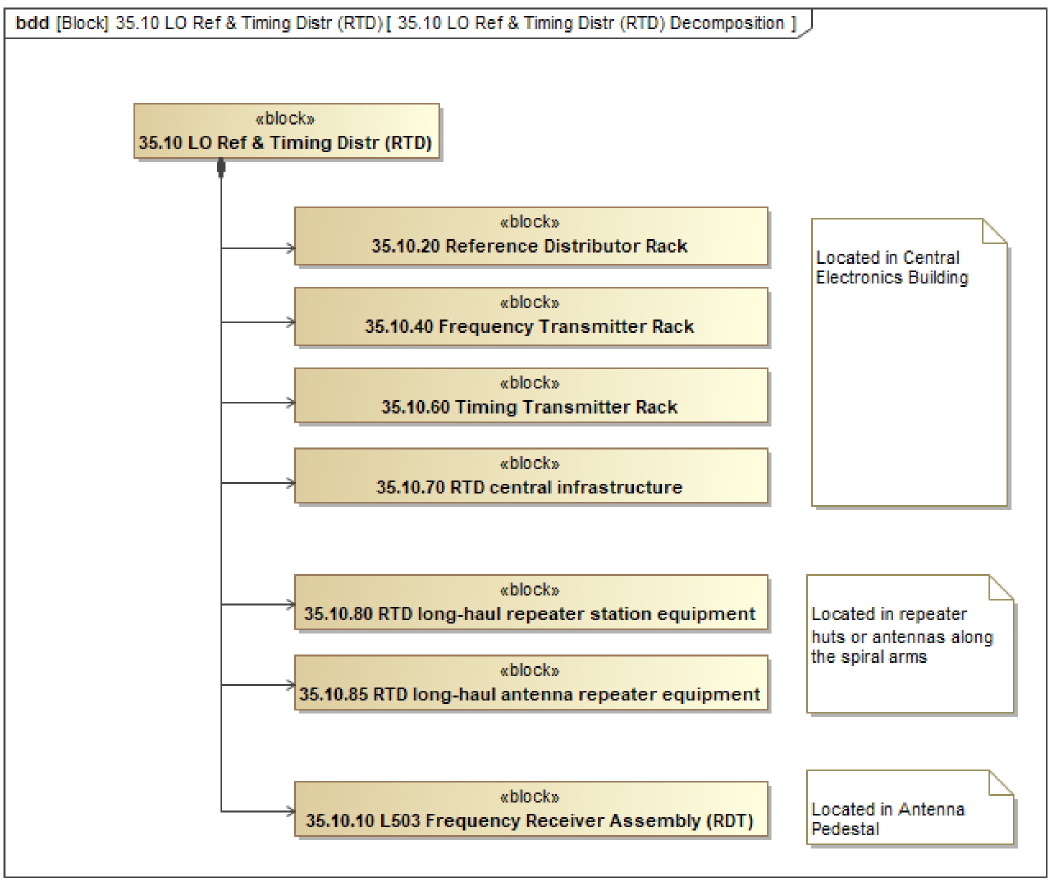

Figure 79: RTD decomposition

The RTD interfaces to the following subsystems as shown in Figure 80:

a) At the Antenna, the Frequency Receiver Assembly and antenna-hosted long-haul repeater equipment interfaces with the BMR, EEC, PSU and HIL subsystems for the support of antenna hosted equipment to provide environmental protection, cooling power, monitoring and control.
b) DBE and WVR for provision of precision timing in the form of a Pulse Per Second (PPS).
c) ATF, for the provision of frequency reference at the secondary focus position and to receive a reflection back from the ATF at the secondary focus (for round trip phase measurement).
d) FIB to provide support needed for the hosting of long-haul repeater equipment located in repeater huts.
e) NSB for the hosting of equipment located at the Central Electronics Building, to provide rack space, environmental conditioning and power.
f) RTG to provide the source time and frequency references signals.

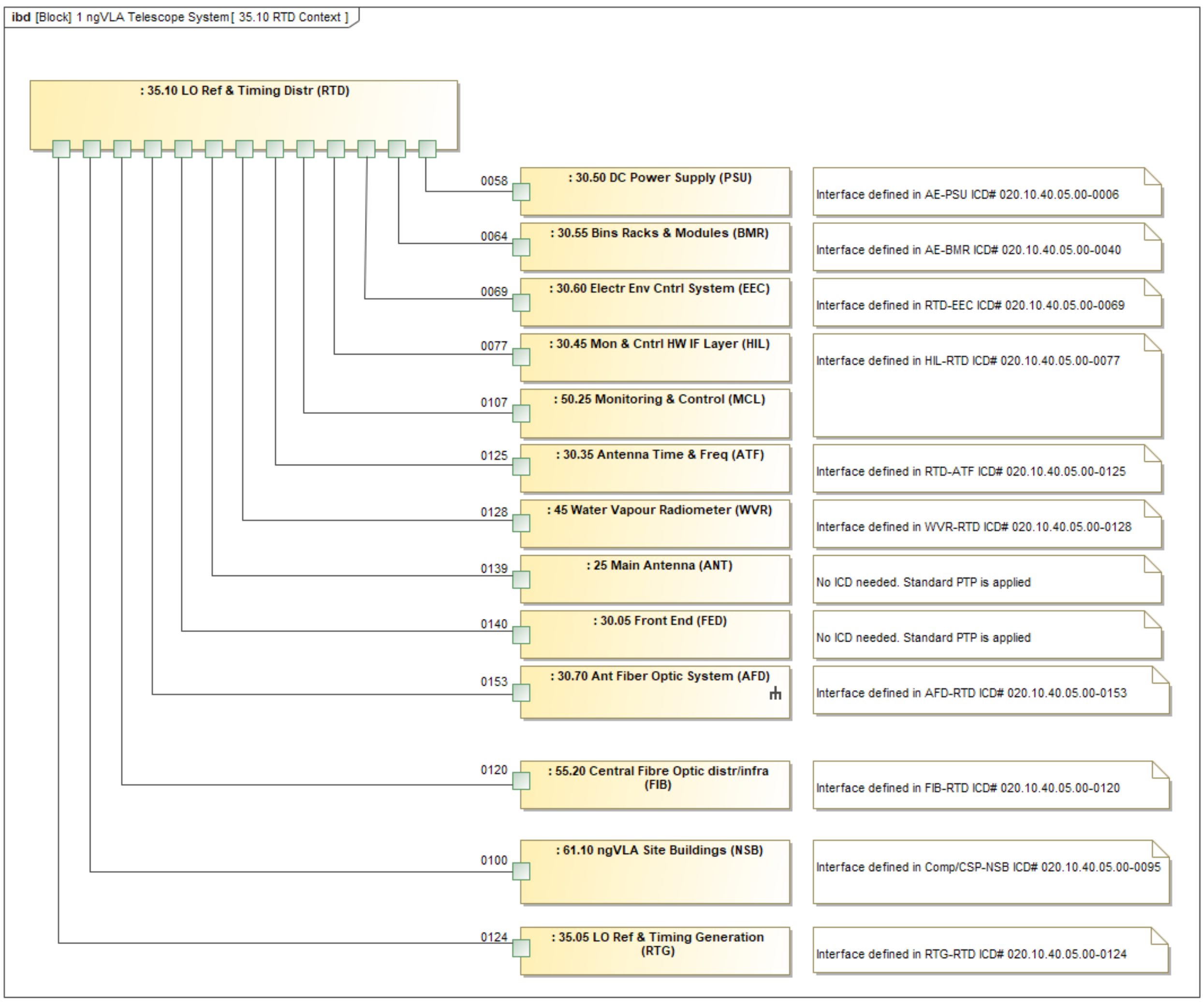

Figure 80: RTD context

4.6.20 Antenna Time and Frequency (ATF)

The ATF performs the local distribution of reference timing and frequency signals for all components located on the Antenna. The ATF also applies the per-antenna frequency offset. The supply of the LO and sampling clocks for Band 1 to 6 receivers (IRDs) is implemented as 20 LO modules located in the front-end enclosure. The LO modules provide down-conversion frequency reference and a sampling clock to each IRD module. A LO module is also required for the WVRs sampler (this forms part of the WVR PBS structure). The decomposition of the ATF subsystem is shown in Figure 81 below. The Repeater equipment is shown for context, but is part of the RTD subsystem.

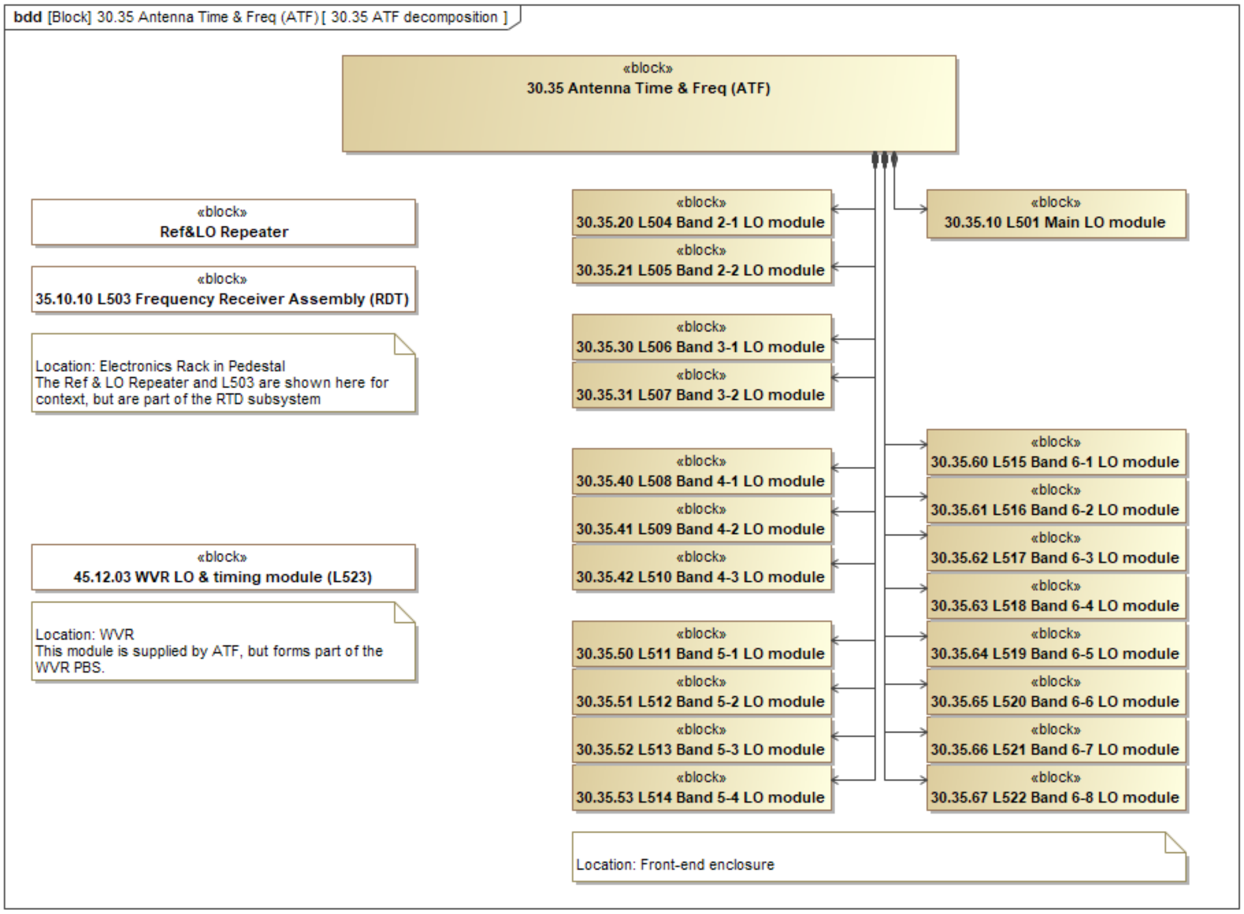

Figure 81: ATF decomposition

The external interfaces of the ATF are shown in Figure 82 below and include:

a) Provision of down-conversion frequency reference and sampling clocks to the IRD modules.
b) Power required from PSU.
c) Environmental and RFI shielding required from BMR.
d) Cooling capacity required from EEC.
e) Control and monitoring of the ATF modules via HIL to MCL.
f) Provision of fiber infrastructure from AFD.
g) Provision of the central time and frequency reference from RTD.

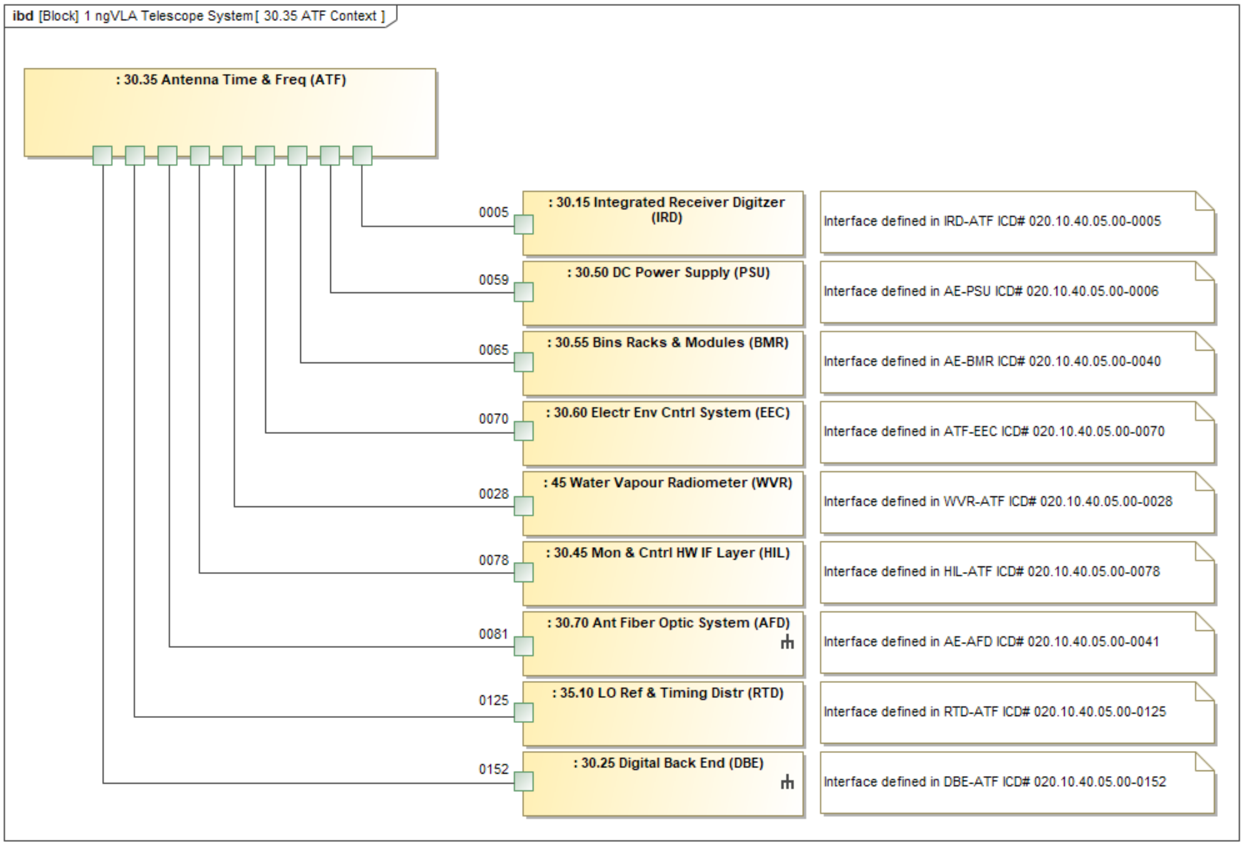

Figure 82: ATF external interfaces

5 Functional Architecture

The functional architecture defines the overall functionality that is required of the system to meet its functional requirements, a breakdown of the functionality into lower level functions, functional sequence and a definition of the main data flows between functions.

5.1 System Modes

The System Requirements define the following functional operating modes:

1. Correlation modes (formerly Interferometric)
    a. Total Power mode
    b. Interferometry
    c. OTF Mapping mode.
2. Phased Array modes (concurrent correlation possible)
    a. VLBI mode
    b. Pulsar Timing mode
    c. Pulsar and Transient Search mode

From a science user perspective, each functional operating mode represents a unique science capability, requires a scheduling block of a specific format, and produces a specific set of data products.

However, multiple options are available for setting up each of these modes, depending on which hardware and software resources are used, which calibrators and targets are observed and how the signal path is configured for data processing. This results in a very large number of available options for system observing modes.

To reduce the number of observing modes to a practical set that can be commissioned and validated for standard observing, a System Observing Modes Framework is defined in [AD06]. This framework provides a limited space framework for observing modes in the form of a matrix. This framework enables the prioritization and planning of specific observing modes to be commissioned and validated.

The details of the observing modes framework are not repeated in this document and the reader is referred to [AD06] for more details on system modes.

The system functions defined in the following sections support the observing modes framework by enabling the configuration of subsystems to implement these modes.

5.2 Functional decomposition

5.2.1 System Functions

The structure of the System Functions, shown in Figure 83 below, is based on a commonly used framework for defining system functionality:

a) **Core flow functions**: that define the main flow of material or data through the system. In this case, the core flow is the astronomical data, flowing through the signal path functions from antenna to final astronomy data product. The signal path flows from left to right, starting with the antenna signal path functions and ending in the archived data products on the right.

b) **Control functions**: Functions that are required to configure and control the core functions. In this case, the control of the execution of observations.

c) **Monitoring functions:** Functions required to monitor the core functions, in this case monitoring the successful execution of observations and monitoring the health of telescope equipment.

d) **User interface functions:** In this case, this refers to functions that are needed for (a) astronomer users for the generation of proposals, project tracking and access to observation data (b) operator interfaces for setting up, execution and monitoring of observations.

e) **Support functions:** Functions that are not directly part of the signal path flow, but that are necessary to support its proper flow. This includes signal path hardware support functions (e.g. cryogenic cooling), calibration functions, provision of time and frequency reference, data transportation, data quality assurance, and maintenance management functions.

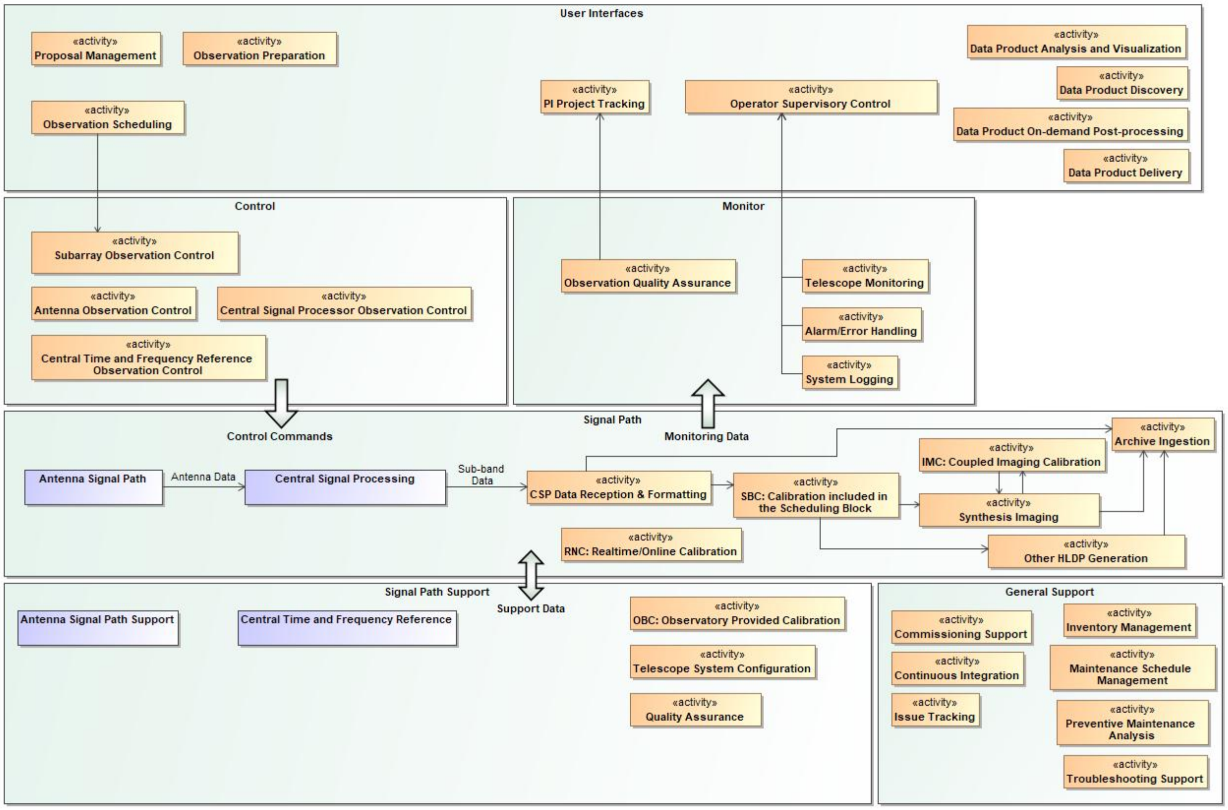

Figure 83: System Functions

Each of the functions shown in Figure 83 are defined on a high level in this document and are allocated to the subsystems.

5.2.2 Signal path functions

The signal path functions and their support functions (shown in blue in Figure 83) are:

a) Antenna Signal Path
b) Antenna Signal Path Support
c) Central Signal Processing
d) Central Time and Frequency Reference

These four main functions are further decomposed to a level where they are allocated uniquely to subsystems, indicated in square brackets in Figure 84. The allocated functions are defined in more detail in the following sections. The greyed-out functions are not defined in more detail, as they are considered to be less critical to the functional architecture. The EEC function was not sufficiently mature at the CDR stage to define a functional model – this will be done during the preliminary design phase.

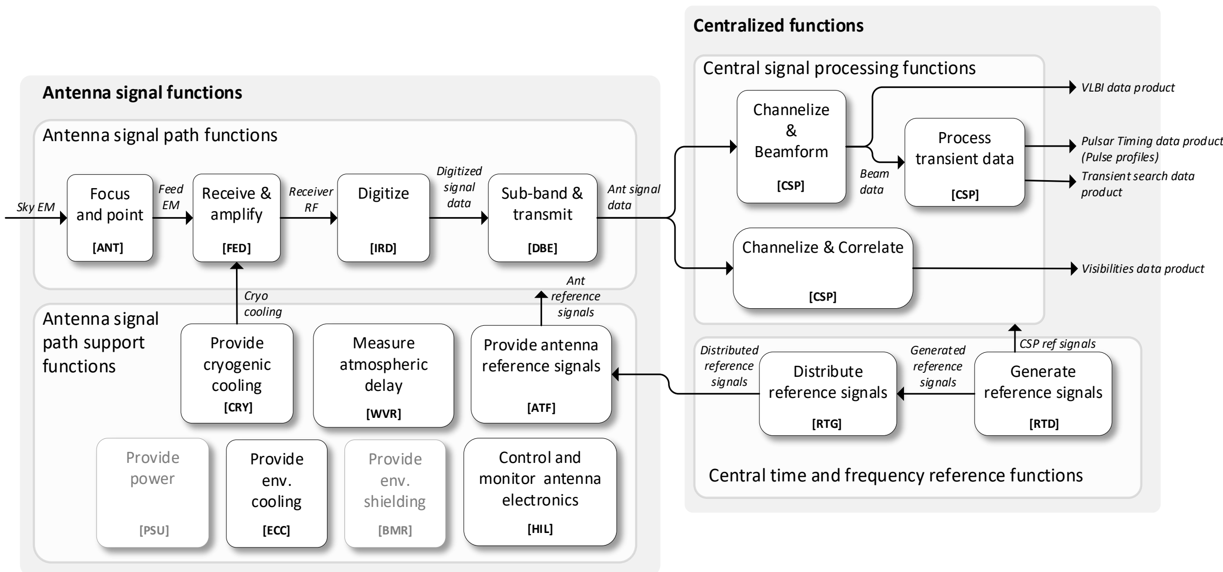

Figure 84: Signal path functions

5.2.2.1 *Antenna signal path: Focus and point*

The focus and point functions are implemented by the Antenna as shown in Figure 85.

A primary function of the Antenna is to focus the incoming electromagnetic signal onto the feed with a high efficiency. To achieve this, it needs to maintain an accurate reflective surface for primary and secondary reflectors and accurately position the feed on the focal point. The feed positioning function allows for selecting the band but also to adjust the focal position. The focal position can be adjusted either as a fixed position for the observation, or as a polynomial function of elevation pointing angle, which may be required for high frequency observations to maintain the specified efficiency.

Another primary function is to point the antenna. The antenna pointing model is configured and implemented external to the antenna (by the MCL software), so the pointing commands applied by the antenna are fully corrected and time tagged Azimuth and Elevation pointing polynomials. Thus, the pointing model corrections typically occur in the MCL subsystem – the details of the pointing model correction framework will be defined in detail as part of this subsystem. To apply these pointing commands correctly, the antenna needs an accurate absolute time reference which it receives through the general telescope network. The antenna may apply some pointing corrections using its own local metrology (e.g. tilt sensor to correct for slow varying tilt). The antenna reports time stamped encoder readings and metrology readings, which are used by the MCL subsystem to estimate achieved pointing positions.

Supporting functions include the management and reporting of states and modes, monitoring of antenna sensors, reporting warnings and alarms and managing the software and firmware versions.

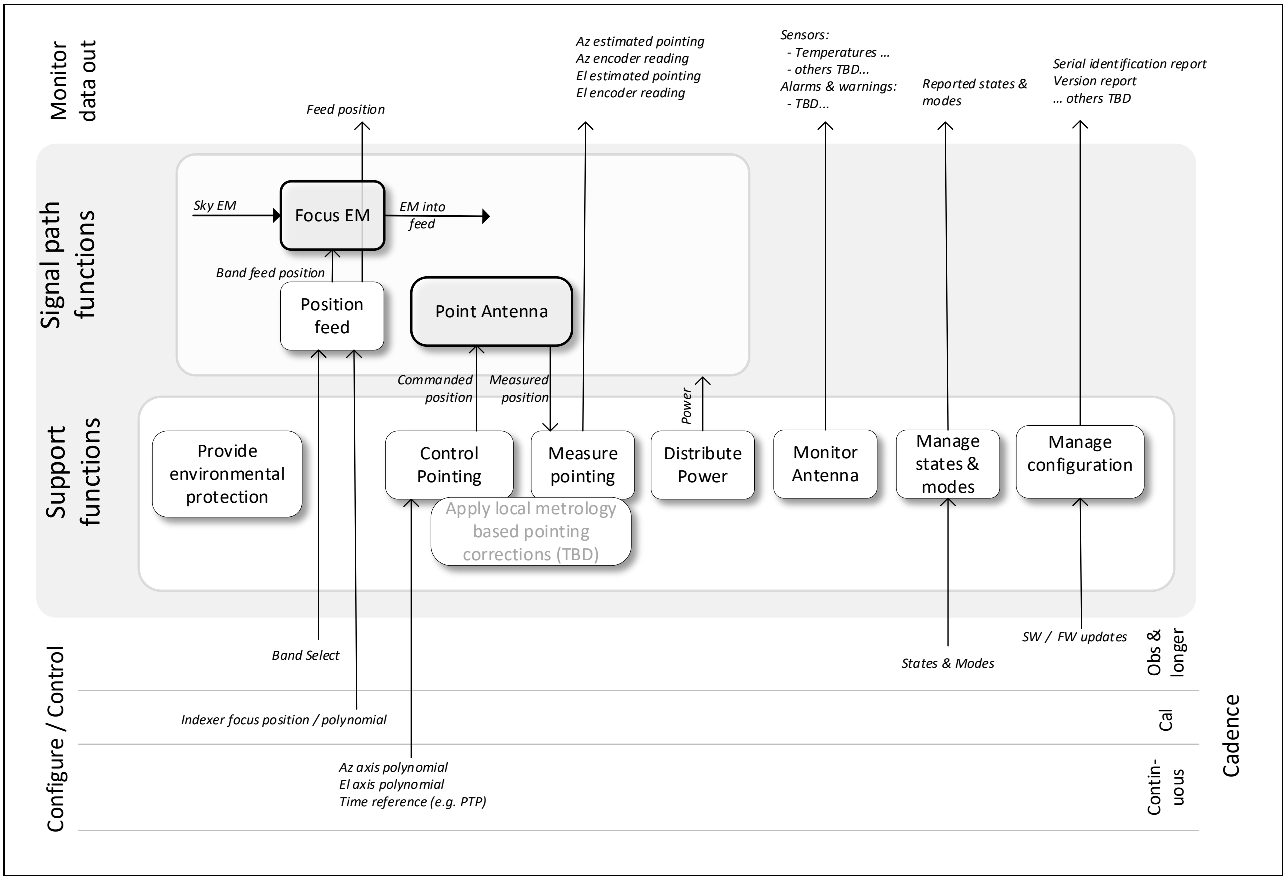

Figure 85: Focus and point functions

5.2.2.2 *Antenna signal path: Receive and amplify*

The functional flow diagram in Figure 86 shows the functions of the Front End (FED). The Front End receives the electromagnetic signals at the secondary focus of the antenna. This subsystem has six dual linearly-polarized receiver bands that each feature a feed horn to receive the signal. Two orthogonal linearly polarized outputs are produced by each receiver.

Calibrated noise is injected in the signal path to support calibration during observation. The calibration noise diode is temperature controlled by the FED internally to achieve the required calibration accuracy and stability. The noise level and switching waveform are configured via the MCL interface.

The received signal is amplified by cryogenically cooled low-noise amplifier (LNA) per polarization, with LNA bias levels configurable via the MCL interface. No down-conversion is performed by the FED. The amplified signal is transmitted to the digitizer module over short RF connections.

Sensor data is continuously collected and reported to the MCL subsystem. This includes bias levels for all bands. It also includes temperatures for the two cooling stages on each receiver, as well as a number of sensors within the two cryostats.

The FED also supports higher level functions to report alerts and warnings and to remotely update firmware/software configurations.

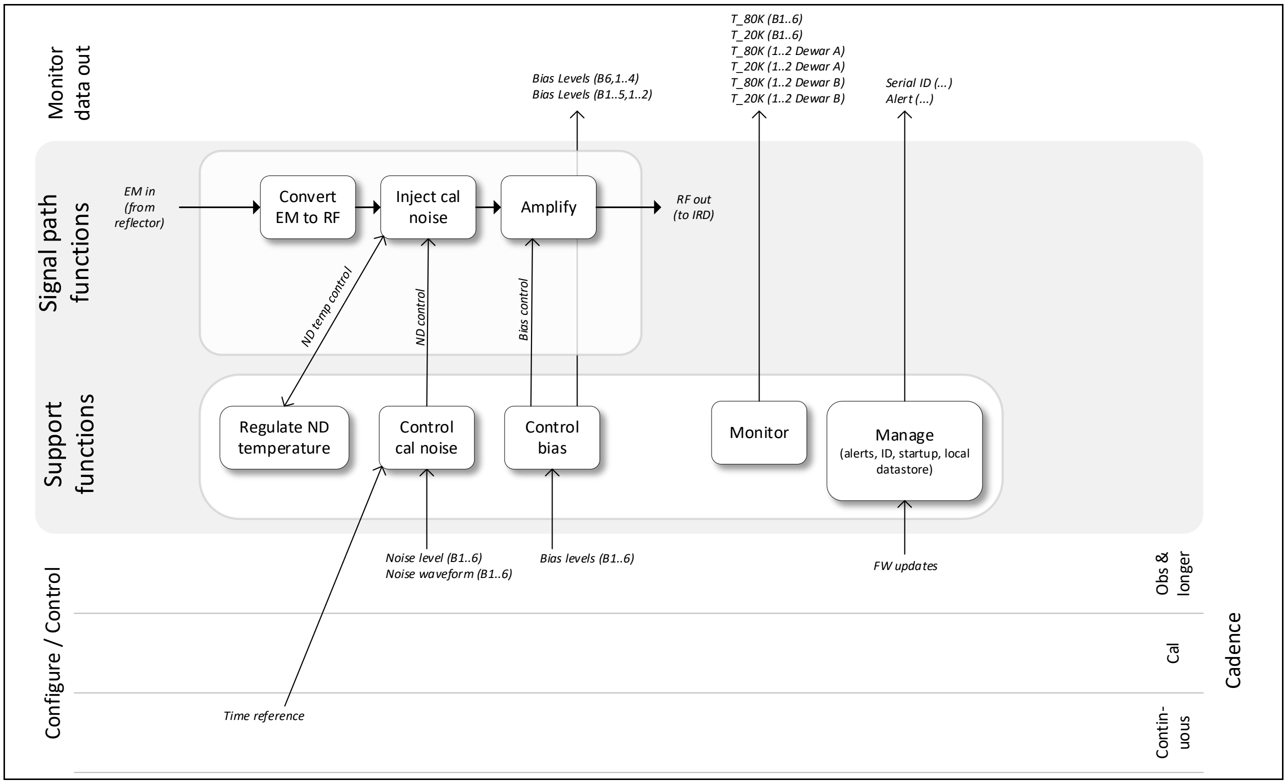

Figure 86: Receive and amplify functions

5.2.2.3 *Antenna signal path: Digitize*

The IRD is physically located at the secondary focus of the antenna, close to the FED and performs the down-conversion and digitization functions as shown in Figure 87.

A RF power measurement is performed on the incoming signal from the FED to help with fault finding in the signal path (to identify failed components or connectors up-stream from the IRD).

The RF signals are next filtered to eliminate out of band interference.

The signals require a further stage of amplification to achieve the power level required by the sampler, to activate the required number of sampling levels in the ADC. The amplification level is adjusted for each observation by an adjustable attenuator, which is configured via the MCL subsystem.

For Band 1, the signal is then directly sampled. For all other bands, the signal is first down-converted by a dual sideband down-conversion stage, with LO received externally from the antenna time and frequency reference system (ATF). The dual sideband down-converted channels are then sampled using the clock reference that is also provided by the ATF. The power levels of the IF signals going into the sampler are measured and reported to the MCL subsystem to monitor the sampled signal levels.

After sampling, the digitized signals are serialized and transmitted to the DBE (for time stamping and sub-banding), which is located in the pedestal of the antenna.

Besides the signal path functions, the IRD also performs management functions including mode control, firmware updates and the reporting of versioning, sensors, alerts and errors.

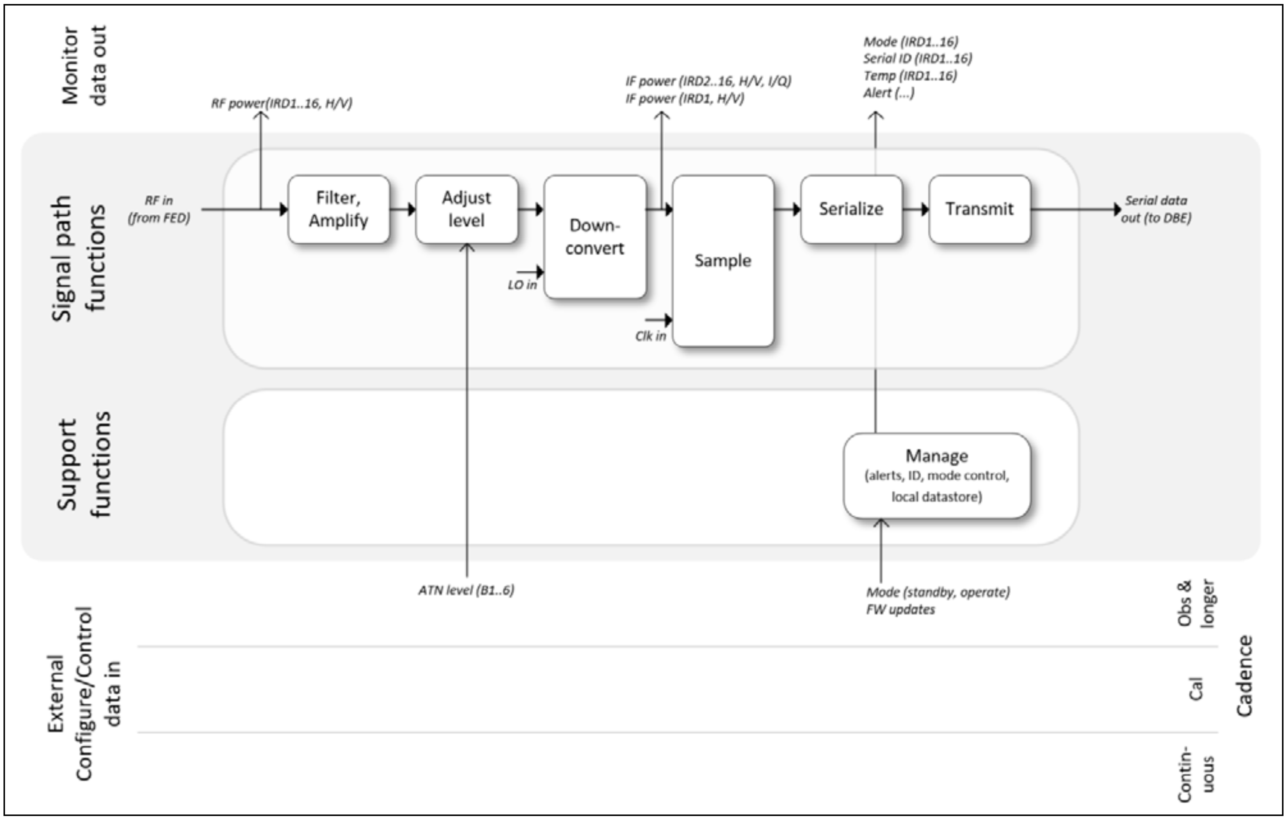

Figure 87: Digitize function

5.2.2.4 Antenna signal path: Sub-band and transmit (DBE)

This function is performed by the DBE. The details are shown in Figure 88.

The first function is to correct leakage between the sidebands that is a result of imperfections in the analog down-conversion process in the IRD. The DBE performs a digital sideband separation operation on the incoming signal to correct for this leakage. The details of the design and rationale for the method are described in the DBE design document. The coefficients for the sideband separation correction are stored on the DBE, but are configurable via the MCL subsystem.

At the same time, the DBE also applies a bandpass gain equalization correction, with coefficients received from calibration tables via MCL subsystem.

The DBE performs a frequency shift operation to (a) coarsely remove the per-antenna LO offset and (b) tune the sub-band's frequency range to align across antennas to minimize correlation losses.

The DBE then breaks up the signal into 32 sub-bands of 218.75 MHz. The sub-band bandwidth has been chosen so that the central signal processing nodes can efficiently process the sub-bands.

The sub-bands are then requantized before transmission to reduce the transmission data rates between antennas and the central signal processor. The standard quantization resolution is 8 bits, but a 16-bit resolution can be configured if needed, and if the transmission bandwidth is available.

The data is then timestamped and packaged for transmission to the central processing facility. The sub-bands to be transmitted can be configured via the MCL interface.

The support functions include: the generation of a local DBE time reference, with input from the antenna time reference; monitoring of signal power levels and RFI detection as input to the data quality monitoring; managing the device modes and configurations; reporting of sensors, alerts and warnings.

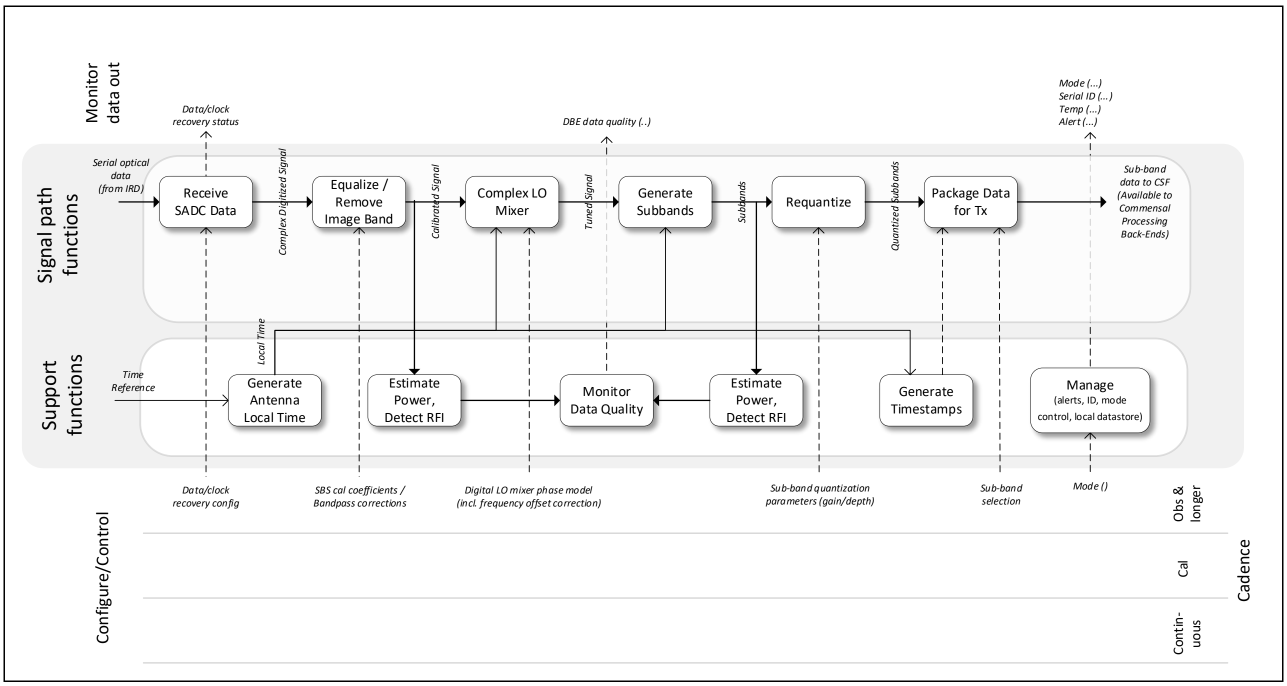

Figure 88: Sub-band and transmit functions

The data sent from the DBE to the central processing facility is sent to a large central data switch for routing of the data from the DBE to the Subband Processors (SBPs) and between SBPs.

Data for a pair of sub-bands (or a single sub-band in high resolution mode) for all antennas in a sub-array are sent to an SBP to perform the next stage of signal processing. The processing that is performed on each sub-band depends on the observing mode. In the correlator (interferometric) modes, the SBPs perform channelization and correlation as described in Section 5.2.2.5. In the beamforming modes, the SBPs perform channelization and beamforming as described in Section 5.2.2.6. In transient processing modes, the SBPs use the beam formed data and perform the transient processing functions, either in pulsar monitoring or in transient search mode. The pulsar search function is described in Section 5.2.2.7.

5.2.2.5 Central signal path: Channelize and Correlate

In the interferometric mode, the SBPs first performs a coarse time delay correction to the antenna data streams for the bulk of the antenna delays so that the signals from different antennas are time-aligned at the correlator input. This also accounts for any variable network delay compensation.

The delay model is received via the MCL subsystem at calibration intervals. The SBP splits the delay into coarse and fine delay and phase correction which are applied at different processing stages.

The antenna signal is then resampled to a common, central reference time scale. The fine delay correction is applied during this process. This resampling process also compensates for any differences in sampling clocks at the various antenna sites (intentionally or unintentionally inserted, if known).

Next, a time-variable phase correction is applied from the delay model for fringe stopping.

Fine channelization is then applied to break the sub-band bandwidth into narrow frequency channels. Alternatively, spectral zooming is applied, which involves a digital down conversion and decimation process prior to the frequency channelization.

The resulting data streams are then re-quantized to reduce data rates, packetized and transmitted internally across the SBP computing nodes for cross-correlation.

The correlator then performs a complex multiply-and-accumulate operation on a baseline pair basis according to the desired time resolution. Channel averaging may be carried out as well at the correlator. System requirements call for accumulation times between 5 s and 100 ms, with a goal of reaching 1 ms.

Finally, the uncalibrated visibilities are sent to the CBE for further processing and archiving.

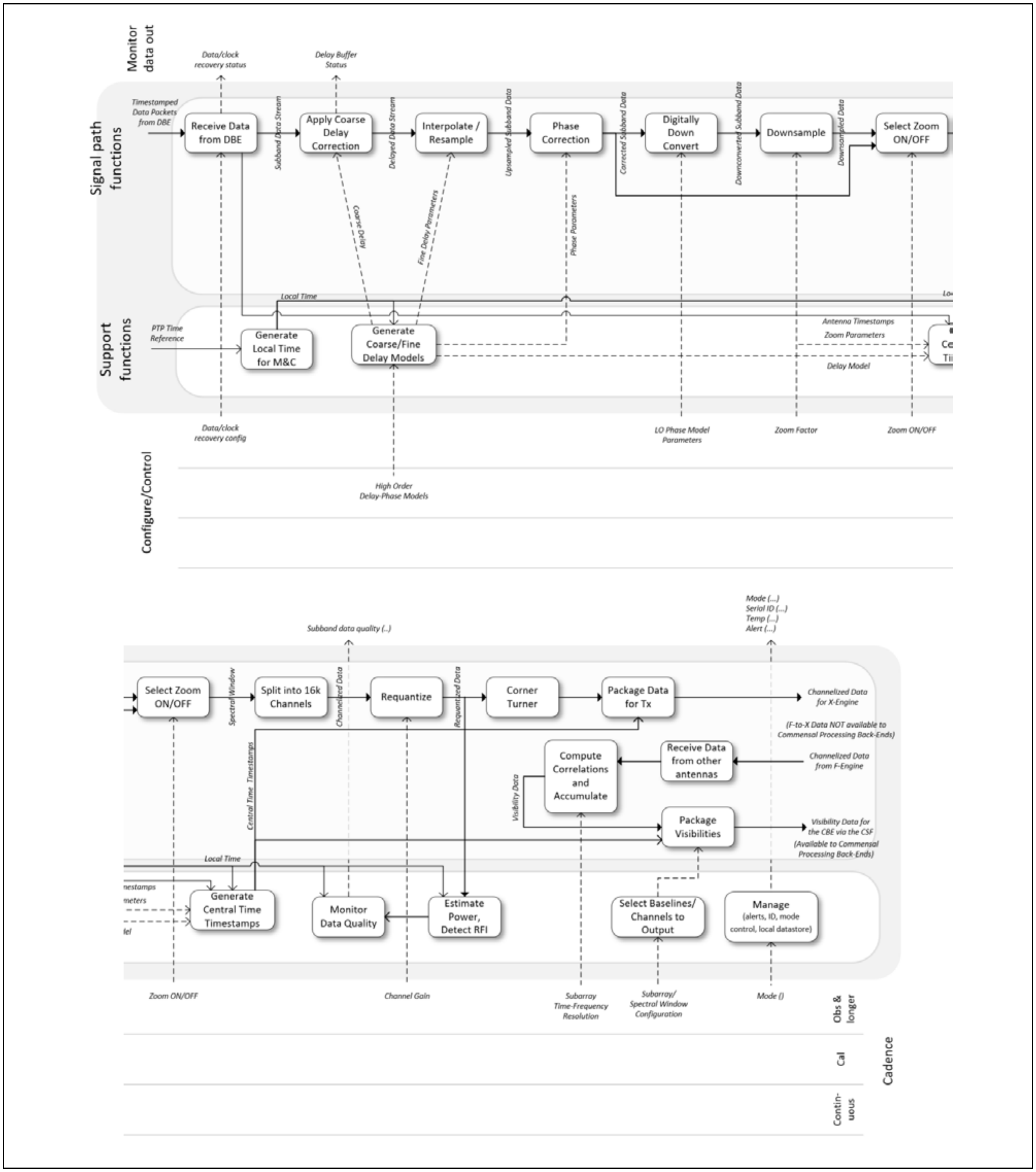

Figure 89: Channelize and Correlate function

5.2.2.6 Central signal path: Beamforming

In this mode, the SBP processes of delay correction, resampling, phase correction, channelization and re-quantization are applied in a similarly way as described in the previous section. But instead of cross-correlating, the frequency channels from the antennas composing a subarray are linearly combined to form up to 10 beams. The per antenna complex coefficients for the beamforming are received via the MCL subsystem. To meet ngVLA beamforming efficiency requirements, True Time Delay (TTD) beamforming is required. Polarization correction functionality is provided to correct for polarization before combining the signals.

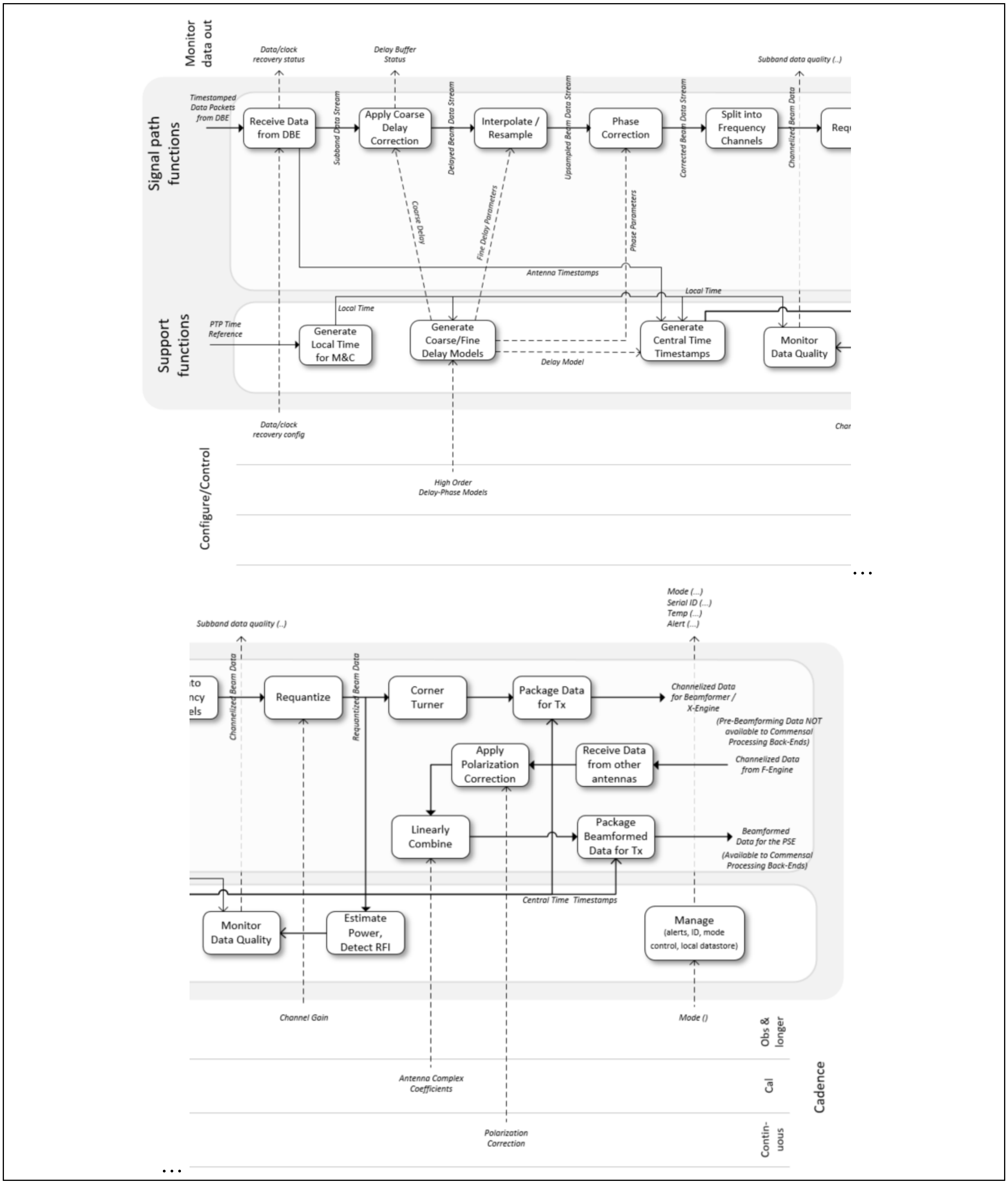

Figure 90: Beamforming function

The beam formed data is routed to either one of three further processing functions:

a) In VLBI operating mode, the beam formed data is sent to a VLBI data recorder to be stored in standard VLBI format.
b) In transient search operating mode, the beam formed data is sent to a PSE node for additional processing and finally recorded for offline processing, external to the ngVLA system. A custom backend could be connected eventually to process the transient search data online, but this is not currently in the scope of the ngVLA.
c) In Pulsar Timing operating mode, the beam formed data is sent to a PSE node to perform the pulsar timing function.

The functionality of the transient search and pulsar timing operating modes is similar and is defined in the next section.

5.2.2.7 Central signal path: Pulsar timing and Transient Search

After receiving the beamformed data streams from the SBP via the CSF, the PSE carries out coherent de-dispersion onto the data, with de-dispersion parameters as received via the MCL subsystem. This process may be preceded by a spectral re-channelization as needed. After de-dispersion, Stokes parameters are generated through detection. Next, data can be folded according to a timing model and then integrated (in Pulsar Timing mode), or simply accumulated in the absence of a timing model to reduce the output data rate as needed (in Transient Search mode). The accumulated data is finally packetized and sent to the CBE for further processing and archiving.

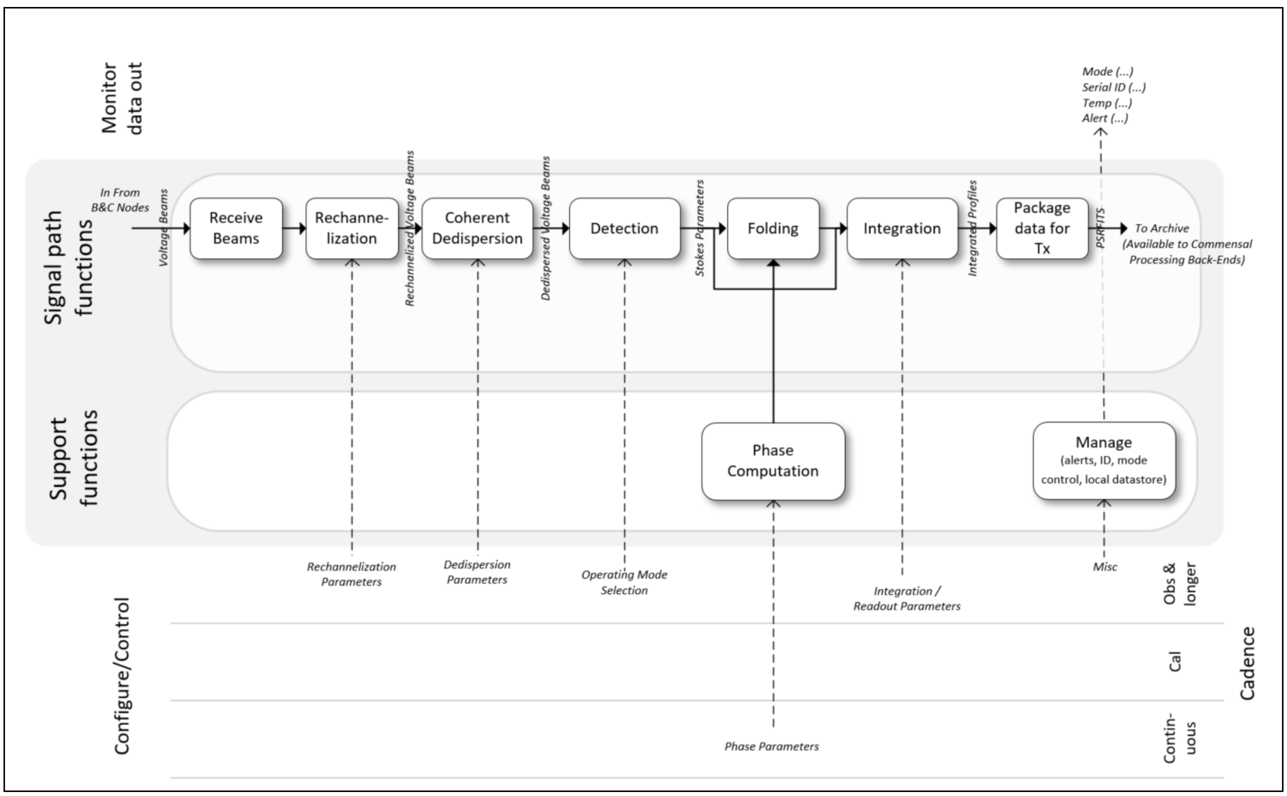

Figure 91: Transient processing functions

5.2.3 Signal Path Support Functions

5.2.3.1 Antenna signal path support: Provide cryogenic cooling

The core function of the cryogenic system is to provide cooling with sufficient heat lift capacity to the LNAs in the two cryostats (Cryostat A for Band 1 and Cryostat B for Bands 2-6). The main enabling functions are the supply of high-pressure helium to the two coolers and the supply of a vacuum for the two Cryostats.

The control functions supporting these three core functions are:

a) **Cooling control**: There is a high-level function to manage the cooling capacity of the system by controlling the speeds of both the cold heads and the compressor. The purpose of this variable speed control is to ensure that there is sufficient cooling capacity, while reducing the speed when less capacity is needed to reduce power consumption. To enable this control function, the Helium supply and return pressures are monitored and reported to the cooling management function. Temperatures of both cooling stages (80K and 20K) for both Cryostats and all six bands is measured in the Front-End system and reported to the cooling management function.

b) **Vacuum control**: In the steady operational state, the Cryostats generally maintain their vacuum through cryogenic cooling, which does not require vacuum pumping. The vacuum control is only needed occasionally, when the Cryostats lose their vacuum and it needs to be re-generated. If a re-generation of vacuum is required, there are controls to heat the coolers (to release frozen gasses), control the vacuum valves and activate the vacuum pump until the pressure in the Cryostats is sufficiently low for the cryogenic cooling to be turned back on.

The monitoring of the cooling control, cold heads, helium system and vacuum system are shown in Figure 92. The various sensor data is streamed via the MCL subsystem for remote monitoring and storage.

The monitor and control functions are implemented on various controller platforms across the antenna. An indication of where the controllers for the different functions will be located is shown in Figure 92. This allocation will be refined during the preliminary design phase by identifying specific controller parts for these functions.

The function for overall management of the cryogenic system includes the control of states and modes, management of system configuration and the reporting of overall cryogenic system states, alerts and warnings.

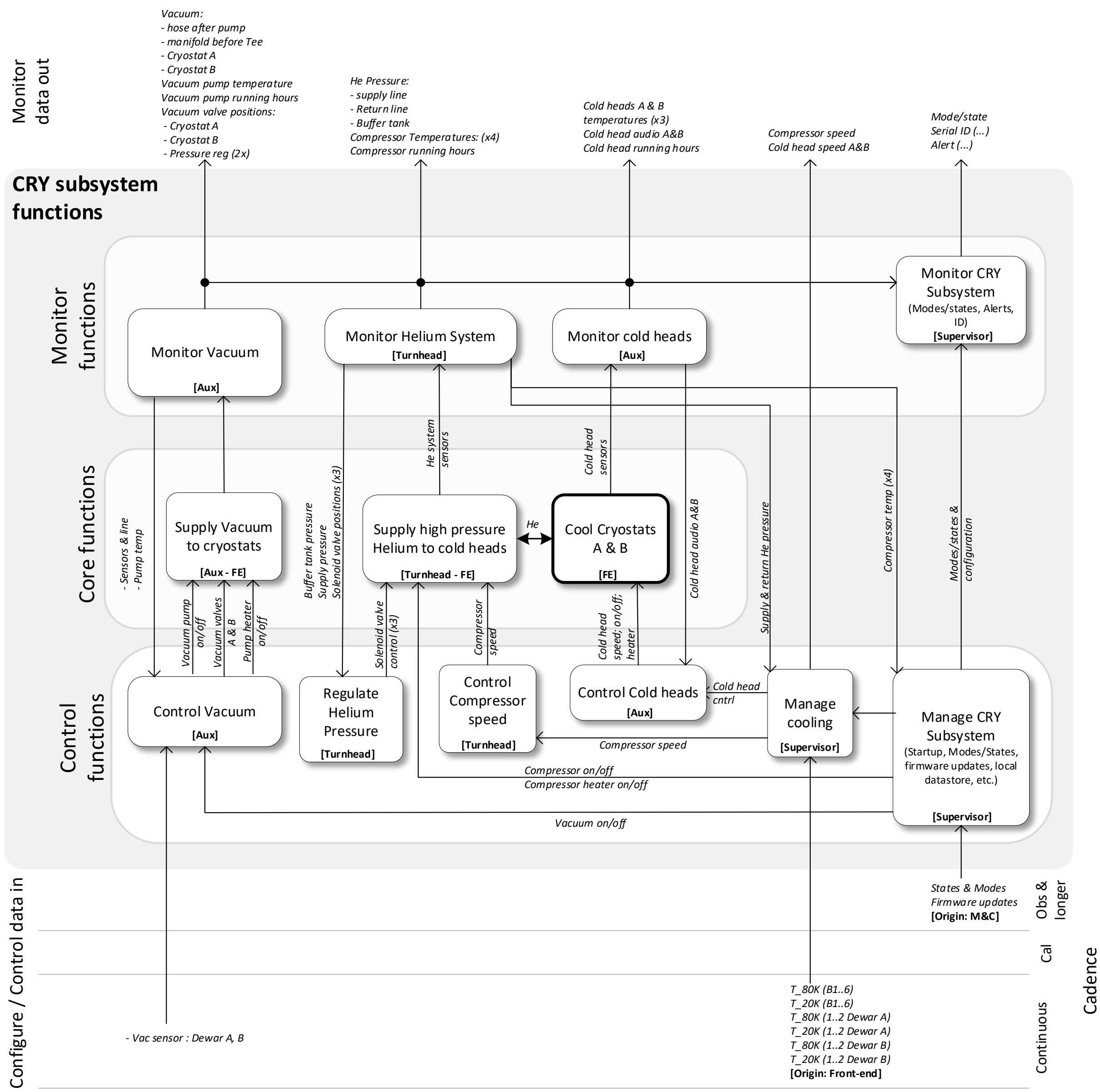

Figure 92: Cryogenic cooling function

5.2.3.2 *Antenna signal path support: Measure atmospheric delay*

The overall purpose of this function is to estimate the variations in the atmospheric delay of the incoming electromagnetic signal on timescales shorter than the normal array calibration cycle. This function is implemented by a Water Vapor Radiometer (WVR), which is an independent total power telescope which has its own dedicated receive antenna, receiver chain and digital signal processing system. The high-level functions of the WVR are shown in Figure 93 below.

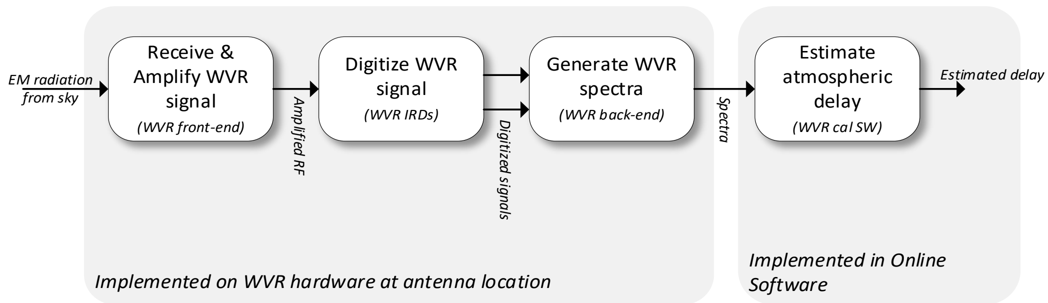

Figure 93: WVR functions overview

Receive & amplify WVR signal: The WVR antennas and receivers are mounted on each main array antenna and on its own pedestal for the SBA. The functions of the WVR receiver are summarized in Figure 94. One of the main challenges of the WVR is to maintain a very stable gain in the receiver. This requires tight thermal control and supply voltage regulation. A switched waveform calibration noise is injected in the signal path ahead of the low noise amplifier to enable accurate calibration of the total power levels. The supporting functions include the heating of the feed to remove condensation on the radome; supply a regulated source of power; provide regulation of temperature; provide local frequency references; monitor the front end and manage the overall modes, states and configuration of the WVR.

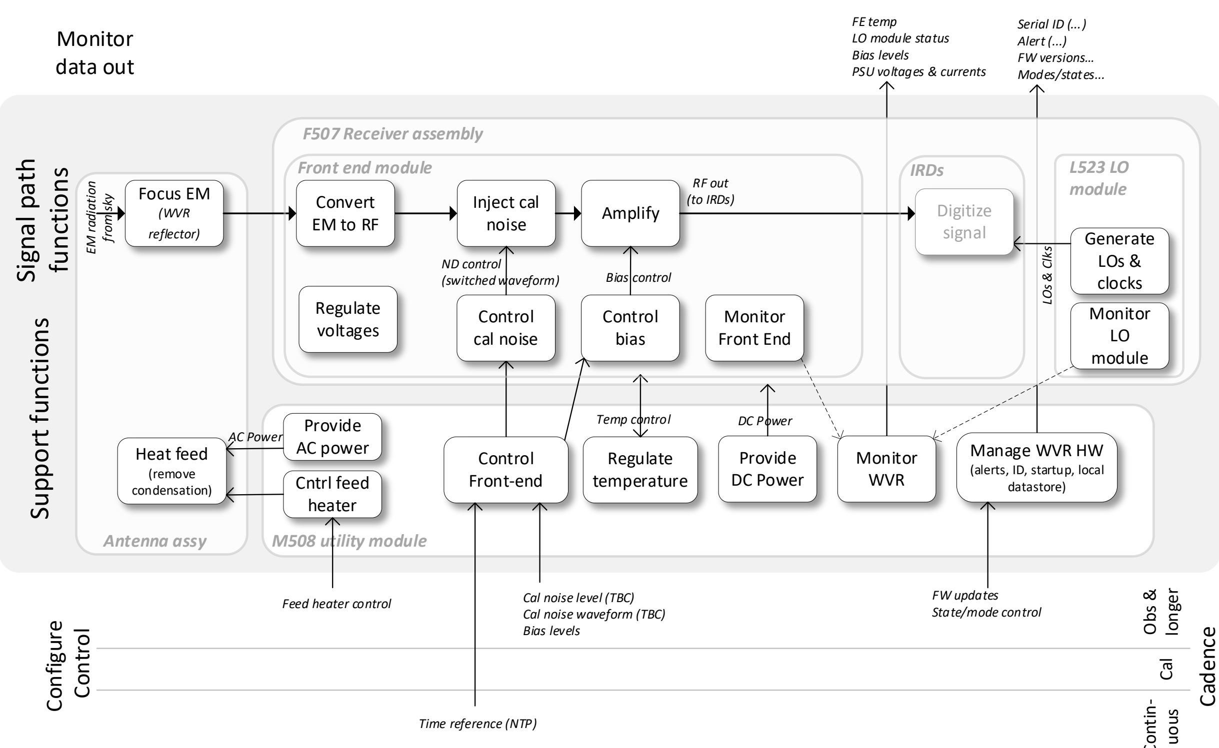

Figure 94: Receive and amplify WVR signal functions

Digitize WVR signal: The amplified signal is sent to two IRD modules to sample the two frequency bands (19.7 – 25.5 GHz and 25.2 – 31 GHz). The functionality of these two modules is very similar to the main system IRD modules as defined in Section 5.2.2.3 and is not repeated in this section.

Generate WVR spectra: The digitized signals from the two IRDs is sent to the WVR digital back-end to generate the spectra. These functions are similar to the DBE functions as defined in Section 5.2.2.4, but are modified slightly for the purpose of the WVR as shown in Figure 95. Sideband separation is performed to compensate for imperfections in the digitizer, while at the same time it also applies equalization to correct for bandpass gain. The signal is then channelized into 100MHz bands, in which the total power is integrated and time-sampled. The total power sampling of the spectrum is synchronized with the on/off cycles of the injected calibration noise. The sampled total power spectra are then packaged for transmission to the offline processing system where the estimation of atmospheric delay is performed.

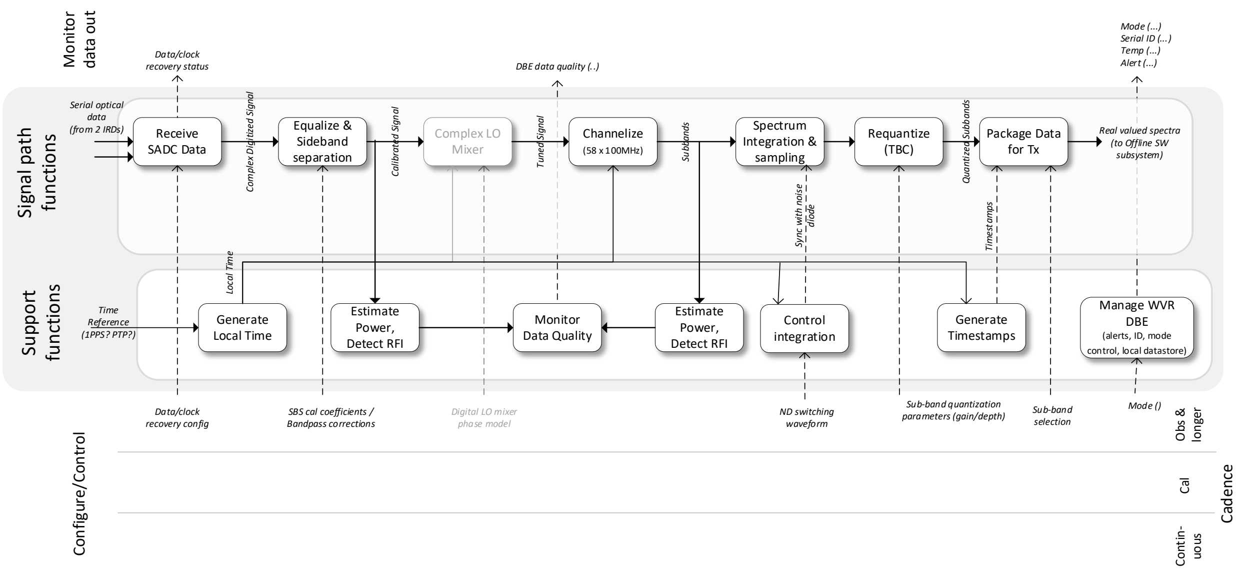

Figure 95: Generate WVR spectra functions

5.2.3.3 Central signal path support: Reference signal generation

The RTG uses a GNSS receiver and a Hydrogen maser as primary sources to generate an accurate local System clock domain (time reference) and stable frequency reference source. These are used as primary source to generate the various time and frequency references for all the antennas and central processing equipment:

a) Coded timescale for various system components to be distributed on the general telescope network. The implementation to be used is Precision Time Protocol (PTP).
b) Fixed frequency source and System clock domain reference (Pulse Per Second - PPS) for the CSP, where they are used for system synchronization.
c) Stable frequency reference to be distributed to antennas via the RTD and ATF systems for local oscillators and sampling clocks on the antennas.

d) System clock domain reference in the form of PPS for distribution to all antennas for data time stamping at the antennas.

To achieve the absolute time accuracy requirements for Pulsar Timing, it is required to track and measure the offset of the System clock domain in relation to the global clock domain. The tracked offsets are then applied retrospectively to the pulsar timing data. The current concept is to track and report the System clock domain offset and not to actively steer it.

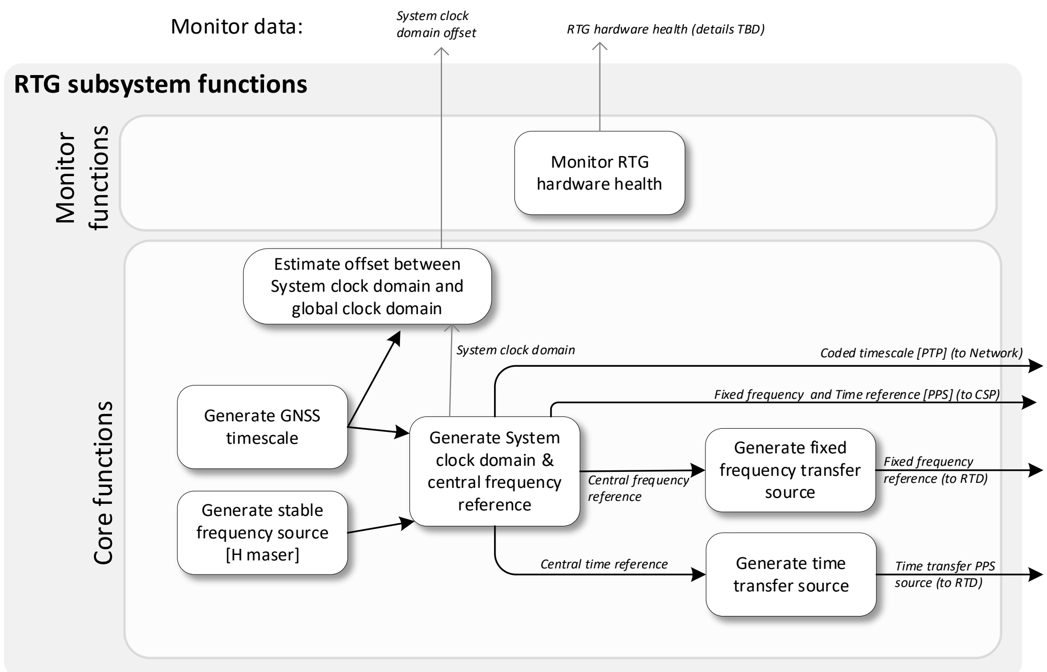

Figure 96: Reference signal generation functions

5.2.3.4 *Central signal path support: Reference signal distribution*

The RTD distributes the centrally generated time and frequency references to all fiber-connected antennas. "Connected antennas" excludes the LB antennas and antennas that are not directly connected by fiber. The number of connected antennas is designated with (N) in Figure 97.

The RTD performs the following functions for distributing the frequency reference:

a) Transmit a fixed frequency reference to all connected antennas.
b) Amplify the signal along the propagation path as needed, depending on the length of the fiber connection. The amplification equipment will be housed in repeater huts and antennas along the way.
c) Receive the frequency reference in the pedestal of the antenna and distribute it to the ATF at the secondary focus.
d) Measure the round-trip phase from the central reference signal distribution point to the Antenna Pedestal and report the time stamped round-trip phase to the MCL subsystem. This is used to compensate for instrumental delay/phase drift between array calibration intervals.

The RTD performs the following functions for time distribution to connected antennas:

a) Transmits a fixed frequency reference to all connected antennas.
b) Measures the round-trip phase difference between the transmitted fixed frequency reference and its reflection from the ATF located in the secondary focus of all connected antennas.
c) Transmits the System domain clock in the form of a PPS signal on the fibers to all connected antennas.
d) Amplifies the PPS signal along the propagation path as needed, depending on the length of the fiber connection. The amplification equipment will be housed in repeater huts and antennas along the way.
e) Receives the PPS signal at the antenna pedestal and reflects it back through the propagation path to the central location.
f) Measures and reports the round-trip time delay between the central distribution point and pedestal for all connected antennas.
g) Generates an estimated (proxy) System domain clock PPS at the antenna by adjusting the Antenna received PPS with the measured round-trip time delay.
h) Generates an Antenna domain clock. The Antenna domain clock is a PPS that is synthesized as an integer multiple of the sampling clock intervals. It is aligned with the RTD PPS at the "Re-synch epoch" which is coordinated across the array at intervals TBD.
i) Measures and reports the difference between the proxy System domain clock and the Antenna domain clock.
j) Synchronizes the Antenna domain clock with the proxy System domain clock on command of the MCL subsystem.
k) Provides a PTP functionality to the Antenna subsystems. Note that FIB supplies the infrastructure (fiber network and switches), while RTD specifies and configures the network.

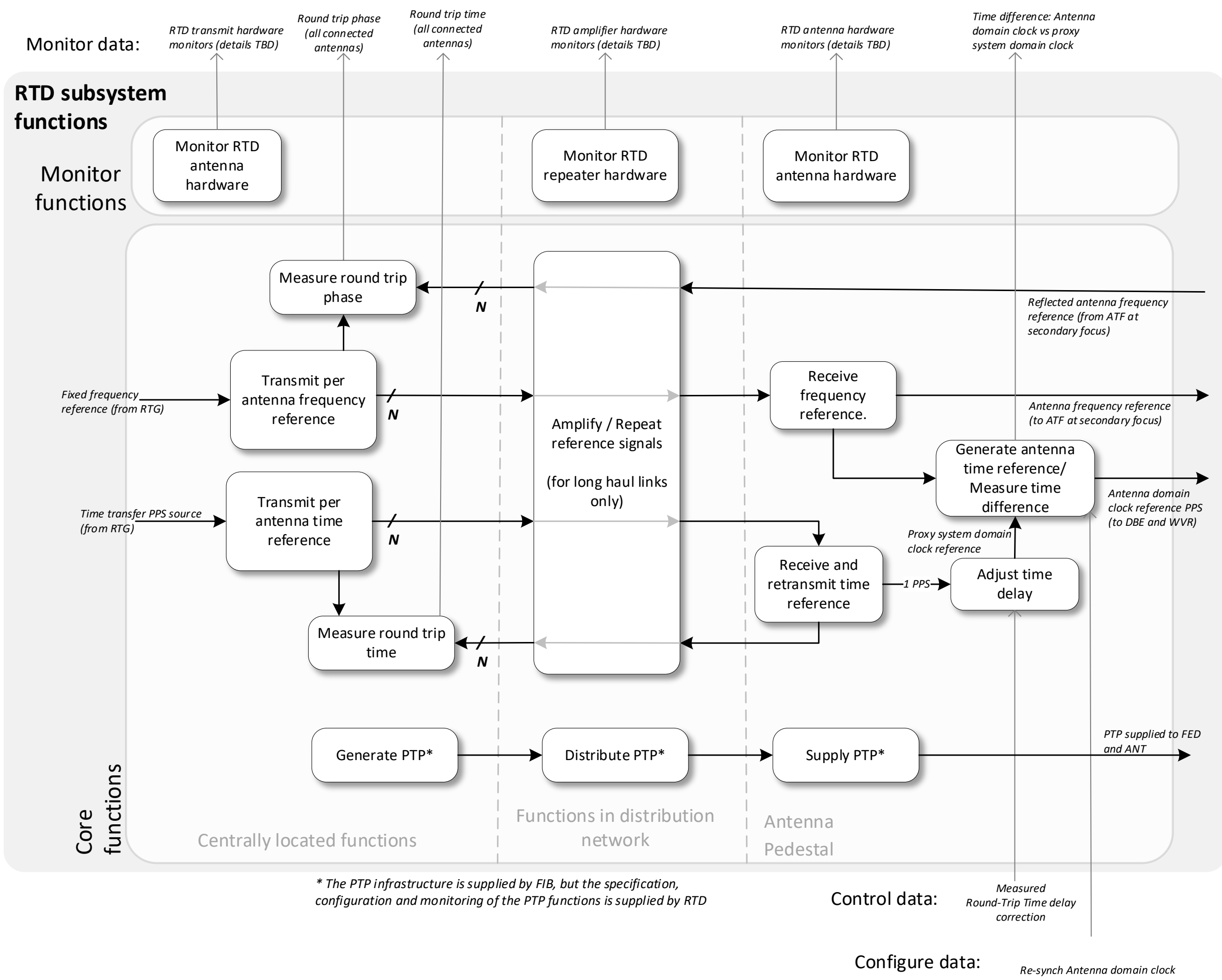

Figure 97: Reference signal distribution functions

Note that the Antenna control unit needs a time reference for pointing control, that is accurate to within a few µs from the central System domain clock. This is implemented through the provision of a PTP time code transmitted over the general telescope network. The same time reference is used by the Front End controller for controlling the noise diode. This time reference distribution function is not provided by the RTD but by the FIB subsystem.

5.2.3.5 Antenna signal path support: Provide antenna reference signals

This function is implemented by the Antenna Time and Frequency (ATF) Subsystem. An overview of the functionality is shown in Figure 98:

a) The ATF receives the frequency reference at the secondary focus on a fiber (it is transmitted by the RTD in the pedestal) and reflects it back to RTD for the purpose of round-trip phase measurement.
b) The ATF offsets the frequency reference with a unique value that is set on a per antenna basis.

c) The offset frequency reference is used to generate sampling clocks for the digitizers in the IRDs for all frequency bands and for the WVR digitizer.
d) The offset frequency reference is also used to generate the down-conversion LOs for the IRDs (Bands 2-6) and the WVR receiver.
e) The Antenna domain clock is transmitted to the DBE where it is used for time stamping the astronomical signal data.

ATF Control functions include the selection of currently operating frequency band. Monitoring functions include sensor reporting, health monitoring, configuration and version identification. Specific sensors that are reported on the LO modules are shown in Figure 98. The ATF supports the remote update of firmware.

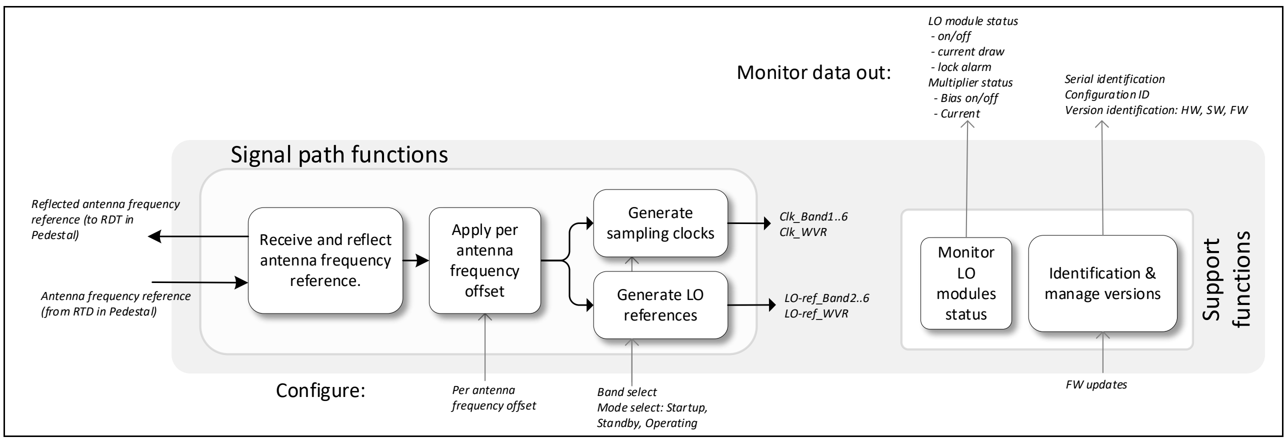

Figure 98: Antenna time and frequency reference function

5.2.4 Software Functions: Proposal Management and Observation Preparation

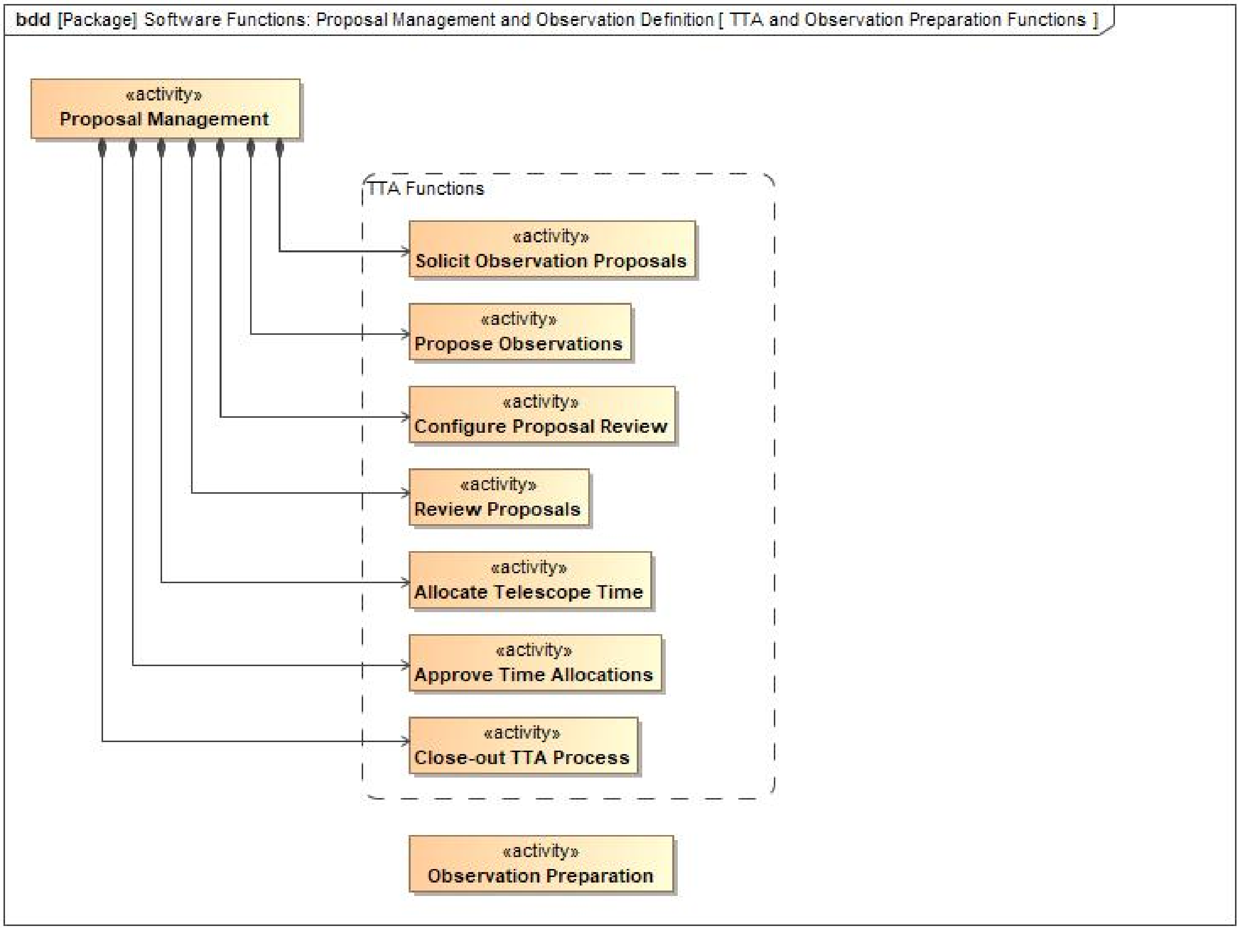

Figure 99: Proposal management and observation preparation activities.

(a) **Allocate Telescope Time**: The information produced by various review processes is used to allocate telescope time in Time Allocation Committee meetings or Observatory Site Committee meetings or External Committee meetings. Allocation Disposition entities model awards and include technical information related to facility resources as well as comments from review groups. Allocation Disposition entities are associated with Allocation Request entities.

(b) **Approve Time Allocations**: After committees make allocation recommendations, Directors (or their delegate) finalize allocation decisions which are expressed in reports.

(c) **Close-out TTA Process**: The Closeout package includes place-holder concepts related to the final steps of the TTA process. These concepts will be further refined in subsequent phases.

(d) **Configure Proposal Review**: NRAO primarily conducts two types of review processes, Panel Proposal Reviews and Observatory Site Reviews. The Panel Proposal Review consists of Feasibility Reviews, Individual Science Reviews and Consensus Reviews. Feasibility and Individual Science

Reviews require panels to be created and maintained throughout the review process while adhering to rules governing the relationships between reviewers, panels, and review materials.

(e) **Observation Preparation**: The TTAT system creates Observation Specification structures, which are a telescope-agnostic representation of an observation. These structures are transformed into telescope-specific Scheduling Blocks, which can be executed on the telescope to perform an observation. Interfaces are provided to modify Scheduling Blocks, create them manually, and support triggered observations. Manual creation of Scheduling Blocks is necessary to support AIV and CSV activities.

(f) **Proposal Management**: Root activity for proposal management activities. See its sub-activities for details.

(g) **Propose Observations**: Telescope users create proposals describing how and why they want to use facility resources.

(h) **Review Proposals**: NRAO primarily conducts two types of review processes, Panel Proposal Reviews and Observatory Site Reviews. The Panel Proposal Review consists of Feasibility Reviews, Individual Science Reviews and Consensus Reviews; information from the Feasibility and Individual Science Reviews is used in the Consensus Review to quantitatively rank proposals. The ranking is expressed in the Proposal Review entity. For Observatory Site Reviews, TTA Group Members generate Proposal Reviews with qualitative scores.

(i) **Solicit Observation Proposals**: Telescope users submit proposals to access AUI NA telescopes in the context of solicitations. Solicitations define the resources available to proposers and the time period over which approved proposals execute.

5.2.5 Software Functions: Operational Observation User Interfaces

(a) **Observation Quality Assurance**: The system provides interfaces for the Science Staff and Operator to assess the quality of the observation while the observation is being executed (QA0). Typically, this interface integrates monitoring data and calibration results (e.g. plots for the phase RMS, pointing/focus offsets, WVR, etc.)

(b) **Observation Scheduling**: The array operator uses the scheduling tool to decide how to partition the array in subarrays, and which scheduling blocks are executed in each subarray. The scheduling tool can be executed in several modes: fully automatic, advisory (where the tool asks the operator to confirm the schedule), or manual. When executing in automatic or advisory mode, the scheduling tool is prompted to create a new schedule upon the reception of several events: the completion of a previous schedule, changes in weather conditions, the reception of a triggered observation request, or a manual request by the operator.

(c) **Operator Shift Logging**: The occurrence of several events that happen during operations are logged automatically by the system or manually by the operator. Examples are the creation/destruction of a sub-array, the start/end of an observation execution, and calibration results from TelCal. The system provides an application that automatically annotates such events, and allows the array operator to annotate other relevant information.

(d) **Operator Supervisory Control**: A graphical user interface allows the operator to visualize the status of the array systems, and perform troubleshooting and recovery operations.

The system provides summary views of large collections of equipment, such as the antennas or the CSP, from where the operator can "zoom-in" into detailed views of specific LRUs.

An Alarm view informs the Operator of abnormal conditions. The system incorporates logic for analyzing the root cause of failures, to avoid overwhelming the Operator with large numbers of derived or secondary alarms. The interface allows the Operator to acknowledge and confirm alarms, following standard alarm management practices. ("Acknowledge" is used by the operator to notify reception of the alarm and that he/she has started looking into the problem. "Confirm" is used to notify when a corrective action has been taken and the system is returning to the normal condition.)

5.2.6 Software Functions: Observatory User Interfaces

(a) **Data Product Analysis and Visualization**: This activity represents the provision of services and tools to visualize data products.

(b) **Data Product Delivery**: This function refers to the capability of retrieving the metadata and binary files of data products from the Science Archive.

(c) **Data Product Discovery**: This function encompasses the capability of interacting with the Archive to search its contents, visualize results, save queries or results, and select data products for later use.

(d) **Data Product On-demand Post-processing**: Once one or more data products have been selected using the Archive interfaces, they can be used as inputs in data processing pipelines. The system allows the customization of the execution parameters.

(e) **PI Project Tracking**: This function refers to the provision of interfaces for PIs to track the status of their accepted proposals. This includes the capability of tracking the status of scheduled observations and quality assurance processes for the raw and derived data products.

5.2.7 Software Functions: Control

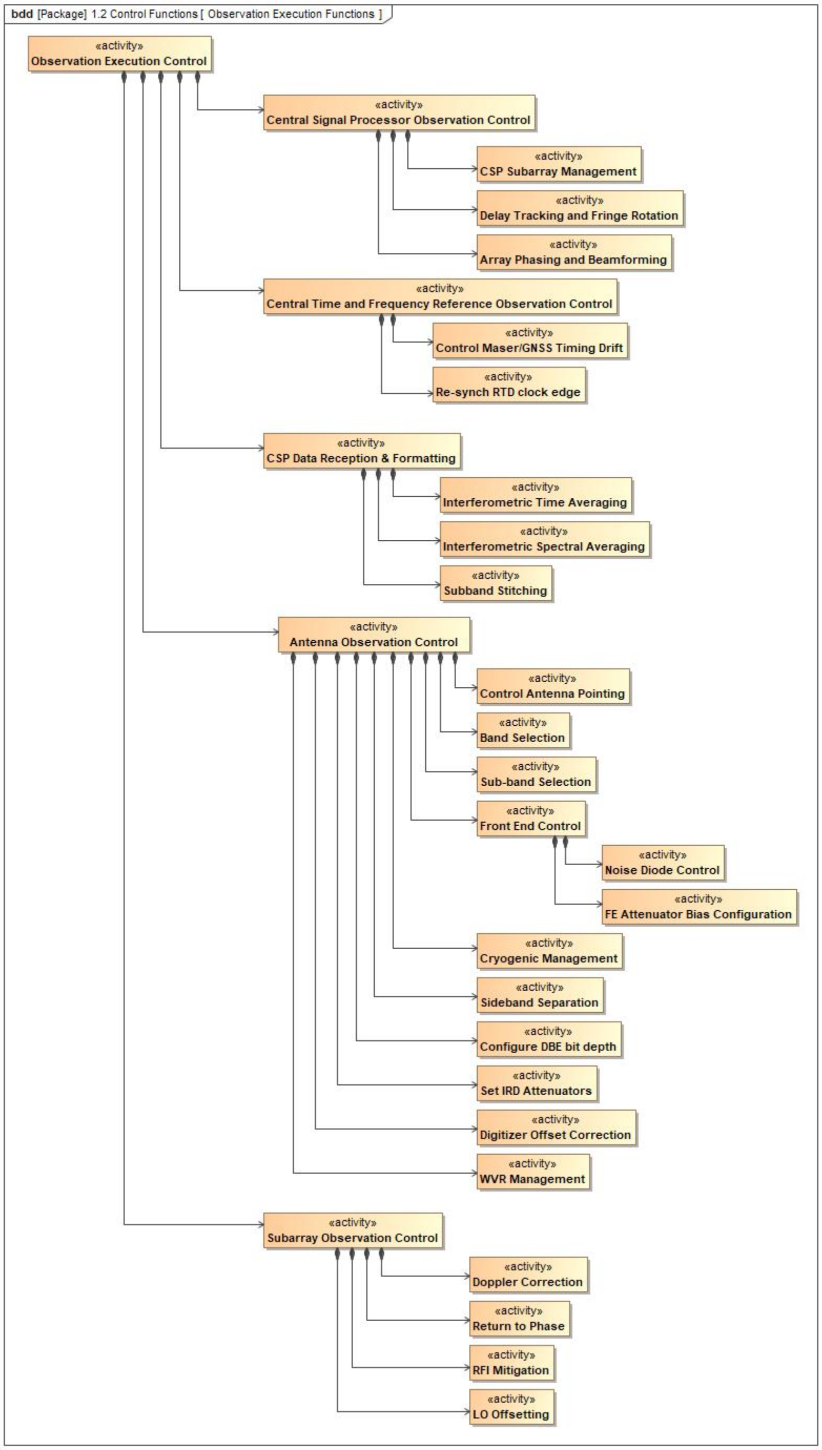

Figure 100: Observation execution activities.

(a) **Antenna Observation Control**: Root activity for antenna control activities. See its sub-activities for details.

(b) **Array Phasing and Beamforming**: The CSP supervisor sends delay/phase corrections and beamforming coefficients to the CMC to phase the antenna voltage streams and support multiple beams.

(c) **Band Selection**: The band is selected by controlling the IRD input to be processed in the DBE.

It may be necessary to turn on/off the optical transmitters, avoiding sending the signals from the bands that are not being used to the DBE. Alternatively, the DBE inputs maybe multiplexed, instead of all of them being connected to the IRDs. The multiplexer would switch between bands 1-5 or band 6.

(d) **Central Signal Processor Observation Control**: The CSP Supervisory Control activity is responsible for the configuration of subarrays in the CSP and their operation in one of the following operating modes:

- Interferometric,
- Pulsar Timing,
- Transient Search, and
- VLBI

The CSP is divided in to the Subband Processor (SBP), the Pulsar Engine (PSE), the CSP Monitoring & Control (CMC), and the CSP Switched Fabric (CSF) that routes data products from each antenna to a corresponding SBP and CSP data products to the Data Reception and Analysis subsystem (within ONL). The supervisory activity commands the coordinated operation of these subelements through the CMC. Hardware resources allocated to SBP and PSE must be configured for each sub-array and scan execution during an observation. For Phased Array modes (Pulsar, Transient and VLBI) several beams are created by means of individual delay and phase models that are communicated to the CSP. The supervisory activity computes complex beamforming weights that the CSP applies to each beam after the delay and phase model that created those beams. The supervisory control also transmits the necessary information for Doppler correction, fringe tracking and LO offsetting.

(e) **Central Time and Frequency Reference Observation Control**: Activities related with controlling the timing synchronization and LO reference devices.

(f) **Configure DBE bit depth**: The DBE can support 2/4/6/8/12/16-bit quantization per sub-band. In practice, 8-bit is the default and 16-bit is available when the transmitted bandwidth is < 10 GHz (bands 1, 2, 3).

Lower bit-depth modes (2/4/6) may be used in subarrays that have limited network bandwidth (i.e., the long baseline stations).

(g) **Control Antenna Pointing**: The antenna pointing is controlled by sending a stream of positions to the Antenna Control Unit (ACU) in horizon coordinates (azimuth and elevation). The software translates equatorial or galactic coordinates into horizon coordinates. Ephemeris objects are supported as well.

The antenna pointing data are included in the observation metadata. The pointing data includes both the commanded coordinates and the coordinates where the antenna was actually pointed (read from the axis encoders).

(h) **Control Maser/GNSS Timing Drift**: The time difference between the Maser and the GNSS system is tracked as part of the MCL monitoring streams. A re-sync command is issued if necessary for this error to remain inside its defined boundaries.

(i) **Cryogenic Management**: Control and monitor the Front End cryostats. These may incorporate a power saving mode.

It is not necessary to actively control the internal feedback loops (variable frequency drives), although there are alarms and parameters that need to be supervised.

The cryostat vacuum system needs to be controlled, possibly in an automated way. If there are temperature oscillations, where the temperature increases momentarily, then it will be needed to trigger a pump-out. If the problem repeats, then a maintenance ticket should be submitted.

(j) **CSP Subarray Management**: The CSP supervisor creates and destroys subarrays in the CMC (CSP Monitor and Control) subsystem by means of its OPC UA interface. When a CSP subarray is created:

- the CMC allocates and configures resources in the SBP or PE subsystems,
- creates streaming nodes for receiving delay tracking polynomials, beamforming coefficients, and other calibration coefficients (e.g., Jones matrices),
- creates streaming nodes for the schedule of scans, setting the time boundaries for the sub-band data that the CSP transmits to ONL, and
- configures the data transmission to the ONL Data Reception & Analysis subsystem.

A library/API provided by the CMC allows the ONL system to keep track of the resources allocated so far in the CSP, and the resources needed to create additional subarrays. This library is used by the Scheduling subsystem.

(k) **Delay Tracking and Fringe Rotation**: The CSP supervisor sends delay polynomials to the CMC for delay tracking and fringe rotation compensation. Note that this activity intersects with the activities defined in the calibration section.

(l) **Digitizer Offset Correction**: The digitizer clock in the antennas is generated from the LO reference signal. However, as this signal includes an offset, the generated signal does not have the correct frequency and must be corrected in the antenna electronics.

(m) **Doppler Correction**: The system will implement Doppler setting (performing the Doppler frequency correction at the beginning of an observation), and not Doppler tracking (performing the Doppler shift dynamically during the observation).

(n) **FE Attenuator Bias Configuration**: Configuring the attenuators bias from values kept in the configuration database. These parameters don't need to be actively controlled.

(o) **Front End Control**: Front-end control activities.

(p) **Interferometric Spectral Averaging**: The CBE must average the spectral products of visibilities and autocorrelation by a configurable number of channels. The end result of this operation are spectral windows with a reduced spectral resolution, which can be used for online calibration (e.g. when phasing the array), without incurring the cost of using the full visibility data. TBC: there might be a need to average at different resolutions based on baseline parameters (e.g. length).

(q) **Interferometric Time Averaging**: The Data Reception & Analysis subsystem must time average CSP interferometric data products (visibilities and autocorrelations) during a configurable lapse of time. Normally, the lapse of time is expected to be an integer number of the integration used by the CSP to produce each result. TBC: there might be a requirement to average for different time durations based on some baseline parameters (e.g. length).

(r) **LO Offsetting**: To suppress spurious signals, fill the small (<1 MHz) gap in RF coverage around the LO frequency, suppress unwanted sideband power in interferometric modes, and other effects (such as frequency aliasing in the CSP frequency slicing), a distinct offset is introduced in the LO signal for each antenna and is removed before correlation in the CSP.

(s) **Noise Diode Control**: The noise diodes are turned on/off, and their gain and bias are adjusted. Adjusting the gain is necessary for solar mode. For solar observations the signal should remain proportional to the Tsys value, which is higher when pointed at the Sun.

(t) **Observation Execution Control**: Root activity for observation execution control activities. See its sub-activities for details.

(u) **Re-synch RTD clock edge**: TBD.

(v) **Return to Phase**: The system shall avoid introducing phase jumps in the signal path when switching frequencies during an observation (going from f1 to f2 and then returning to f2). All LO mixing operations performed in the signal path must be considered, in such a way that the phase returns to the value it would have had if the frequency would not have been switched. Returning to phase is necessary, for example, to jointly calibrate scans observed at different times without bracketing them with additional phase calibration scans. The system is designed to return to phase without software control.

(w) **RFI Mitigation**: RFI mitigation strategies that are presently deployed or under development for ngVLA may be aggregated into three categories:

- Avoidance: RFI avoidance strategies that adapt observing schedules to predictable and current RFI patterns.
- Detection and Flagging: Outlier detection algorithms that generate flags to mask RFI-affected data from further processing.
- Modeling and Subtraction: Algorithms that attempt to recover sky signals from beneath the RFI.

This function is implemented in different stages: at the antenna-based voltage streams in the DBE; before correlation in the CSP, after correlation in the CSP; in the CBE; and in the post-processing systems, depending on the required time resolution.

This function also requires the development of an RFI Database for expected sources and observed events and an RFI Manager component.

(x) **Set IRD Attenuators**: Control the IRD attenuators, from statistics retrieved from the DBE.

An alternative design incorporates total power detectors in the IRD, although it may be difficult to calibrate them properly.

(y) **Sideband Separation**: After LO mixing and sampling in the IRD module, the signal received from the sky is transformed into an IQ pair at baseband. In the DBE, the IQ pair is converted to USB/LSB and the sidebands are separated. The sideband separation process filters and combines the in-phase and quadrature components such that sideband rejection is maximized and the bandpass equalized. Subbands are then generated again as IQ signals which are transmitted from the antennas to the CSP. The software is required to store the set of sideband separation coefficients in the Configuration Database. The coefficients are IRD-dependent, so it is necessary to load the proper coefficients into the DBE depending on its selected IRD inputs.

(z) **Sub-band Selection**: Selection of the ~218 MHz sub-bands being processed by the DBE and transmitted to the CSP.

(aa) **Subarray Observation Control**: A Scheduling Block is executed on a subarray to perform an astronomical observation. An observation is divided in time intervals called scans, which have associated intents. The intent differentiates scans performed for the purpose of calibration from those performed over science targets.

(bb) **Subband Stitching**: Each spectral window is composed by one or more bandwidth slices processed as a subband in the CSP. As final science spectral windows may encompass several sub-bands, it may be necessary to concatenate them as a continuous array of spectral channels. The result of this operation is then formatted as a single spectral window data product in the archive data format.

(cc) **WVR Management**: This function is to configure the Water Vapor Radiometers for an observation and includes the control of the feed heater, the calibration noise level and waveform, and the bias level.

5.2.8 Software Functions: Monitor

(a) **Alarm/Error Handling**: This function refers to the detection and handling of system faults and errors.

(b) **System Logging**: This activity represents the collection of system logs for troubleshooting and support activities.

(c) **Telescope Monitoring**: This function refers to the acquisition, transmission, archival and use of monitoring data from the telescope hardware and software systems.

5.2.9 Software Functions: Signal Path Functions

(a) **Archive Ingestion**: As an observation proceeds, the ONL Data Reception & Analysis subsystem sends the raw data products to the Data Transport subsystem, part of TI. The Data Transport subsystem transmits the products to the Science Operations and Data Center. As the data arrives, it is ingested into the SDA.

Besides the data collected from single-dish and interferometric modes, pulsar timing/search data is ingested into the archive as well. Storing the data into disk-based VLBI data systems such as Mark 6, to be physically shipped to other observatories for offline correlation, is not currently a requirement, although spare capacity will be allocated in the CSP switch to allow the integration of the necessary equipment.

(b) **CSP Data Reception & Formatting**: Science data is received from the CSP, averaged and formatted to be transmitted to the archive subsystem. The final data products are a function of the observing mode:

- Interferometric visibilities (XRADIO format),
- Pulsar Timing Profiles in PSRFITS format,
- Transient Search data in PSRFITS format, and
- VLBI data recorded in VDIF format.

Phased Array data products are formatted by the CSP itself in the PSRFITS or VDIF data formats. For these observing modes the software just tags the data products with a unique identifier and gathers other meta-data needed to ingest the datasets into the archive.

(c) **Data Transport**: Activities related with transporting the raw science data from the Central Electronics Building to the Science Data Center.

(d) **IMC: Coupled Imaging Calibration**: Calibration and imaging are intimately coupled, in particular in the calibration approach being adopted for the ngVLA for bands 1-3, and partly 4, that leverages the large array size and high sensitivity for self-calibration. This calibration information is generated and applied as part of the coupled calibration-imaging loop. The calibration information is implicit in the science data and not obtained through separate calibration measurements.

(e) **Other HLDP Generation**: Activities related with the generation of other HLDP besides images/cubes, for example, catalogs.

(f) **RNC: Realtime/Online Calibration**: Realtime/Online Calibration (RNC). These are calibration activities that are performed on-line, as the observation is executed, and solves for parameters whose values are needed in the on-going observation or are necessary for scheduling decisions. This calibration includes:

- Delay computations and antenna gains which are inputs to the phasing system,
- Pointing solutions from reference pointing observations and elevation and weather dependent components of the pointing model.

See section 5.2.11 for more details.

(g) **SBC: Calibration included in the Scheduling Block**: These are calibration data specific to individual observations and are obtained as part of the scheduling block to track parameters that change within an observation or are too specific and not generally applicable for the observatory to devote time to maintain under Observatory Provided Calibration (OBC). The observatory selects the calibrators used, consistent with the observing frequency and the goals of the observation. An option for the PI to include specific choices shall be possible when such non-standard observations are adequately justified. Calibration activities performed post-correlation by the SDP subsystem. See section 5.2.11 for details.

(h) **Synthesis Imaging**: Activities related with the generation of synthesis images and spectral cubes. The imaging process typically runs the CLEAN algorithm. This algorithm iteratively executes gridding, degridding, FFT and deconvolution operations in a major cycle, with the embedded deconvolution operation being iterative itself, executing several minor cycles during each major cycle. The gridding operation includes a convolution operator to correct for wide field effects and primary beam direction-dependent distortions.

5.2.10 Software Functions: Signal Path Support Functions

(a) **OBC: Observatory Provided Calibration**: These are single dish and array calibration parameters maintained by the observatory through periodic measurements on a cadence appropriate for the individual parameters. This information will be provided to individual observations to ensure adequate calibration of the data obtained. The time scale for OBC parameters is long, expected to be few to several weeks with the final cadence being determined by field experience with the realized instrument. The parameters derived are maintained and updated in corresponding databases.

For example, these calibrations include:

- the antenna positions,
- the delays in fiber optic cables and electronics,
- the antenna pointing and focus coefficients,
- the antenna surface deviations.

See section 5.2.11 for details.

(b) **Quality Assurance**: Activities related with performing quality assurance over the products generated by the SDP system.

(c) **Telescope System Configuration**: The telescope systems (electronic, computing, and software) require a set of configuration data that is loaded during the system initialization. This data is kept in the Telescope Configuration database, under version control.

5.2.11 Software Functions: Calibration Functions

The activities defined in this section are based on the ngVLA Calibration Plan spreadsheet [RD03], but must be consider preliminary. Many of these calibration functions are being revisited in the context of the ngVLA Calibration Working Group. Still, the identification of functions described herein is useful for setting up a model for documenting future decisions in this area. To facilitate cross-matching the functions defined in [RD03] with the diagrams, each calibration function has been given an ID defined as CAL.{ONL,OFF,SYS}.{ROW}, where ONL are online calibration functions, OFF are offline post-processing calibration functions, SYS are system calibration functions associated with Observatory-Facing

(Non-PI) observing modes, and ROW corresponds to the row in the corresponding sheet in the calibration plan spreadsheet. This section only presents a summary for each calibration function, see [RD03] for additional details.

As specified in requirement SYS1063, the system "shall store and recall prior calibration corrections and apply them if the projected accuracy (given the time elapsed) still meets the requirement for a given observation". This requirement implies a pattern where the online calibration functions will first query the Calibration Database and only execute scans on calibrator targets if a suitable calibration solution cannot be found. After observing a calibration scan and computing new solutions, these will be pushed into the Calibration database to be used in subsequent observations. This interaction applies to most of the online calibration functions. For simplicity, this interaction is not shown in the diagrams below.

Some the calibration solutions are applied on the data that flows through the signal path (e.g., WVR phase corrections), while other calibration solutions are applied on the hardware devices (e.g., attenuator levels or pointing model coefficients). For the second case, the parameters derived from the solutions are part of the configuration information of the corresponding hardware device. These configuration parameters will be cached locally in the antenna (probably at the HIL level) and pushed into the Configuration Database. These interactions are not shown in the diagrams either.

As pointed out in the Observing Mode Calibration Strategy document, several system calibration observing modes exist, and the execution of online calibration scans will rely on calibrator data maintained in the Calibrator Database, which will be kept updated through the execution of Calibrator Survey observations.

TelCal components in the Data Reception and Analysis subsystem solves calibration tables, which are then sent to the supervisory modules, where they are translated into hardware parameters and applied in the hardware devices. The details of these flows, along with the interactions between the Calibration, Configuration and Calibrator databases, will be elaborated in their own diagrams, to be presented as part of the software architecture document in the software PDR. Of particular importance are timing considerations that could impact the signal path performance. For example, when phasing the array, the interactions between TelCal and CSP need particular attention. The goals of the diagrams in this section is mostly a (preliminary) identification of the calibration functions and the flow of data between them and the Calibration and Calibrator databases.

5.2.11.1 Pointing, Focus, Attenuator Levels and Requantizer Gains Calibration Functions

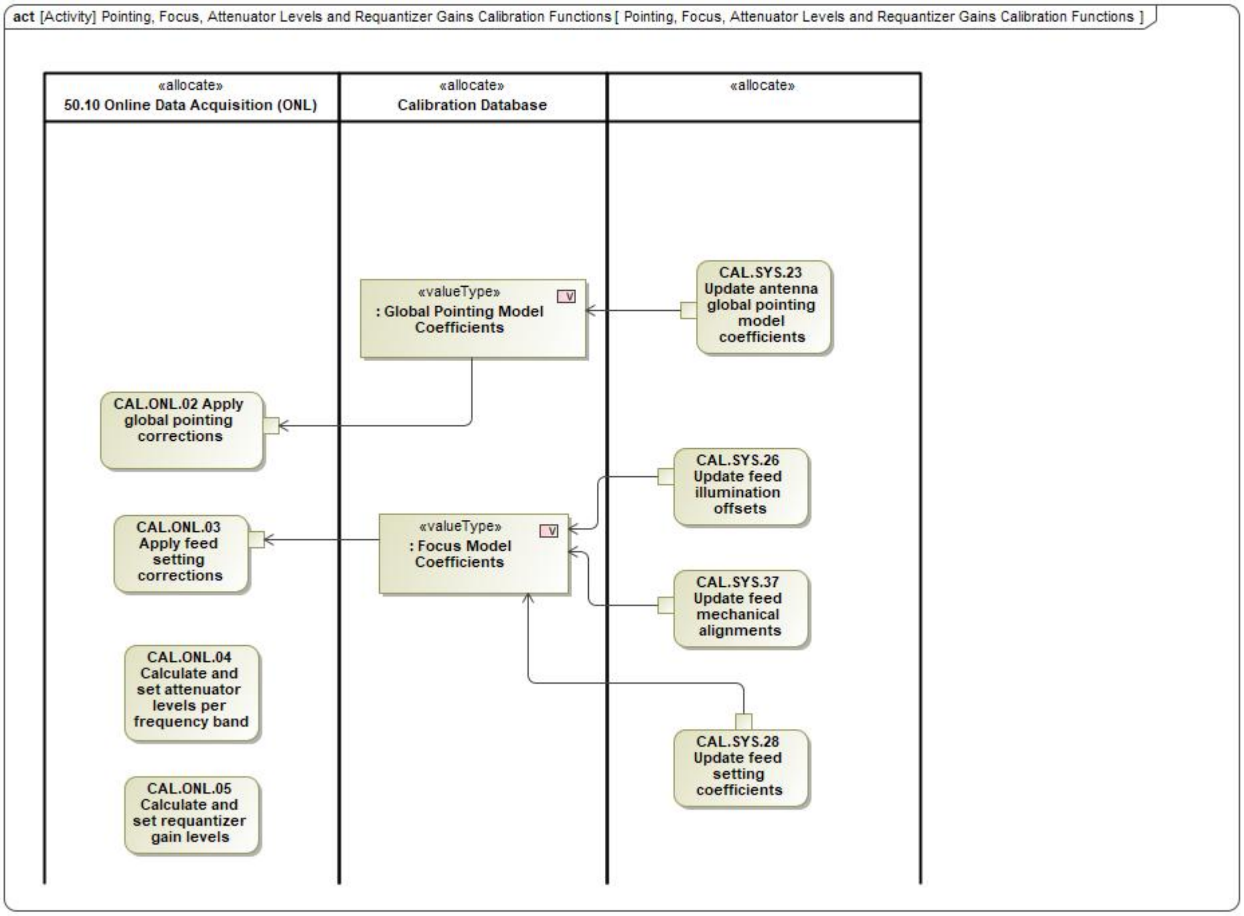

Figure 101: Pointing, focus and attenuator level and requantizer gains calibration activities.

(a) **CAL.ONL.02 Apply global pointing corrections**: Apply global pointing model coefficients to the antenna control system.

(b) **CAL.ONL.03 Apply feed setting corrections**: Apply coefficients for optimizing the feed selection and focus positioning, as functions of elevation and temperature.

(c) **CAL.ONL.04 Calculate and set attenuator levels per frequency band**: By default, the local supervisory software solves for the attenuation levels from DBE provided sampler statistics (or the the IRD total power sensor data) at the start of each observation. The system checks that the antenna is not pointing near the sun or the Clarke belt.

(d) **CAL.ONL.05 Calculate and set requantizer gain levels**: By default, solve the requantizer gain levels per frequency sub-band at the start of each observation and band switch, checking that the antenna is not pointing near the sun. On the other hand, if observing the sun, solve for the requantizer gain levels for each scan.

(e) **CAL.SYS.23 Update antenna global pointing model coefficients**: Perform an All-Sky Pointing Calibration to measure global pointing coefficients for each receiver band.

(f) **CAL.SYS.26 Update feed illumination offsets**: Measure changes to feed illumination offsets using holography (in a similar way as described in ALMA memo 402).

(g) **CAL.SYS.28 Update feed setting coefficients**: Determine optimal feed setting model coefficients for depth of focus.

(h) **CAL.SYS.37 Update feed mechanical alignments**: Observe a strong source that is linearly polarized at a selected frequency. The absolute angle does not need to be known as long as all baselines see the same position angle (it may be necessary to impose a baseline length constraint). Measure the mechanical feed alignment relative to the design orientation. This activity may be included as part of the polarization system calibration procedures.

5.2.11.2 Delay/Phase Calibration Functions

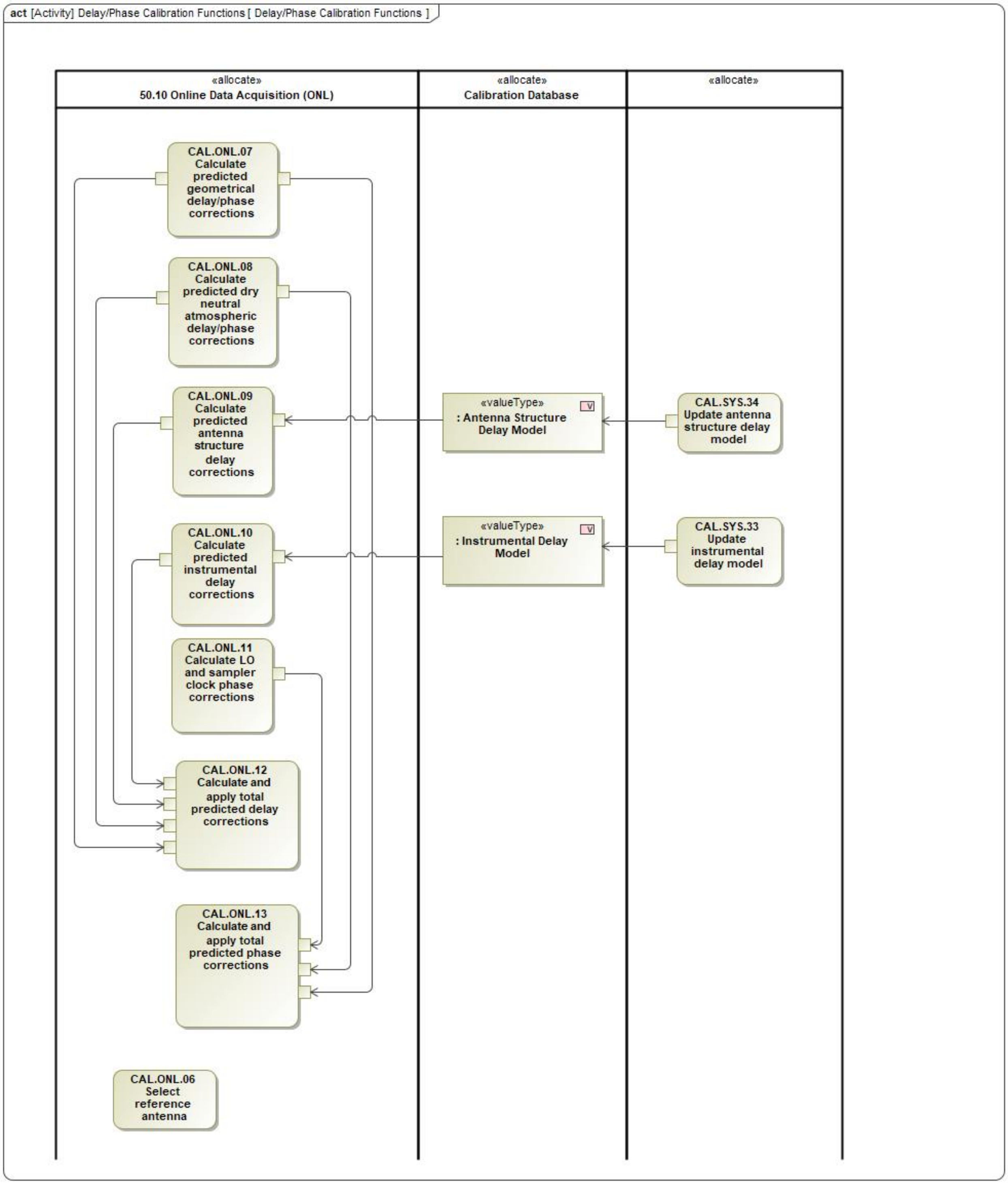

Figure 102: Delay and phase calibration activities.

(a) **CAL.OFF.03 Select reference antenna**: Select same antenna as selected by the activity CAL.ONL.06.

(b) **CAL.ONL.06 Select reference antenna**: One possible way of selecting the reference antenna would be to pick the first antenna from a pre-identified shortlist of well characterized antennas which is also included in the sub-array. Another way of selecting the reference antenna would be to use the RFI statistics from the RFI Database. If the execution block (an execution of a scheduling block) is part of a multiple execution block observation (several executions of the same scheduling block), then the system should attempt to force the selection of the same reference antenna.

(c) **CAL.ONL.07 Calculate predicted geometrical delay/phase corrections**: TelCal calls a program like CALC, supplying the following inputs:

- antenna positions from Calibration Database.
- coefficients for different effects, stored in the Calibration Database and automatically updated from external repositories on appropriate timescales (for example, USNO).
- ephemerides for solar system objects, stored in the Calibration Database and automatically updated from external repositories on appropriate timescales (ephemerides are used to account for gravitational deflection due to the solar system potential).
- doppler tracking details.

This calculation accounts for as many effects as possible, including coefficients associated with Earth orbit and orientation, polar motion, geophysical effects tides, aberration, parallax, etc.

This calculation excludes the atmospheric propagation delay.

This calculation must be able to generate a polynomial that can forward-predict not only sidereal antenna motion, but also super-sidereal tracking to support OTFI.

This calculation considers static refraction only (quasi-static). It excludes dynamic refraction from the fluctuating atmosphere (this is not within the capability of the geometrical model, as it requires astronomical and WVR corrections).

(d) **CAL.ONL.08 Calculate predicted dry neutral atmospheric delay/phase corrections**: Online Calibration calls a program similar to ATM, supplying as input the surface meteorological parameters (temperature, humidity, pressure) at each antenna, from the monitoring data stream. This calculation considers static refraction only (quasi-static). It excludes the dynamic refraction from the fluctuating atmosphere (this would require astronomical and WVR corrections).

(e) **CAL.ONL.09 Calculate predicted antenna structure delay corrections**: These corrections correspond to the repeatable part of antenna structure delay, accounting for factors such as the reflector gravity sag with elevation, the axes not intersecting, and bearing asymmetries. This function assumes no need for corrections for feed positioning, as this is covered by function CAL.ONL.03, "Apply feed setting corrections"; and geometrical prediction, which is covered by CAL.ONL.07, "Calculate predicted geometric delay/phase corrections".

(f) **CAL.ONL.10 Calculate predicted instrumental delay corrections**: These coefficients correspond to the repeatable part of the instrumental delay between the feed and the CSP. It is expected that these coefficients will change as the instrument configuration is modified, for example, after swapping a front-end module. This function assumes no need for corrections for geometrical prediction, which is covered by CAL.ONL.07, "Calculate predicted geometric delay/phase corrections".

(g) **CAL.ONL.11 Calculate LO and sampler clock phase corrections**: The Online Calibration module (TelCal) to pull the antenna-dependent LO offsets from the Configuration Database and the DBE sampler clock frequency offsets from the monitoring data stream. The relative cable delays between LO signals could introduce an additional phase change that may need correction as well. For non-connected antennas (long baselines) these offsets will probably need to be measured, and may also require a more complex model to account for delay drift and other second-order effects.

(h) **CAL.ONL.12 Calculate and apply total predicted delay corrections**: The Online Calibration module (TelCal) combines all predicted delay contributions (geometric, dry neutral atmosphere, antenna structure, instrumental) into a polynomial model, and sends this to the CSP Supervisory module, which in turn sends them to the CSP for its application in the antenna data streaming from the DBE. TelCal sends a stream of periodic updates, with each update being valid for a given time interval in the future. The polynomial model excludes the WVR delay corrections due to the fluctuations of the wet atmosphere. It assumes that the contributions are polarization-independent. Note: the CSP splits the combined corrections into a coarse (bulk) delay and a fine delay. The former corrects for the integer (in samples) delay at the start of the scan (where delay buffers are applied), and the fine accounts for the reminder, applying it per integration as part of the interpolation/re-sampling step.

(i) **CAL.ONL.13 Calculate and apply total predicted phase corrections**: The Online Calibration module (TelCal) combines all predicted phase contributions (geometric-relativistic, atmosphere-refraction, LO, sampler clock) and sends them to the CSP Supervisory module, which in turns sends them to the CSP, which applies them after the re-sampling step.

(j) **CAL.SYS.33 Update instrumental delay model**: Calibrates the repeatable part of instrumental delay.

(k) **CAL.SYS.34 Update antenna structure delay model**: Calibrates the repeatable part of antenna structure delay.

5.2.11.3 Bandpass Calibration Functions

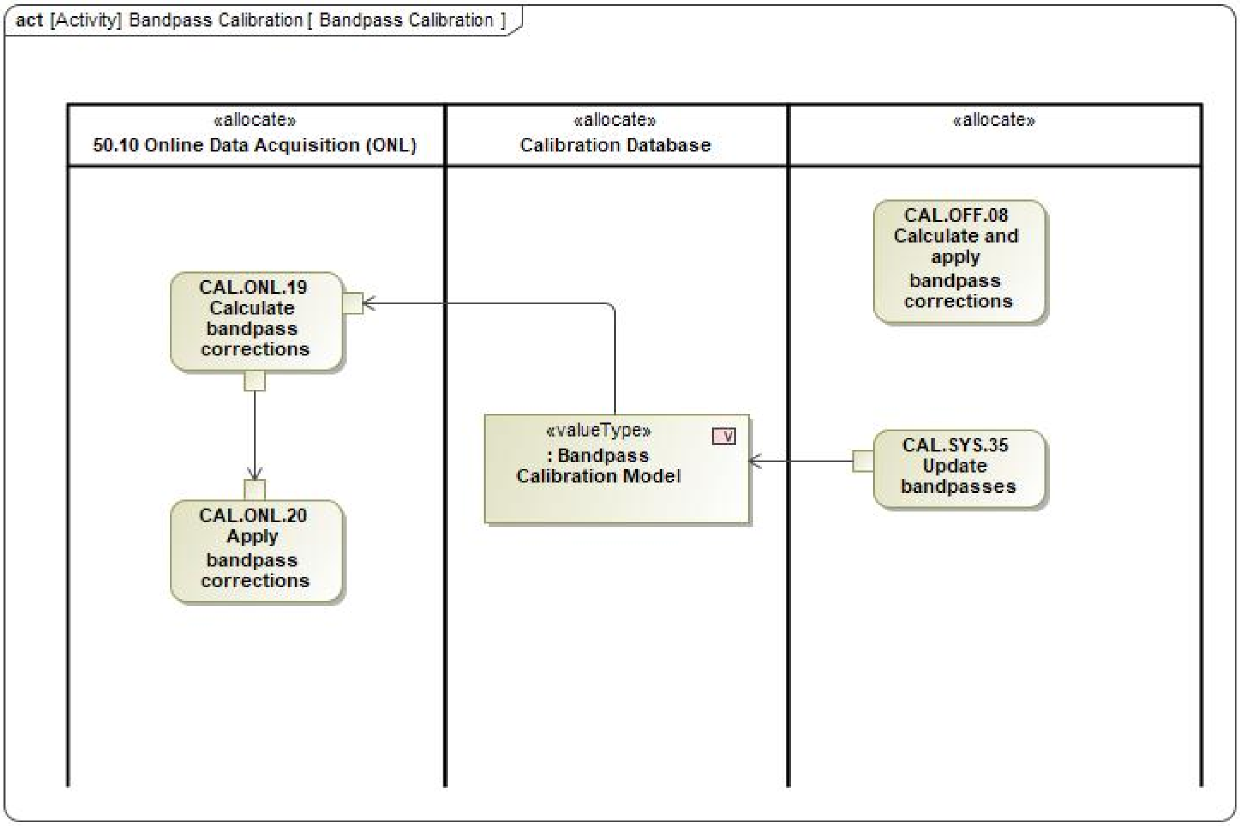

Figure 103: Bandpass calibration activities.

(a) **CAL.OFF.08 Calculate and apply bandpass corrections**: The bandpass solutions are pulled from the Calibration Database, interpolating if necessary. The bandpass solutions are corrected to the relative phase frame of the selected reference antenna, from activity CAL.OFF.03. Dynamically attenuate the bandpass solutions using the opacity measurements from activity CAL.OFF.05. Apply the bandpass solutions to all calibrators and targets.

(b) **CAL.ONL.19 Calculate bandpass corrections**: The bandpass solutions are pulled from the Calibration Database, interpolating if necessary. The bandpass solutions are corrected to the relative phase frame of the selected reference antenna from activity CAL.ONL.06. Dynamically attenuate the bandpass solutions using the opacity measurements from activity CAL.ONL.15 and the atmospheric model. Apply the bandpass solutions to all calibrators and targets.

(c) **CAL.ONL.20 Apply bandpass corrections**: This correction is necessary both for interferometric observations before channel averaging and beamforming observations. The bandpass solutions are sent to the CSP and DBEs from TelCal. The CSP applies the solutions to per-antenna data stream prior to beamforming. The DBEs apply the solutions to the per-antenna data stream prior to correlation.

(d) **CAL.SYS.35 Update bandpasses**: Remove the atmospheric attenuation from bandpasses to be stored in Calibration Database. Include any drift factors (e.g. temperature from frontend cryostats).

5.2.11.4 Gain Amplitude Calibration Functions

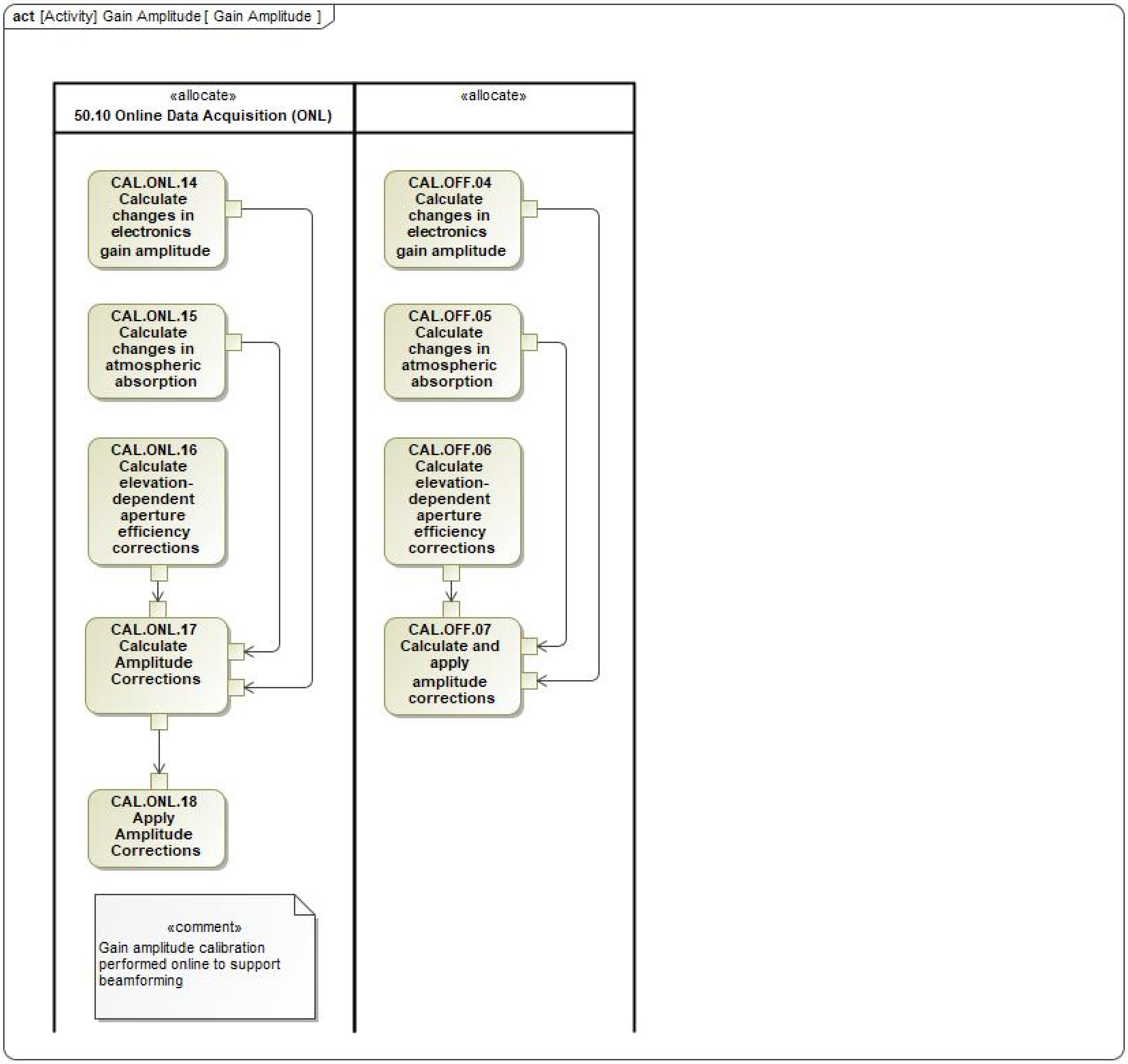

Figure 104: Gain amplitude calibration activities.

(a) **CAL.OFF.04 Calculate changes in electronics gain amplitude**: Perform signal processing/filtering/flagging to prevent RFI from contaminating the switched power data, account for known RFI from the RFI database. Use these data to track changes in electronic gain amplitude (analog), utilizing T_{cals} pulled from the Calibration Database.

(b) **CAL.OFF.05 Calculate changes in atmospheric absorption**: Use same input data as activity CAL.OFF.04, but in this case process filtered switched power data to track changes in atmospheric opacity. It is not necessary to use of the model opacities as the switched power system is intended to be sufficiently stable. For synthesis array radar observations, it will be necessary to include a correction for opacity due to the transmission through the atmosphere. For this it will be necessary to retrieve the transmission location and the pointing information, and probably use a model opacity to make the correction.

(c) **CAL.OFF.06 Calculate elevation-dependent aperture efficiency corrections**: Pull frequency and elevation-dependent gain curves from the Calibration Database, and combine them with factors like illumination taper to calculate aperture efficiency corrections.

(d) **CAL.OFF.07 Calculate and apply amplitude corrections**: Calculate the combined absolute and relative amplitude calibration corrections, incorporating the electronics gain amplitude, opacity, the aperture efficiency, retrieving gain factors from the Calibration Database to convert from cross-product spectral power to absolutely-scaled spectral flux densities. For synthesis array radar observations, it will be necessary to pull the radar transmission power information from the observation metadata. Apply solutions to all calibrators and targets.

(e) **CAL.ONL.14 Calculate changes in electronics gain amplitude**: The CSP produces channelized switched power data, which needs to be processed or filtered to prevent RFI contamination. Telcal process these filtered data to track changes in electronic gain amplitude (analog), utilizing T_{cal}s pulled from calibration database. Do this throughout the observation.

(f) **CAL.ONL.15 Calculate changes in atmospheric absorption**: Use same input data as above in activity CAL.ONL.14, but in this case TelCal process the RFI-filtered switched power data to track changes in atmospheric opacity. There is no need to use the model opacities or empirical opacities (e.g. tipping scans with atmospheric temperature model) as the switched power system is intended to be sufficiently stable.

(g) **CAL.ONL.16 Calculate elevation-dependent aperture efficiency corrections**: TelCal pulls frequency- and elevation-dependent gain curves from the Calibration Database, which are then combined with factors like the illumination taper to calculate the aperture efficiency corrections.

(h) **CAL.ONL.17 Calculate Amplitude Corrections**: TelCal calculates the combined absolute and relative amplitude calibration corrections, incorporating factors like the electronics gain amplitude, opacity, and the aperture efficiency, pulling gain factors from the Calibration Database to convert the cross-product spectral power to absolutely-scaled spectral flux densities.

(i) **CAL.ONL.18 Apply Amplitude Corrections**: The CSP receives the amplitude corrections from TelCal, which account for both relative and absolute amplitude calibrations. The CSP sub-band processor applies these corrections to the antenna data streams prior to beamforming. The CSP X-Engine applies the corrections to the antenna data stream prior to correlation. This will only be performed when a calibrator is observed interferometrically (in-beam or during the slew) to support a beamforming observation.

5.2.11.5 Gain Phase/Delay Calibration Functions

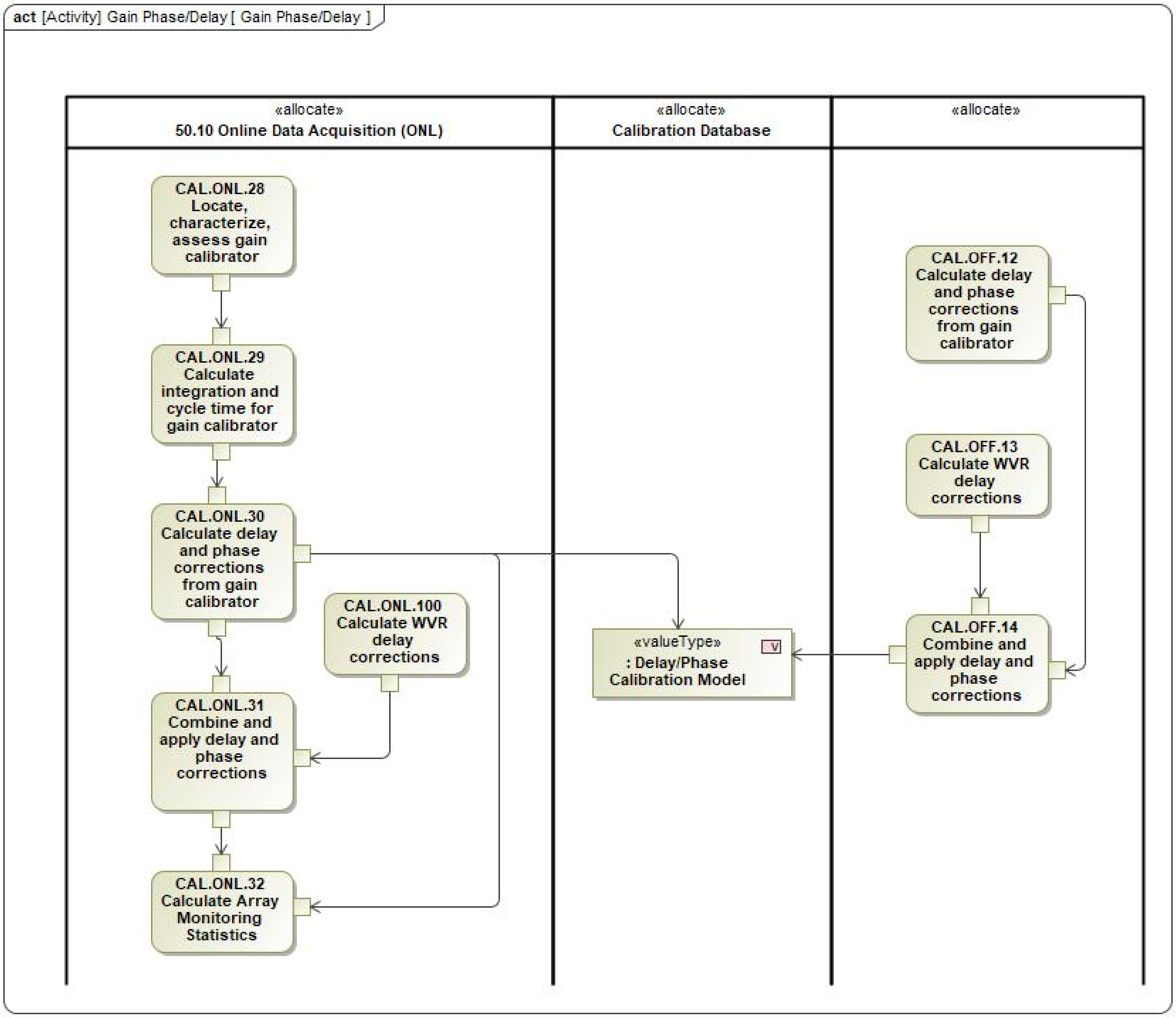

Figure 105: Gain phase and delay calibration activities.

(a) **CAL.OFF.12 Calculate delay and phase corrections from gain calibrator**: Using the gain calibrator observations, calculate the correction model capturing residuals from the neutral atmosphere (dry, wet), the antenna structure, and the instrumentation. Accounting for known RFI using input from RFI database, apply any necessary additional flagging. If observations were performed in band 2 (higher bands probably not relevant) with suspected significant ionospheric or interplanetary disturbances (based on near real-time spatio-temporal measurements and predictions for ionosphere and possibly interplanetary medium, pulled from public databases), in such a way that band 1 calibration observations were interleaved, then measure the ionospheric delays using the parallel hand band 1 data and apply them to the band 2 observations. If the observation is performed purely in band 1, then apply the corrections directly, i.e., there's no need for band transfer in this case.

(b) **CAL.OFF.13 Calculate WVR delay corrections**: Process the channelized WVR data and associated weather data (e.g. ngVLA weather station surface data) that was appended to the science dataset metadata by the Online system. Pull and process any associated data necessary, e.g. vertical temperature profile model constrained by publicly available measurements (may be consider purchasing oxygen sounders to measure the wings of the 60 GHz absorption lines). Perform RFI flagging, pulling data from the RFI Database. Calculate the full path (between calibrator and target) delay corrections for wet fluctuations. The corrections will likely be a hybrid between absolute and empirical.

(c) **CAL.OFF.14 Combine and apply delay and phase corrections**: Interpolate the gaincal solutions (all atmospheric delay residuals, antenna structure residuals, instrumental residuals), and add the WVR corrections (fast wet fluctuations). Apply the corrections to the targets only.

(d) **CAL.ONL.100 Calculate WVR delay corrections**: Process the channelized WVR data and associated weather data (e.g. ngVLA weather station surface data) that was appended to the science dataset metadata by the Online system. Pull and process any associated data necessary, e.g. vertical temperature profile model constrained by publicly available measurements (consider oxygen sounders to measure the wings of the 60 GHz absorption lines, TBD). Perform RFI flagging, pulling data from the RFI Database. Calculate the full path (between cal and target) delay corrections for wet fluctuations. The corrections will likely be a hybrid between absolute and empirical.

(e) **CAL.ONL.28 Locate, characterize, assess gain calibrator**: The system selects the nearest suitable gain calibrator for a science target using the Calibrator Database. If the nearest calibrator is beyond a pre-identified range (which may depend on data from the monitoring stream, for example, local wind speeds, temperature gradients, or solar angle), it will be necessary to search for a calibrator observationally that meets the pre-identified criteria. In both cases, observe the calibrator and process the (possibly averaged) data to determine if it is a suitable calibrator. It is necessary to characterize it using a standardized approach, e.g. by a histogram of amplitude ratios over binned baseline lengths, or ideally generating a model of the calibrator (the snapshot uv coverage should be sufficient for ngVLA). If the identified calibrator is OK, the select it. If not (e.g. the calibrator light curve over last 3 months looks highly variable beyond some threshold), then keep looking.

(f) **CAL.ONL.29 Calculate integration and cycle time for gain calibrator**: TelCal calculates a suitable integration time based on the flux density of a selected calibrator. Pull the current weather data from the monitoring stream, and use it to calculate the cycle time.

(g) **CAL.ONL.30 Calculate delay and phase corrections from gain calibrator**: Using the gain calibrator scan data (possibly averaged to reduce the data volume), calculate the correction model capturing residuals from the neutral atmosphere (dry, wet), the antenna structure, and the instrumentation. If observations were performed in band 2 (higher bands probably not relevant) with suspected significant ionospheric or interplanetary disturbances (based on near real-time spatio-temporal measurements and predictions for ionosphere and possibly interplanetary medium, pulled from public databases), in such a way that band 1 calibration observations were interleaved, then measure the ionospheric delays using the parallel hand band 1 data and apply them to the band 2 observations. If the observation is performed purely in band 1, then apply the corrections directly, i.e., there's no need for band transfer in this case. However, it is still not clear whether this correction is needed for beamforming. If not, then it may still be useful for array monitoring for regular interferometric observations.

(h) **CAL.ONL.31 Combine and apply delay and phase corrections**: Add the WVR corrections (fast wet fluctuations) to the solutions obtained from the gain calibrator. TelCal sends the corrections to the CSP Supervisory module, who applies them in the CSP. The CSP Sub-band processor applies these corrections to the antenna data streams prior to beamforming.

(i) **CAL.ONL.32 Calculate Array Monitoring Statistics**: TelCal uses the gain calibrator observational data to calculate statistics to support array monitoring and scheduling, e.g. check the spectrum for amplitude discontinuities across the band, measure polarization properties, report the variability in delay solutions vs time. Store this data in the observation dataset and possibly broadcast it to other components that can make use of it, for example the Scheduling module. This activity is not a calibration step, but it is included here for clarity because it is closely related to activity CAL.ONL.30 and forms part of a feedback loop that could lead to significant data improvement for PI observations (e.g. the observation is interrupted and then re-observed under better conditions).

5.2.11.6 Reference Pointing

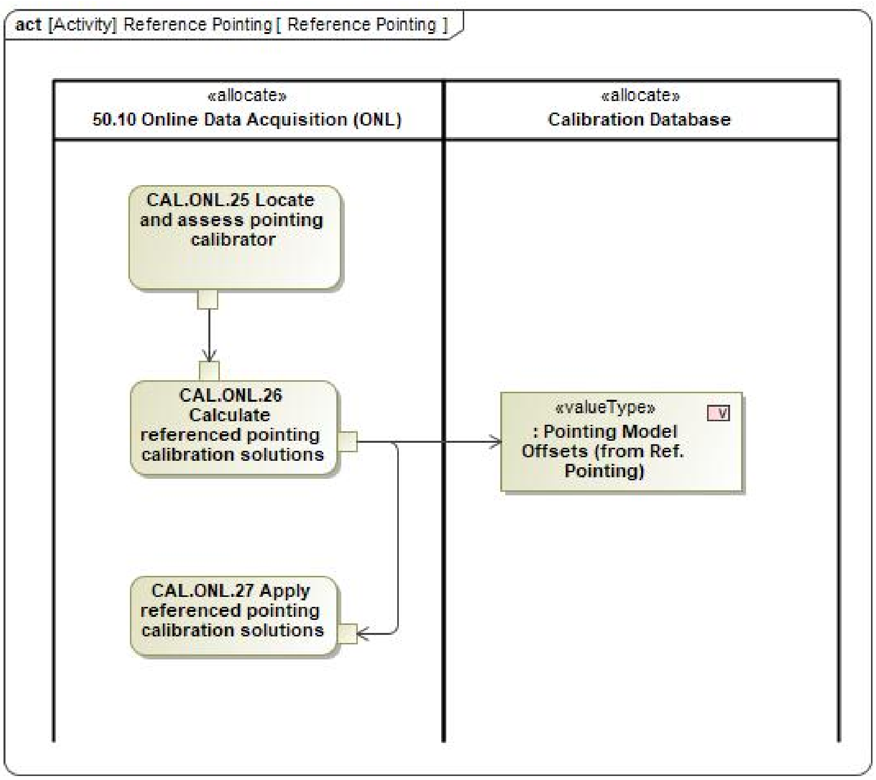

Figure 106: Reference pointing calibration activities.

(a) **CAL.ONL.25 Locate and assess pointing calibrator**: The system selects the nearest suitable pointing calibrator for a science target using the Calibrator Database. If the nearest calibrator is beyond a pre-identified range (which may depend on data from the monitoring stream, for example, local wind speeds, temperature gradients, or solar angle), it will be necessary to search for a calibrator observationally that meets the pre-identified criteria. Once a suitable calibrator is located, its details are saved in the Calibrator Database. In both cases, observe the calibrator and process the (possibly averaged) data to determine if it is a suitable calibrator. It is necessary to characterize it using a standardized approach, e.g. by a histogram of amplitude ratios over binned baseline lengths, or ideally generating a model of the calibrator. If the identified calibrator is suitable, the select it. If not, then keep looking. By default, all bands use referenced pointing. Optionally, bands 1 and 2 could be excluded for observations where a low dynamic range is acceptable.

(b) **CAL.ONL.26 Calculate referenced pointing calibration solutions**: Calculate solutions for the calibrator observed in activity CAL.ONL.25.

(c) **CAL.ONL.27 Apply referenced pointing calibration solutions**: The pointing corrections solved by TelCal are applied in the antenna control system. The pointing solutions and the identification of the pointing calibrator are included in the science dataset metadata.

5.2.11.7 *Polarization Leakage Corrections*

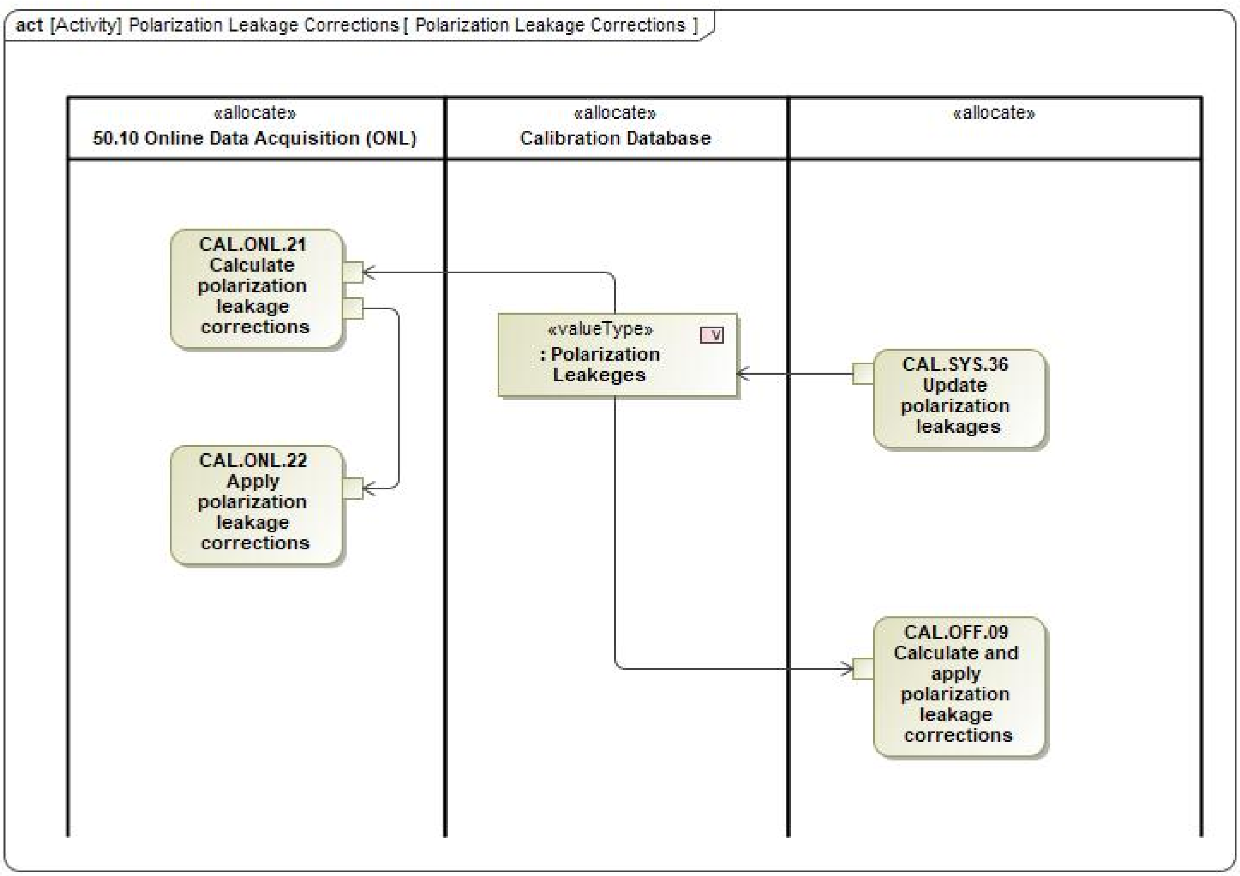

Figure 107: Polarization leakage calibration activities.

(a) **CAL.OFF.09 Calculate and apply polarization leakage corrections**: Pull the absolute polarization leakages from the Calibration Database, interpolating where necessary. Correct the leakages to the relative phase frame of the selected reference antenna from activity CAL.OFF.03. Apply to all calibrators and targets.

(b) **CAL.ONL.21 Calculate polarization leakage corrections**: TelCal retrieves the absolute polarization leakages from the Calibration Database, interpolating where necessary. TelCal corrects the leakages to the relative phase frame of the selected reference antenna from activity CAL.ONL.06.

(c) **CAL.ONL.22 Apply polarization leakage corrections**: TelCal sends the polarization leakages to the CSP Supervisory module, which sends them in turn to the CSP. The CSP Sub-band Processor applies them to the antenna data streams prior to beamforming. The CSP X-Engine applies them to the antenna data streams prior to correlation. This will only be performed when a calibrator is observed interferometrically (in-beam or slew) to support a beamforming observation.

(d) **CAL.SYS.36 Update polarization leakages**: Observe over a range of parallactic angles for calibrators. Include the measurement of the mean level (zero-point) of circular polarization from a sample of circularly polarized calibrators. It may be desirable to perform additional checks to assess the accuracy of the ionospheric Faraday rotation correction for lower bands performed in activity CAL.ONL.11. The absolute leakages, not relative leakages, should be stored. Push resulting calibrator polarization details to the Calibrator Database, but only for the purpose of being able to determine if they exhibit significant variability in which case they should be avoided. Push leakages to the Calibration Database.

5.2.11.8 Crosshand Bandpass Phase Corrections Functions

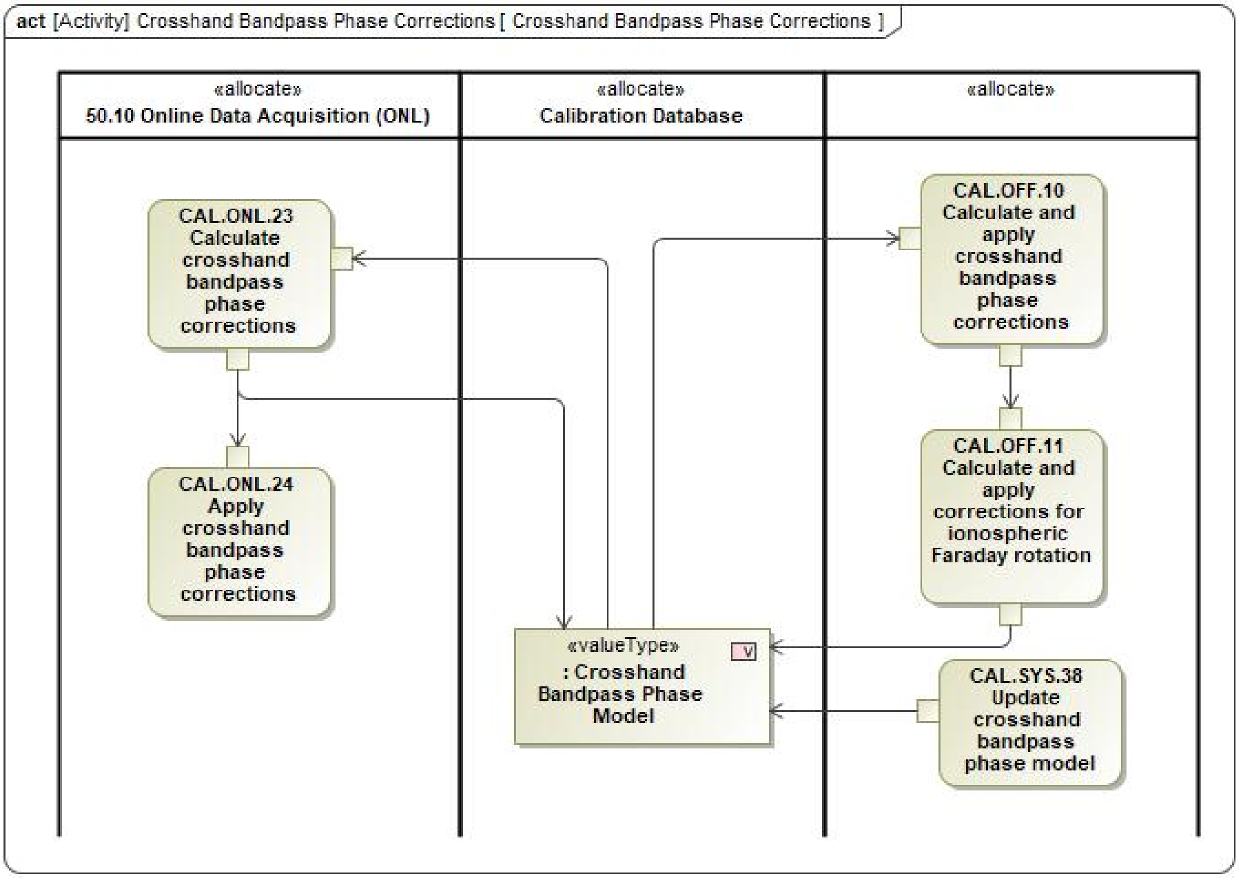

Figure 108: Cross-hand bandpass phase calibration activities.

(a) **CAL.OFF.10 Calculate and apply crosshand bandpass phase corrections**: Use the same or similarly-processed input data as activity CAL.OFF.04, but in this case process the filtered switched power data to extract the cross-hand bandpass delay/phases at the appropriate spectral resolution (it may be necessary to interpolate to get to fine spectral resolution relevant to observation). It may be necessary to incorporate the lab-determined contribution between the feed and the noise injection point; if so, retrieve this from the Calibration Database. Note that the temperature dependence is unlikely to be significant because the feeds are cooled. It is likely that this function only needs to be executed at the start of an observation and the recorded solutions can be used afterwards. Apply to all calibrators and targets.

(b) **CAL.OFF.11 Calculate and apply corrections for ionospheric Faraday rotation**: If observations were performed in band 2 (higher bands probably are not relevant), retrieve spatio-temporal measurements of Faraday rotation from public databases (e.g. GPS-derived VTEC maps published ~2 weeks after the epoch of interest) and correct crosshand data. Given the delay in obtaining the VTEC maps, the observation will probably needs to be marked not to be reduced immediately by post-processing, but wait until the VTEC maps are available.

(c) **CAL.ONL.23 Calculate crosshand bandpass phase corrections**: Use same or similarly-processed input data as activity CAL.ONL.14, but in this case TelCal process filtered switched power data to extract cross-hand bandpass delay/phases at the appropriate spectral resolution (may need to interpolate to get to fine spectral resolution relevant to observation). It may be necessary to incorporate the lab-determined contribution between feed and the noise injection point; if so, retrieve this from the Calibration Database. Note that the temperature dependence is unlikely to be significant because the feeds are cooled. It is likely that this activity only needs to be executed at the start of an observation start and use the solutions afterwards.

(d) **CAL.ONL.24 Apply crosshand bandpass phase corrections**: TelCal sends the solutions to the CSP Supervisory module, which in turn sends it to the CSP. The CSP Sub-band Processor applies the solutions to the beamformed data stream. The CSP X-Engine applies the solutions to the antenna data stream prior to correlation. This will only be performed when a calibrator is observed interferometrically (in-beam or slew) to support a beamforming observation.

(e) **CAL.SYS.38 Update crosshand bandpass phase model**: The plan is to use phase-matched noise diodes to measure cross-hand bandpass phase. However, the contributions that originate upstream from the noise injection point, i.e., the feed and possibly the antenna structure, need to be evaluated. These contributions can be measured using a celestial calibrator, but other alternatives like measuring in the lab, using a drone, a local transmitter on a tower or satellite, are also possible.

5.2.11.9 Pulsar Binning Calibration

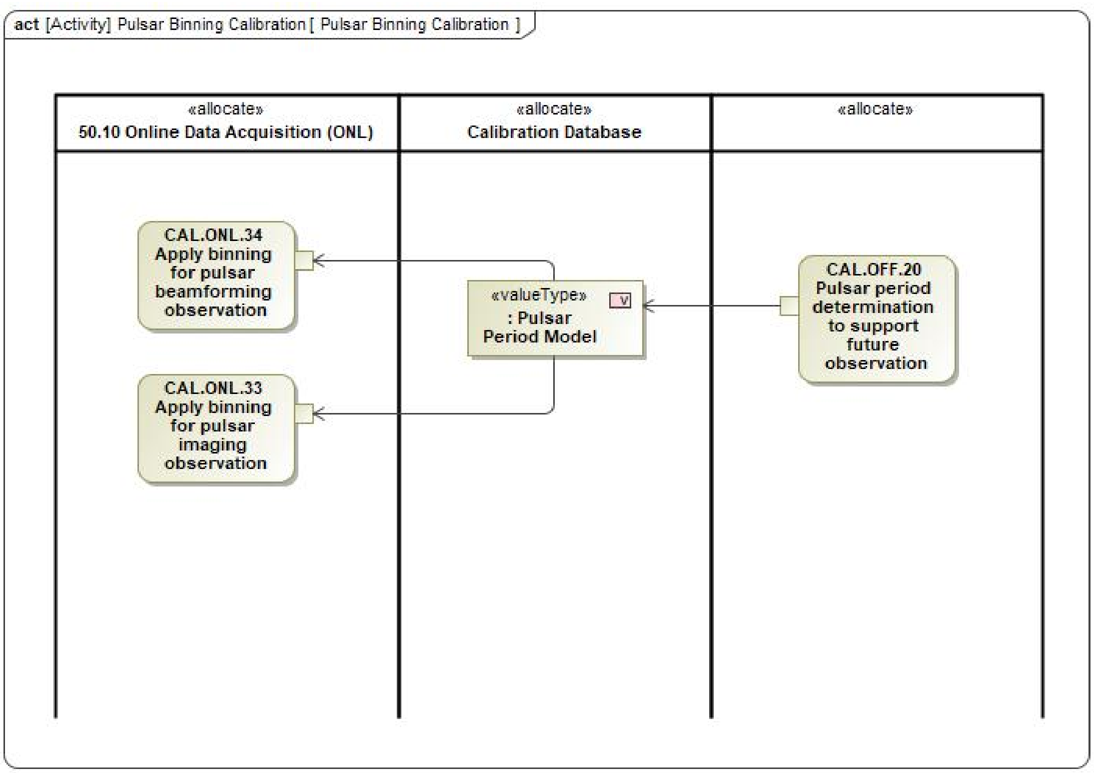

Figure 43: Pulsar binning calibration activities.

(a) **CAL.OFF.20 Pulsar period determination to support future observation**: Determine the pulsar period from a pulsar timing observation, to be used by the ONL system for online binning (probably in the CBE). The solution is saved in the Calibrator Database.

(b) **CAL.ONL.33 Apply binning for pulsar imaging observation**: Retrieve the pulsar period from the Calibrator Database (determined from an earlier observation).

(c) **CAL.ONL.34 Apply binning for pulsar beamforming observation**: Retrieve the pulsar period from the Calibrator Database (determined from an earlier observation).

5.2.11.10 Other Offline Post-processing Functions

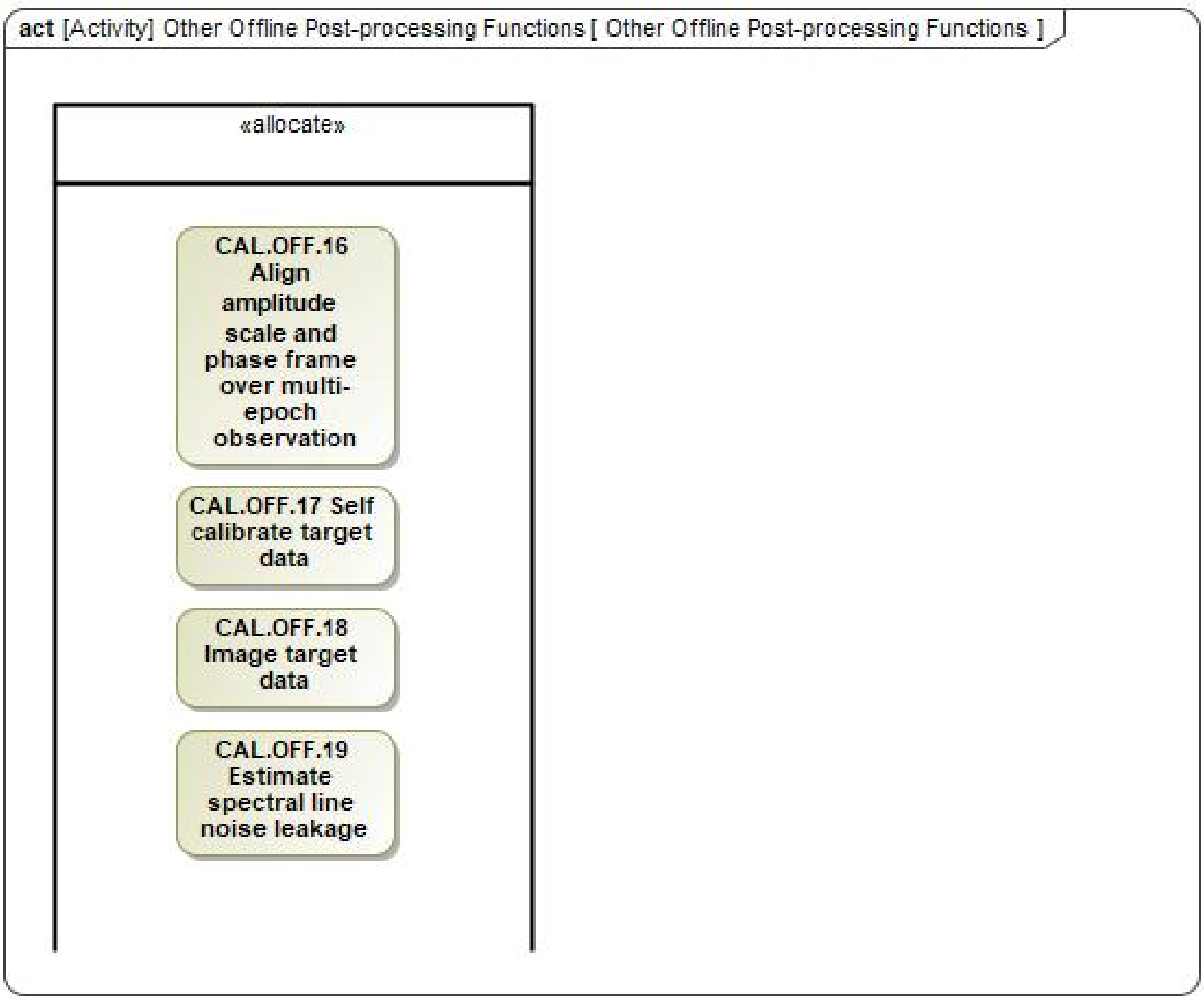

Figure 109: Other offline post-processing activities.

(a) **CAL.OFF.16 Align amplitude scale and phase frame over multi-epoch observation**: Perform this activity if relevant, e.g. for the last execution block (the last execution of a scheduling block). Perform amplitude and phase self-cal using per-observation gain cal solutions. This aims to correct for any small differences between observations, e.g. noise diode drift during the interval between flux density service mode calibrations.

(b) **CAL.OFF.17 Self calibrate target data**: A self-calibration stage is expected to be included in the imaging pipeline in order to minimize residual calibration error on science targets with sufficient strength and to reach the theoretical sensitivity level and desired dynamic range on these targets. As with the imaging stages, the imaging aspect of self-calibration will need to pull antenna primary beams from Calibration Database and, in some cases, the antenna tracking errors from the metadata.

(c) **CAL.OFF.18 Image target data**: If it is an imaging project, pull the antenna primary beam models from the Calibration Database and, in some cases, the antenna tracking errors from the metadata.

(d) **CAL.OFF.19 Estimate spectral line noise leakage**: Perform this activity if processing a spectral line project. See requirement CAL0202, it may be required due to pointing error. Retrieve the estimated pointing error from the statistics of referenced pointing data in the Calibration Database. This activity is included in this list of calibration activities because it is needed to support automated source detection and characterization.

5.2.11.11 Other Array System Calibrations

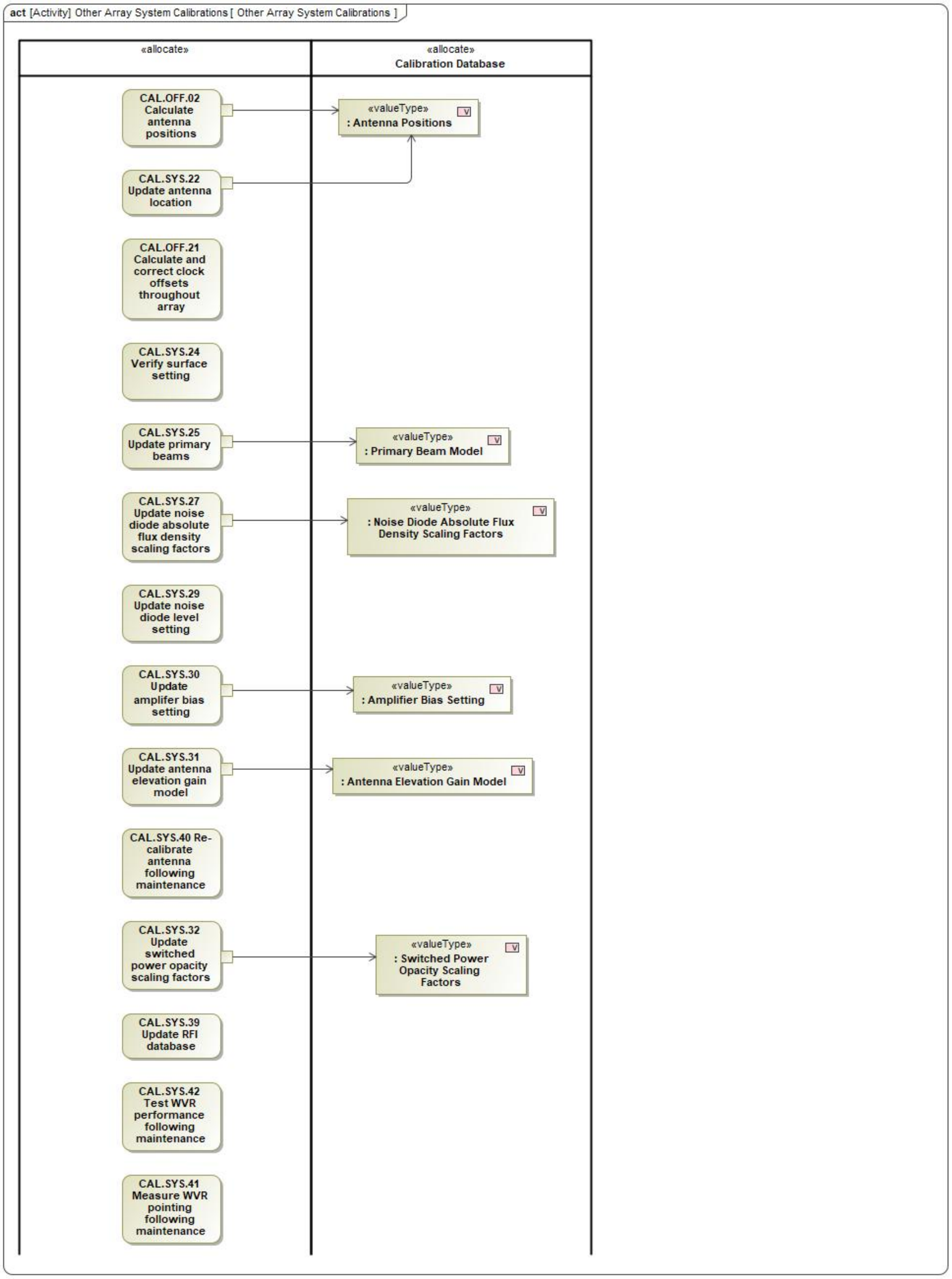

Figure 110: Other array system calibration activities.

(a) **CAL.OFF.02 Calculate antenna positions**: Antenna positions are recorded in the observation metadata and are stored in the Calibration Database. Although the locations of the antennas are fixed, the positions include a drift behavior. Calculate positions at time of observation using the coefficients stored in the Calibration Database.

(b) **CAL.OFF.21 Calculate and correct clock offsets throughout array**: Observe a well-known pulsar, retrieving the timing details from the Calibrator Database. Calculate accuracy relative to prior observations at ngVLA or other observatories, and use these data to assess the validity of the array timing and make the necessary corrections to the clock offsets.

(c) **CAL.SYS.22 Update antenna location**: Measure the relative position of the antennas using an all-sky calibrator survey. Measure the drifts and possibly higher order trends, and save these data into the Calibration Database.

(d) **CAL.SYS.24 Verify surface setting**: Measure the reflector perturbations as functions of azimuth, elevation and temperature for a selected frequency using holography. May also consider other techniques (e.g. surface photogrammetry), which may involve a technician visiting the site.

(e) **CAL.SYS.25 Update primary beams**: Measure (changes to) the complex primary beam as functions of frequency, parallactic angle (az, el), and temperature using holography with a strong celestial calibrator.

(f) **CAL.SYS.27 Update noise diode absolute flux density scaling factors**: This activity is relevant for regular monthly observations of celestial flux density standards. The procedure is as follows:

1. Pull calibrator models from calibrator database.
2. Calculate changes to flux density ratios and coefficients for time behavior as function of frequency, also determine if light curves show excessive variability to warrant (possibly temporary) calibrator exclusion (non-automated) from the sample of standards.
3. Calculate (changes to) scaling factors corrections necessary to convert from the noise diode instrumental amplitude scale to the celestial absolute scale, push to calibration database.

It will be necessary to consider gain and loss factors in this procedure to enable conversion from cross-product spectral power to spectral flux density.

(g) **CAL.SYS.29 Update noise diode level setting**: Measure and update if necessary the diode level setting (regular, solar) and T_{cals}.

(h) **CAL.SYS.30 Update amplifier bias setting**: If necessary, check and update the LNA bias settings.

(i) **CAL.SYS.31 Update antenna elevation gain model**: Measure (changes to) antenna gain curve, as a function of elevation, temperature, and frequency. Other factors such as illumination taper are needed along with its elevation gain dependency to enable the calculation of the antenna aperture efficiencies.

(j) **CAL.SYS.32 Update switched power opacity scaling factors**: Incorporate data from calibrator observations, tipping scans and an atmospheric model to measure (changes to) the scaling to ensure atmospheric opacity is correctly tracked using the switched power system.

(k) **CAL.SYS.39 Update RFI database**: Perform an RFI sweep to update RFI database. Include observation of calibrator(s) with known spectrum.

(l) **CAL.SYS.40 Re-calibrate antenna following maintenance**: Following antenna maintenance (e.g. a swap of the front end), it will be needed to re-calibrate elements following most of the other activities defined in this package. As the calibration plan matures, a plan will be defined specifying which activities are necessary to bring an antenna back into the array after specific types of maintenance activities, and in what order these need to be performed.

(m) **CAL.SYS.41 Measure WVR pointing following maintenance**: Following antenna or receiver swap, use this activity to confirm pointing or initiate maintenance request for site visit to adjust. The method is TBD, probably involves scanning across a GEO satellite.

(n) **CAL.SYS.42 Test WVR performance following maintenance**: Following a receiver swap, check the calibration performance, variables like T_{cal}, functions like the RFI handling, etc. The method is TBD, probably involves comparing interferometric observations of calibrators with WVR data, and could include tipping scans. This could benefit from careful scheduling the targets so some antennas observe at zenith while others point to a range of elevations, helping the implementation of a hybrid calibrating approach that uses both absolute and empirical WVR calibration methods.

5.2.12 Software Functions: Maintenance and Support Subsystem Functions

(a) **Inventory Management**: This function refers to the management of the spare parts inventory and is allocated in the CMMS system.

(b) **Maintenance Schedule Management**: This function refers to the management of the maintenance schedule. It is allocated in the CMMS system.

(c) **Preventive Maintenance Analysis**: This function refers to the analysis of monitoring data and alarms to detect conditions or trends that can indicate the need to service equipment before problems occur.

(d) **Troubleshooting Support**: This function provides support for troubleshooting operations. This module allows users to search, visualize and correlate data from the Engineering Database.

5.2.13 Software Functions: Development Support Functions

(a) **Commissioning Support**: System functions necessary to support the commissioning activities. This may include the development of special scripts and utilities.

(b) **Continuous Integration**: The software will be developed using a continuous integration system.

(c) **Issue Tracking**: Activities related with reporting problems, prioritizing them, debugging and resolving them.

6 Appendix A: Acronyms

Acronym	Non-Abbreviated Reference
AC	Alternating Current
ACU	Antenna Control Unit
ADC	Analog to Digital Converter
AE	Antenna Electronics
AFD	Antenna Fiber Distribution Subsystem
ALx	Architecture Layer x
ANT	Antenna Subsystem
API	Application Program Interface
ATF	Antenna Time and Frequency Distribution Subsystem
Az	Azimuth
bdd	Block definition diagram
BDLM	Big Data Life Cycle Management
BLD	Buildings Subsystem
BMR	Bins Modules and Racks Subsystem
CAD	Computer Aided Design
CASA	Common Astronomy Software Applications
CBE	Correlator Back End
CDR	Conceptual Design Review
CI	Configuration Item
CMMS	Computerized Maintenance Management System
COTS	Commercial Off the Shelf
CRY	Cryogenic Subsystem
CSF	CSP Switched Fabric
CSP	Central Signal Processing Subsystem
DBE	Digital Back End Subsystem
DC	Direct Current
DCS	Distributed Control System
DMS	Data Management and Software department
DSC	Data Science Center Subsystem
DSS	Development Support Subsystem
DST	Data Stores Software Subsystem
EB	Execution Block
EEC	Electronics Environmental Conditioning Subsystem
FED	Front End Subsystem
FIB	Fiber Optic Distribution and Data Networks Subsystem
FPGA	Field Programmable Gate Array
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPU	Graphics Processor Unit
H/W	Hardware
HIL	Hardware in the Loop Subsystem
HMI	Human-Machine Interface

HVAC	Heating, Ventilation and Air Conditioning
I/O	Input / Output
ibd	Internal block diagram
ICD	Interface Control Document
INF	Infrastructure Subsystem
IRD	Integrated Receiver Digitizer Subsystem
LNA	Low Noise Amplifier
LO	Local Oscillator
Lx	Level x
M&C	Monitoring & Control
MCL	Monitoring and Control Software Subsystem
MDA	Model Driven Architecture
MON	Environmental Monitoring Subsystem
MSS	Maintenance Support Software Subsystem
NBDRA	NIST Big Data Reference Architecture
ngCASA	next generation Common Astronomy Software Applications
NIST	National Institute of Standards and Technology
NRAO	National Radio Astronomy Observatory
NSB	ngVLA Site Buildings Subsystem
OFF	Offline Software Subsystem
OMT	Ortho-Mode Transducer
ONL	Online Software Subsystem
OPC-UA	Open Platform Communications United Architecture
OPS	Operations Buildings Subsystem
OTFI	On the Fly Interferometry
PBS	Product Breakdown Structure
PDR	Preliminary Design Review
PFLOPS	Peta Floating Operations Per Second
PLC	Programmable Logic Controller
PMN	Proposal Management Software Subsystem
PPS	Pulse Per Second
PSU	Power Supply Subsystem
PTP	Precision Time Protocol
QA	Quality Assurance
REST	Representational State Transfer
RF	Radio Frequency
RFI	Radio Frequency Interference
ROP	Reference Observing Program
RTD	Reference LO & Timing Distribution Subsystem
RTG	Reference LO & Timing Generation Subsystem
SBA	Short Baseline Array Antenna Subsystem
SBP	Sub-Band Processor
SCADA	Supervisory Control and Data Acquisition
SEMP	Systems Engineering Management
SQL	Structured Query Language

SW	Software
SysML	System Modeling Language
TBC	To Be Confirmed
TBD	To Be Determined
TelCal	Telescope Calibration software module
TFR	Time and Frequency Reference
TTA	Telescope Time Allocation
TTD	True Time Delay
UI	User Interface
VE	Verification Event
VEX	VLBI Executable
VLBI	Very Long Baseline Interferometry
VR	Verification Requirement
WVR	Water Vapor Radiometer Subsystem

7 Appendix B: Example SysML M&C model implementation

The following figures show a sample implementation of the control and monitoring interfaces implemented in SysML. The model shows a structural and functional view of the interface. The structural view is consistent with the PBS and the physical interface configuration shown in Figure 6. The functional view is consistent with the functional architecture presented in Section 5. Data flowing across the interface is represented in both views, using a shared data model. The M&C interfaces to all Antenna Electronics will be implemented to this level of detail by the time of System PDR.

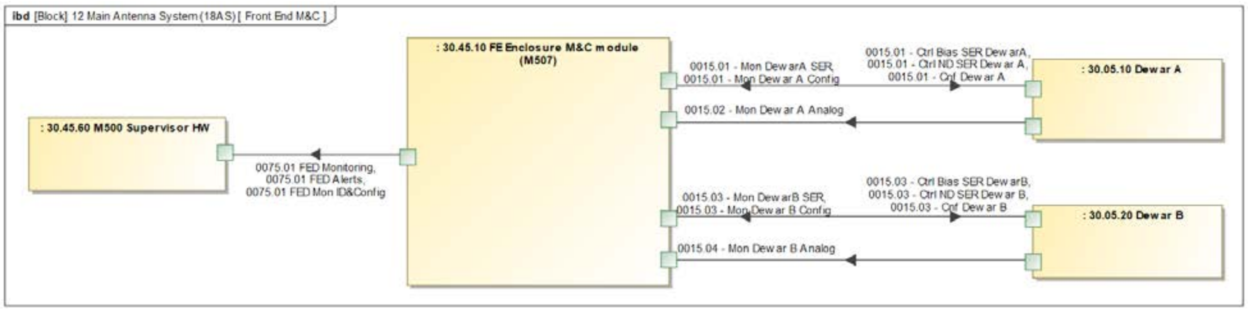

Figure 111: Structural model for Front End M&C

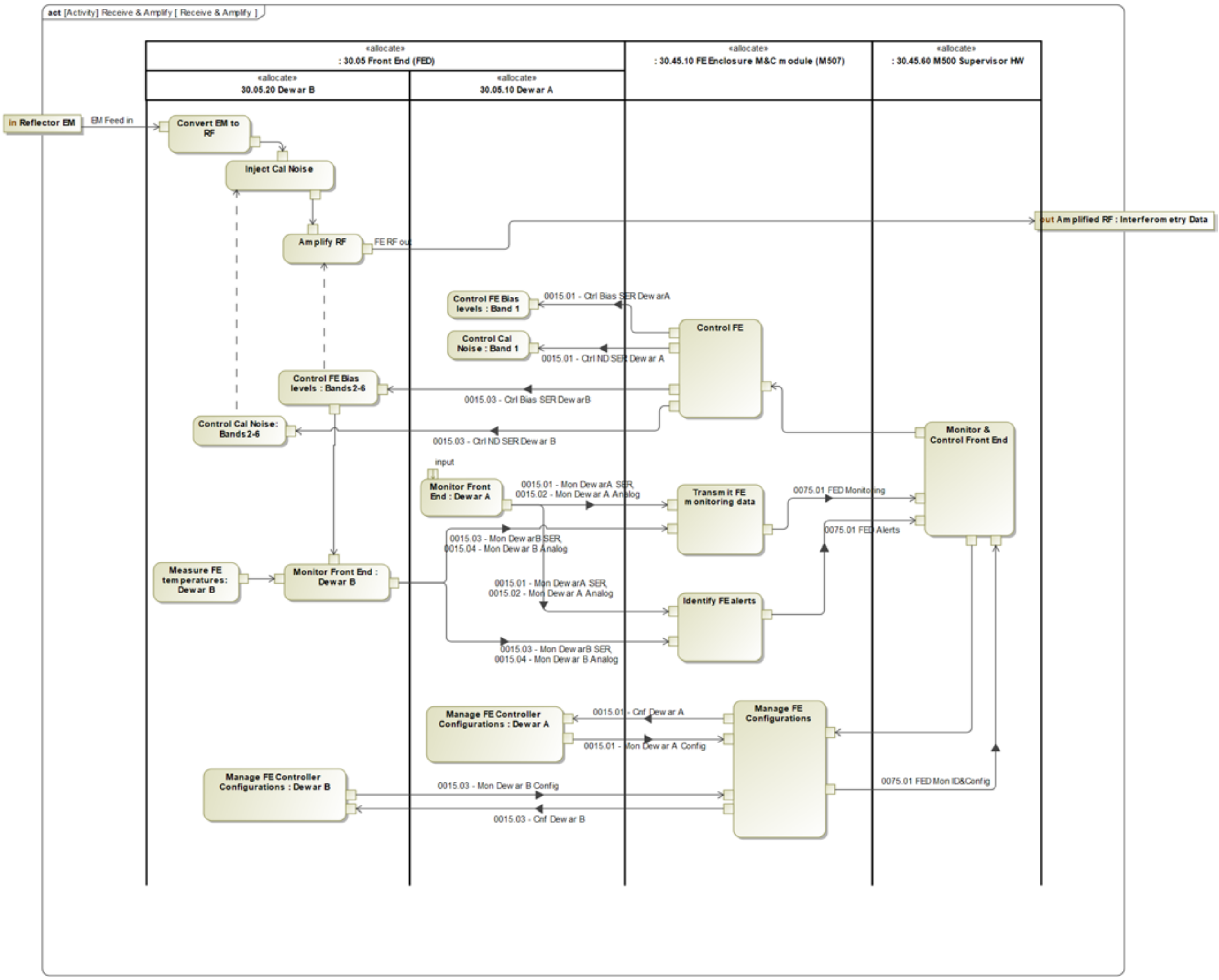

Figure 112: Functional model for Front End M&C

020.10.20.00.00-0002_REP_ngVLA_System_Architecture_Description

Final Audit Report 2024-07-16

Created:	2024-07-16
By:	Pieter Kotzé (pkotze@nrao.edu)
Status:	Signed
Transaction ID:	CBJCHBCAABAAU8j8J4vaht30HepOJDTYZahAH5wZQLq2

"020.10.20.00.00-0002_REP_ngVLA_System_Architecture_Description" History

Document created by Pieter Kotzé (pkotze@nrao.edu)
2024-07-16 - 4:30:40 PM GMT- IP address: 174.56.85.49

Document e-signed by Pieter Kotzé (pkotze@nrao.edu)
Signature Date: 2024-07-16 - 4:32:11 PM GMT - Time Source: server- IP address: 174.56.85.49

Document emailed to Eric Murphy (emurphy@nrao.edu) for signature
2024-07-16 - 4:32:15 PM GMT

Email viewed by Eric Murphy (emurphy@nrao.edu)
2024-07-16 - 4:51:03 PM GMT- IP address: 172.225.214.61

Document e-signed by Eric Murphy (emurphy@nrao.edu)
Signature Date: 2024-07-16 - 6:17:41 PM GMT - Time Source: server- IP address: 50.219.163.3

Document emailed to Rob Selina (rselina@nrao.edu) for signature
2024-07-16 - 6:17:45 PM GMT

Email viewed by Rob Selina (rselina@nrao.edu)
2024-07-16 - 6:58:10 PM GMT- IP address: 66.173.52.81

Document e-signed by Rob Selina (rselina@nrao.edu)
Signature Date: 2024-07-16 - 6:58:22 PM GMT - Time Source: server- IP address: 66.173.52.81

Document emailed to whojnowski@nrao.edu for signature
2024-07-16 - 6:58:26 PM GMT

Email viewed by whojnowski@nrao.edu
2024-07-16 - 9:36:41 PM GMT- IP address: 216.24.212.221

Signer whojnowski@nrao.edu entered name at signing as William Hojnowski

2024-07-16 - 9:37:33 PM GMT- IP address: 216.24.212.231

Document e-signed by William Hojnowski (whojnowski@nrao.edu)

Signature Date: 2024-07-16 - 9:37:35 PM GMT - Time Source: server- IP address: 216.24.212.231

Document emailed to Willem Esterhuyse (westerhu@nrao.edu) for signature

2024-07-16 - 9:37:39 PM GMT

Email viewed by Willem Esterhuyse (westerhu@nrao.edu)

2024-07-16 - 10:51:14 PM GMT- IP address: 73.31.51.29

Document e-signed by Willem Esterhuyse (westerhu@nrao.edu)

Signature Date: 2024-07-16 - 10:51:46 PM GMT - Time Source: server- IP address: 73.31.51.29

Agreement completed.

2024-07-16 - 10:51:46 PM GMT